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Wayne Orchiston
Tsuko Nakamura
Richard Strom *Editors*

Highlighting the History of Astronomy in the Asia-Pacific Region

Proceedings of the ICOA-6 Conference

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Foreword

Since 1993 the International Conferences on Oriental Astronomy have usually been held at 3-yearly intervals in different Asian cities. Prior to ICOA-5 in Chiang Mai, Thailand, there was some discussion about the preferred geographical catchment of the conference and it was decided that it should include Australia and New Zealand, as the most south-easterly outliers of ‘Asia’ and that American scholars from nations bordering the Pacific Ocean would also be welcome. This eventually led to the Centre for Astronomy at James Cook University in Townsville, Northern Australia, hosting ICOA-6 from 7 to 11 July 2008. In order to reflect the expanded geographical focus of ICOA, the chosen theme was “Highlighting the History of Astronomy in the Asia-Pacific Region.”

The hard work involved in organising the logistics of the meeting fell to the Local Organising Committee comprising Leanne Ashmead, Alex Hons, Wayne Orchiston (Chair), Brooke Taylor, Andrew Walsh and Ian Whittingham, while the program was finalised by the Scientific Organising Committee: S.M.R. Ansari (India), John Hearnshaw (New Zealand), Bambang Hidayat (Indonesia), Rajesh Kochhar (India), Liu Ci-Yuan (China), Kim Malville (USA & Australia), Tsuko Nakamura (Co-Chair: Japan), Nha Il-Seong (South Korea), Yukio Ôhashi (Japan), Wayne Orchiston (Australia: Co-Chair), F. Rahimi (Iran), Shi Yunli (China), Irakli Simonia (Georgia), Bruce Slee (Australia), Boonrucksar Soonthornthum (Thailand), Richard Stephenson (UK & Australia), Richard Strom (The Netherlands & Australia), Brian Warner (South Africa & Australia) and Richard Wielebinski (Germany & Australia).

For a variety of reasons there were many last-minute withdrawals, and the final audience at ICOA-6 was disappointingly small, but this did not prevent us from enjoying a vibrant program with oral and poster papers by regular ICOA-attendees plus a number of Ph.D. students from the History of Astronomy program at James Cook University. The final program – adjusted for last minute ‘no shows’ who could not arrange visas in time or whose conference attendance was not approved by their employers – is shown on pages ix–xi.

We also enjoyed an afternoon excursion to Ravenswood, an historic gold-mining town inland from coastally-based Townsville, where the contrast between the mining technology of the late nineteenth century was in stark contrast to the new mining venture there involving a gigantic hole in the ground, where dump trucks wound their way up the terraced sides of the open cast pit like queues of tiny ants, bringing their precious loads of gold-bearing rock to the crusher and processing plant. The scale of this operation was hard to comprehend and only became obvious when the actual size of these enormous dump trucks was realised. Apart from enjoying the interesting historic buildings still present at Ravenswood, on the trip there and back to Townsville most of the overseas delegates caught their first glimpses of wallabies (relatives of the kangaroo) and emus (those flightless birds indigenous to Australia).

After returning to Townsville and resting a little we adjourned to Satay Mas for the Conference Dinner, where the Asian and Australian menu was enjoyed by all. It just happened that this Dinner was held a few days before the 65th birthday of one of the co-editors of this volume (W.O.), and it was a delightful and an unexpected treat when suddenly the restaurant's sound system began playing "Happy Birthday to You …" and a birthday cake suddenly appeared at one of our tables. Unfortunately, the evening did not end on so high a note as this same 'birthday boy' had a major problem with his rapidly deteriorating arthritic hip (which has since been replaced by a bionic version), and he had to be carried out of the restaurant. Fortunately, one of the Indian delegates kindly offered to drive him home, but was not familiar with the car or Townsville roads and ended up being pulled over by the local police! Fortunately, our trusty driver had not been drinking.

From the start we intended publishing the papers from the ICOA-6, and it was a pleasant surprise when Dr Harry Blom from Springer heard about the meeting and made an offer we could not refuse. Many of the papers presented in Townsville were reviewed by peers and are published in this volume, as indicated by those asterisked on pages ix–xi. A few of the non-asterisked papers have been replaced here by substitute papers.

Despite the small and select audience, ICOA-6 was a memorable event, and continued the fine tradition launched by Professor Nha all those years ago. But ICOA-6 also pioneered an expanded program with papers on archaeoastronomy, the emergence of astrophysics and the history of radio astronomy. We felt that these enriched the program, and we hope that they will remain a regular part of future ICOA meetings.

Finally, it is with great sadness that we remember Professor Kwan-Yu Chen who died in 2007, and our condolences go to his wife, Ellen, who also regularly attended the ICOA meetings. Kwan-Yu was a driving force behind the ICOA meetings, and was the lead editor of the Chiang Mai proceedings. He will be sorely missed.

Wayne Orchiston (Co-Chair)
Tsuko Nakamura (Co-Chair)

Participants

Andy Aros (USA)
David Blank (Australia)
Alex Hons (Australia)
Billy McEwen (Australia)
Keo McEwen (Australia)
Colin Montgomery (Australia)
Tsuko Nakamura (Japan)
Ray Norris (Australia)
Yukio Ôhaski (Japan)
Wayne Orchiston (Australia)
John Pearson (USA)
Mitsuru Sôma (Japan)
Ellen Stephenson (UK)
Richard Stephenson (UK and Australia)
Ron Stewart (Australia)
Richard Strom (The Netherlands and Australia)
Kiyotaka Tanikawa (Japan)
Mayank Vahia (India)
Nha Il-Seong (Korea)
Nha Soonhe (Korea)
Andrew Walsh (Australia)
Edward Waluska (USA)
Harry Wendt (Australia)
Susan Wendt (Australia)
Tom Wendt (Australia)
Ian Whittingham (Australia)

Co-authors of Papers Who Were Not Present at the Meeting:

Stella Cottam (USA & JCU Ph.D. student)
Ihsan Hafez (Lebanon & JCU Ph.D. student)

Kim Maville (USA and Australia)
Sarah Nha (Korea)
Bruce Slee (Australia)
Nisha Yadav (India)
Tadato Yamamoto (Japan)
Seiko Yoshida (Japan)

ICOA-6 PROGRAM

Papers published in these Proceedings are followed by an asterisk.

MONDAY 7 JULY 2008

	0900–1045	*Registration and Welcome Reception*
	1045–1100	Nha Il-Seong & Wayne Orchiston: Introduction
Session 1	APPLIED HISTORICAL ASTRONOMY (Chairman: Tsuko Nakamura)	
	1100–1200	F. Richard Stephenson: “Historical Eclipses and the Earth’s Rotation: 700 BC–AD 1600” (Keynote Address)*
	1200–1230	Nha Il-Seong & Sarah L. Nha: “The Possible Interpretation of a Mural in a Sixth Century Koguryo Tumulus as an AD 555 Solar Eclipse Record”*
	1230–1400	*Lunch*
Session 2	APPLIED HISTORICAL ASTRONOMY (Chairman: Richard Strom)	
	1400–1430	Kiyotaka Tanikawa, Tadato Yamamoto & Mitsuru Sôma: “Solar Eclipses at Sunrise and Sunset in the Chunqiu Era”*
	1430–1500	F. Richard Stephenson: “The *Sunjongwon Ilgi* as a Major Source of Korean Astronomical Records”*
	1500–1530	*Afternoon Tea*
Session 3	ETHNOASTRONOMY & ARCHAEOASTRONOMY (Chairman: Mitsuru Sôma)	
	1530–1630	Mayank Vahia & Nisha Yadav: “Archaeoastronomy in an Indian Context” (Keynote Address)*
	1630–1700	Steven Gullberg, J. McKim Malville, & Wayne Orchiston: “The Astronomy of Peruvian *Huacas*”*

TUESDAY 8 JULY 2008

	1000–1030	*Morning Tea*
Session 1	APPLIED HISTORICAL ASTRONOMY, and OTHER RECENT RESEARCH (Chairman: Richard Stephenson)	
	1030–1100	Richard G. Strom: “Statistics of Oriental Astronomical Records: What Can They Tell Us?”*
	1100–1130	Nha Il-Seong & Sarah L. Nha: “An Introduction to Two Star Maps that Predate the 1395 *Cheonsang Yeolcha Bunya-jido*: A Planisphere of King Yi Taijo”*

1130–1200 Yukio Ôhashi: “An Astronomical Problem in a Japanese Traditional Mathematical Text: The 49th Problem in the *Kenki-sanp*ōof Takabe Katahiro”*
1200–1400 *Lunch*

Session 2 THE EMERGENCE OF ASTROPHYSICS (Chairman: Yukio Ôhashi)
1400–1500 Tsuko Nakamura: “The Emergence of Modern Astronomy and Astrophysics in Japan” (Keynote Address)
1500–1530 *Afternoon Tea*

Session 3 THE EMERGENCE OF ASTROPHYSICS (Chairman: Richard Strom)
1530–1630 John Pearson, Wayne Orchiston & J. McKim Malville: “Some Highlights of the Solar Eclipse Expeditions of the Lick Observatory” (Keynote Address)*
1630–1700 Stella Cottam, Wayne Orchiston & F. Richard Stephenson: “The 1874 Transit of Venus, the *New York Times*, and the Popularisation of Astronomy in the USA”*
1730 *ICOA-6 BBQ*

WEDNESDAY 9 JULY 2008

1000–1030 *Morning Tea*

Session 1 ISLAMIC ASTRONOMY (Chairman: Richard Stephenson)
1030–1100 Farhad Rahimi: “Seven Articles in *Sala-al-Sama*, for Determination of the Diameter, Distance and Mass of the Earth and the Seven Planets”
1100–1200 Nha Il-Seong: “History of the ICOA Conferences, and General Discussion about Future ICOA Conferences”
1200–1400 *Lunch*

Session 2 THE HISTORY OF JAPANESE ASTRONOMY & POSTERS (Chairman: Wayne Orchiston)
1400–1430 Mitsuru Soma and Kiyotaka Tanikawa: “Japanese Astronomy in the Seventh Century”*
1430–1440 Tsuko Nakamura and Kiyotaka Tanikawa: “The Book *One Hundred Years of Astronomy in Japan*” (Poster)
1440–1450 Seiko Yoshida and Tsuko Nakamura: “Kiyotsugu Hirayama: Discoverer of Asteroid Families” (Poster)*
1450–1500 General Discussion
1500–1530 *Afternoon Tea*

Session 3 ISLAMIC ASTRONOMY and THE HISTORY OF RADIO ASTRONOMY (Chairman: Wayne Orchiston)
1530–1600 Ihsan Hafez, F. Richard Stephenson & Wayne Orchiston: “Abdul-Rahman al-Sufi and his *Book of the Fixed Stars* – An Overview”*
1600–1700 Edward Waluska: “Quasi-Stellar Objects, The Owens Valley Radio Observatory, and the Changing Nature of the Caltech-Carnegie Nexus” (James Cook University Ph.D. Completion Seminar)

THURSDAY 10 JULY 2008

	1000–1030	*Morning Tea*
Session 1	ETHNOASTRONOMY & ARCHAEOASTRONOMY and THE HISTORY OF RADIO ASTRONOMY (Chairman: Mayank Vahia)	
	1030–1130	Ray P. Norris: "The Astronomy of Indigenous Australians" (Keynote Address)
	1130–1200	Ron Stewart, Harry Wendt, Wayne Orchiston & Bruce Slee: "The World's First Radiospectrograph – Penrith 1949"
	1215	*ICOA-6 Field Trip (to Ravenswood)*
	1800	*ICOA-6 Dinner*

FRIDAY 11 JULY 2008

	1000–1030	*Morning Tea*
Session 1	THE HISTORY OF RADIO ASTRONOMY (Chairman: Tsuko Nakamura)	
	1030–1100	Edward Waluska, Wayne Orchiston, Bruce Slee & Harry Wendt: "Cygnus A in Historical Perspective: Unravelling the Enigma of the first 'Radio Star'"
	1100–1200	Harry Wendt: "The Contribution of the Division of Radiophysics Potts Hill and Murraybank Field Stations to International Radio Astronomy" (James Cook University Ph.D. Completion Seminar)*
	1200–1400	*Lunch*
Session 2	THE HISTORY OF RADIO ASTRONOMY (Chairman: Kiyotaka Tanikawa)	
	1400–1500	Ron Stewart, Harry Wendt, Wayne Orchiston & Bruce Slee: "A Retrospective View of Australian Solar Radio Astronomy – Part 1 (1945–1960)" (Keynote Address)*
	1500–1530	*Afternoon Tea*
Session 3	THE HISTORY OF RADIO ASTRONOMY (Chairman: Nha Il-Seong)	
	1530–1600	Harry Wendt, Wayne Orchiston & Bruce Slee: "From String and Sealing Wax to Serious Science: The First 10 Years of Australian H-line Research (1951–1961)"
	1600–1630	Ron Stewart, Wayne Orchiston & Bruce Slee: "The Sun Sets on a Brilliant Mind: John Paul Wild (1923–2008), Solar Radio Astronomer Extraordinaire"*
	1630–1700	Harry Wendt, Wayne Orchiston & Bruce Slee: "The Contribution of W.N. Christiansen to Radio Astronomy: 1948–1960"*
	1700	Nha Il-Seong & Tsuko Nakamura: Concluding Remarks

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Part III Astronomers, Books, Manuscripts, and Star Charts

Part IV Nineteenth Century Transits of Venus and Solar Eclipses

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Part I
Applied Historical Astronomy

Historical Eclipses and Earth's Rotation: 700 BC–AD 1600

F. Richard Stephenson

Abstract For the whole of the pre-telescopic period, eclipse observations have proved to be by far the best data with which to determine changes in the Earth's rate of rotation. These changes – on the scale of milliseconds – are produced by both the tides and a variety of non-tidal mechanisms. Each individual observation leads to a result for ΔT (the cumulative effect of changes in the Earth's spin rate). Over a period of many centuries, this parameter can attain several hours and thus can be determined using fairly crude observations.

Recently I have extended previous investigations by introducing hitherto unused observations and reinterpreting some of the more reliable existing data: especially in the periods from 700 BC to 50 BC and from AD 300 to 800. This has led to the derivation of revised ΔT values over much of the historical period.

1 Introduction

Historical observations of eclipses have played a major part in the study of changes in the Earth's rate of rotation over the pre-telescopic period. Apart from the geophysical importance of this topic, the results are of considerable significance in historical and chronological studies. In order to compute the circumstances of eclipses (and also occultations of stars and planets by the Moon) in the historical past with accuracy, it is essential to make satisfactory allowance for variations in the Earth's spin rate. This aspect is the main focus of the present paper.

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It is well established that lunar and – to a lesser extent solar – tides are the principal cause of variations in the Earth's rate of rotation, and (correspondingly) changes in the length of the mean solar day (henceforth LOD). Although the tides occur mainly in the terrestrial oceans and seas, there is a small contribution from tides in the solid body of the Earth.

Modern lunar laser ranging results enable the tidal variation of the Earth's spin rate to be estimated with fairly high precision. The reciprocal action of the lunar tides causes a gradual expansion of the Moon's orbit with a consequent (negative) acceleration ($\dot{n}$) of the lunar motion. Recent measurements (e.g. Chapront et al. 2002; Williams and Dickey 2003) yield a result for $\dot{n}$ very close to -26 arcsec/cy^2. Conserving angular momentum in the Earth-Moon system, and allowing for the solar contribution, the tidal rate of increase in the LOD may be deduced as 2.3 ± 0.1 milliseconds per century (ms/cy). In addition, analysis of the acceleration of the node of the orbit of near-Earth artificial satellites (e.g. Cheng et al. 1989) indicates a small but significant non-tidal decrease in the LOD, by roughly 0.5 ms/cy, in opposition to the main tidal trend. This non-tidal term largely arises from a decrease in the moment of inertia of the Earth, due to post-glacial isostatic compensation.

For most of the period since AD 1600, analysis of telescopic timings of lunar occultations of stars proves to be the most effective method of investigating changes in the LOD. Unfortunately, throughout the pre-telescopic period few timings of occultations are preserved. However, numerous reports of both solar and lunar eclipses enable changes in the LOD to be investigated with fair precision as far back as 700 BC. Regrettably, the few eclipse observations which survive from still earlier centuries tend to be of dubious reliability (Stephenson 2008). In general, either the date, place of observation, or even interpretation of the phenomenon as an eclipse, is in doubt for these archaic records. Hence little is known about the history of the Earth's spin prior to 700 BC.

Between 700 BC and AD 1600, several hundred viable observations of eclipses (both timed and untimed) are extant. As might well be expected the temporal distribution of these data – which originate from a variety of sources – is far from uniform. Many observations are preserved from between about 700 BC and 50 BC, and also from about AD 800 to 1600. During both of these periods, changes in the Earth's spin rate can be studied in some detail. However, in the intermediate period of 850 years, the available data are relatively sparse. In particular, there is a severe lacuna between 50 BC and AD 300, during which only two (both untimed) reports of large partial eclipses – in 28 BC and AD 120 – prove of value. Between AD 300 and 800 some 35 useful observations are extant and these give an approximate indication of changes in the Earth's spin rate over this latter period.

Both occultations and eclipses yield results for the cumulative effect of small changes in the LOD. Usually termed ΔT, this parameter is defined as the difference between Terrestrial Time (TT), as determined from the lunar motion, and Universal Time (UT), as measured by the variable rotation of the Earth. Over many centuries, ΔT can attain several hours owing to the huge number of days which have elapsed – almost one million days since 700 BC. As the mean LOD was precisely 86,400.0 s around AD 1820, this epoch is customarily adopted as the zero point from which time intervals are measured. For instance, on the geophysically-reasonable assumption of a constant level of tidal friction over the historical period (Nakiboglu and Lambeck 1991), a tidal lengthening of the day of 2.3 ± 0.1 ms/cy corresponds to a parabolic expression for ΔT of $(42 \pm 2)\ t^2$ s, where t is measured in Julian centuries (each of 36,525 days) from AD 1820. However, as will be discussed below, the eclipse results indicate that although the long-term behaviour of Δ T is mainly determined by the action of the tides, significant, and variable, non-tidal mechanisms also operate. The best fitting parabola to the observational data has the equation $\Delta T = 32t^2$ s, and thus deviates considerably from the tidal parabola.

Useful observations of eclipses in the selected period from 700 BC to AD 1600 fall into two main categories. These are: (1) timed observations of both solar and lunar eclipses; and (2) untimed records of total or near-total solar eclipses. Observations in the former category were exclusively made by astronomers. Their reports – usually in summary form – are to be found in astronomical diaries, treatises on astronomy, etc. The various observations originate mainly from ancient Babylon, ancient and medieval China, ancient Europe and the medieval Arab world. By contrast, untimed reports of large solar eclipses are rarely due to astronomers and are mainly recorded in chronicles and other works of a purely historical nature. The principal sources of observations in this latter category are the town and monastic annals of medieval Europe; these contain numerous descriptions of total and near-total solar eclipses – often in graphic detail. Medieval Arab chronicles provide a few additional observations, while several untimed records by astronomers are preserved in the dynastic histories (*zhengshi*) of China. Only a solitary total eclipse of the Sun (observed by astronomers) is reported in the extant records from Babylon; this dates from 136 BC.

Between about 1980 and 2005, Leslie V. Morrison and I published a series of extensive studies which we had made of Earth's past rotation using a wide variety of historical records of eclipses from 700 BC to AD 1567. Apart from mapping ΔT in some detail throughout this period, we demonstrated that at no time since 700 BC did the value of ΔT deviate from the mean parabola $32t^2$ s by more than about 500 s. The most significant discrepancy occurred between about AD 800 and 1300, when both timed and untimed observations indicated that the spline fit to the data averaged some 500 s below the mean parabola. There is thus clear evidence of variable non-tidal mechanisms – possibly due to global sea-level changes associated with climatic variations.

Recently, I have made revised studies of ΔT over two specific periods: from 700 BC to 50 BC, using only Babylonian observations (Stephenson 2006); and from AD 300 to 800, working mainly with Chinese data (Stephenson 2007). These investigations are discussed in Sects. 2 and 3 below. Further results obtained between AD 800 and 1600, some of which are based directly on my work with Morrison, will be briefly considered in Sect. 4.

Throughout this paper I have expressed dates in terms of BC and AD. It is, of course, customary to use this system for general chronological purposes. However, there was no year zero on this scheme: by definition, AD 1 followed immediately after 1 BC. Hence astronomers have often tended to use negative and positive years instead. However, whereas the year − 1 = 2 BC, and so on, the year + 1 = AD 1, etc. This distinction has not always been understood by authors and confusion has arisen in several printed texts. In particular, Joseph Needham in his series of books on *Science and Civilisation in China* (1954–) consistently equated – with BC. In this paper, I have systematically used the BC and AD system.

2 Babylonian Eclipse Observations: 700–50 BC

The Late Babylonian astronomical texts (henceforth LBAT) are in the form of inscribed clay tablets. Thanks to the painstaking work of scholars, the cuneiform script found in the texts is well understood. Most LBAT were recovered from the ruins of Babylon in the 1870s and 1880s, and these are now largely in the British Museum. The numerous observations which the Babylonian astronomers recorded include a variety of lunar and planetary phenomena – in addition to eclipses of both Moon and Sun. Extensive translations and transliterations of the datable texts have been made by Sachs and Hunger (1988–2006), while Huber and de Meis (2004) have made independent translations and transliterations of the eclipse records. A few further Babylonian measurements are recorded in Ptolemy's *Almagest*.

Without doubt, the most valuable Babylonian observations of a specific eclipse relate to the total solar obscuration of 136 BC. In fact, no other record of a similar event contains more precise details (assertion of totality, timings, and visibility of stars and named planets) until after AD 1700! Figure 1 is a photograph of a Babylonian tablet in the British Museum, dating from 118 BC. This tablet mainly contains a selection of what were then recent lunar and planetary observations. The Babylonian astronomers used these various data in the preparation of an almanac for the year SE 157 (equivalent to 118 BC). Both this tablet, and a second text in the form of an astronomical diary, clearly describe totality 18 years previously – in 136 BC.

Translations of the two Babylonian inscriptions describing the solar eclipse of 136 BC are shown in Figure 2. The observation that the eclipse was total at Babylon sets firm limits on the value of ΔT in 136 BC. Computations reveal that in order for the total phase to have been visible at Babylon – in keeping with the records – ΔT must have been between 11,200 and 12,150 s (i.e. between 3.11 and 3.38 h). If the Earth had rotated at a completely uniform rate throughout the intervening centuries, the shadow would have passed some 50° to the west of Babylon (see Figure 3). The three measured timings (beginning, totality and end) – expressed in US or time degrees – yield results for ΔT of 12,600 s (3.50 h), 12,100 s (3.36 h) and 12,250 s (3.40 h). These results are in remarkably close accord with the limits set by the observation that the eclipse was total at Babylon.

Unfortunately, no other Babylonian observation of a total solar eclipse is extant. Nevertheless, numerous timings of lunar and solar eclipses are preserved on the LBAT. A translation of one of the many lunar eclipse reports is given in Figure 4.

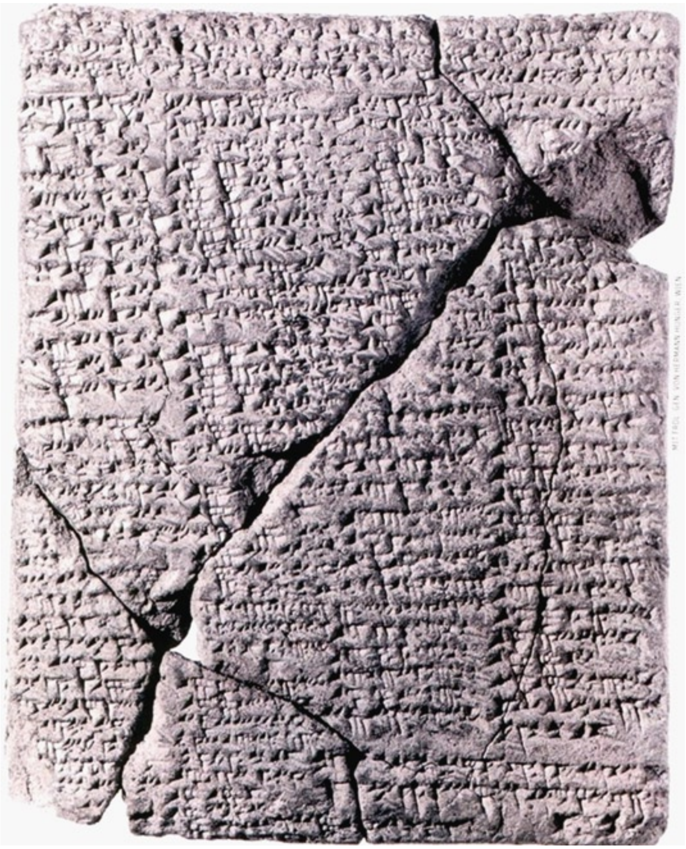
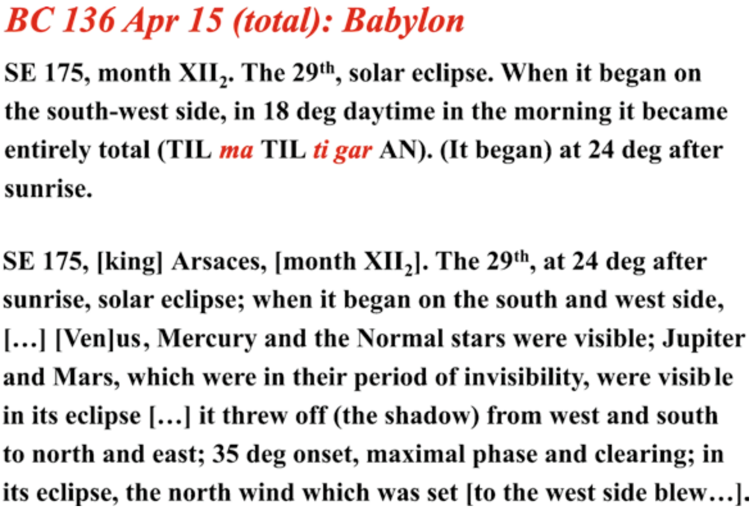


Fig. 1 Babylonian tablet in the British Museum, containing a record of the total solar eclipse of BC 136 April 15 (Photo: courtesy H. Hunger).



BC 136 Apr 15 (total): Babylon

SE 175, month XII$_2$. The 29th, solar eclipse. When it began on the south-west side, in 18 deg daytime in the morning it became entirely total (TIL *ma* TIL *ti gar* AN). (It began) at 24 deg after sunrise.

SE 175, [king] Arsaces, [month XII$_2$]. The 29th, at 24 deg after sunrise, solar eclipse; when it began on the south and west side, […] [Ven]us, Mercury and the Normal stars were visible; Jupiter and Mars, which were in their period of invisibility, were visible in its eclipse […] it threw off (the shadow) from west and south to north and east; 35 deg onset, maximal phase and clearing; in its eclipse, the north wind which was set [to the west side blew…].

Fig. 2 Translations (by H. Hunger) of Babylonian records of the total solar eclipse of 136 BC.

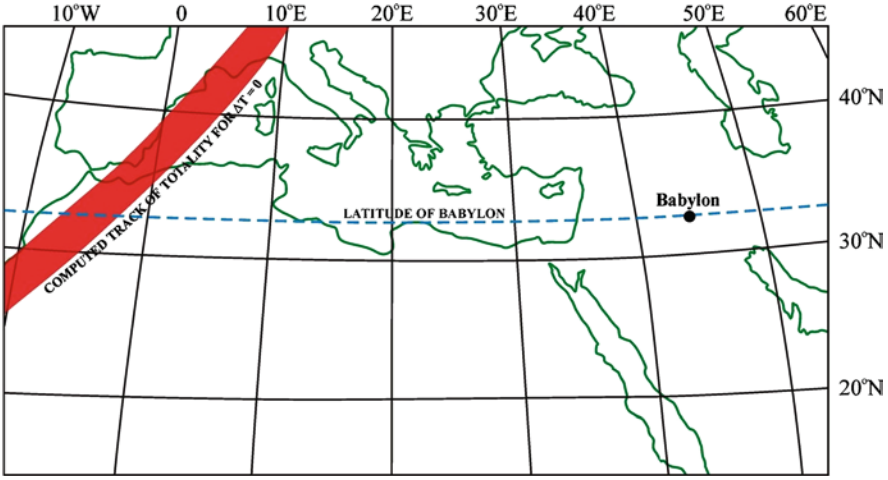
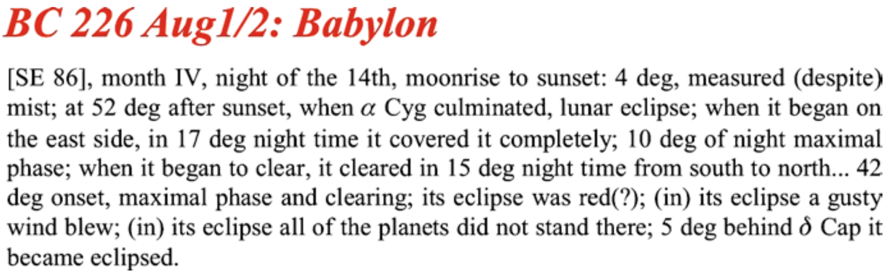


Fig. 3 Map showing the track of totality in 136 BC, computed on the assumption of a constant rate of Earth rotation of the Earth (ΔT = 0).



BC 226 Aug1/2: Babylon

[SE 86], month IV, night of the 14th, moonrise to sunset: 4 deg, measured (despite) mist; at 52 deg after sunset, when *α* Cyg culminated, lunar eclipse; when it began on the east side, in 17 deg night time it covered it completely; 10 deg of night maximal phase; when it began to clear, it cleared in 15 deg night time from south to north... 42 deg onset, maximal phase and clearing; its eclipse was red(?); (in) its eclipse a gusty wind blew; (in) its eclipse all of the planets did not stand there; 5 deg behind *δ* Cap it became eclipsed.

Fig. 4 Translation (by H. Hunger) of the Babylonian record of the total lunar eclipse of BC 226 August 1/2.

This observation of a total lunar eclipse, which dates from 226 BC, is recorded on an astronomical diary. Although the date of this diary is broken away, it may readily be restored by computation using the numerous lunar and planetary observations which the diary contains. In particular, the fact that the eclipsed Moon was said to be "… 5 cubits [approximately 10°] behind δ Cap …" provides confirmation of the derived date.

The total lunar eclipse report from 226 BC lists the following timings: first contact (52° after sunset); beginning of totality (17° after first contact); end of totality (10° after start of totality); last contact (15° after end of totality). The recorded complete duration of the eclipse (42°) is presumably not based on a separate measurement, but is merely the sum of the durations of the three individual phases. Calculations based on the above four measurements yield values for ΔT of respectively 17,550 s (=4.88 h), 17,550 s (=4.88 h), 18,950 s (=5.26 h) and 19,350 s (=5.38 h).

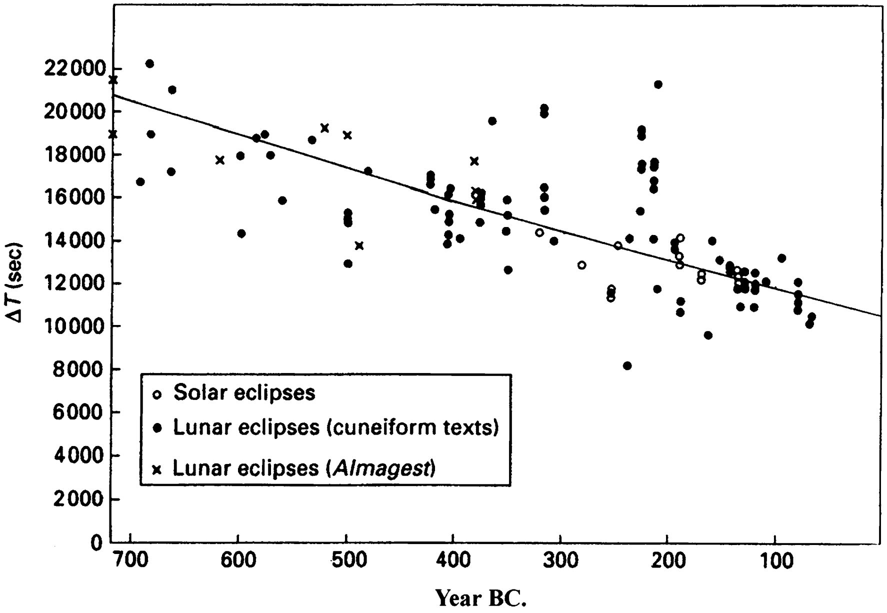


Fig. 5 ΔT as obtained from a variety of timed Babylonian observations (all contacts) of lunar and solar eclipses (after Stephenson 1997).

A graph of the various ΔT results obtained from Babylonian timings of both lunar and solar eclipses – as derived by Stephenson (1997) – is shown in Figure 5. The mean long-term parabola ($\Delta T = 32t^2$) is shown for comparison. From Figure 5 it is evident that, although the typical scatter about the long-term mean is around 1,500 s, several sets of points lie well above the mean. These discrepancies mainly are due to three total lunar eclipses: in 215 BC (four measurements), 226 BC (discussed above: four measurements) and 317 BC (two measurements). Possible explanations of these discrepancies are twofold: (1) the cumulative effect of one or more scribal errors arising from the Babylonian method of expressing time; and (2) the difficulty experienced by the unaided eye in judging the beginning and end of totality – as I personally noted whilst observing the total lunar eclipse of 2007 Mar 3 without optical aid. I shall discuss these aspects separately below.

1. Whereas Chinese astronomers measured the clock times of solar and lunar eclipse phases directly, in Babylon the astronomers systematically measured time *intervals* instead. The time of first contact was expressed relative to sunrise or sunset, while all other times were quoted relative to the immediately previous phase. This system can thus easily lead to systematic errors when the measurements are converted to local times. For instance, as shown in Figure 4, the total lunar eclipse of 226 BC was said to begin 52° after sunset. If, for instance, this first time interval was in error, all the local times of the various phases of the

eclipse will be correspondingly in error. Similarly an error in the duration of the first phase of the eclipse (17°) would lead to systematic errors in the equivalent local times of second, third and fourth contact – and so on. Similar considerations apply to solar eclipse observations.

Of the three anomalous lunar eclipse records cited above (215, 226 and 317 BC), a textual error is clearly apparent in the record from 215 BC. This report gives the time of first contact as 30 *beru* after sunset. As 1 *beru* was equal to 30 US, this would lead to an impossibly long interval of 900 deg (60 h). Babylonian arithmetic was sexagesimal, and Sachs and Hunger (1989) suggested rendering the time-interval after sunset as "... one half (=30/60) *beru* ..." rather than 30 *beru*; this would be equivalent to 15°. However, Huber and de Meis (2004) proposed reading "... 30 deg (=1) *beru* ..." after sunset instead. In a reply to my request for clarification of this issue, Hermann Hunger (personal communication, October 2008) affirmed that the latter interpretation – "... 30 deg (=1) *beru* ..." – is correct. Since I had assumed a reading of "15 deg" in Chap. 6 of my monograph (Stephenson 1997), the four ΔT results which I obtained from the timings measured from sunset for this eclipse should all be diminished by 3,600 s. The amended result for first contact (14,150 s) now confirms the independent value of ΔT (also 14,150 s) which I derived from the culmination of the *ziqpu* star *α* Per.

Some general comments on the timing of lunar eclipses using star culminations are appropriate here. By the late third century BC in Babylon, it became the practice to estimate the time of first contact of a lunar eclipse relative to the culmination of any one of a series of some 30 reference stars (known as *ziqpu* stars), in addition to quoting the sunrise or sunset interval. For example, in 226 BC (the earliest preserved observation) the eclipse was said to begin when "... the bright star of the Breast ..." (= *α* Cyg) culminated. There are also frequent examples when a lunar eclipse was said to begin several degrees before or after a *ziqpu* star culmination. For instance, in 143 BC it is stated that the eclipse began 5° after "... the Hand of the Crook ..." (= β Aur) culminated.

Although there are no textual grounds for questioning the sunset timings of first contact in both 226 and 317 BC, it is noteworthy that the appropriate result deduced for the eclipse of 226 BC is some 2,500 s less than that derived from the culmination of the *ziqpu* star α Cyg.

2. In the extant LBAT, lunar eclipse observations tend to be recorded much more frequently than their solar counterparts, as well as covering a much longer time-span. The durations of the various stages of a lunar eclipse (unlike those of a solar obscuration) are independent of the values of ΔT. It is thus interesting to test the accuracy of measurement by comparing the recorded time-intervals with their computed equivalents. In my recent paper on Babylonian eclipse contacts (Stephenson 2006) I compared the measured durations of totality for 18 lunar eclipses observed in ancient Babylon with the computed values. I noted that although 12 of the reported durations were in tolerable accord with computation (mean error 3°), 6 results were in serious error. These were: a measurement of 14° instead of 23.7° and one of 25° instead of 16.7° for two eclipses in 501

BC; a measurement of 7° instead of 21.6° in 327 BC; 5° instead of 20.9° in 317 BC; 22° instead of 11.0° in 284; and 10° instead of 16.1° in 226 BC. Hence, in this sample alone, as many as one-third of the measurements were decidedly faulty. Evidently, the observers frequently found it difficult to resolve second and third contact for lunar eclipses.

It was mainly for the above two reasons that in my 2006 paper I chose to restrict my attention almost exclusively to Babylonian timings of *first* contact. The only exceptions were four lunar eclipses which ended soon after moonrise in (563, 465, 364 and 67 BC); in each case the interval between moonrise and fourth contact were measured directly. My interest in first contact observations was heightened by the fact that of the many further reports of lunar eclipses which have come to light in recent years, most cite only the time of first contact. It should be emphasised that these additional observations have not been discovered as the result of recent excavations but, instead, due to renewed studies (Sachs and Hunger 2006) on the existing texts (see also Steele 2000).

Figure 6 shows the ΔT values which I obtained in my 2006 paper, except that the sunset timing for the lunar eclipse of 215 BC (previously omitted) is now included. As well as timings expressed relative to sunrise or sunset (together with the four lunar eclipse timings measured relative to *moonrise*), I have included the ΔT limits obtained from the total solar eclipse of 136 BC and the values deduced from 18 measurements relative to the time of culmination of *ziqpu* stars.

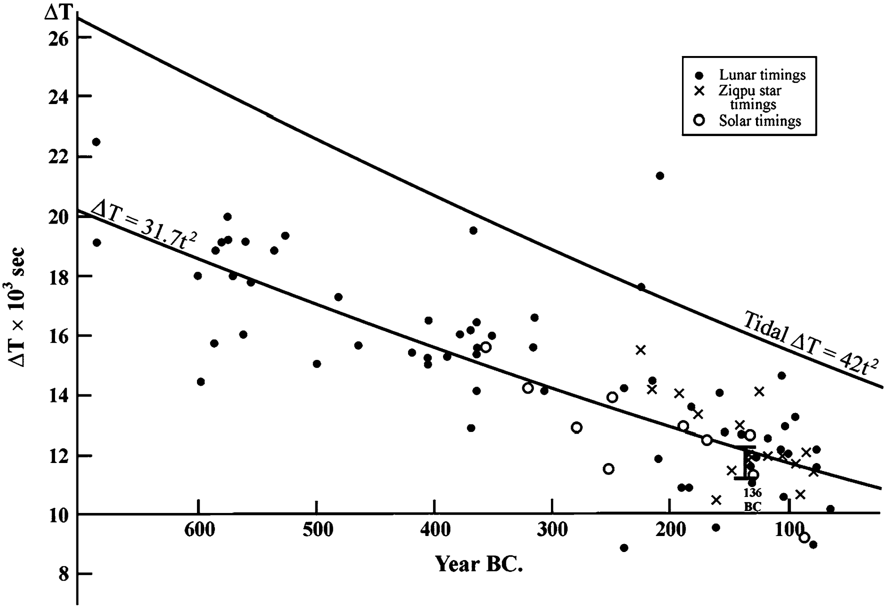


Fig. 6 ΔT values as derived from Babylonian timings (largely first contact) of lunar and solar eclipses.

In Figure 6, it is clear that there are several obviously discordant ΔT values. These discrepant results are all obtained from sunrise or sunset timings of lunar eclipses. Values determined from *ziqpu* star observations and solar eclipse timings prove to be more self-consistent. Remarkably high results for ΔT were derived from lunar eclipses in 367 BC (19,500 s), 226 BC (17,600 s), and 212 BC (21,300 s). Correspondingly low values were calculated from the timings in 599 BC (14,400 s), 239 BC (8,800 s), and 136 BC (4,000 s: not shown in the diagram). Comparison of the last result with the firm limits set by the total solar eclipse of 136 BC (ΔT between 11,200 and 12,250 s) indicates a serious scribal error in the lunar eclipse measurement. As noted above, comparison of the sunset measurement in 226 BC with the corresponding figure obtained from the *ziqpu* star culmination in 226 BC reveals a further significant scribal error. The parabola of best fit (rejecting only the above 6 of the 89 data points) has the equation $\Delta T = 31.7\ (\pm 0.3) t^2$ s. This expression is indistinguishable from the mean long-term parabola: $32t^2$ s.

It should be emphasised that the general form of the scatter in the data points in Figure 6 is not to be understood as providing evidence of short-term changes in the LOD. Casual inspection by eye might suggest a roughly sinsoidal variation in ΔT about the mean parabola with perhaps an amplitude of around 2,000 s and periodicity of a few hundred years. However, this is purely a data artifact, as such a marked oscillation, if real, would require extreme rates of change in the LOD: of the order of 100 times the average over the past 2,700 years.

3 Mainly Chinese Eclipse Observations: AD 300–800

In general, reliable Babylonian eclipse observations cease after about 50 BC. Steele (2000) calculated the date of an observation of a very large eclipse of the Sun recorded in Babylon as 10 BC. However, the brief text, which is badly damaged, was dated by retrospective computation based on the data in the eclipse report itself. This event apart, between 50 BC and AD 300 probably only two observations of eclipses – both untimed solar obscurations recorded in China – are helpful in determining ΔT. The earlier of these events occurred in 28 BC. The *Hanshu* (Chap. 27) states that "The Sun was eclipsed; it was not complete and like a hook …" A further account of the same event in Chap. 97 of the *Hanshu* asserts that "The Sun was eclipsed … A moment later it was almost exhausted; it was not much different from a total eclipse." Computations indicate that for this eclipse to have been not quite total at the capital (Chang'an), only values of ΔT less than 8,090 s or more than 9,530 s are permitted. Intermediate results – which would lead to a fully total eclipse at Chang'an – are prohibited. In AD 120, the *Houhanshu* (Chap. 28) describes a further solar eclipse which was not quite total: "It was almost complete; on the Earth is was like evening." On this occasion, results for ΔT between 8150 and 8,970 s are excluded since they would lead to totality at the capital (Luoyang). For comparison, on these two dates, the values of ΔT corresponding to the mean parabola $32t^2$ s would be respectively 10,930 s and 9,250 s. Both of these figures lie above the respective forbidden zones, but the observations offer little help in defining ΔT.

Compared with the Babylonian eclipses observations during the interval from 700 BC to 50 BC, as just discussed, the data from the selected period between AD 300 and 800 are spasmodic. However, they are still sufficiently numerous to yield useful results for ΔT – as described in Stephenson (2007). The various eclipse observations come into much the same categories as those from Babylon: timings of lunar and solar eclipses and untimed records of total and near-total solar eclipses. Most reports – both timed and untimed – are from China, the principal source being the astronomical treatises of the various dynastic histories. As such, they may be assumed to be based on the observations of the court astronomers. I have also included in my investigation detailed European records of two solar eclipses, occurring in AD 364 and 484. I shall begin by discussing the timings of the phases of both lunar and solar eclipses, after which the observations of large solar eclipses will be considered.

Throughout the period under discussion, Chinese astronomers measured the times of solar eclipses in *shi* (double hours) and *ke* ('marks'). There were 100 marks in a combined day and night, so each unit was equal to 0.24 h. Lunar eclipses times were measured in terms of units which varied with the seasons. The night from dusk (2.5 *ke* after sunset to 2.5 *ke* before sunrise) was divided into five equal *geng* (night watches). In turn, each *geng* was subdivided into five equal units, variously termed either *cheng* (calls), *chou* (rods) or *tian* (points) in different dynasties. In the latitudes of central China (typically around 35° N), each subdivision varied in length from about 0.3 h in summer to 0.5 h in winter. In addition to the Chinese measurements, careful timings of the stages of the partial solar eclipse of AD 364 were made by the astronomer Theon of Alexandria.

Several Chinese reports which allege total solar eclipses, but without giving any qualifying details such as darkness or the visibility of stars, are recorded in Chinese history between AD 300 and 800. However, I have given reasons for believing that such brief records are often of doubtful reliability (Stephenson 1997). Fortunately, observations of two total eclipses – in AD 454 and 761 – are much more specific, both mentioning the appearance of many stars by day. Also of importance are five partial solar eclipses, which were described in unambiguous terms: in each instance "… not complete but like a hook …" A total or almost total eclipse of the Sun observed near sunrise at Athens in AD 484 – "… which was so pronounced as to turn day into night and the darkness was deep enough for the stars to be visible …" completes the set. However, on this occasion totality is not alleged directly; unfortunately, from the viewpoint of Athens, in the early morning the eclipsed Sun would be hidden behind a fairly high mountain.

In my 2007 paper, I investigated the various lunar and solar eclipse timings which are preserved from China and Europe, reinterpreting several of the solar eclipse reports which I had analysed previously and also introducing a number of hitherto unused observations. For each observation I calculated the appropriate ΔT values or limits. However, for the reasons given in Sect. 2(2) above, I have since rejected three results which were based on timings of the beginning of total

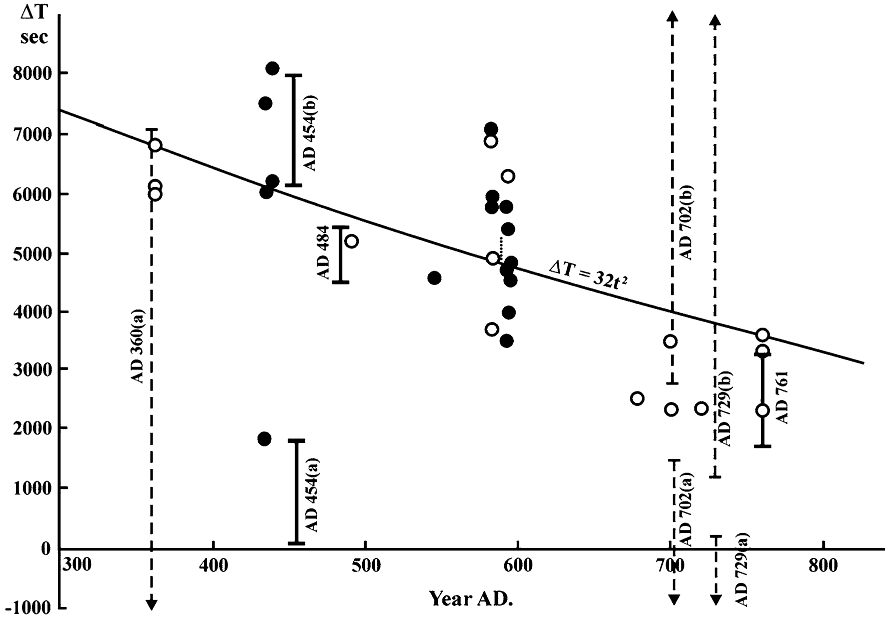


Fig. 7 ΔT values and limits as obtained from lunar and solar eclipses observed mainly in China between AD 300 and 800.

lunar eclipses. The individual ΔT values are plotted in Figure 7, together with the long-term mean parabola $32t^2$.

With regard to the timed measurements, there prove to be two sets of obviously discordant values – derived from timings of the start of a lunar eclipse in AD 434 (ΔT = 1,700 s) and of the start, middle and end of a solar eclipse in AD 585 (offscale mean ΔT = 10,300 s). These large discrepancies presumably arise from scribal errors. However, the remaining 30 or so measurements are fairly self-consistent. In particular, the cluster of 14 timings around AD 590 (excluding the three anomalous solar observations in AD 585), lead to a useful result for ΔT of 5,200 ± 200 s at this epoch.

The observations of total and large partial solar eclipses shown in Figure 7 fall into two distinct groups: those between AD 360 and 484 and those from AD 702 to 761. In principle, each total eclipse observation fixes ΔT between two firm limits: e.g. from 1,700 to 3,250 s in AD 761. On the other hand, partial eclipse reports exclude values of ΔT between two discrete limits: intermediate figures corresponding to a fully total (or central annular) eclipse instead. Thus, for example in AD 702 the eclipse was described as "… not complete and like a hook …" Hence any value of ΔT between 1,450 and 2,750 s is excluded at this date since it would lead to a total eclipse at the Chinese capital (Chang'an) of the time. Similar remarks apply in AD 360 and 729. (N.B. In AD 360, the upper limit of 9,400 s is not shown in Figure 7; it lies above the region covered by the diagram).

The situation in AD 454 is somewhat complex. As implied by the text in the *Songshi*, this eclipse was manifestly total at the Chinese capital of the time (Jiankang), where it was reported that "… the constellations were brightly lit." However, because of the configuration of the eclipse track, two quite separate ranges of ΔT would yield a total eclipse at Jiankang: either from 50 to 1,800 s (labelled 454a) or between 6,150 and 7,900 s (labelled 454b). Fortunately, the almost contemporary report from Athens of an extremely large eclipse in AD 484 enables a reliable selection to be made between these two sets of limits. Assuming a magnitude of at least 0.99 in AD 484, the indicated value for ΔT at this date lies between about 4,150 and 5,450 s. The observation thus closely supports the option 454b.

Taking into consideration the results obtained from the bulk of the timed data, and – in particular – the firm limits set by totality in AD 761, it is evident from Figure 7 that the alternatives AD 702a and 729a (especially the latter, which would require a major increase in ΔT in just 32 years) should be rejected. Additionally, the option AD 360b lies so far above the mean parabola $32t^2$ (by at least 2,500 s) that it must scarcely be regarded as a viable choice.

Figure 8 is an edited version of Figure 7 in which the redundant limits AD 360b, 454a, 702a, and 729a have been removed in order to simplify the diagram. In this figure, deviations from the mean long-term parabola of at least 200 s in AD 454 and 300 s in AD 761 (as indicated by the total solar eclipses in these 2 years) are implied. In particular, the decline in ΔT relative to the mean parabola around the latter date corresponds well with the gradual decrease in this same parameter over

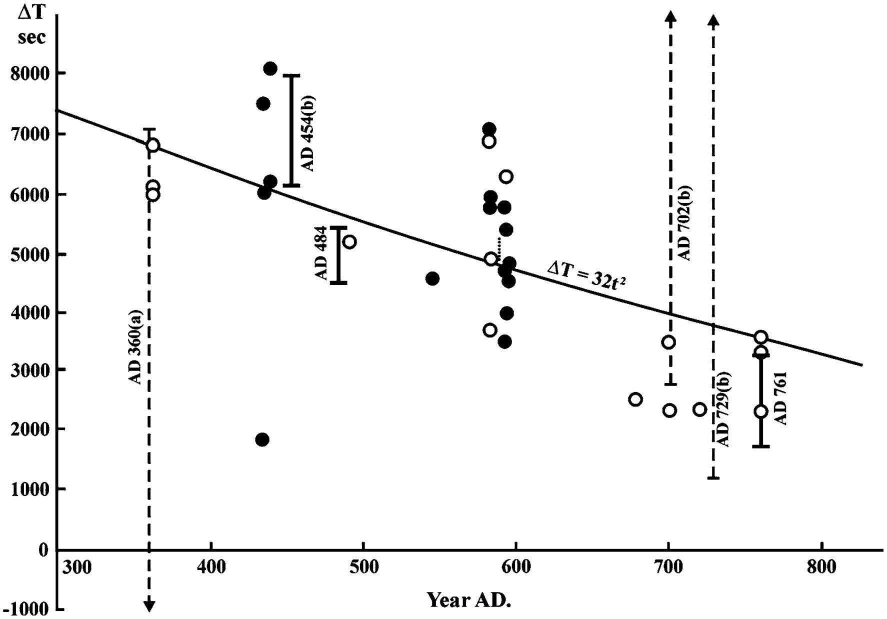


Fig. 8 An edited version of Figure 7 with redundant limits removed.

the succeeding few centuries – see Sect. 4 below. In summary, although the data between AD 300 and 800 are rather sparse, they provide evidence of minor but still significant variations in ΔT about the mean parabola throughout this interval.

4 Eclipse Observations from AD 800 to 1600

The various observations – Arab, Chinese and European – between AD 800 and 1600 were investigated in detail by Stephenson and Morrison (1995) and each individual observation was separately discussed in the monograph by Stephenson (1997). Since then, virtually no further observations have come to light.

Between about AD 800 and 1020 Arab astronomers, working mainly at Baghdad or Cairo, made frequent determinations of eclipse times. These observers preferred to deduce times indirectly – by measuring the altitude of the Sun during a solar eclipse, or of the Moon or a selected bright star during a lunar eclipse. Altitudes were mainly quoted to the nearest degree. At the latitudes of Baghdad and Cairo (close to 30°) the altitude of a celestial body (except when near the meridian) typically changes by 1° in about 0.1 h. Although few Chinese eclipse timings are preserved between AD 800 and 1000, over the succeeding three centuries numerous timings are recorded in the official histories of China. At this period the astronomers measured the times of both solar and lunar eclipses to the nearest *ke* (0.24 h). Interpretation of *most* of the individual records (Arab or Chinese) between about AD 800 and 1100 presents few problems. I have slightly edited the existing set of timed data (e.g. rejecting timings of the beginning and end of the total phase for a lunar eclipse).

The Arab timings of both solar and lunar eclipses mainly fall into two discrete groups with mean epochs close to AD 900 and 1000. Rejecting only the very few timings of the total phase for lunar eclipses (as discussed above), the Arab timings lead to results for ΔT of 2,020 ± 130 s at AD 900 and 1,520 ± 100 s at AD 1000. Chinese timings of solar and lunar eclipses also fall into two main groups, with mean epochs around AD 1100 and 1250. Data in the former set yield a result for ΔT of 1,070 ± 110 s at AD 1,100. However, due probably to a number of major scribal errors the scatter in the data in the later set (mean epoch AD 1250) is very large and a ΔT result based on the timed data alone would be suspect (Stephenson 1997).

Between AD 1300 and 1600 there are few useful eclipse timings from any part of the world. Over this interval, ΔT probably declined from around 500 to 150 s; in general the precision of measurement – whether in China or Europe – was inadequate to enable this parameter to be satisfactorily determined.

Fortunately, many untimed observations of total and very large partial solar eclipses are carefully described in chronicles and other works between about AD 800 and 1600. These mainly originate from Europe, although there are also a few Arab and Chinese observations. Especially after AD 1100, these provide a valuable alternative to the timed data, critical observations sometimes defining the value of

ΔT within narrow limits. Examples are as follows: ΔT value between 960 and 1,150 s at mean epoch AD 1129; between 630 and 820 s at mean epoch AD 1254; and between 145 and 165 s at AD 1567.

5 Results

Based on extensive researches, Morrison and Stephenson (2004; 2005) published in tabular form a series of ΔT values extending back to the epoch 1000 BC. The results between 700 BC and AD 1600 were mainly derived from eclipse observations – both timed and untimed – using spline fitting. Prior to 700, extrapolation using a parabolic trend was used. In Table 1 the results obtained by Morrison and Stephenson (ibid.) from 1000 BC to AD 1600 (at century intervals) are compared with the values obtained from the expression $32t^2$ s.

Table 1 ΔT values in s at century intervals derived from the parabola $32t^2$, compared with the results of Morrison and Stephenson (2004, 2005)

Year	$32t^2$	Morrison & Stephenson
BC 700	20,320	21,000
600	18,740	19,040
500	17,220	17,190
400	15,770	15,530
300	14,380	14,080
200	13,060	12,790
100	11,800	11,640
0	10,600	10,580
AD 100	9,470	9,600
200	8,400	8,640
300	7,390	7,680
400	6,450	6,700
500	5,580	5,710
600	4,760	4,740
700	4,010	3,810
800	3,330	2,960
900	2,710	2,200
1000	2,150	1,570
1100	1,660	1,090
1200	1,230	740
1300	870	490
1400	560	320
1500	330	200
1600	160	120

Table 2 Revised ΔT values in s at century intervals as derived in the present paper

Year	Revised
BC 700	20,150
600	18,550
500	17,050
400	15,600
300	14,250
200	12,950
100	11,700
0	10,500
AD 100	9,550
200	8,600
300	7,650
400	6,700
500	5,750
600	4,800
700	3,850
800	2,900
900	2,000
1000	1,500
1100	1,070
1200	740
1300	490
1400	320
1500	200
1600	130

In Table 2, which covers the period from 700 BC to AD 1600, I have slightly revised the ΔT values obtained by Morrison and Stephenson over three separate intervals: from the years 700 BC to AD 100 (as derived from the Babylonian data discussed in Sect. 2), from AD 200 to 800 (using largely Chinese data, as discussed in Sect. 3), and finally between AD 900 and 1100 (using Arab and Chinese timings). However, from AD 1200 to 1600, I have made no alterations to the results obtained by Morrison and Stephenson.

All ΔT results between 700 BC and AD 1100 in Table 2 are rounded to the nearest 50 s; attempting higher precision seems pointless. Later figures are quoted to the nearest 10 s. Over the interval from 700 BC to the epoch 0, I have used a slightly revised expression $\Delta T = 31.7\ t^2$ s to calculate values of ΔT at century intervals. This parabola is a very good fit to the Babylonian first contact timings. Between AD 300 and 800, during which observations are relatively scarce and widely spaced, I have felt it best to use a simple linear fit to the largely Chinese data, applying the tight constraints imposed by the partial solar eclipse of AD 360 and the total solar eclipses of AD 454 and 761. This straight line also agrees well with the result of 5,200 ± 200 s at AD 590, as deduced from Chinese lunar and solar timings near this date. Approximate figures for ΔT at the epochs AD 100 and 200 have been estimated by extrapolation on each curve; there are no significant discontinuities.

ΔT figures at AD 900 (2,000 s) and 1,000 (1,500 s) are obtained directly from the two sets of Arab timings, and at AD 1100 (1,050 s) from the Chinese timings around this epoch. Results from AD 1200 to 1600 are taken direct from Morrison and Stephenson (2004). Comparing the figures in Tables 1 and 2, it will be evident that the main discrepancies between the results of Morrison and Stephenson (2004; 2005) and those obtained in the present paper are to be found before 100 BC. In this early period, selection of the Babylonian timings of first contact results in a significant improvement on the use of a more general set of data.

6 Conclusion

Over the entire interval from 700 BC to AD 1600 the best-fitting simple curve is the parabola $\Delta T = 32t^2$ s. At all times, this lies considerably below the tidal parabola. Presumably much of this discrepancy is due to the effect of postglacial isostatic compensation. However, the eclipse data reveal marked variations from simple parabolic behaviour, especially from AD 800 to 1300. Clearly, substantial non-tidal variations have occurred in the Earth's spin rate. Although these changes may in part be caused by changes in global sea-level associated with climatic variations there could well be other significant mechanisms at work.

It is hoped that revised ΔT table (Table 2) will prove of use to historians of astronomy. Although I have not extended the table beyond 700 BC because of the lack of suitable data at earlier epochs, use of the long-term parabola $\Delta T = 32t^2$ s should prove helpful back to around 1000 or even 1200 BC. However, there is a danger that at more remote epochs, attempts at extrapolation may be misleading.

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Solar Eclipses at Sunrise or Sunset in the Chunqiu Period

Kiyotaka Tanikawa, Tadato Yamamoto, and Mituru Sôma

Abstract In the Chinese chronicle ‘Chunqiu’ (‘The Spring and Autumn Annals’) which describes the history of the Chunqiu Period (771 BC–403 BC), there are 37 solar eclipse observations recorded, starting in 720 BC and ending in 481 BC. Among these, there are ten records which lack either the day of the 60-day cycle or the statement that the eclipse occurred at a ‘new Moon’ (shuo 朔) or both. A Japanese astronomer, Toshio Watanabe, conjectured that these eclipses may have been observed at sunrise or sunset. In the present paper, we intend to confirm Watanabe’s conjecture, and after confirming it, we use these eclipses to accurately determine the range of ΔT in this period. Our results from five solar eclipses which were accompanied by near-contemporaneous eclipses are:

$20{,}153 < \Delta T < 21{,}094$ at around February 2, 720 BC,
$18{,}526 < \Delta T < 20{,}686$ at around April 15, 676 BC,
$19{,}409 < \Delta T < 20{,}402$ at around April 6, 648 BC, if the site is Paros
$18{,}353 < \Delta T < 19{,}235$ at around April 6, 648 BC, if the site is Thasos
$19{,}172 < \Delta T < 20{,}910$ at around March 6, 598 BC,
$16{,}134 < \Delta T < 19{,}101$ at around May 31, 558 BC.

Finally, we discuss the meaning of the lack of information. Our tentative conclusion is that most (seven out of nine) eclipses without the statement of the first day of the month took place at sunrise or sunset.

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1 Introduction

Knowledge of variations of the Earth's rotational velocity in the pre-telescopic past is important not only for astronomy and geophysics but also for history. It is well known that ancient solar and lunar eclipses are essential for determining the Earth's rotation period. Conversely, we have basically two unknown parameters by which the place and time of eclipses are determined. These are ΔT and the lunar tidal acceleration (LTA) along its orbit.

Let us first introduce ΔT. Homogeneously-flowing time is denoted by TT, the abbreviation for Terrestrial Time. The time measured by the rotation of the Earth is denoted by UT (Universal Time). Then, we denote the difference of these two as

$$\Delta T = TT - UT. \tag{1}$$

ΔT represents the delay of the Earth's clock compared to a correct clock.

We know that ΔT was roughly 3 h 2,000 years ago. The Moon is receding from the Earth by 3.8 cm/year at present (Chapront et al. 2002). This corresponds to a LTA of $-25.83''/\mathrm{cy}^2$ where the minus sign means that the Moon actually decelerates due to the tidal interaction with the Earth. In the past, the decrease rate might have been different. We expect that our research may more accurately determine the values of these two parameters. The results can also be used for the study of ancient history.

The number of historical astronomical records before the fifth century BC is extremely small. So the eclipse records of the Chunqiu (the original manuscript and its copies have been lost) are very valuable. Stephenson (1997) expressed the long-term variations of ΔT by a fitted spline curve assuming the present value of the LTA. There, the dispersion of the data around the spline curve is so large that we suspect that the spline fitting may conceal large amplitude variations of shorter periods.

Now, we turn our attention to the eclipses in the Chunqiu Period. The study of the eclipses in the 'Chunqiu' (The Spring and Autumn Annals) has a long history. The first study already appeared in the Zhanguo Period (Warring States Period: BC 403–221). Three explanatory books, the *Zuoshi-zhuan* (左氏伝, 1981), *Guliang-zhuan* (穀梁伝, 1993) and *Gongyang-zhuan* (公羊伝, 1993), edited in the Zhanguo Period or in the early Han Dynasty, have different interpretations concerning eclipse records which fail to mention either the day of the 60-day cycle ('ganzhi') or the first day of the month ('shuo' 朔), or both. The *Zuoshi-zhuan* simply says that Royal Astronomers forgot to record these data. The *Guliang-zhuan* says that these eclipses were observed on the last day of the month or in the evening. The *Gongyang-zhuan* says that they were mainly observed on the second day of the month. A famous astronomer of the Han Dynasty, Liuxin, argued along the same lines as the *Gongyang-zhuan*. These discussions are related to the problem of establishing the precise calendar system in the Chunqiu Period. The controversy continues to this day.

In more recent times, Shinzo Shinjo (1928) published the *Long Calendar of Chunqiu*, in which he lists many earlier Chinese authors who studied the Chunqiu calendar. Shinjo reconstructed the calendar of the Chunqiu Period based on the periodicity of ganzhi of eclipse records with the aid of dates (which he determined) of 33 reliable solar eclipse records. On the basis of astronomical calculations, Watanabe (1984) found sunrise and sunset eclipses and mentioned them in his *Canon of the Solar and Lunar Eclipses*. However, the theory used in his calculation was from the 1920s, so his conclusions may contain systematic errors.

In order to better determine the value of ΔT, total eclipses observed from known sites are the most useful. However, records of this type are rare. Instead, we are particularly interested in eclipse records which lack either ganzhi or mention of the first day of the month, or both, among 37 solar eclipses recorded during the Chunqiu Period. These are our ‘target eclipses’, and they are listed in Table 1. From the beginning (during the Han Dynasty), they were suspected to have occurred at sunrise or sunset (Hanshu 1962).

The purpose of the present paper is to actually show that these were eclipses at sunrise or sunset, and by way of this to obtain limits to the range of ΔT. We also discuss the reasons for the lack of descriptions of some of these eclipses.

The values of ΔT obtained from the same eclipse or contemporaneous eclipses should be identical or nearly identical. Fortunately, in some cases, there are records of total eclipses observed close to the years of the target eclipses. We will show that by considering multiple eclipses at one time we can obtain a narrower range of ΔT. We will also point out the utility of non-total eclipses.

2 Target Eclipses and Auxiliary Eclipses

2.1 Previous Studies

In Chinese history, eclipse records were fundamental for determining future calendars. In particular, solar eclipses should take place on the first day of the month. Astronomers Royal had a duty to record the serial number of the day in the month, in addition to the day in the 60-day cycle, which is called the ganzhi cycle. The latter tradition goes back to much earlier times. Some Chunqiu eclipse records lack the serial day number in the month or the day in the ganzhi cycle, or both. These facts were already the subject of discussion in the following books edited during the Zhanguo Period: *Zuoshi-zhuan*, *Gongyang-zhuan*, and *Guliang-zhuan*. In fact, Wuxing-chi (Volume 7) says as follows:

> (01) Duke Yin, 3rd year, 2nd month, day jisi [6], the sun was eclipsed.
>
> The Guliang-zhuan says that here the ganzhi day is recorded but ‘shuo’ (the first day of the month) is not mentioned, so the eclipse took place on the last day of the month. The Gongyang-zhuan says that the eclipse was on the second day of the month.
>
> The Shiji generally considered that when a (solar) eclipse took place, in some cases, ‘shuo’ is written but the day is not ‘shuo’, in other cases, ‘shuo’ is not written but the day is ‘shuo’, in yet other cases, both ‘shuo’ and ganzhi were not written; all these mean that the astronomers lost the data.
>
> (03) Duke Huan, 17th year, 10th month, 1st day, the sun was eclipsed.

Table 1 List of solar eclipses that occurred during the Chunqiu period[a]

		Julian date			Chunqiu period									
No	Oppol. no.	Year	Month	Day	Duke	Year	Month	Day	Shuo?	*Z-z*	*Go-z*	*Gu-z*	Liuxin	Watanabe
01	1,147	–719	02	22	Yin	03	02	Jisi[6]	–	Lost	2nd	Last	2nd	Sunrise
02	1,176	–708	07	17	Huang	03	07	Renchen[29]	Shuo.T					Total
03	1,211	–694	10	10		17	10	–	Shuo	Lost		2nd		
04	1,257	–675	04	15	Zhuang	18	03	–	–	Lost	Last	Last	Last	
05	1,275	–668	05	27		25	06	Xinwei[8]	Shuo				2nd	
06	1,278	–667	11	10		26	12	Guihai[60]	Shuo				2nd	
07	1,288	–663	08	28		30	09	Gengwu[7]	Shuo					
08	1,311	–654	08	19	Xi	05	09	Wushen[45]	Shuo					
09	1,328	–647	04	06		12	03	Gengwu[7]	–	Lost	2nd	Last		Sunset
10	–	–644				15	05	–	–	Lost	Last	Night	Shuo	Non-eclipse
11	1,383	–625	02	03	Wen	01	02	Guihai[60]	–	Lost	2nd	Last	Shuo	
12	1,419	–611	04	28		15	06	Xinchou[38]	Shuo				2nd	
13	1,449	–600	09	20	Xuan	08	07	Jiazi[1]	–.T	Lost	2nd	Last	2nd	
14	1,452	–598	03	06		10	04	Bingchen[53]	–	Lost	2nd	Last		Sunrise
15	–					17	06	Guimao[40]	–	Lost	2nd	Last	last	Non-eclipse
16	1,516	–574	05	09	Cheng		06	Bingyin[3]	Shuo				2nd	
17	1,519	–573	10	22		17	12	Dingsi[54]	Shuo					
18	1,555	–558	01	14	Xiang	14	02	Yiwei[32]	Shuo				2nd	
19	1,559	–557	05	31		15	08	Dingsi[54]	–	Lost	2nd	Last	2nd	Sunrise
20	1,572	–552	08	31		20	10	Bingchen[53]	Shuo					
21	1,574	–551	08	20		21	09	Gengxu[47]	Shuo					
22	–					21	10	Gengchen[17]	Shuo					Error
23	1,579	–549	01	05		23	02	Guiyou[10]	Shuo				2nd	
24	1,582	–548	06	19		24	07	Jiazi[1]	Shuo.T					Total
25	–					24	08	Guisi[30]	Shuo					Error
26	1,590	–545	10	13		27	12	Yihai[12]	Shuo					

27	1,616	–534	03	18	Zhao	07	04	Jiachen[41]	Shuo	
28	1,636	–526	04	18		15	06	Dingsi[54]	Shuo	
29	1,642	–524	08	21		17	06	Jiaxu[11]	Shuo	2nd
30	1,652	–520	06	10		21	07	Renwu[19]	Shuo	2nd
31	1,655	–519	11	23		22	12	Guiyou[10]	Shuo	
32	1,659	–517	04	09		24	05	Yiwei[32]	Shuo	2nd
33	1,678	–510	11	14		31	12	Xinhai[48]	Shuo	2nd
34	1,690	–504	02	16	Ding	05	03	Xinhai[48]	Shuo	2nd
35	1,709	–497	09	22		12	11	Bingyin[3]	Shuo	2nd
36	1,717	–494	07	22		15	08	Gengchen[17]	Shuo	
37	1,751	–480	04	19		14	05	Gengshen[57]	Shuo	2nd

[a] The first column is the serial number; the second shows the Oppolzer number; the third is the Julian year, month, and day; the fourth is the Chinese Duke, year, month and day of the Chunqiu Period; the fifth lists when shou is mentioned, and T = total; the sixth, seventh and eighth columns represent the understanding of the target eclipses according to the *Zuoshi-zhuan*, *Gongyang-Zhuan*, and *Guliang-zhuan*; the ninth column shows the interpretation according to Liuxin; and the tenth column shows Watanabe's interpretation

> The Guliang-zhuan says that the record talks of 'shuo', but it does not mention the ganzhi day, hence the eclipse took place on the second day of the month.
>
> (04) Duke Yan, 18th year, 3rd month. The sun was eclipsed.
>
> The Guliang-zhuan says that the record does not give the ganzhi day, and does not give 'shuo', hence it took place in the evening. The present historian (historian of the Hanshu) guesses that the conjunction of the Sun and Moon was on the night of the first day of the month, and the next morning, the Sun rose being eclipsed by the Moon, and after sunrise, the eclipse was over. The Gongyang-zhuan says that the eclipse was on the last day of the month. (Hanshu 1962: Volume 27).

In the above, (01), (03) and (04) denote the serial number of data in Table 1. Duke Yan in (04) is also called Duke Zhuang.

Now at this point we summarize what three Zhuans thought of the target eclipses. From (01), if the ganzhi day is mentioned and shuo is lacking, the eclipse was taken to be one which occurred on the last day of the month in the *Guliang-zhuan*, whereas in the *Gongyang-zhuan* it was taken to be on the second day of the month.

From (03), if shuo is mentioned and the ganzhi day is not, the eclipse was taken to be one which occurred on the second day of the month in the *Guliang-zhuan*. From (04), it was taken to be on the last day of the month in the *Gongyang-zhuan*.

In the case of the *Guliang-zhuan*, an eclipse with neither shuo nor the cyclic day number mentioned was considered to be a night eclipse. In the *Guliang-zhuan*, it was taken to be an eclipse on the last day of the month. These interpretations are listed in the seventh and eighth columns of Table 1.

In the case of the *Zuoshi-zhuan*, there is a comment only on the data of (01). The *zhuan* says that data with shuo but without a ganzhi day result from the fact that Royal Astronomers forgot to record them.

The Hanshu (1962) summarizes Chunqiu eclipses as follows:

> There were 12 Dukes in the Chunqiu Period, and the Period continued for 242 years, during which there were 36 solar eclipses. The *Guliang-zhuan* calculates that there were 26 eclipses on the first day of the month, 7 eclipses on the last day, 2 were night-time eclipses and one was on the second day. The *Gongyang-zhuan* calculates that there were 27 eclipses on the first day of the month, 7 eclipses on the second day, and 2 were on the last day. The *Zuoshi-zhuan* calculates that there were 16 eclipses on the first day of the month, 18 eclipses on the second day, one was on the last day, and 2 were without cyclic day number. [Our English translation is from the Japanese translation by Kotake (1997).]

It seems that the number of eclipses on the first day in the *Zuoshi-zhuan* is too small. The problem posed by the above summary is related to the calendar system of the Chunqiu Period. The *Gongyang-zhuan* and *Guliang-zhuan* followed a definite rule for second-day eclipses, last-day eclipses, and night-time eclipses. Our purpose is to obtain a clear-cut conclusion on the astronomical logic behind this rule (Figure 1).

Churyo Noda and Kiyoshi Yabuuti (1947) introduced the public to the calculation of Liuxin in the Hanshu, and we list it in the eighth column in Table 1. Toshio Watanabe (1958) calculated the time of the day of the Chunqiu eclipses based upon the theory of Schoch (1927). From this calculation, he concluded that eclipses (01), (14), and (19) were at sunrise, while eclipse (09) was at sunset. Eclipse (04) was

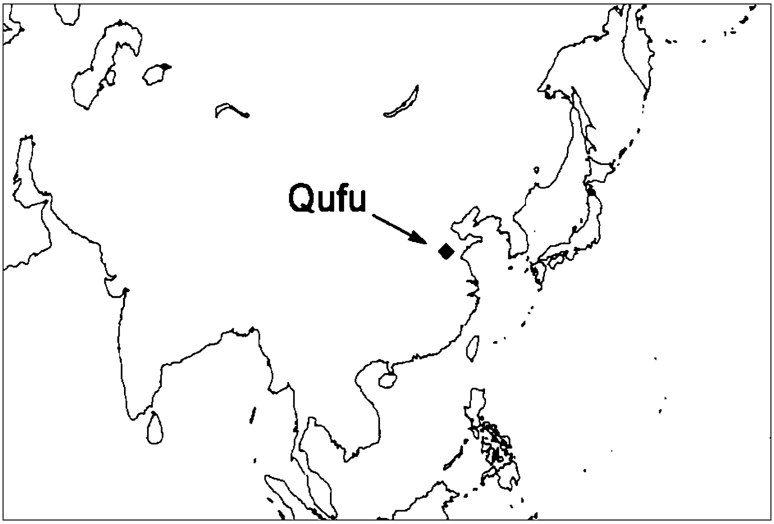

Fig. 1 The position of Qufu.

almost at sunset according to the same calculation. However, Watanabe does not say anything about this eclipse. Later, Kuniji Saito and Kenji Ozawa (1992) added eclipse (04) to the list of eclipses at sunset. In addition, they added eclipse (22) to the same list by changing the date from Duke Xiang, 21st year, 10th month, day gengchen [17], shuo to Duke Xiang, 26th year, 10th month, day gengchen [17], the last day of the month. Stephenson and Yau (1992) introduced the Chunqiu to an English-speaking audience. They compared the ΔT of the Chunqiu eclipses with the parabolic curve of long-term variations in ΔT obtained from Babylonian-timed lunar eclipses, and confirmed the results of the previous authors as to the reliability of eclipse records.

In this present paper, we treat eclipses (01), (04), (09), (14) and (19) using the method we developed, and decide whether these were eclipses at sunrise or sunset, and with these results, obtain better ranges for ΔT. In Sect. 5, we discuss the remaining target eclipses and the meaning of our results.

2.2 Target Eclipses and Observing Sites

There are ten 'target eclipses' in Table 1, and we list them anew in Table 2.

In what follows we do not treat all of these eclipses. Our actual targets are eclipses (01), (04), (09), (14) and (19). We will explain in Sect. 5 why we do not consider eclipses (03), (10), (11), (13) and (15).

Table 2 List of target eclipses[a]

	Oppol.	Julian date			Chunqiu period					Watanabe
No.	number	Year	Month	Day	Duke	Year	Month	Day	Shuo?	& Wangtao
01	1,147	–719	02	22	Yin	03	02	Jisi[6]	–	Sunrise
03	1,211	–694	10	10	Huang	17	10	–	Shuo	
04	1,257	–675	04	15	Zhuang	18	03	–	–	Sunset
09	1,328	–647	04	06	Xi	12	03	Gengwu[7]	–	Sunset
10		–644			Xi	15	05	–	–	Non-eclipse
11	1,383	–625	02	03	Wen	01	02	Guihai[60]	–	
13	1,449	–600	09	20	Xuan	08	07	Jiazi[1]	–.T	Mag. 0.87
14	1,452	–598	03	06	Xuan	10	04	Bingchen[53]	–	Sunrise
15					Xuan	17	06	Guimao[40]	–	Non-eclipse
19	1,559	–557	05	31	Xiang	15	08	Dingsi[54]	–	Sunrise

[a] The first column is the Chunqiu serial number; the second shows the Oppolzer number; the third is the Julian year, month, and date; the fourth is the Chinese Duke, year, month, day of the Chunqiu Period; the fifth lists when shuo is mentioned, and T = total; and sixth column lists the interpretations of Watanabe (1958) and Wangtao (see Shinjo 1928)

3 Preparations

In Sect. 4 we make our calculations for the individual eclipses and obtain the ranges of ΔT. Here we prepare for that calculation. We assume that all eclipse observations were made at Qufu, the capital of Lu. Watanabe (1958: 351) suggests that eclipse (13) (Duke Xuan reign period, 8th year, 7th month) might have been observed at a place other than Qufu because the magnitude was 0.87 according to his calculation, based on Schoch's theory. This might be possible. However, if we admit variable observing sites, then one more free parameter is added. We do not consider this possibility, and for the purpose of this investigation fix on Qufu as the observing site.

We now introduce the Sôma Diagram. We take as the abscissa the value of the LTA or its correction to the present value (unit: arcsec/century^2), and take as the ordinate the value of ΔT (unit: sec). We plot on this plane the curves of the boundary of total eclipse(s) observed at sites of known positions. It is cumbersome to give this figure a name based on its properties so we simply call it the 'Sôma Diagram'. The positions on the Earth's surface of the total eclipse band of an eclipse depend on these parameters. The present value of the lunar tidal acceleration is –25.83″ cy^{-2}. The utility of the Sôma Diagram is that contemporaneous eclipses can be expressed in the same figure and the possible ranges of LTA and ΔT are obtained as the intersections of multiple bands.

According to Sôma, Tanikawa and Kawabata (2004) the present value of the LTA may be consistently extended to the past 2,000 years. Basically, in the present work we adopt the present value. Nevertheless, our analysis shows that there is uncertainty of 1″/cy^2. So, we keep in mind that the value of the LTA is still uncertain within this error, and always use the Sôma Diagram for confirmation.

The method adopted in the present paper has been developed in Tanikawa and Sôma (2002, 2004a, b), and in Sôma, Tanikawa and Kawabata (2004). In this method, multiple phenomena are used to simultaneously determine the range of ΔT for the year or years of observation. In the present paper, the eclipses which will be the object of analysis are called *target eclipses*, and the other contemporaneous eclipses will be called *auxiliary eclipses*. Auxiliary eclipses do not necessarily exist in close temporal proximity to the target eclipse. Here we estimate the errors due to the difference in years of observation. We use as a reference the curves proposed by Stephenson (1997):

$$\Delta T = 31 \times ((\text{year} - 1820)/100)^2 - 20\text{s}. \tag{2}$$

According to this formula, ΔT decreases by 15 s/year on average from 700 to 500 BC. We adopt this value to estimate the errors in the ΔT obtained. It is to be noted that if we use an auxiliary eclipse observed n years earlier or later, then the errors are $n \times 15$ s.

An intuitive explanation of the effect of ΔT is that if ΔT increases the eclipse band shifts to the east, while if ΔT decreases the eclipse band shifts to the west. On the other hand, the effect of the difference in LTA is difficult to explain intuitively. However, basically the eclipse band moves to the west if the correction to the adopted acceleration is positive, and to the east otherwise.

We explain what the *eclipse at sunrise* and the *eclipse at sunset* at Qufu is by using Figure 2. If the observation site lies in the region bounded by curve ADCE in the figure, the Sun rises eclipsed. If, in addition, the site is to the right of arc ABC, the maximum obscuration is observable, whereas if the site is to the left, the maximum obscuration takes place below the horizon. If the observation site is in the region bounded by curve HKJL, the Sun sets while eclipsed. If, in addition, the site is to the left of arc HIJ, the maximum phase of eclipse can be observed, whereas if the site is to the right of the arc, the maximum obscuration takes place below the horizon.

In determining the range of ΔT using the supposed sunrise eclipses or sunset eclipses, we have some remarks to make. In the case of an eclipse at sunrise, the upper limit to ΔT is rather strictly fixed because for a larger ΔT the eclipse ends when the Sun is fully risen. The lower limit of ΔT is not so clear cut. In the case of a sunset eclipse, the situation is reversed.

If the eclipse takes place in the arctic region, either arc AFH or arc CGJ degenerate into a point (see the lower panel of Figure 2). In these cases, some subtlety is present, but we will not go into the details.

Since all of the target eclipses were surely observed, the cases in which the Sun rises after the eclipse or the eclipse starts after sunset will not be considered further here.

4 Individual Eclipses

In this section we carry out an analysis of the individual eclipses, in chronological order. There are two eclipse records which are not from China (see Table 3), and these represent very useful independent observations. In Table 4 we list the observation sites, together with their latitudes and longitudes.

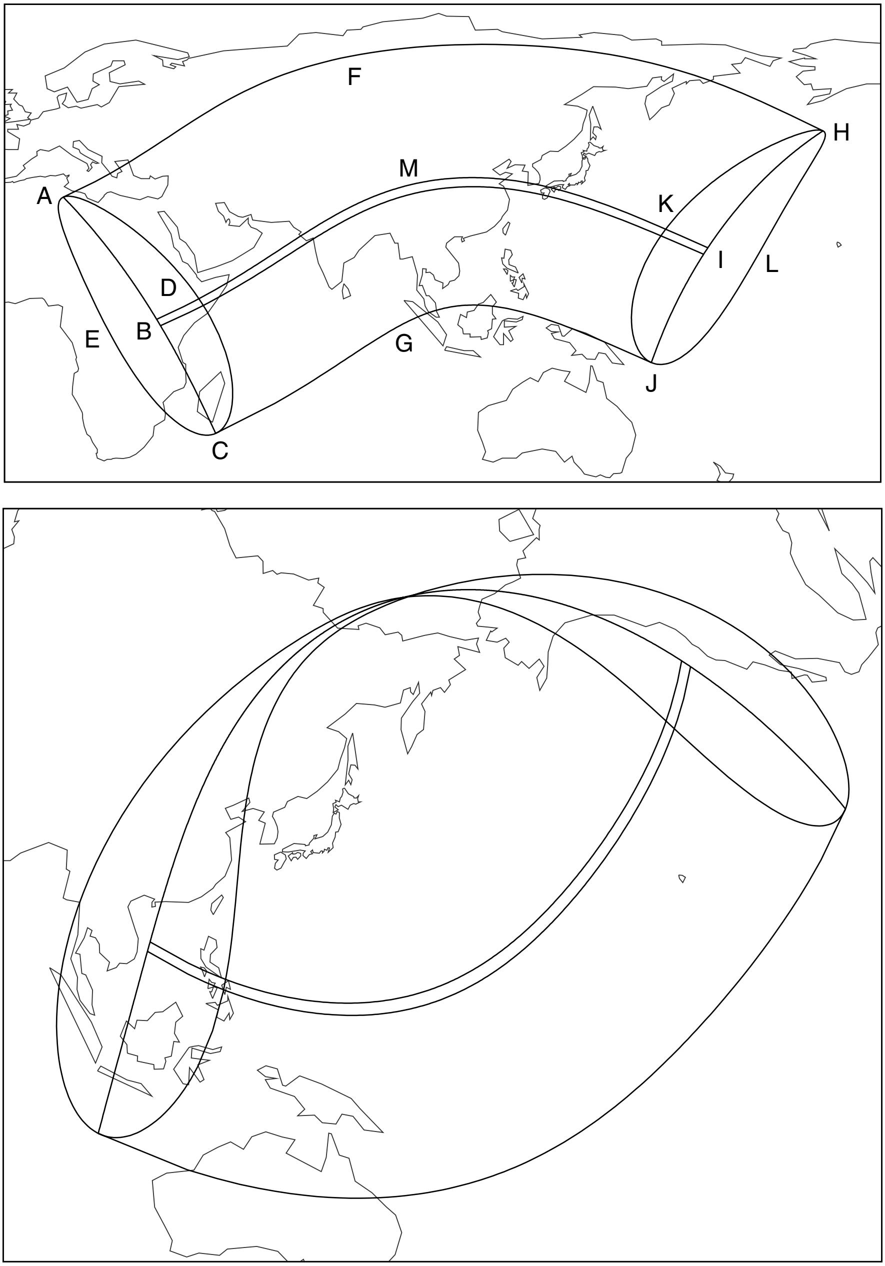

Fig. 2 Shadow of the Moon. The *upper panel* shows the eclipse band for a general eclipse at low latitude, while the *lower panel* shows a general eclipse at high latitude. The eclipse takes place at sunrise if the observation site is in a region bounded by curve ADCE, whereas the eclipse takes place at sunset if the observation site is in a region bounded by curve HKJL. The band BDMKI shows the sites for a total eclipse.

Table 3 Auxiliary eclipses observed at places other than China

	Julian date			
Opp. no.	Year	Month	Day	Remarks
1,328	–647	4	6	Total either at Paros or Thasos. Eclipse (09)
1,489	–584	5	28	Total at Pteria

Table 4 Observation sites

Place	East Longitude (°)	North latitude (°)	Remarks
Qufu	117.02	35.53	Capital of Lu
Paros	25.10	37.07	Island in the Aegean sea
Thasos	24.70	40.77	Island in the Aegean sea
Pteria	34.23	39.77	Asia Minor

Table 5 Target and auxiliary eclipses for 22 February –719

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
01	Target	–719	02	22	Yin	03	02	Jisi[6]		
02	Auxiliary	–708	07	17	Huan	03	07	Renchen[29]	Shuo	Total eclipse

4.1 The Sunrise Eclipse of 22 February –719

As shown in Table 5, the record of the target eclipse lacks any mention of shuo. The auxiliary eclipse is considered to be total at Qufu. The two eclipses were observed 11 years apart, so the errors of our estimates amount to 165 s.

The range of ΔT is given as a function of the LTA. We could provide a table of the data. However, we are afraid that our paper may then become too long, so we omit the table and only show the range in the figures.

Figure 3 shows how to determine the ranges of ΔT and the LTA (or its correction to the present value). As we pointed out above, the two eclipses are 11 years apart, so errors of ±165 s should be taken into account. The band for the target eclipse covers the band for the total eclipse over a wide range of LTA. In particular, it is true if the absolute value of the correction to the LTA is less than $1''/\mathrm{cy}^2$. This means that as long as the auxiliary eclipse was total, the target eclipse was an eclipse at sunrise. We adopt the range of ΔT for the present value of the LTA (in Figure 3, this corresponds to zero for the abscissa value), so the range is

$$20{,}153\ \mathrm{s} < \Delta T < 21{,}094\ \mathrm{s}.$$

In addition, the range is below the central dotted curve, which means that the maximum obscuration was observed after sunrise.

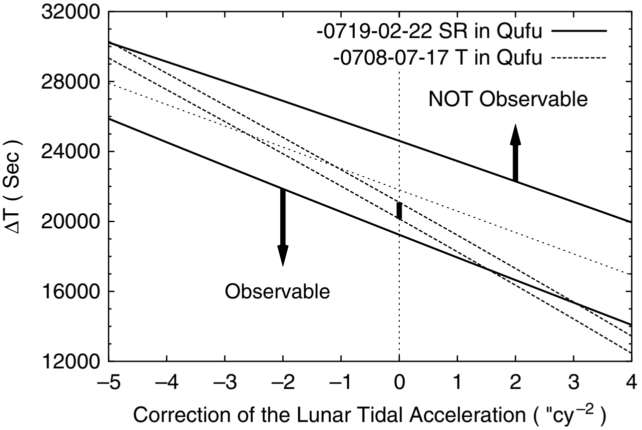

Fig. 3 The Sôma Diagram for the target eclipse of 22 February –719. The *band with solid curves* is for the sunrise eclipse on 22 February –719, and the *band with dotted curves* is for the total eclipse on 17 July –708. The *vertical thick line* indicates the candidate range of ΔT.

4.2 The Sunset Eclipse of 15 April –675

As seen in Table 6, we have four auxiliary eclipses within 20 years of the observed date of the target eclipse. The four eclipses were all partial because the word ‘total’ is missing. So, in the Sôma Diagram, candidate areas are out of the bands for a total eclipse. The resulting Sôma Diagram is shown in Figure 4.

The candidate areas are between thick parallel lines and out of several parallel curves. Adopting the present value of the LTA, we have two separate ranges of ΔT as shown by the two thick lines in Figure 4.

$$15{,}810\ \text{s} < \Delta T < 17{,}193\ \text{s or } 18{,}526\ \text{s} < \Delta T < 20{,}686\ \text{s}$$

Let us check which of these ranges is appropriate. We obtain the range of ΔT for year –708 of 20,153 s < ΔT < 21,094 s. The time difference is 30 years. Thus the difference in ΔT may be at most 500 s. Then the second range is preferable since otherwise we need to consider a 4,000 s jump over 30 years.

The auxiliary eclipse in –654 gives almost the same condition for ΔT as the eclipse in –668 for the zero correction to the LTA. Then we can dispense with the eclipse in –654. In this case, the maximum time difference becomes 12 years and the results become more reliable.

As a conclusion, we obtain as the candidate range of ΔT:

$$18{,}526\ \text{s} < \Delta T < 20{,}686\ \text{s}.$$

This range is consistent with ranges obtained from other target eclipses. This means that the probability that the eclipse was at sunset is very high.

Table 6 Target and auxiliary eclipses for15 April –675

		Julian date			Chunqiu period				
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?
04	Target	–675	04	15	Zhuang	18	03		
05	Auxiliary	–668	05	17	Zhuang	25	06	Xinwei[8]	Shuo
06	Auxiliary	–667	11	10	Zhuang	26	12	Guihai[60]	Shuo
07	Auxiliary	–663	08	28	Zhuang	30	09	Gengwu[7]	Shuo
08	Auxiliary	–654	08	19	Xi	05	09	Wushen[45]	Shuo

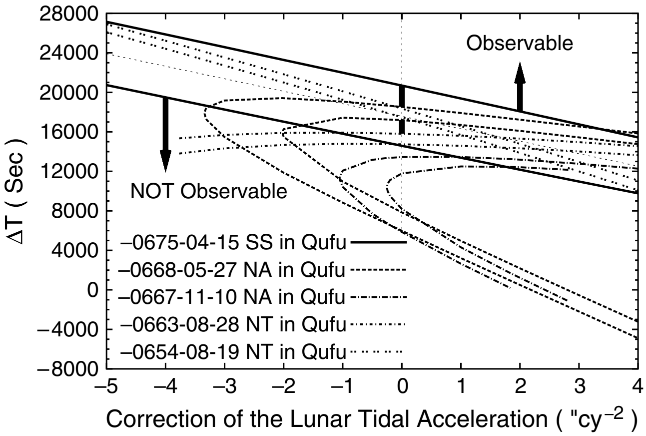

Fig. 4 The Sôma Diagram for the target eclipse 15 April –675. The *band with solid curves* is for the sunrise eclipse on 15 April –675, and the *band with dotted curves* is for the total eclipse on 17 July –708. The *vertical thick line* indicates the candidate range of ΔT. *Dashed lines* are for the annular eclipse of 27 May –668, *dot-long dash lines* are for the annular eclipse of 10 November –667, *dot-short dash lines* are for the total eclipse of 28 August –663, and *dotted lines* are for the total eclipse of 18 August 654. The *thick vertical intervals* are the candidate ranges of ΔT.

4.3 The Sunset Eclipse of 6 April –647

Table 7 lists two auxiliary eclipses. Eclipse (08) was already used in the preceding subsection. The other one is the record of an eclipse observed either in Paros or Thasos (see Figure 5). Both are cities on islands in the Aegean Sea. The most interesting feature of the eclipse is that it was observed in both China and Greece.

The eclipse was recorded in an undated poem of Archilochus. We need to identify this eclipse with the one in Oppolzer's canon. Fortunately, according to Fotheringham (1920), the poet was known to have been in Paros or Thasos on the day of eclipse. Newton (1970) and Stephenson (1997) listed several eclipses as candidates, and Stephenson (ibid.) calculated ΔT for them. He had no definite criterion to choose one above the others. He concluded that in either Paros or Thasos, a total solar eclipse took place, and selected the eclipse of 6 April –647 as the most probable candidate. Our conclusion is more definite.

The corresponding Sôma Diagram is shown in Figure 6. It is apparent that we could not have had a total eclipse at both Paros and Thasos. At zero correction to the

Table 7 Target and auxiliary eclipses for 6 April –647

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
09	Target	–647	04	06	Xi	12	03	Gengwu[7]		
	Auxiliary	–647	04	06						Total at Paros or Thasos
08	Auxiliary	–654	08	19	Xi	05	09	Wushen[45]	Shuo	

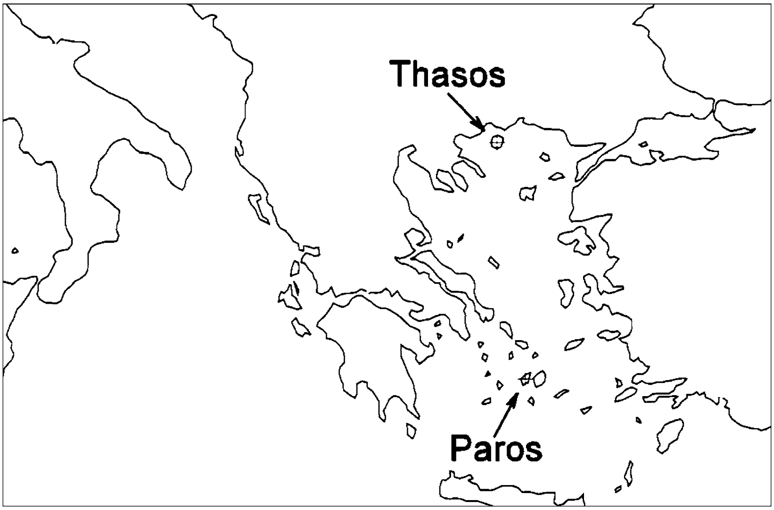

Fig. 5 The positions of Paros and Thasos.

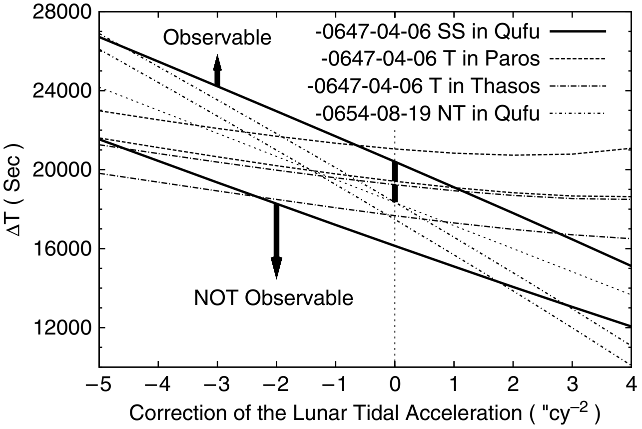

Fig. 6 The Sôma Diagram for the target eclipse 6 April –647. The *band with solid lines* is for the eclipse on 6 April –647 at Qufu. The *dashed band* is for Paros, the *dot-dash line* is for Thasos, and the *band with dot-short dash* is for the eclipse on 19 August –654 at Qufu. The *vertical thick lines* show the candidate ranges of ΔT.

present LTA, we have two separate ranges of ΔT. If we adopt Thasos, then we can impose an additional restriction on the range of ΔT for an eclipse that was not total at Qufu in –654. The two ranges are

$$19{,}409\ \text{s} < \Delta T < 20{,}402\ \text{s for Paros}$$
$$18{,}353\ \text{s} < \Delta T < 19{,}235\ \text{s for Thasos}$$

In either case, the target eclipse satisfies the sunset condition. In addition, both cases are plausible. We cannot say which is a better candidate.

4.4 The Sunrise Eclipse of 6 March –598

As shown in Table 8, we have two auxiliary eclipses within 16 years. The record says that eclipse (13) was total, but Watanabe (1958) says that it was not. The total eclipse in –584 at Asia Minor was a famous eclipse which was said to have been predicted by Thales. Although Stephenson (1997) does not specify the observation site, Özel, and Kacar (2007) say that it was Pteria (see Figure 7), and we adopt this idea.

Table 8 Target and auxiliary eclipses for 6 March –598

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
14	Target	–598	03	06	Xuan	10	04	Bingchen[53]		
13	Auxiliary	–600	09	20	Xuan	08	07	Jiazi[1]	Shuo	
	Auxiliary	–584	05	28						Total at Pteria in Asia minor

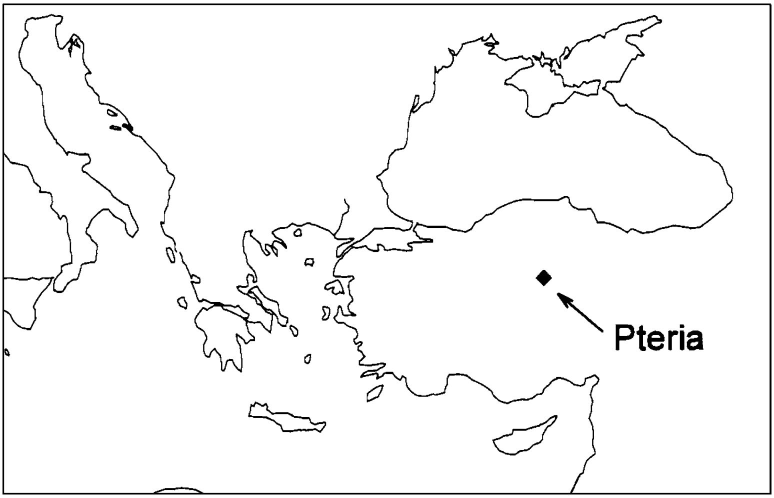

Fig. 7 The position of Pteria.

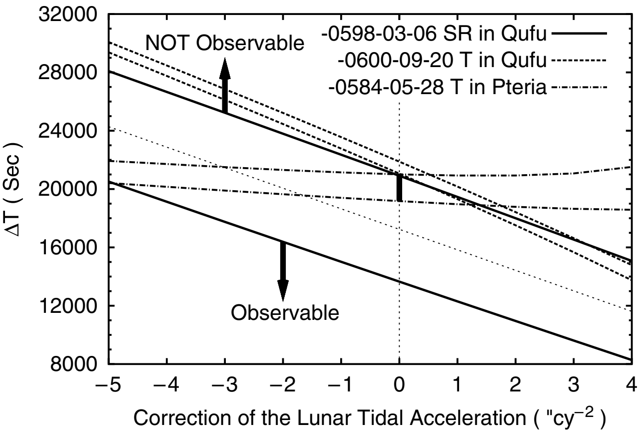

Fig. 8 The Sôma Diagram for the target eclipse 15 April –598. The *band with solid lines* shows the sunrise eclipse of 6 March –598 at Qufu. The *band with dashed lines* is for the total eclipse on 20 September –600 at Qufu. The *band with dot-long dash lines* is for 28 May –584 at Pteria. The *vertical interval* is the candidate range of ΔT.

We give the corresponding Sôma Diagram in Figure 8. As seen in the figure, the range for the target eclipse and the range for eclipse (13) do not overlap for zero correction to the LTA. This means if the eclipse was total in –600, then the eclipse in –598 could not have been observed since the eclipse took place just below the horizon. Conversely, if the eclipse in –598 was observable at sunrise, then the eclipse in –600 was not total at Qufu but almost total. The eclipse in –598 was surely observed. So we consider that the eclipse in –600 was not total but almost total. This idea is strengthened if we add the eclipse observed at Pteria to the figure. In fact, the total eclipse band of this eclipse at Pteria overlaps the sunrise condition for the eclipse in –598. The errors are about 250 s due to the time difference of 16 years.

Let us consider the possibility that three eclipses were observed as the records tell us. In order for this to happen, the bands for –598 and –600 must overlap. If we move to the right in Figure 8, that is, if we take the correction to larger LTA, this can be realized. However, the eclipse band for (24) superimposed in Figure 9 indicates that the correction should be less than $1''/\mathrm{cy}^2$ in order for this eclipse to have been total at Qufu. The overlap is negligibly small. The correction to the LTA has little effect in this case.

The eclipse in –647 satisfies the condition of zero correction to the LTA. This also strengthens our conclusion. Another possibility is that the observation site may have been different. We do not have any information on this, so we ignore this case. We may conclude that the eclipse in –600 was not total in Qufu.

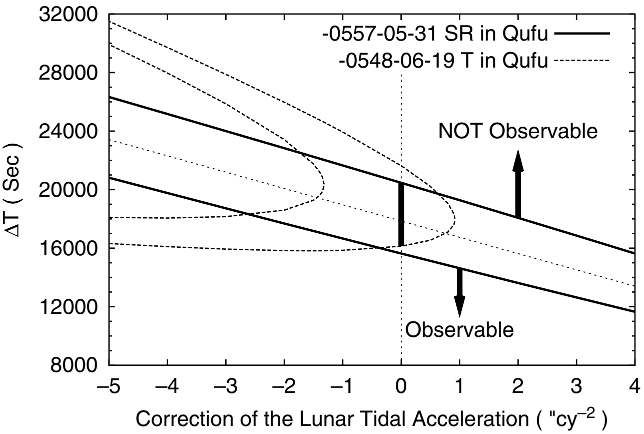

Fig. 9 The Sôma Diagram for the target eclipse 15 April –598. For reference, the total eclipse band for the eclipse of 18 June –548 is added (a folded band in the figure) to Figure 8.

Table 9 The maximum magnitude of the eclipse on 20 September –600 at Qufu

ΔT	Maximum magnitude
20,910	0.99156
19,172	0.90211

If the correction to the LTA is zero, the eclipse in –600 was almost total, and the eclipse in –584 was total at Pteria, then the range of ΔT is given by

$$19{,}172\ \mathrm{s} < \Delta T < 20{,}910\ \mathrm{s}$$

The maximum magnitude of the eclipse of 20 September –600 at Qufu is given in Table 9. The eclipse at Pteria can be considered total. This is consistent with the sunrise eclipse of Qufu.

4.5 The Sunrise Eclipse of 31 May –557

As shown in Table 10, there were two auxiliary eclipses within 9 years. According to the records, eclipse (24) was total, whereas eclipse (23) was partial. The corresponding Sôma Diagram is shown in Figure 10.

According to Figure 10, the intersection of the eclipse bands of the target eclipse and total eclipse is rather large due to the form of the eclipse band of eclipse (24).

Table 10 Target and auxiliary eclipses for 31 May –557

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
19	Target	–557	05	31	Xiang	15	08	Dingsi[54]		
23	Auxiliary	–668	05	17	Xiang	23	Spring	Guiyou[10]	Shuo	
24	Auxiliary	–667	11	10	Xiang	24	07	Jiazu[1]	Shuo	Total eclipse

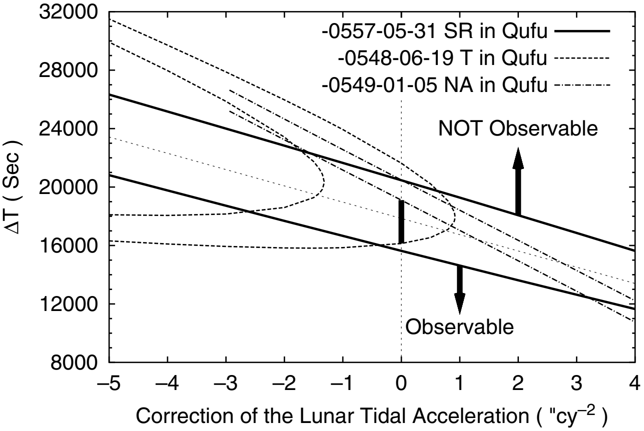

Fig. 10 The Sôma Diagram for the target eclipse 31 May –557. The *band with solid lines* shows the sunrise eclipse of 31 May –557 at Qufu. The *band with dashed lines* is for a total eclipse on 19 June –548 at Qufu. The *band with dot-long dash lines* is for 5 January –549 at Qufu. The *vertical interval* is the candidate range of ΔT.

As before, the zero correction to the LTA is included in the area. That the correction should be less than 1″/cy^2 was already mentioned before. The non-totality of eclipse (23) gives an additional restriction to the range of ΔT. We, as before, adopt the range of ΔT for zero correction to the LTA as

$$16{,}134\ \mathrm{s} < \Delta\mathrm{T} < 19{,}101\ \mathrm{s}.$$

4.6 The ΔT Curve

Let us compare our ranges of ΔT with those found by Stephenson (1997) and in Equation (2) in Sect. 3. Figure 11 shows that the two results almost coincide. However, it is apparent that the change of ΔT is not along a parabolic curve. We already pointed out in several places that there can be variations of shorter period in the ΔT curve. The enlargement in the lower panel in Figure 11 shows that if we adopt Thasos, ΔT approaches Stephenson's value, whereas if we adopt Paros the value deviates from his value.

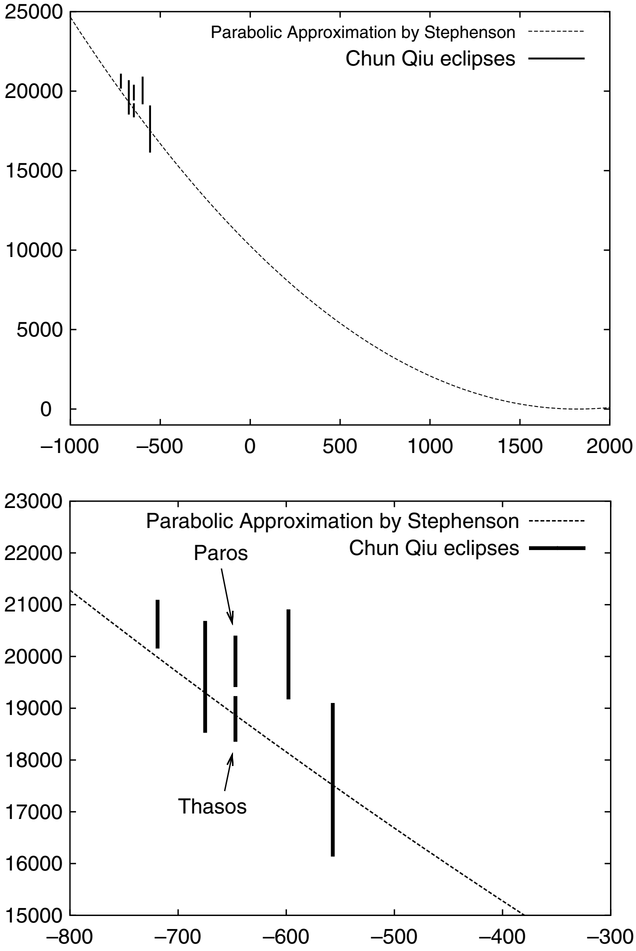

Fig. 11 Long-term variations of ΔT. The present results and Stephenson's curve. The *lower panel* shows an enlargement.

5 Discussion

5.1 Other Eclipses Which Lack Some Information

There are five remaining eclipses which lack information on the date or shuo. These are eclipses (03), (10), (11), (13) and (15) in Tables 1 and 2. Let us examine these eclipses one by one.

Eclipse (03) took place on 10 October –694. Watanabe (1958) considers that the cyclic day number was simply missed. According to our calculation, this eclipse occurred at sunset for ΔT = 17,000 s. This value is inconsistent with the ranges of ΔT given by eclipses on 22 February –719 and on 15 April –675, though they were close to the sunset eclipse.

Eclipse (10) is judged to be a non-eclipse by Watanabe because no corresponding Oppolzer eclipse exists. Saito and Ozawa (1992) changed the date to 7 June –650, and suggested that this eclipse was at sunset. We confirm this with the range of ΔT similar to that for eclipse (09).

Eclipse (11) took place on 3 February –625. The record has shuo in the *Gongyang-zhuan*. Our calculation says that this eclipse was neither at sunrise nor at sunset. According to Shinjo (1928: 250), an old version of the *Gongyang-zhuan* has no shuo for this eclipse. If so, it would be very interesting to know why shuo was added to the record in later years.

Eclipse (15) does not have a corresponding Oppolzer eclipse. According to Shinjo (1928: 284; our translation), Wangtao of the late Qing Dynasty considered that the record should read "Duke Xuan reign period, 7th year, 6th month, guimao [40], shuo" instead of "Duke Xuan reign period, 17th year, 6th month, guimao [40]":

> Wangtao says that the record is the mis-location of the eclipse of the Duke Xuan reign period, 7th year, 6th month, guimao [40], shuo (May 8, –601). According to calculation, there was an eclipse on that day in China, but I do not like to revise the record by changing the year of the record.

Shinjo was not sympathetic to this alteration. Let us examine whether this eclipse was either at sunrise or sunset. Figure 12 shows the result. The figure is almost the

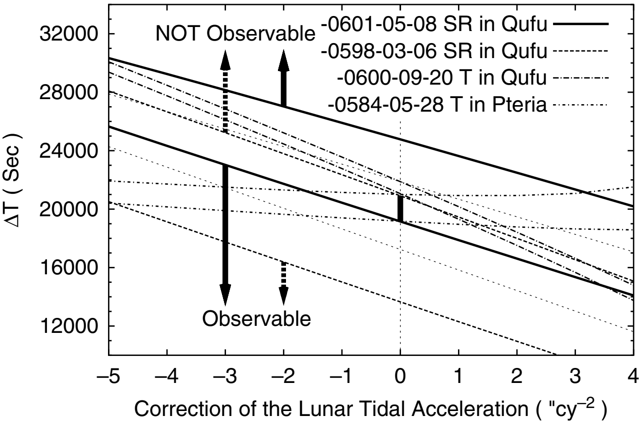

Fig. 12 The Sôma diagram for the target eclipse 8 May –601. The *band with solid lines* shows the sunrise eclipse of 6 March –598 at Qufu. The *band with dashed lines* is for total eclipse on 20 September –600 at Qufu. The *band with dot-long dash lines* is for 28 May –584 at Pteria. The *vertical interval* is the candidate range of ΔT.

same as the figure in Sect. 4.4 for eclipse (14). The figure strongly suggests that the eclipse was at sunrise. Therefore, Wangtao's alteration is justifiable.

As a tentative conclusion, we may say that eclipses without the word shuo were eclipses at sunrise or sunset. There are only two exceptions among nine: eclipse (11) and (13). Eclipse (13) was described as total.

5.2 Paros or Thasos

Stephenson (1997: 341) found several candidates for the eclipse versified by Archilochus taking into account previous research. Apart from the eclipse on 6 April –647, he listed eclipses on 28 July –690, 15 April –656, 8 September –645, and 29 August –636 which were seen as total at Paros or Thasos, and gave the range of ΔT.

These four additional eclipses give quite different ranges of ΔT. So we conclude that these were not the eclipse Archilochus saw. Newton (1970) listed eclipses on 11 January –688, 12 January –661, 27 January –660, and 15 April –656. Among them, the eclipse on 11 January, –688 gives us a wide range of ΔT. Stephenson (1997) omitted this eclipse because it was annular. The remaining eclipses do not give appropriate ranges of ΔT. Thus, the eclipse on 6 April –647 is the unique candidate for the eclipse of Archilochus.

5.3 Relations Between Lack of Data and Sunrise or Sunset

Starting from the fact that there was almost no lack of data in the latter half of the Chunqiu records, Shinjo (1928) discusses the setting up of the Chinese calendar system in this era. According to our calculation, however, eclipses of the latter half of the Chunqiu Period happened at neither sunrise nor sunset. This may mean that the lack of information was not related to the setting up of the calendar system.

The *Gongyang-zhuan* and *Guliang-zhuan* recorded our eclipses at sunrise or sunset as eclipses on the last day of the month or on the second day of the month. This may be important for reconstructing the calendar system of the Chunqiu Period. The problem is whether dusk or dawn belongs to today, tomorrow or yesterday. In Volume 7, Wuxing-zhi, Volume 27 of the Hanshu (1962), there is a record: Duke Yan reign period, 18th year, 3rd month, eclipse (eclipse (04) in Table 1). It is written: "The historian guesses that the conjunction was at night. The next day, the Sun rose eclipsed, and the eclipse finished after sunrise. This is said to be a night eclipse." The historian of the Hanshu interpreted the night eclipse in the *Guliang-zhuan* as an eclipse at sunrise. The historian did not consider the possibility that the eclipse was at sunset. In fact, this was a sunset eclipse.

The terms 'eclipse at sunrise' and 'eclipse at sunset' appeared in the *Xin-Wudaishi*. However, it is clear that the notion already existed during the Hanshu Period. Even the *Guliang-zhu*an might have called an 'eclipse at sunrise' or 'eclipse at sunset' a night eclipse. In that case, modern usage of ‘night eclipse’ meaning an eclipse which takes place on the night side of the Earth may be different from the historical usage.

6 Conclusions

In the present paper we have taken solar eclipse records with no mention of shuo or the day of the 60-day cycle, or both, calculated the ranges of ΔT given by these eclipses, and checked whether Watanabe’s supposition that these were eclipses at sunrise or sunset is true, and obtained narrower ranges of ΔT compared with previous studies.

We have several results.

1. The following eclipses were eclipses at sunrise or sunset at Qufu, the capital of Lu:

   Sunrise
   –719 02 22
   –598 03 06
   –557 05 31

   Sunset
   –675 04 15
   –647 04 06

2. We obtain narrower ranges of ΔT by incorporating near-contemporaneous eclipses. We give here the following ranges of ΔT assuming the present value for the lunar tidal acceleration:

   –719: $20{,}153\ \mathrm{s} < \Delta T < 21{,}094\ \mathrm{s}$
   –675: $18{,}526\ \mathrm{s} < \Delta T < 20{,}686\ \mathrm{s}$
   –647: $19{,}409\ \mathrm{s} < \Delta T < 20{,}402\ \mathrm{s}$ for Paros
   $18{,}353\ \mathrm{s} < \Delta T < 19{,}235\ \mathrm{s}$ for Thasos
   –598: $19{,}172\ \mathrm{s} < \Delta T < 20{,}910\ \mathrm{s}$
   –557: $16{,}134\ \mathrm{s} < \Delta T < 19{,}101\ \mathrm{s}$

   Note that there are two different candidate ranges of ΔT for the year –647.
3. In the present paper, we use auxiliary eclipses to narrow the candidate range of ΔT. There is no doubt that total eclipses are most useful. However, data such as ‘non-total’, ‘at sunrise’, and ‘at sunset’ turn out to be useful in some cases.
4. We have again confirmed that the correction to the LTA is less than $\pm 1''/\mathrm{cy}^2$ in Figure 10.
5. The lack of data in the records of eclipses turns out to have an important meaning. In particular, the lack of shuo corresponds to eclipses at sunrise or sunset, but the lack of the ganzhi is not important. As a result, the change from “Duke Xuan, 17th year, 6th month, day guimao[40]” to “Duke Xuan, 7th year, 6th month, day guimao[40]” seems plausible.

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The Possible Interpretation of a Mural in a Sixth Century Koguryo Tumulus as an AD 555 Solar Eclipse Record

Nha Il-Seong and Sarah L. Nha

Abstract Large numbers of tumuli are a feature of the Koguryo Kingdom (37 BC to AD 668), one of the Three Kingdoms in ancient Korea, and their interiors contain an extremely diverse range of murals. Quite a number of these murals include astronomical motifs, including the stars, the Sun and the Moon.

The No. 5 Tomb in the Five Tombs group is thought to date to the sixth century AD, and this contains a mural with an unusual figure of the Sun partially shielded by the legs and tail of a strange flying animal. In this paper we suggest that this tomb was associated with King Yangweon who died in AD 558, and that this distinctive mural depicts a partial solar eclipse that was visible in this region on 6 February 555 and acted as a warning of his forthcoming death.

1 The Koguryo Tumuli

Koguryo occupied a large area to the north of two other ancient Korean kingdoms, Paekche and Shilla. These are well illustrated in Figure 1 with different colors: Koguryo in white, Paekche in pink and Shilla in green. There is a fourth kingdom, Kaya in brown, located near the southern tip of the Korean peninsula between Paekche and Shilla. Associated with all four kingdoms are a large number of tumuli, but their structures and interiors are very different from each other, so that archaeologists can identify them without difficulty. In this paper we will confine ourselves to Koguryo tumuli only.

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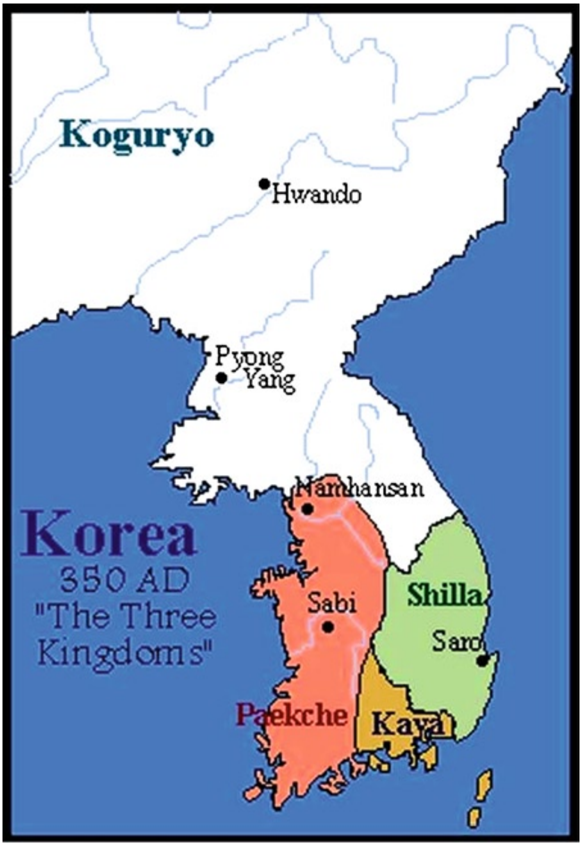

Fig. 1 Map showing the Three Kingdoms of ancient Korea, Koguryo, Paekche and Shilla, plus Kaya, a fourth Kingdom that also existed at this time. The Koguryo Kingdom occupied a much larger area than all of these other kingdoms combined.

1.1 Geographical Locations of Koguryo Tumuli

There are two major locations containing Koguryo tumuli. The larger group is located in Ji-an on the northern side of the Aprok (Yalu) River near Hwando, the first capital of the Koguryo Kingdom. This area is now Chinese territory. The other concentration of tumuli occurs on the outskirts of Pyongyang, the later capital of the Koguryo Kingdom. These two capitals are shown in the upper part of Figure 1. More than 10,000 tumuli have been identified in the Hwando area, and locations where these are concentrated are indicated in Figure 2.

1.2 A Sample of Koguryo Tumuli and Murals

While many Koguryo tumuli have been damaged with the passage of time, a goodly number have survived and are in reasonable condition. By way of example, the appearance and pictorial reconstruction of the interior of a large impressive Koguryo tumulus are shown in Figure 3.

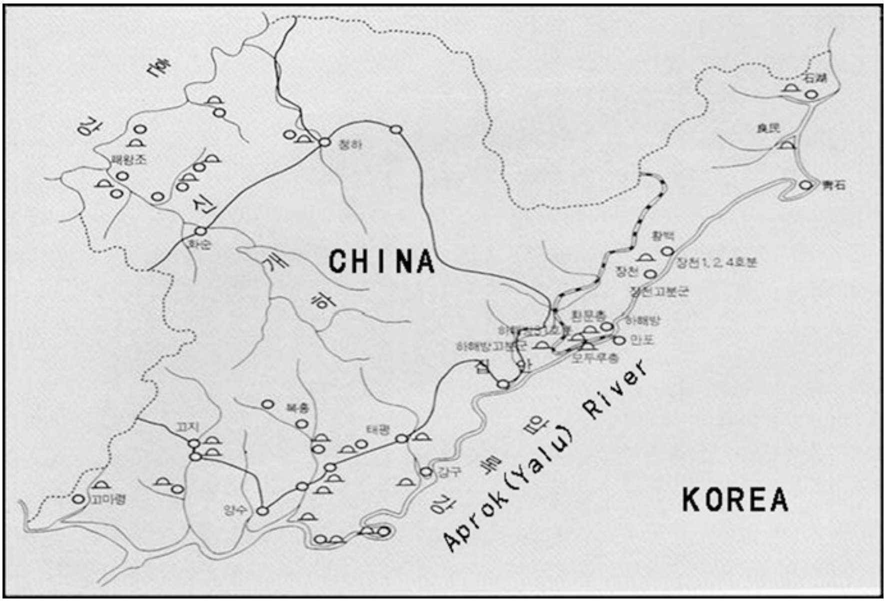

Fig. 2 The distribution of groups of Koguryo tumuli in Ji-an, to the north of the Aprok (Yalu) River near the old capital of Hwando.

We know from surviving examples that the interior walls and even the ceilings of Koguryo tumuli featured a variety of attractive murals. One of the best preserved examples in illustrated in Figure 4.

1.3 Murals of the Sun and the Moon, the Dragon and the Tiger

Two mythical animals, a black bird and a frog, are always centered inside of the circle of the Sun and the Moon, respectively, in Koguryo tumuli and also in some ancient Chinese and Japanese tumuli. Figure 5 shows dignified figures of the Sun and the Moon in two Koguryo murals. Some Koguryo tumuli also have paintings that link together the Sun with a blue dragon and the Moon with a white tiger, and good examples of these are given in Figure 6.

2 The Mural of a Solar Eclipse in the No. 5 Tomb in the Five Tombs Group at Ji-an

Symbolic artistic depictions of solar eclipses are well known to archaeoastronomers, and from among the many examples we introduce two in Figure 7. Figure 7a is a stone carving that is on the wall of an Indian temple and shows the Sun having

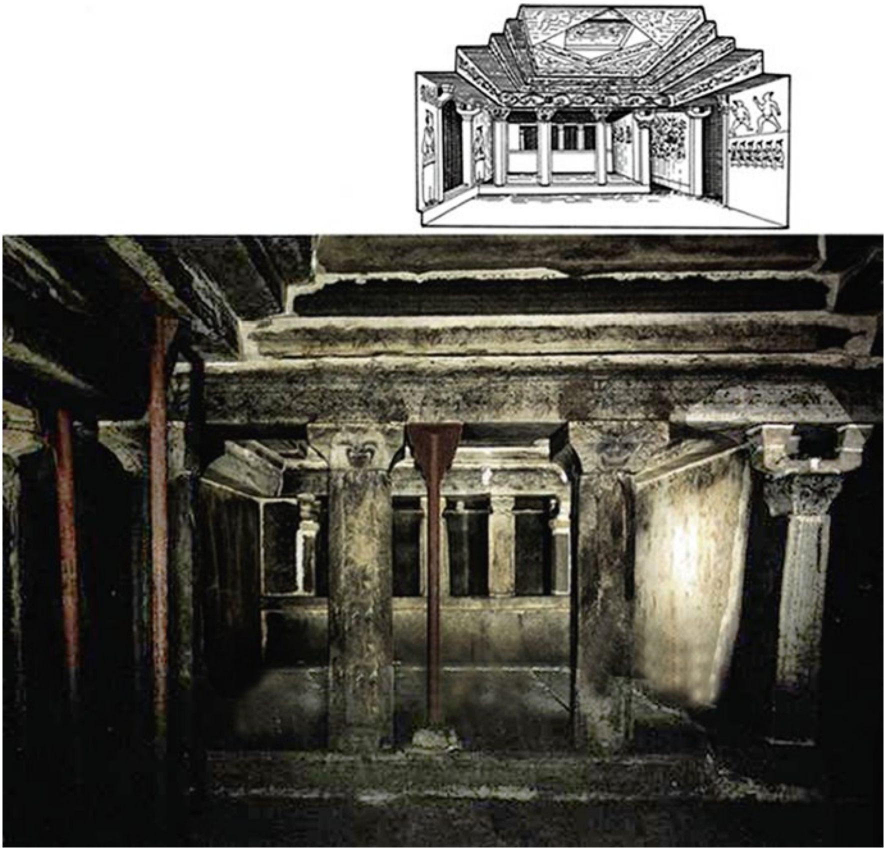

Fig. 3 Current appearance of the interior of the An-ak Tombs No. 3 tumulus. This gigantic Koguryo tumulus dates to the mid-fourth century AD, and a reconstruction of the original appearance of the interior is shown in the sketch.

been attacked by two snakes, which is interpreted as a symbol of a solar eclipse. However, this is an exaggerated figure that exhibits a degree of ‘artistic license’ in that the Sun would not be eclipsed on two different sides simultaneously. Meanwhile, Figure 7b is an example of a solar eclipse shown in a Chinese painting. A flying dragon approaches the Sun, impressively showing the beginning of the solar eclipse. Although we have more examples of this kind, none of them shows the date when the eclipse actually occurred. The question arises, therefore, as to whether they represent actual records of observed events or are merely symbolic of an eclipse.

A mural on a wall of the No. 5 Tomb in the Five Tombs group at Ji-an seems different from these examples as far as a solar eclipse is concerned. Up until 1945, the name of this tumulus was ‘Tonggu 17th tomb’, but it is now listed as No. 2105 tumulus (JYM2105) by Chinese authorities (Figure 8a). Many of the other tumuli in the Ji-an area were also renumbered by them in this way. Figure 8b shows that the primary axis of this tomb is oriented 22° west of north. It has a diameter of 28 m and is 7 m high.

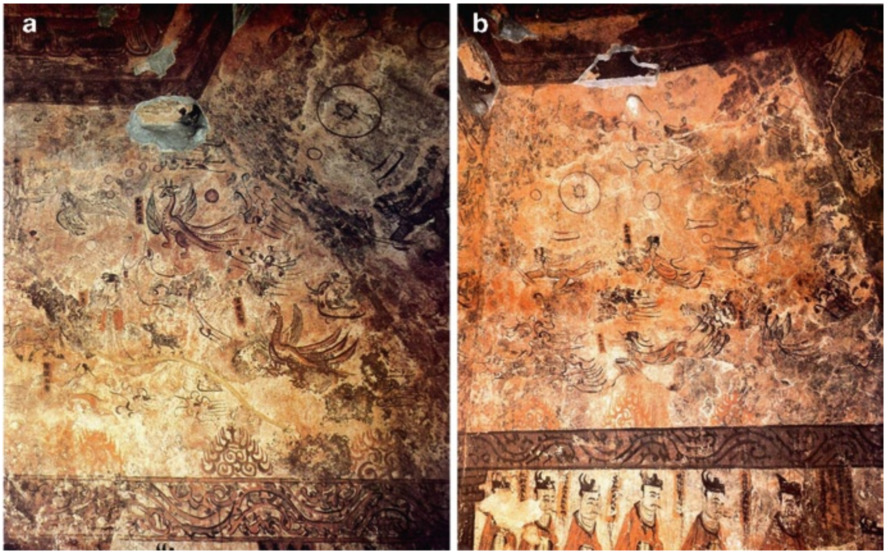

Fig. 4 Parts of southern and western upper walls (**a**) and the western upper wall (**b**) of the early fifth century tomb at Deokheung-ri. *Large circles* with a frog in the *center* on both (**a**) and (**b**) represents the Moon. Both walls also contain many smaller circles which represent stars. The murals on these walls are extremely diversified.

Just like many other Koguryo tumuli, murals were painted on both side walls in the entrance area and on the walls and the ceiling in the main rectangular chamber of the No. 5 Tomb. Among the many images on walls of this tumulus, one particular mural caught our attention. This is reproduced in Figure 9, and shows an image of the Sun shielded partly by the legs and tail of a strange-looking flying animal (perhaps a dragon) carrying a man. What makes this image of the Sun so unusual is that there is a long-lasting tradition in Korean culture that images of the Sun or the Moon could only be corrupted in this way if the gods wanted to provide warnings for the Korean kings. So we can assume that this mural was painted as a warning for the king who was later to be buried in this tomb. Careful examination of the mural shows clearly an image of part of a black bird with three legs located inside the Sun. This black bird with three legs symbolizes a circle the Sun (cf. Figure 5), and the Sun customarily was accompanied by a blue dragon, which guarded the eastern sky.

What we can learn from this mural in Figure 9 would make us to interpret it as the record of the solar eclipse with a possible date of erection of the tomb. In another word, the mural would certainly not be a simple figure only to decorate the wall, but has an objective purpose for unknown occasion.

According to Koguryo Munwha-Jeon Silhaeng Wiwoenhoe (n.d.: 80) and Joseon Whabo-Sa (1985): Plate 222), the tumuli in the Five Tombs group were erected in the sixth century, but precise dates are not available for the individual tombs in this group. We searched the sections relating to the Koguryo Kingdom in the *Samguk Sagi*, the Chronicles *of Three Kingdoms* (57 BC to AD 935) (see Kim 1973) and the

Fig. 5 The Sun and the Moon as depicted in the sixth century No. 4 Tomb in the Five Tombs group at Ji-an. The *upper* example shows a three-legged black bird inside the Sun, and the *lower* mural a frog inside the Moon. This tomb now has the registration number 2104, and is located immediately to the left of the No. 5 Tomb (2105) shown below in Figure 8.

Fig. 6 A blue dragon with the Sun and a white tiger with the Moon, as painted on the walls of the early fifth century Yaksu-ri Tomb. The dragon guards the eastern sky and the white tiger the western sky. A black bird inside the Sun is not clear in this figure because of its small size.

Fig. 7 Two symbols of a solar eclipse, as explained in the text. (**a**) is adapted from Seeds 1988: Figure 3-1, and (**b**) is from an unknown source.

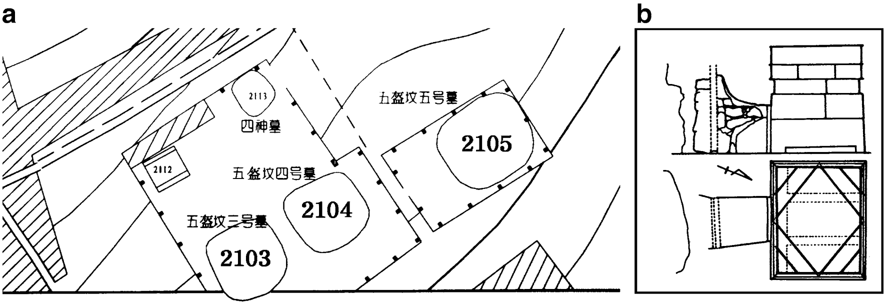

Fig. 8 (**a**) The location of Tomb 2105 in the Ji-an region, which was originally known as the No. 5 Tomb in the Five Tombs group. Only three tombs in this group, Nos. 3, 4 and 5, are shown here. (**b**) Gives plan and side elevation views of this tomb.

Fig. 9 The painting at the *upper* shows the mural depicting a solar eclipse which was painted on one of the walls in the No. 5 Tomb in the Five Tombs group. The drawing *below* brings out the features of this mural more clearly. The two stars near the *right hand* border of this figure form part of an unidentified constellation.

Jeungbo Munheon Bigo (see Pak 1908), and found just one short record of a solar eclipse that occurred during the sixth century. This was on the last day of the 12th winter month of the 10th year of King Yangweon, which corresponds to 6 February 555 AD in the Julian calendar. King Yangweon reigned from 545 to 558, and therefore died just 3 years after this eclipse, lending support to the hypothesis that this was his tomb, since such tombs were generally constructed some years before their associated kings died. In some cases, the construction of a tomb would begin when a new prince was born. On the other hand, the mural in the No. 5 tumulus shows that the legs and tail of the dragon-like figure do not cover the whole of the Sun, suggesting that this may have been a minor partial eclipse of short duration rather than a total solar eclipse. In order to investigate this hypothesis we checked the Shilla and Paekche sections of the *Samguk Sagi* but failed to find any evidence of such an eclipse, and nor could a relevant record be found in the Chinese manuscripts that we consulted (e.g. see Liu and Ma 2006). We therefore conclude that this mural was intended to depict the partial solar eclipse in 555 and fore-warn the Kingdom of the forthcoming death of their king. As it happened, King Yangweon died just 3 years later. In this context, it is significant that Chinese scholars recently used non-astronomical data to associate this particular tomb with King Yangwon (Seo Gilsu personal communication 2007).

Acknowledgements We wish to thank Professor Seo Gilsu for his kind comments on the Chinese sources and Mrs Kim Myeongju for her help in finding references.

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Statistics of Oriental Astronomical Records: What Can They Tell Us?

Richard G. Strom

Abstract For well over two millennia, Chinese astronomers observed and recorded a wide variety of phenomena in the heavens: eclipses, comets, sunspots, aurorae, strange clouds and other meteorological phenomena. For a somewhat shorter period, there were also recorded Japanese and Korean observations of the skies. In terms of numbers over the relevant time intervals, significantly more observations can be found in the Chinese annals. From AD 600 to 1600, the Chinese records preserve some 220 sightings of comets and guest stars, while from Japan there are nearly 150, and 120 from Korea. By comparing records of transient objects, we can learn something about the statistics of the phenomena themselves.

1 Introduction

The fact that there have been systematic astronomical observations in a number of ancient civilizations enables us to carry out statistical investigations of the archival data which have been preserved. Particularly suitable for such studies are Chinese, Japanese and Korean records: Japanese and Korean dynasties modeled much of their structure, including their astronomical practices, upon the Middle Kingdom of China. The signs they looked for in the heavens, as well as the nomenclature used (both adopted Chinese characters for their written languages), were the same (Ho 1962). These facts make them particularly well suited for statistical comparison.

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The reliability of ancient records has been tested in several ways, usually confirming their fidelity. Clark and Stephenson (1977), for example, checked on conjunctions of planets and were able to confirm the reported dates and descriptions. The returns of 1P/Halley are both consistent with its orbital elements, and have provided useful data to extend its ephemeris back over two millennia and investigate non-gravitational forces (Yeomans and Kiang 1981). Some of the supernovae which have been recorded can be matched up with remnants, on the basis of positional information, and the association can be tested if the age of the remnant can be estimated (Stephenson and Green 2002). Notable examples are the Crab Nebula, where both the kinematics of the nebula and the age of the central neutron star have been used, and 3C10, the remnant of SN1572, whose expansion has been well determined (Kamper and van den Bergh 1978; Strom et al. 1982). An additional check is provided by independent records of transient objects (SN1572 was observed in Europe – notably by Tycho Brahe – as well as in the Far East; see Stephenson and Green 2002). There are, however, cases where data have been falsified. In the course of Chinese history, algorithms were developed to predict solar eclipses, with a degree of success. Instances have been found where an eclipse was claimed (and recorded), while modern ephemerides show that no eclipse would have occurred on the date and at the location specified (e.g. see Liu et al. 1998).

Another kind of check is hinted at by one of the comments above. That is to compare transients recorded in China, Japan and Korea, the three cultures which had similar traditions of recording what appeared in the heavens. Such an exercise can be used not only to verify specific events, but to evaluate the completeness of independent samples. For sufficiently extensive data samples, an estimate can be made of the population of the original ensemble from which the datasets were drawn in different regions of parameter space. The resulting reconstruction can then be used to estimate parameters (such as brightness) of, or look for patterns in, the distribution of the original ensemble.

2 Method and Results

Meteors aside, night-time transient objects are dominated by comets. 1P/Halley is something of a benchmark when it comes to testing both the observing capacity of astronomers down the ages, as well as the system for recording and preserving the information gathered. From 240 BC until the end of the Qing Dynasty in 1911, only one return of 1P/Halley is missing from the Chinese records (and that one, in 164 BC, was recorded and preserved in Babylonian clay; Eddy et al. 1989). Of course the comet is usually fairly bright for at least part of its passage into the inner Solar System, but observations can be disrupted by weather, and even if observed, the information has to be written down, preserved, and ultimately incorporated (usually centuries after the fact) in a dynastic history or similar record. Given all that can go wrong, it is a remarkable fact that only one return out of 29 is missing. Japanese and Korean records are only extant in a reliable form from about AD 600. Taking the millennium from 600 to 1600[1] for a simple comparison, there were 13 returns of Halley, all of which were, of course, recorded in China. Over the same period, annals from Japan note Halley's return 11 times and those of Korea 8 times.

As with apparitions of Halley, so also with comets and (super)novae (or 'guest stars'), we find the most extensive set of records emanating from China, followed by Japan and then Korea. For the 1000-year period 600–1599, we find 216 such objects in Chinese annals, 146 in Japanese (Ho 1962; supplemented by Beijing Astronomical Observatory [BAO] 1988), with 74 common to both samples. On the face of it, we then have a total observed sample of 216 + 146–74 = 288 objects. This is of course only a lower limit to the total number which might have been observed, some of which were missed due to weather, observer failure, loss of records or editorial whim. Can this be improved upon?

There is a pretty standard statistical method for estimating the total size of an incomplete data set from independently drawn samples. In astronomy it is used, for example, in assessing the completeness of observed meteor samples (Öpik 1928). Suppose we have an ensemble of N objects. If one sample draws a fraction, f, from the ensemble, then the number drawn is n_1
Where

$$n_1 = fN \tag{1}$$

and if a second sample extracts a fraction, g, then

$$n_2 = gN \tag{2}$$

The overlap between the two samples, n_0, is just

$$n_0 = fgN \tag{3}$$

Substituting for f and g, and solving for N, we get:

$$N = n_1 n_2 / n_0. \tag{4}$$

Since the three values on the right-hand side are known, we can calculate N. For the method to work, samples 1 and 2 have to be independently drawn from the same ensemble. It is not applicable to 'local' phenomena, if the samples are drawn in locations separated by too great a distance. For meteors, it is typically used by observers within 1 km of each other. As a trivial example, based upon the Halley numbers above for China (13 returns observed) and Korea (8), with 8 (= n_0) in common, we have $N = 13 \times 8/8 = 13$, the number in the complete ensemble, as expected.

We can then also apply it to the comets and novae observed in China and Japan from 600 to 1599, as presented above. We have, $N = 216 \times 146/74 = 426$. Hence the completeness of the original combined sample from China and Japan was 288/426 = 68%. We can also conclude that by itself, the Chinese sample of night-time

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[1] AD 1600 was set as the cut-off point for after this date Jesuit influence and improved communication may have led to 'cross-contamination' of the records.

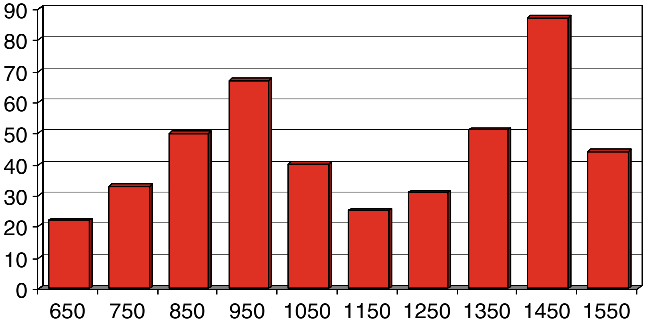

Fig. 1 Number of night-time transients per century for the period AD 600–1599, based upon Chinese and Japanese records.

transient objects (excluding meteors) over the 1000 year period was half complete, while the Japanese sample was about one-third complete. The method provides a reliable estimate of the ensemble population as long as the events missed by the independent samplers are not systematically correlated. There should, for example, be no correlation between instances of records lost or destroyed. Given the haphazard way that original documents have disappeared (fire, natural disaster, war), a correlation between events in China and Japan seems highly unlikely.

In an attempt to see if there have been temporal variations in the number of transient objects over the years, the data have been binned into 100-year sets, and the above exercise repeated. The results were plotted as a histogram (see Figure 1), which shows considerable variation in the numbers. In particular, in the tenth and fifteenth centuries, almost four times as many objects appeared as in the lowest periods (the seventh and twelveth centuries). Similar variations can also be seen in the original data from China and Japan, but the comparison gives one more confidence in the reality of the result. These data on night-time transient objects will be dominated by comet observations and only a small fraction of the objects observed will have been novae. What the reason is for a larger number of bright comets in certain periods of time is unknown.

3 Conclusions

Statistical intercomparisons of the kind presented here provide a method for estimating the total population in an undersampled dataset. It remains unclear why certain kinds of object are well represented in Oriental records, while others were very sparsely sampled. Why was almost every return of 1P/Halley recorded in China, and roughly half of all comets, while only a tiny fraction of sunspot appearances (Yau and Stephenson 1988) found its way into the archives? This question is unanswered at present. One fact which may be relevant is the recorded number of meteors in China over the course of time, which shows huge variations. There are peaks, particularly in the eleventh and fifteenth centuries, when 15 to 20 times as many meteors were recorded as in more typical periods 100 years earlier or later. So even within one kind of object, the fraction of reports can vary immensely.

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Part II
Archaeoastronomy

The Origin and Growth of Astronomy, as Viewed from an Indian Context

M.N. Vahia and Nisha Yadav

Abstract We attempt to create a comprehensive model for the origin and growth of astronomy in a culture. We show that it primarily follows four distinct phases that we classify as the initial, settlement, civilization and technology-based phases. Using examples from Indian prehistory and history we show that these phases mark distinct steps in the growth of astronomy in a culture. While the examples are taken from Indian culture, we suggest that it also should be possible to identify these phases in other cultures.

1 Introduction

We are what we are because our ancestors were who they were. Their attitudes and approach to problems relating to the existence and understanding of the Universe shaped not only their present and future but deeply affected the course of history. Hence, a study of our ancestors is a study about ourselves in the deepest sense of the word.

Normally such a study is done using archaeology. However, archaeology depends essentially on human remains and residues of ancient life. These may contain some well-preserved examples but largely they are the remains of routine life of ancient people. Therefore they are more representative of their lifestyle and hence of the technological skills. They give few clues to their intellectual growth and hence provide only a limited access to our past since many intellectual developments are not directly related to technology. The purpose of developing a specific technology and the solution they may have applied for a particular problem are profoundly interesting in their own right but the intellectual needs that drove the development of ideas

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and technologies are also of great interest. One such purpose is astronomy, where technology, mythology and science all merge. In the present paper, we attempt to create a map of how astronomy evolves over time in any culture. For a general discussion on archaeoastronomy and enthnoastronomy see for example Baity (1973), and for a broad summary of the growth of astronomy in India see Kaye (1924).

2 Astronomy and Myths

Attempts made by humans in trying to understand the heavens are of profound interest and importance. Astronomy[1] is such a field, which at one level is highly utilitarian because of its ability to predict weather, and at another level is completely abstract in that it relates to the place of humans in the vastness of the Universe. At one level, rain, thunder, lightning and other extraordinary events provided a source of life. At another level, the steady and unaffected movement of stars and the serenity of heavens on a clear night must always have fascinated humans. Completely arbitrary but spectacular events such as the appearance of comets and meteor showers would have a profound impact on the human psyche. The study of astronomy therefore must have attracted the attention of some of the best minds of that time. It must have also profoundly affected the growth of mathematics as humans tried to keep track of these complex, if subtle, movements of heavenly objects.

The only activity comparable to acquiring astronomical knowledge was the search to understand the relevance of human life within the context of nature through the creation of myths. These fantastic complex stories of events past or yet to come helped place human existence in perspective and have been used since time immemorial in a variety of ways, from consoling people upon the death of their dear ones to explaining irrational events as activities of mighty beings and hidden variables that were introduced by the gods. In most cases, these myths begin to formalize and revolve around a common, if complex, theme of supernatural powers and their relation to humans.[2] Religion, in many ways was a natural evolutionary outcome of myths. Each enriched the other, both for their breadth of reach and the profound philosophy and symbolism that they provided. Just as astronomy fed mathematics, myths and religion fed literature, and the human intellect grew to reach far beyond where it initially was designed to go and achieved what it was never meant to achieve.

Yet, at a more profound level, these two pillars of human intellectual growth, astronomy and mythology, are deeply connected. The life-giving ability of the sky, through rain and the Sun, to invigorate and fertilize the Earth must have been noticed very early in human history. Most religions therefore begin with the concepts

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[1] Initially the word ‘astronomy’ was used to indicate all events or objects above the Earth. It is only with the development of ideas and observations that the distinction arose between Earth-related events in the atmosphere, like rain, and heavenly phenomena. Today the word astronomy is restricted to the latter objects and events.

[2] For a general discussion on the history of myths see Armstrong (2005).

of Mother Earth and Father Sky, where rain from Father Sky invigorates and impregnates Mother Earth with new life. From this start to making the heavens an abode of the gods would seem a linear progression.

The purpose of myths is manifold. These include giving a sense of purpose to life, giving meaning to life's irrational experiences such as birth and death, or speculating on rebirth or a higher existence, and so on. In the original form of Hinduism, for example, the structure of the religion is that of a tripartite relation between gods, humans and ancestors (Jamison and Witzel 1992), where each appeases the others by giving boon depending upon their powers, and receives favors in turn. Myths also give a sense of purpose to life, especially by providing heroes whose examples can be emulated by others; they also provide a yardstick by which actions of others can be measured. Lastly, in many ways myths hold out a promise of manipulating gods who control the cosmos so that humans can live under favorable conditions. Myths therefore offer a sense of connectivity between humans and the magnificence of nature, and provide a sense of belonging and proportion against this vast expanse of the Universe which can often disorient human life. Like all human concepts, myths also change and evolve with time as societies become more sophisticated.

In various ways, many cultures have seen life's dramas being played out in the heavens and have assigned revered stories to the various imagined patterns seen in the sky. Myths and astronomy therefore have a closer relationship than we normally appreciate.

Through Mother Earth and Father Sky the myths and the sky are interrelated to an extent that most profound beings and gods have corresponding stellar associations, while special gods drive the wheel of life: time, the winds, the rains, the Sun, the stars and everything magnificent. Thus, in many ways the heavens control human life, and some of the most creative human arts explore these inter-relations. In Figure 1 we present an example of such an intermix of images and ideas. The rock

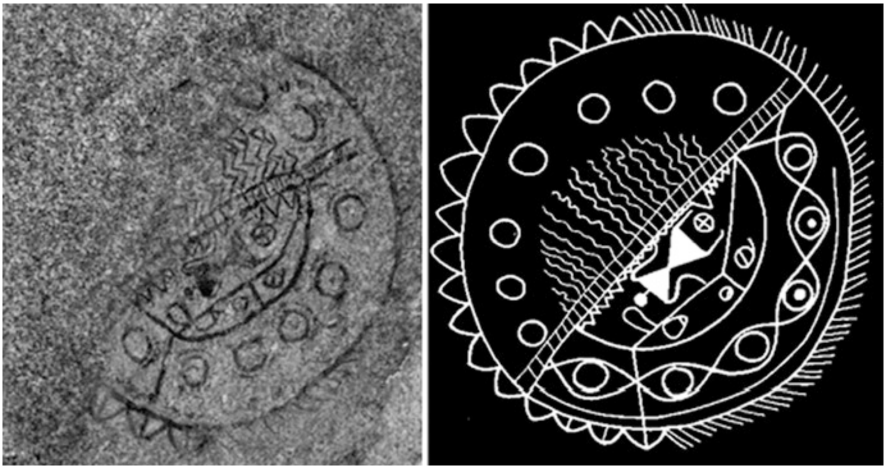

Fig. 1 Rock painting from Onake Kindi hill, Chikka Rampur, Raichur District, Karnataka (image by Erwin Neumayar reproduced in Moorti 1994). The picture shows a complex representation of a human burial with the Sun, the Moon and other complex images.

art shown in this figure is found in a cave on Onake Kindi hill in Karnataka. Its complex imagery includes a human figure with burial item in the center, with waves coming out on the one side. Beyond this is an outer ring of seven circles in the left hand semicircle and six circles in the right hand semicircle. In the semicircle with the human figure, the small circles are further enclosed in a pattern and two of them contain central dots. The outermost rim of the figure is decorated by a wavy pattern and dashed lines, but this transition does not occur at the division of the inner circles. The image seems to depict of human burial and astronomical images of the Sun and the Moon (including lunar phases). The left side of the picture appears to show rays emanating from the centre, which probably indicates day while the dark half on right, including the human burial, suggests night (this is the Moon side). The outer rims seem to extend into each other's territory. While this may not be the only interpretation that can be assigned to this rock art, the relationship between a human burial and the cosmos seems to be quite interesting.

In this paper we will not only explore the complex relationship between myths and astronomy but also between astronomy and the continuing human struggle to define themselves and to understand the complex set-up of heavenly beauty.

3 A Summary of Basic Astronomical Ideas

Astronomical knowledge requires understanding of some basic concepts and we shall briefly summarize these here for the sake of completeness.

Even for the most casual observer, there are two prominent objects in the sky, the Sun and the Moon. While the Sun seems to have a steady and overwhelming presence in the sky, the Moon waxes and wanes. When coupled with variations in day time and night time temperatures, it takes little to realize the importance of the Sun as a life-giver and the Moon as a time-keeper, with each day and night different from the preceding or succeeding one. The importance of the Sun therefore would have been obvious even to hunter-gatherers communities. More careful study, especially against a structured backdrop of geological features, soon made it clear that the Sun does not always rise exactly in the East and does not always set exactly in the West; rather, it rises somewhere in the East and sets somewhere in the West. The exact point of sunrise in fact drifts from a point in the North East to one in the South East in the course of a periodic cycle of about 365 days. The Sun rises exactly in the East and sets exactly in the West only twice a year and these days are marked by 12 h of sun light and 12 h of darkness. These mark the equinoxes. The day of northernmost extreme point of sunrise is the longest day in the northern hemisphere and is called the summer solstice. Similarly, the day of southernmost sunrise is the shortest day of winter in northern hemisphere and is called the winter solstice. The seasons (and their corresponding names) are 6 months out of phase in the southern hemisphere.

The next object of interest is the Moon. Twelve full lunar cycles bring the sunrise point nearly to the same place, short by a little more than 11 days. The Moon therefore provides an important calendar. However, the relationship between the phase of the Moon and its rise time is a complex one. The Moon rises at sunset on full Moon. It rises at midday when the Moon is halfway towards Full Moon, and rises at midnight when the Moon is halfway to New Moon.

Beyond this there is the relation of these celestial objects to the stars. The Sun and the Moon seem to have a fixed relation to stars in the sky, moving through a rather narrow band of stars. The stars can be divided into small constellations so that they can be easily comprehended and memorized. Civilizations in cold regions, sensitive to the warmth given by the Sun, are more likely to notice the exact points of sunrise or sunset and the constellation that is there just before sunrise. These constellations would certainly have an important position amongst other constellations, and are known collectively as the zodiacal constellations. Similarly, for people sensitive to the calendar and using the night sky for navigation, the stars visited by Moon would also be considered important, and these are called lunar mansions. In an Indian context, the constellations (*tārā samuha*) of Sun are called *rashi* while the lunar mansions are called *nakshatras*. Meanwhile, the term for constellations (*tārā samuha*) is a very general and generic one and means a ‘group of stars’. It appears very late in Indian literature and ancient Indian astronomy is mainly restricted to *rāshi* and *nakshatra*.

The next point to be noted is that on a clear moonless night ~6,000 objects are visible in the night sky. Apart from Sun and Moon, five other objects are not stationary with respect to the stars but move in the sky. These are the planets. These ‘wanderers’ also move along a narrow in the sky which somewhat overlaps the Sun’s path. Also, each of the wanderers has its own preferred period. For two of them (Mercury and Venus) the farthest distance from the Sun, is limited.

Sometimes eclipses would have been observed, and their apparent random occurrence created fear. There also would have been observations of transient objects like comets and meteors, which were rare and non-periodic in occurrence. The ancient astronomers may also have observed novae and supernovae (see e.g. Joglekar et al. 2010).

The last of such naked eye observations would be to note the drift in the zodiacal signs in which sunrise at the equinoxes occurs. This result of precession of the equinoxes also changes the time of the year when a specific season occurs. With its annual drift of 0.72′ per year, the motion is very subtle and requires long-range observations before it can be noticed.

The very process of acquiring such astronomical knowledge must have taken a lot of time, and would have required a society to invest considerable intellectual, technological and financial resources.

4 The Development of Astronomical Ideas

The advancement of astronomical knowledge in a culture primarily depends on the following factors:

1. The specific requirements of that society
2. The available technology
3. The available caliber of the people

All these factors are sensitive to the age of the culture, but the first two are more or less monotonic, with both requirements and available technology becoming more sophisticated with the passage of time. We will briefly discuss each of these below.

The requirements of a society, while linearly increasing with time, is a curious entity. These requirements can change in sudden 'jumps' as societies become more sophisticated. In hunter-gatherer societies for example knowledge of animal migratory patterns and a general feeling of warmth are sufficient. With the initiation of farming, or even in the immediate pre-farming era, a high sensitivity to the seasons emerges. Farming requires more precise knowledge and predictability of the seasons and of the sunrise point. Once a society acquires a certain level of sophistication and wealth, preservation of wealth, good fortune and the desire to pass on the wealth and good fortune offspring results in the development of astrology and associated studies. Once a civilization reaches a level of sophistication, where it has enough resources to spare and stability to pursue pure curiosity, cosmogony and other fields begin to emerge.

Available technology is a predictable parameter based on the general technological sophistication of the culture. Introduction of a specific inspired piece of technology can result in a critical sudden spurt in that culture, and history is replete with such examples. Invention of radio receivers and highly-accurate clocks are two such examples. But even without such sudden spurts, all societies either acquire or circumvent the needed technology and broadly move towards a higher level of sophistication.

Against this, the caliber of people exhibits enormous variation, and is practically unpredictable. Given a broad idea of the caliber of the most accomplished people, their influence on the advancement of knowledge can be estimated. So we have to establish the caliber of the most influential thinkers at any time if we are to understand the growth in astronomy in that culture. Such persons can produce dramatic changes, but their appearance or caliber is impossible to predict. In societies such as the Indian one, with a rather poor sense of history, most recorsds of important individuals are missing, and must be inferred from the ideas that emerge at any time. In spite of this limitation, a general idea that people become increasingly more sophisticated with the passage of time permits some measure of predictability about the growth of astronomy within a culture.

In all this, we have disregarded sudden catastrophic social and ecological changes which can set societies back by centuries if not millennia. We have also implicitly ignored the cross-cultural spread of knowledge which can also allow civilization to make dramatic transitions to higher levels of learning and sophistication by borrowing the learning of other cultures. While these induced changes are often conspicuous, it is not always appreciated that such sudden spurts can only be introduced to civilizations already prepared (or due) for such spurts of knowledge, and the external infusion only accelerates the process of knowledge gain rather than changing the track of the civilization.

The combined effect of all these factors is that societies go through various transitions in their knowledge of astronomy, in a manner that is almost analogous to phase transitions in physics. In an international context we can identify four major transitional phases in the evolution of astronomy:

- The Initial Phase (marking of sunrise and the seasons)
- The Settlement Phase (marking of stars and constellations)
- The Civilization Phase (the development of astrology and cosmogony)
- The Technology-based Phase (‘modern astronomy’, with all its trappings)

We discuss these phases individually below, taking examples from Indian civilization.

5 The Initial Phase

The initial phase consists of understanding and appreciating the fact that the Sun is related to warmth and life and that the changing point of sunrise (e.g. see Figure 2) decides the level of warmth.

At this stage, a human group or a culture can identify the following aspects of nature:

- The Sun is the source of warmth and light
- Rains, the Sun and the heavens are crucial life-givers. The sky rejuvenates the Earth, and this becomes an everlasting image in the human (even Neanderthal?) mind
- Due of its elegance and importance, the sky becomes the abode for the gods
- Astronomical observations are recorded on stones, in the form of rock art
- Early astronomy is developed, to the level of defining the seasons and their relation to sunrise points

In Figure 3 is an example of a rock art image from Chillas in Kashmir, which shows a common form of expression of personal and social experiences at this stage of evolution (see e.g. Lewis-Williams 2002 for a more extensive discussion on the Neolithic mind).

Fig. 2 Location of the sunrise point over the period of 1 year.

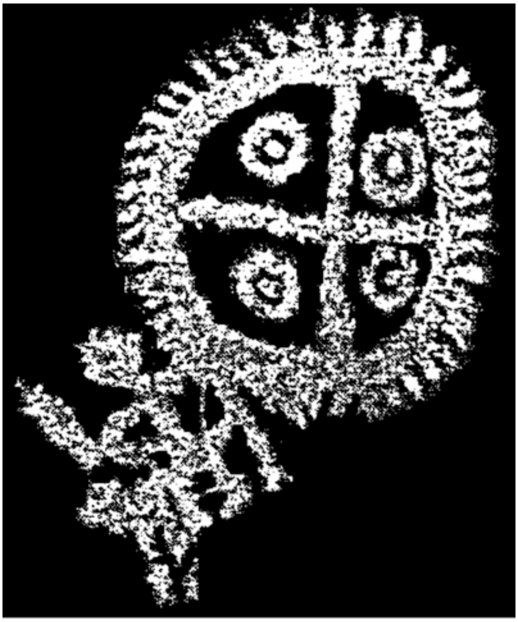

Fig. 3 A rock art image found at Chillas in Kashmir, which shows the Sun god with the disk of the Sun just behind him. The division of the disk into four quadrants is probably indicative of the four seasons.

Fig. 4 A stone engraving from Burzaham in Kashmir (courtesy: the Indira Gandhi National Centre for the Arts, New Delhi).

These images can often be very sophisticated and complex, making it difficult to interpret them, but they are likely to be important in helping us understand the astronomical observations made by ancient people. Joglekar et al. (2010) have discussed one such example. In Figure 4, we reproduce a stone engraving found in Burzaham near Srinagar. While it has been variously interpreted, we (Joglekar et al. 2010) have argued that since it is not possible to have two Suns in the sky and nor is it possible to have Sun and Moon so close to each other with comparable brightness, one of the 'Suns' must be a transient object such as a supernova (Joglekar et al. 2010) or a comet (see e.g. Strom, private communication 2008). Since the image is symmetrical, we argued that it was more likely intended to depict a transient object. We then searched David Green's on-line supernova catalogue for a possible supernova that had an apparent magnitude comparable to that of the Sun or the Moon, was close to the ecliptic, and occurred between 0 and 10000 BC (since the rock art was known to pre-date 2000 BC). We found only one supernova that satisfied all these criteria and it was dated to around 5000 BC. By projecting the supernova on a chart of the sky we found that the hunter in the figure matched Orion, and when the image was enlarged to fit Orion the other images, such as the stag, the dog and the other hunter, fitted well with Taurus, Andromeda and the Arietis-Cetus region. This may be the first recorded image of a prehistoric supernova (Joglekar et al. 2010). However, this is not the only possible explanation and other possible interpretations are that it is a simple hunting scene with two Sun's indicating the movement of the Sun (Richard Strom, private communication 2009) or a possible presentation of the creation myth of Rig Veda where the great god is about to perform incest with his daughter who has taken the shape of a deer and is prevented by another great god (Rudra) (see e.g. Kramrich 1981: 3). Nonetheless, we feel that the image is of a supernova (HG9) that had an apparent magnitude comparable to the Moon at its brightest and which must have left a deep impression in the minds of people at that time. Other possible astronomical examples are discussed by Iqbal et al. (2009) and Vahia et al. (2009).

These observations and recordings of transient events and other aspects of the sky were made by Palaeolithic people who were semi-settled. Following this, human culture becomes more settled and we enter the Settlement Phase.

6 The Settlement Phase

Once people settle down in an area, they live either by hunting, as long as the population is small and the land is rich enough to support them, or by farming (see e.g. Jain 2006: 57). With farming, they begin to be far more sensitive to the environment and its changes. Apart from observing that the Sun does not rise *exactly* in the east and does not set *exactly* in the west, they soon find it necessary to keep track of the exact movement of Sun, the Moon and stars in the sky. They therefore:

- Create large structures to study sunrise and sunset patterns; thus, megaliths become essential for calendrical purposes
- Study various aspects of the Moon (and perhaps the planets)
- Define the different constellations, the zodiac and *Nakshtra*
- Note eclipses and attempt to determine their periodicity
- Record transient events or objects, such as comets
- Create new myths, and explain these through observations
- Develop cosmogonical ideas

One of the most conspicuous features of the Megalithic Period[3] in Indian culture is the presence of huge stones which were arranged in a specific manner. While these may well have been used for ritualistic purposes, there is a fair case to be made that their primary role was to keep track of the movements of astronomical bodies such as the Sun and perhaps certain stars or constellations (e.g. see Baity 1973). Iqbal et al. (2009) have briefly summarized the astronomical significance of some sites in Kashmir and discussed one such megalithic site at Burzaham where the stone engraving shown in Figure 4 was found. It has been suggested that the large megalithic stones erected there have specific astronomical orientations, but this needs to be investigated further.

In India, the lunar mansions (*Nakshatras*) were established at an early date, but the Moon no longer goes close to all of the *Nakshatras*. http://www.tifr.res.in/~vahia/period-of-nakshatras.pdf have suggested that this may be due to the precession of the equinoxes, which produces subtle changes in the apparent path of the Moon in the heavens over time. Using modern astronomical software we calculated the average distance of the path of the Moon from all of the *Nakshatras* as a function of time and found that the distance was minimum around 3000 BC. We therefore suggested that the *Nakshatras* were probably designed around that period, when the first large settlements were beginning to emerge in the subcontinent (Jain 2006).

6.1 Vedic Astronomy

An ancient document known as the *Rig Veda* contains the basis of the Hindu religion, and although its dating is steeped in controversy its antiquity as the earliest-known Indian document has not been doubted (e.g. see Goodall 1996: x). The *Rig Veda* is a document of a settled community and includes elaborate discussions about rituals and philosophy. However, it also has a separate addendum, the *Vedanga Jyotisa* (or the astronomical treatise of the *Rig Veda*) that insists that "Just like the combs of peacocks and the crest jewels of serpents, so does Jyotiṣa (astronomy) stand at the head of the auxiliaries of the Veda." (see Subbarayappa and Sarma 1985: 1).

Subbarayappa and Sarma (1985) have compiled a list of astronomical references contained in various ancient Indian documents, and from this it is clear that the authors of the *Rig Veda* were aware of the discrepancies between the duration of the lunar year and the solar year and the need to add an intercalary month to synchronize the two. The *Yajur Veda* (Subbarayappa and Sarma 1985: 50) actually recommends the addition of two intercalary months in 5 years. The days are named according to the phases of the Moon. The author(s) of the *Yajur Veda* knew that 12 lunar months amounted to 354 days, and the synchronization was done using the *Ekādaśarātra* ceremony. This made 365 days in a year, leaving an error of just 0.25 days per year. But the Vedic year consisted of 12 months, each with 30 days which

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[3] The term 'Megalithic Period' is a general term, and the specific historical time period to which it applies varies from culture to culture.

gives the duration of the year as 360 days. This was synchronized to the seasons simply by adding 5 days to the calendar. Solstice days were also noted in the literature. The concept of the *Yuga* was introduced as a more sophisticated attempt to synchronise the solar and lunar calendars. The five *Yugas* were *Samvatsara, Parivatsara, Idāvatsara, Anuvatsara and Idvatsara.* Two intercalary months, *Amhaspati* and *Samsarpa*, were added to complete a *Yuga*. While commenting on the *Yuga Lagadha*, the author of the *Vedanga Jyotisha*, which dates to 1350 BC (Sastry and Kuppanna 1985), had a fairly good idea about the year including a fraction of a day (see Narahari Achar 1997). Hence, their understanding of astronomy was good. However, it is interesting that this knowledge is not just applicable to a settled population but seems to be more suited to a fairly advanced culture with needs for a long-term calendar, unique numbering of days, and other concepts. We will return to this point later in our discussion, when we talk about the astronomy of civilization.

One further aspect of this stage of astronomical evolution is the birth of some basic ideas about cosmology. One of the verses in *Rig Veda* (X, 129), for example, speculates on the origin of the Universe[4] in the following terms:

1. At first was neither Being nor Non-being.
   There was not air nor yet sky beyond.
   What was its wrapping? Where? In whose protection?
   Was water there, unfathomable and deep?

2. There was no death then, nor yet deathlessness; of night or day there was not any sign.
   The One breathed without breath, by its own impulse.
   Other than that was nothing else at all.

3. Darkness was there, all wrapped around in darkness,
   And all was water indiscriminate: Then
   That which was hidden by the Void, that One, emerging,
   Stirring, through power of Ardor, came to be.

4. In the beginning Love arose,
   Which was the primal germ cell of the mind.
   The Seers, searching in their hearts with wisdom,
   Discovered the connection of Beings with Nonbeing.

5. A crosswire line cut Being from Nonbeing.
   What was described above it, what below?
   Bearer of seed there were and mighty forces,
   Thrust from below and forward move above.

6. Who really knows? Who can presume to tell it?
   Whence was it born? Whence issued this creation?
   Even the Gods came after its emergence.
   Then who can tell from whence it came to be?

7. That out of which creation has arisen,
   Whether it held it firm or it did not,
   He who surveys it in the highest heaven,
   He surely knows – or maybe He does not!

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[4] This is generally referred to as *Nasadiya Sukta.*

We have taken this translation from Panikkar (1977: 58). As one can see, the verse itself is very beautiful, and even though it may appear startlingly presumptive of the current ideas of cosmology, clearly it is a poet's impression of the origin of the Universe. However, it is more indicative of the religious thinking of the period rather than of the evolution of great scientific insight. The format of Hinduism at the time of creation of this verse was that of a tripartite relation between humans, ancestors and gods (see Jemison and Witzel 1992). Hence, gods were a part of a group that exchanged favors with each other. Gods were not all-powerful, everlasting representations of nature, and hence any speculation on the origin of the Universe had to go beyond the gods. However, read in the background of today's knowledge of the origin of the Universe, the verse appears far more perceptive than how it must have appeared when it was originally created.

Another poem, in a slightly later *Atharva Veda*, includes interesting speculation about time:

> Time, drives like a horse with seven wheels
> Seven are the hubs; its axle is immortality
> At the head of all beings, Time proceeds
> Unceasingly, the first amongst Gods. (53–2)
>
> Time has gathered together all beings that are;
> He has passed through all the gathered beings.
> He who was father has become their son
> There is no glory higher than this. (53–4)
> Time generated the Sky above
> And this vast Earth. The passing moments,
> Present and future, by set swinging,
> Are reckoned out in due proportions. (53–5)
>
> In Time is energy, in Time the highest good.
> In time is the Holy Utterance.
> Time is the lord of all there is,
> The Father, he, of the Creator (53–8)
> Sent forth by him, from him, all this
> Was born. On him is it established.
> So soon as he has become Brahman,
> Time supports the highest Deity. (53–9)
>
> Having conquered the worlds by the Holy Word,
> Time, the God Supreme, goes on. (54–6)[5]

This translation of the poem from the *Atharva Veda* (XIX, 53, 54) is taken from Panikkar (1977: 217–219). Again, this poetic imagery of time is beautiful in its own right. It is acknowledged that time is universal and the father of all. But time ends up being the son of his own creation, obeying his wishes like a good son. And yet, he remains the god supreme who goes on well beyond the period of his own creation. This self-contradictory nature of time is beautifully illustrated in this poem.

These kind of poetic expressions of rather abstract ideas about the Universe and mankind's place in it are typical of the period. They are also often intimately

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[5] These two verses, 53 and 54, are referred to as *Purnah Kumbhah* and *Kala* respectively.

Table 1 Dating of some ancient documents based on their astronomical references

No	Document	Dating (BC)	Comments	Reference
1	Yajur Veda	2300–2950	Vernal Equinox in *Kritika*	Sastry and Kuppanna (1985: 12)
2	Maitreya Bramhana – Upanishad	1660	Winter solstice at midpoint of *Sravistha* and summer solstice at the beginning of *Magha*	Sastry and Kuppanna (1985: 12)
2	Yajur – Vedanga Jyotisha	1370	Summer Solstice in *Uttarasadha*	Sastry and Kuppanna (1985: 12)
3	Period of Lagadha	1340	Polar latitude of *Sravishtha*	Sastry and Kuppanna (1985: 13)
4	Mahabharata	1200	*Saptarshi* calendar	Sule et al. (2007)

connected with the mythology of the period. Their relation to religious ceremonies, on the other hand, is not clear (Staal 2008). However, stripped of their poetic imagery, these poems are rather simple, and are driven essentially by philosophical ideas.

Even in this period, astronomical observations were accurate enough to permit the dating of some of the ancient documents on the basis of their astronomical references (see Table 1). However, it must be added that in many cases, the dating is considered controversial, and even the same data have been differently interpreted by different workers. The most interesting of this is the dating of the *Mahabharata*.

Following this stage, this intense process of creativity and study takes the evolution of astronomy to the next phase, namely that of civilization.

7 The Civilization Phase

During this stage, society tends to be far more organized, and with organization comes increased efficiency. This efficiency allows society to develop specialized tasks and create specialists (such as teachers and pupils), resulting in the emergence of knowledge. Such a society can have people who will spend a lifetime studying and speculating on nature. It was at this stage that the disciplines of astronomical mythology, cosmogony and astrology begin to take root. With increasing wealth, not only does the hierarchy within a society begin to strengthen, but more interesting consequences arise. The owners of wealth become possessive enough to become seriously worried about their future, particularly the conservation or increase of their wealth, as well as passing it on to their offspring. Hence, predicting the future becomes an obsession. Astronomy, with its moving Sun, Moon and planets, provides one of the means of predicting the future. Astrology therefore becomes the driving force for astronomy. In the absence of other knowledge, such activities gain a certain degree of respectability. Also, by then astronomical information becomes more precise, and often the documents created in this Phase can be dated using astronomical information (see Table 1).

Society also begins a systematic reinterpretation of old ideas and the creation of new ideas. Speculation about astronomy and the Universe becomes more sophisticated, and an interesting mixture of religious beliefs, astronomy and architecture emerges, reflecting the cosmogony of the period. With the need to predict and calculate planetary motion and eclipses, some mathematical astronomy also begins to emerge at this stage. Astronomical references in the post Vedic literature clearly show this to be true.

7.1 Post Vedic Astronomy

Several complex ideas can be seen in the astronomy of the late Vedic period. Sule et al. (2007) have discussed the *Saptarshi* calendar that *a priori* seems to be absurd. It states that the constellation of *Saptarshi* (Ursa Major) visits different lunar mansions, spending 100 years in each mansion and then moves on. A particularly important event in the Indian epic *Mahabharata* discusses this calendar and since none of the constellations moves in the sky it is assumed to be more philosophical than real. However, Sule et al. (2007) have shown that the original reference is more specific. It states that if you take the vector joining the North Pole with the midpoint of the first two stars of Ursa Major, that vector points to a specific lunar mansion. This is defined as the house of Ursa Major and it is this vector that moves over a period of 100 years. Sule et al. (2007) have simulated the movement of the vector and shown that around the period of 1200 BC the vector did move from one lunar mansion to another. However, its subsequent movements were slower and not monotonic. It therefore seems that for a short period of observations, totaling perhaps ~150 years, this method of calendar-making must have appeared attractive – even if it was later discarded because it was not accurate enough.

The cosmogony of the post-Vedic Upanishad Period in India is equally fascinating. In the Brihadaranyaka Upanishad (the sixth Brahmana, dated to the eighth and seventh centuries BC), Yagnavalkya describes the Universe to Gargi in the following terms (Max Muller 1962: 130):

> Everything on earth is wrapped in water
> Water is wrapped in air
> Air is wrapped in sky
> Sky is wrapped in the world of Gandharvas (planets?)
> Worlds of Gandarvas is wrapped in Aditya (Sun)
> The world of Sun is wrapped in the world of Chandra (Moon)
> The world of Moon is wrapped in the world of Nakshatra
> The world of Nakshatra is wrapped in the world of Deva's
> The world of Deva's is enclosed in the world of Indra
> The world of Indra is wrapped in the world of Prajapati
> The world of Prajapati is wrapped in the world of Bramhana

Clearly, this is far more sophisticated than the poetic speculations of the *Rig Vedic* period. Interestingly, only the placement of the Moon beyond the Sun is in error, otherwise the first seven points are fairly close to our present understanding! Meanwhile, through the last four points we end up with a more metaphysical description of the Universe. The order of the various points is instinctive rather than scientific, and the last three levels – the worlds of Indra, Prajapati and Bramhana – are really beyond physical description.

7.1.1 Temple Architecture

One of the important aspects of this Period is the mix of astronomy and religion in the form of architecture. While megaliths of unknown use are known to exist in India from prehistoric periods (see Moorty 2008), an interesting off-shoot of the work in this period is the design of temples in a manner that is of significant astronomical interest (Kameshwar Rao 2005). At least some of the megaliths in Europe are known to have astronomical significance (Baity 1973), and it seems likely that these megaliths soon acquired a ritualistic importance in the community. They can then acquire a central place in the life of the community, a place that is later occupied by temples. Since, Indian temples are known to be constructed with a certain amount of astronomical accuracy, this may well be a legacy of the merger of astronomical megaliths with places of ritualistic and religious focus. An exception to this is the cave temples which were used in some places.

Indian temples are designed with two specific aspects in mind. Firstly, the central idol itself and the entrance leading to it are oriented east-west so that the light coming from outside is collimated in such a way that the idol is illuminated only on a specific day. In more elaborately worked out temples, the outer pillars that support the temple structure also cast their shadows at a specific location. Some of these important pillars are also marked with astronomical signs.

7.2 The Astronomy of Indus Culture

The earliest of civilizations in India is the Indus Culture. However, due to an apparent discontinuity between the Indus Culture and the rise of the second urbanization in India (Petraglia and Allchin 2007) there is no clear idea about Indus astronomy. Even so, the Indus Culture itself is very sophisticated (Lawrel 2008; Possehl 2002), and hence may have had fairly advanced astronomy. The Indus Culture has several features unique to this period. Its large population stayed in well-planned cities with wide and narrow streets, entrance gates, large central halls and other features that are typically urban. Their sense of geometric precession can be gauged from the fact that even on the scale of the city, the streets tended to be nearly orthogonal in their layout and also along cardinal directions. At least one city, Mohenjo Daro, was build on fresh land which had been prepared, and plans for the street layout and water and drainage systems were probably finalized before construction of the town began (Possehl 2002). Hence, it was an urban civilization by any standard. It was also known to have had extensive maritime connections with West Asia, several 1,000 km away. At the peak of the Indus Culture (2500–1900 BC) contact was probably maintained by sea, so astronomy would have been a constant travelling companion.

There has been speculation about Indus astronomy. For Example, Parpola (1994: 198–210) discusses Vedic astronomy in the context of Indus culture and points out that the *Nakshatras* appear fully formulated in the tenth (and the most recent) book of *Rig Veda*. The original texts that formed the *Rig Veda* are found in family (source) books which were preserved by the various families of the priests who wrote the *Rig Veda*. However, the *Nakshatras* appear directly in the *Rig Veda* without reference to these earlier family books. Vedic literature has an elaborate luni-solar calendar that is of little use to nomadic people but is crucial for the administration of cities. Time reckoning using 10,800 bricks to account for 10,800 moments in a year (360 days × 30 mahurats/day) appears suddenly and fully developed in the *Yajurveda*. The date of *Rig Veda* (between 2000 and 1500 BC) is much recent than some of the observations reported in it (e.g. see Table 1). All this indicates that Vedic astronomy was very advanced for the semi-nomadic Indo-Iranians who were the creators of the Sanskrit language that they brought from western Asia. One more point is that while horses are central to Vedic culture, they are absent in the design of the *Nakshatras*, indicating that the latter were not designed by Vedic people (Vahia 2008).

Architecturally, one feature of interest in Indus civilization are the long collimated structures to the left of the great circles in Figure 5. While these were originally identified as granaries by Wheeler (1966) recent studies of the sediments and the reconstruction patterns of this region shows that they were not granaries (see Possehl 2002). These collimated structures are several tens of meters long and several meters high and seem to point exactly north-south. It therefore seems that this region of Harappa was designed for astronomical purpose, but this needs to be confirmed.

Similarly, at Mohenjo Daro there are structures that are also aligned in cardinal directions. Wanzke (1987)) discusses their orientations in detail and has shown that they probably had astronomical significance. In addition, Maula (1984) has looked at the large stone donuts found at Mohejo Daro which have outer diameters of about 45 cm and thicknesses of the order of 26 cm. Upon looking at the markings and other records he suggests that they were designed to keep track of the solstices and the equinoxes. These were especially necessary since the distant landscape of Mohenjo Daro was rather featureless, unlike the distant landscape at other sites which provided natural markers for various observations.

Hence, although no exhaustive study of the astronomy of the Indus people exists, there are sufficient grounds to be optimistic about this.

A well-established civilization in fact is a complex structure and can take astronomy to a level where it becomes far more exacting. It therefore seems that Indus culture must have had strong astronomical traditions that need to be systematically researched.

8 The Technology-Based Phase

Modern astronomy involves a large number of broad fields of study. The first of these is mathematics, where astronomers attempt to make accurate measurements of planetary motion, the movement of the equinoxes etc. A second field is physics, where real or imagined properties are attached to all objects – including the ones in the heavens – and attempts are made to create a physical view of the Universe. Astrology also becomes important at this stage. There are some excellent reviews of

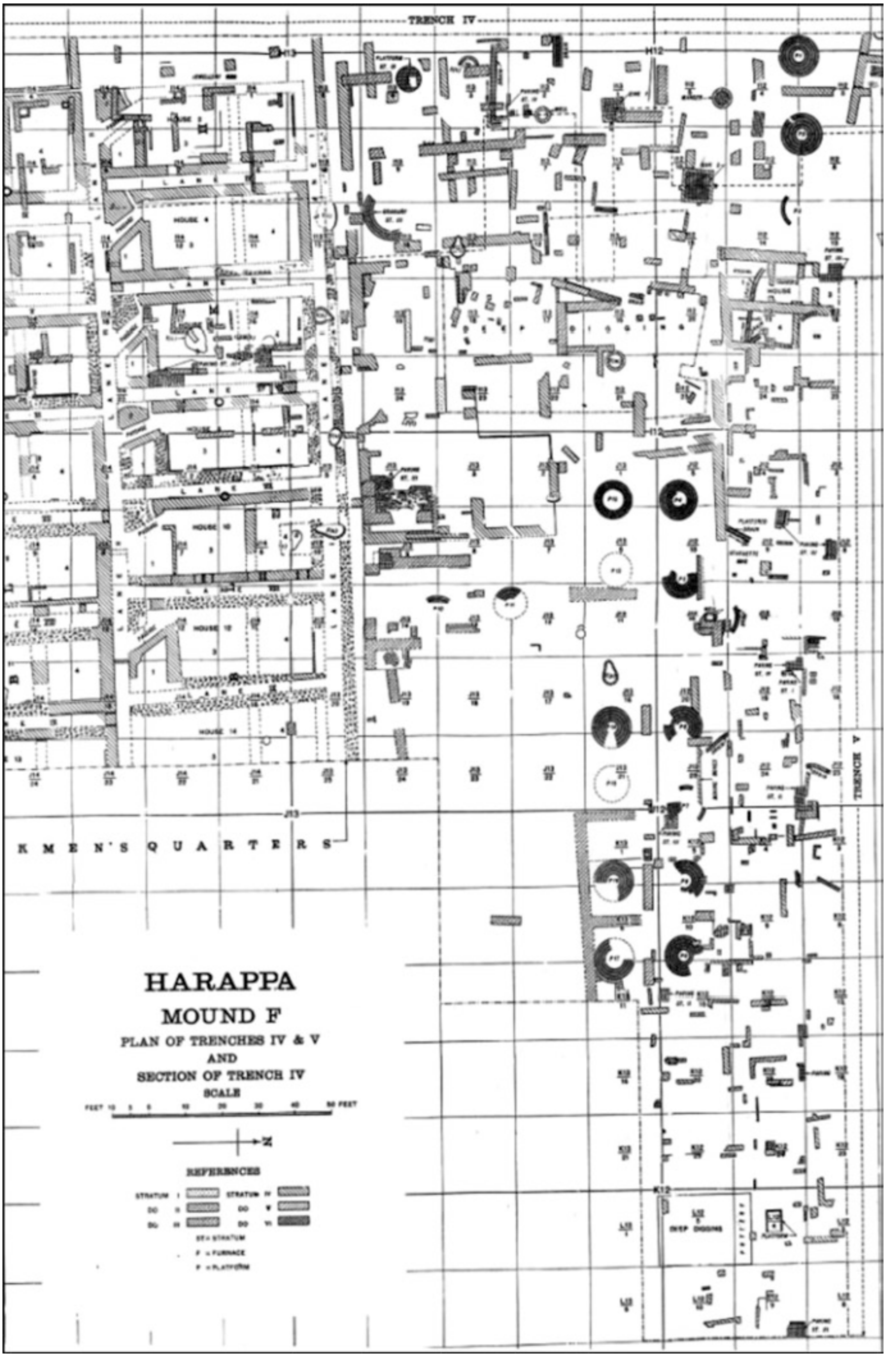

Fig. 5 Layout of the Great Hall at Harappa (after Wheeler 1966).

astronomy and other sciences during this period (e.g. Kochhar 1999), and we will only discuss this in a broader context.

Once a civilization grows beyond a certain level of sophistication, specialized tasks begin to emerge and not everyone is expected to be proficient in all aspects of life. This translates into specialized education programs that come in a variety of forms. However, a common feature of most of these is state patronage. Depending upon the capability, developments in astronomy will be driven by mathematical and/or technological factors. Interaction with neighboring cultures can also inspire growth or change. From here on, the growth of astronomy follows the same growth plan as the rest of the society.

In an Indian context, this phase begins around 500 AD with the advent of Siddhantic (mathematical or computational) astronomy and great astronomers like Aryabhata. There was also strong influence from Greek astronomy. The preoccupation of Indian astronomers for the next millennium was the calculation of geocentric planetary orbits and development of algorithms for solving mathematical equations arising in the process, with instrumentation and observation playing a secondary role to computations.

With the advent of formal and large-scale education and specialized teachers, for example, the requirements for a good astronomer become stringent. According to Brihad Samhita of Varahamihira (Subbarayappa and Sarma 1985: 10), an astronomer should be a man of great personal strength and should:

- Know the time divisions of a *yuga*, a year, the solstices, the seasons, a month, a fortnight, a day, a night, *yama* (90 min), *mahurta* (48 min), *nadi* (24 min), *prana* and *truti*, and be able to calculate their starting and ending times
- Be able to prepare *sauras* (planetary calendars, including the retrograde motion of planets and their different speeds in the sky) and *savanas* (terrestrial calendars)
- Understand and calculate solstices
- Calculate the times of eclipses
- Understand the Earth's rotation and revolution, including concepts of differences in the lengths of day and night
- Calculate latitude and longitude of a location (from Ujjain)
- Understand *nakshatras* and zodiacs and identify them in the sky
- Teach all this to a learned person

Note that knowledge of astrology is not one of the requirements.

8.1 Evolution of Ideas

There are many myths and stories that evolve and the meanings assigned to them change with time to incorporate new ideas. For example, in the early mythologies, eclipses were caused by the demons *Rahu* and *Ketu* trying to eat up the Sun and the Moon respectively. However, once the mathematics of eclipses was known, *Rahu* was referred to as the ascending node of the orbits of the Sun and the Moon and *Ketu* as the descending node of the orbits of Sun and Moon, and were assigned the names of pseudo-planets. Equations are formulated to determine the times of eclipses.

8.2 Time Units

Similarly, the idea of time underwent significant change. We have already discussed philosophical ideas about time in Section 6. The Vedas defined a 12 month luni-solar calendar and recognized the fact that there was a discrepancy between the seasons and the 12 lunar months. They therefore proposed the idea of intercalary months (two every 5 years) to resynchronize the two. In the *Vedanga Jyotisha*, which reviews Vedic astronomical knowledge (see Subbarayappa and Sarma 1985, footnote on page 51), 5 solar years is defined as one *yuga*; 366 days or 12 solar months as 1 year; 30 *mahuratas* as 1 day (i.e. 1 *mahurata* is 48 min); two *nadikas* as one *mahurata* (i.e. one *nadika* is 24 min); 201/20 *kala* as one *nadika* (one *kala* is therefore 2.4 min); and the *kala* itself is subdivided so that 124 *kasthas* (about 1.1 s) make a *kala* and five *gurvaksaras* or ten *matras* comprise one *kasthas*. However, while these ultra-fine steps of time were defined, there was no clear outline as to how they should be measured or utilized. Most activities stopped with the *nadika* (i.e. 24 min), although time up to the *kastha* could be measured by using a heartbeat or the recitation of verses of a specific length.

By the time of Vateswara (904 AD, see Subbarayappa and Sarma footnote on page 53 and page 313 for period of Vateswara), the division of time had been extended. One hundred years of Bramha is his life span; 1 year of Bramha is 725,760 human *yugas* and 1 *yuga* is therefore 4,320,000 human years. At the opposite end of the time-scale, 2.5 *kasthas* or *asu* make 1 *as* or 4 s (the time taken to complete one breath); one *kastha* is the time taken to recite four long syllables; 1 *nimesa* is the time taken for the eye to blink; and 4.5 nimesa equal one long syllable or ¼ of a *kastha*. The *nimesa* itself is divided into 100 *lavas*, and one *lava* is divided into 100 *trutis*. One *truti* is defined as the lotus pricking time! While some ideas about the time units are given, they seem to have been designed more for the pleasure of defining them rather than using them for any specific purposes.

However, Vateswara (ibid.) also clarifies that there are nine basic time reckonings, as listed below in Table 2.

The concept of a *yuga* is also a complex one that has been significantly modified over time. Indeed, the word *yuga* itself has three different meanings (Kochhar 2007). During the Vedic period, it was used to construct cosmic chronology while in mathematical astronomy it was applied to calculate planetary periods. During the Puranic period, the term *yuga* was employed in the context of human existence. But even when it was assigned a specific time interval, its duration varied from 5 years in Vedic literature to several millions years in later literature.

Table 2 Time reckoning according to Vateswara

Reckoning	Unit used	Definition
Sidereal	Sidereal day	One star rise to the next
Lunar	Lunar month	One new moon to the next
Solar	Solar year	Period of one solar revolution
Civil	Civil day	One sunrise to the next
Brahma	Day of Brahma	Period of 2 *kalpas* or 2,016 *yugas*
Jovian	Jovian year	Period of Jupiter's motion through a zodiacal sign
Paternal (Manes)	Day of Manes	1 lunar month
Divine	Day of Gods	1 solar year
Demoniacal	Day of demons	1 solar year

8.3 Numerology

The numbers 12, 60 and 360 have astronomical significance, starting with 12 months in a year and hence the movement by the Sun through $^1/_{12}$ of the sky in the course of 1 month. A day is made up on 60 *nadikas* and 12 civil days make a year. To avoid fractions the sky is divided into 360° (12 × 30), so the Sun moves one unit per day.

These numbers form the basic units of time and could be astronomical in origin. Also, some of the ancient civilizations, including the Babylonians, used 60 as a base for their number system (i.e. the sexagesimal system). It is generally believed that the selection of 60 over other numbers could have been in order to make calculations easier, as 60 has 10 integral factors (2, 3, 4, 5, 6, 10, 12, 15, 20 and 30), more than any other number of comparable size. Thus, we have the division of hours into 60 min, a minute into 60 s, a circle into 360°, each of 60 min (each minute of 60 arc seconds), and so on.

8.4 The Drive of Technology

Another feature of this period is the construction of large structures that were used to study astronomy. Refined versions of the original megalithic structures now appear as large observatories which were used by astronomers in an attempt to measure stellar parameters and their variations with great accuracy. In India these are called *Jantar Mantars*, and one of the finest examples is in Delhi (see Figure 6). It was built between 1724 and 1727 AD, and its primary purpose was to measure stellar parameters. However, by this period, telescopes had been invented and were in regular use. The era of telescopic astronomy in India is well documented (e.g. see Kochhar 1985, 1991; Kochhar and Narlikar 1995) and is not discussed here.

Fig. 6 Jantar Mantar, New Delhi, an astronomical observatory.

8.5 Navigational Astronomy

One of the biggest uses of astronomy is in navigation. In an Indian context, astronomy has long been used for navigation, and Arunachalam (2002) has detailed ways astronomy was used from the fourteenth century onwards for maritime purposes. This exhaustive study discusses the astronomical tools and methods used by Indian fishermen. Sea-farers along the west coast of India typically made use of a chart of the rising and setting points of various constellations (Figure 7), drawn according to their personal preferences. To reach another port, they would follow the rising or setting location of a particular constellation for a certain period and then turn towards another constellation. In order to monitor their progress they used simple knotted floatation devices and other tools.

9 Concluding Remarks

Throughout human history, astronomy has evolved in a gradual manner. Starting with the first attempts to understand the Sun and Moon and their relevance to human life, the journey to telescope and satellite-based astronomy has been a long and difficult one.

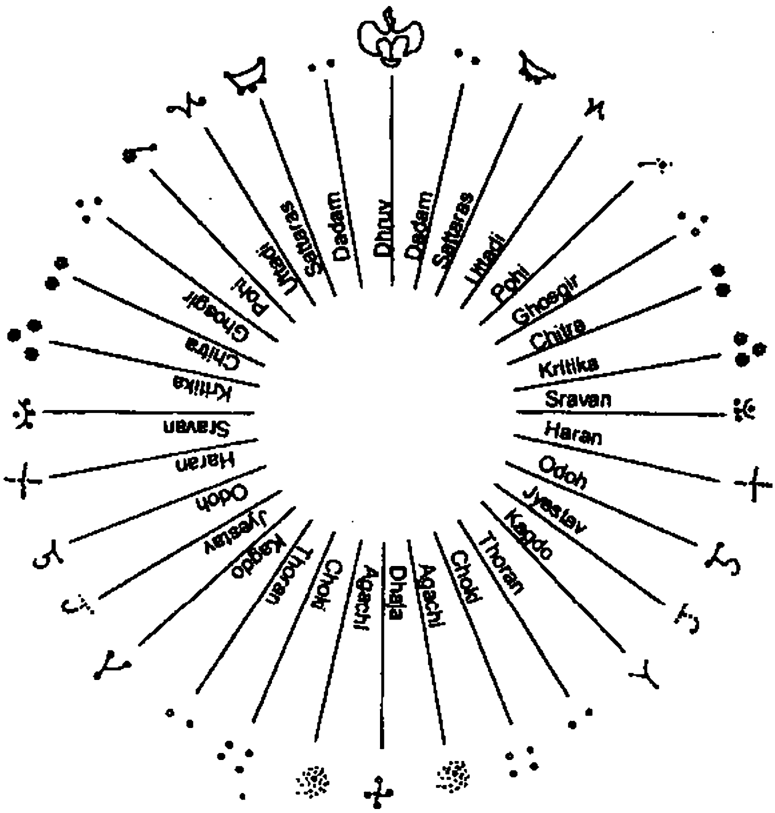

Fig. 7 The sky chart used by Indian fishermen.

In this paper we have attempted to trace this growth by identifying a succession of distinct stages or phases. Using examples from India, we have attempted to illustrate the various phases, but the formulation is general enough to be applicable to a wide variety of cultures throughout the world.

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The Astronomy of Peruvian *Huacas*

Steven Gullberg and J. McKim Malville

Abstract The Incas honored and venerated many features of both natural and man-made landscapes that they felt to be endowed with superhuman powers. In Quechua these shrines were known as *huacas*, and at the time of the Spanish conquest there were thousands of them. Soon after invading the Incan homeland the Spaniards began a campaign against the indigenous religion that included a systematic eradication of *huacas*. Shrines that were large carved stones and outcroppings survived, however, and form part of our study. A number of these were found to have astronomical meaning, marking events such as solstices and equinoxes. Water channels are associated with the majority of astronomical *huacas*. Ritual stairways are also common features, symbolizing shamanic movement between the three worlds of Incan cosmology.

The Incas built as many as 16 pillars on the horizons of Cusco to mark the positions of the rising or setting Sun on significant dates of the year. All were destroyed. Two pillars above the modern village of Urubamba that escaped the Spanish purge mark the rising Sun at June solstice as viewed from a large granite boulder in the center of the courtyard of the palace of Huayna Capac. Viewed also from the boulder, in the direction of the December solstice sunrise we have located stone structures on the distant summit of Cerro Unoraqui. The major axis of the courtyard of the palace is oriented approximately toward Cerro Unoraqui.

1 Introduction

The Incas honored and venerated a large variety of features of the natural landscape such as mountains, caves, springs, lakes and rocks that were endowed with transcendent and superhuman power (Bauer and Stanish 2001; D'Altroy 2002;

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Salomon 1991). In Quechua these objects or places were known as *huacas* (*wak'a*) (Zuidema 1964). In 1653 the Jesuit priest Bernabe' Cobo compiled a list of *huacas* in the vicinity of Cusco. He gave the names, descriptions, locations and offerings of each. Although his list contained 385 *huacas*, only 324 of them can be actually identified. Of these, most *huacas* (261) are natural features of the landscape; 89 involve water, 83 are geographic features such as hills, plains, passes, and 83 are stones.

The most powerful *huacas* required maintenance and care-taking. Gifts were made to the powers of the shrines. Animals and produce were sometimes sacrificed to the shrine and used to support the attendants. The carved *huacas* are bedrock features with their roots in the earth, like ancestor trees which produce life in the form of fruit. The tree and rock link the three worlds of the shaman.

Around Cusco the *huacas* were organized along lines or *ceques* (*zeq'e*). *Ceques* were important features of the shrines in the Cusco valley, and one of their symbolic roles may have been to affirm and supplement the inherent directionality of *huacas* (Zuidema 1964). They may have been part of an ancient Andean tradition which included the Nazca lines, for which, again, there are a variety of interpretations such as water rituals, astronomical sightlines, and depictions of star patterns. Some of the *ceques* may have been organizational in intent, indicating sequences of ritual visits, responsibilities for individual families and groups, panaquas and aylluas, and assignment of territory and irrigation sources. Some may also have marked ritual pathways or simply convenient routes of movement.

Shortly following their invasion of the Incan homeland, the Spanish destroyed the most important shrines such as the Temple of Pachacamac and the Coricancha of Cusco. In 1539 the Spanish began a campaign against the indigenous religion and proceeded systematically to destroy *huacas*, with the consequences that attendants and worshippers of known *huacas* were prosecuted, sometimes tortured, and even put to death. The foundations of the shrines were dug out, the objects of worship were destroyed, anything flammable was burned, and finally a cross was often built over the site. An unintended consequence of this campaign of destruction was that the names and locations of *huacas* were recorded so that they could be examined in the future to make certain no religious activity continued. Some of the *huacas*, such as large carved rocks, could not be destroyed and remain to this day at sites such as Kenko, Chinchero, and Saihuite. Shrines such as these serve as the focus of our field research.

The meaning, numbers and locations of *huacas* probably evolved under different dynasties, and there are different approaches to the carving of *huacas* between Pachacuti and his son and grandson, Topa Inca, and Huayna Capac. The concepts manifested in stone *huacas* were probably dynamic instead of rigid and fixed according to a pre-existing rule (Niles 1987).

The Spanish were confounded by the variety, complexity and alien symbolism of the *huacas* and failed to comprehend their fundamental meaning. A Peruvian witness recorded in seventeenth century court documents commented that the Spanish had their *huacas*, but they did not feed them. As we have come to learn, *huacas* have many levels of meaning and great time depth in Andean culture.

1.1 Ancestor Worship

A valuable perspective for understanding Andean *huacas* has been provided by the great Peruvian archaeologist, Julio Tello, who recognized that ancestor veneration has been one of the major and enduring features of Andean civilization (DeLeonardis and Lau 2004). *Huacas* appear to be major elements in Andean cosmology extending back to the second millennium B.C. and often were shrines to ancestors who, it was believed, could influence the living. The division between the living and the dead was blurred if not non-existent. Feeding of *huacas* was a major motivation for communication with ancestor-gods and for sacrifices. Blood, *chicha* (corn beer), and water were valuable nourishments. Mummies and images of ancestors were carried in processions, placed on platforms, consulted and fed. The Incas believed that the Sun was their ancestor, a connection affirmed by the Sun to Pachacuti on the eve of the epic battle against the Chancas when the Sun emerged from a spring (Zuidema 1982). Caves may have contained mummies at Kenko, Lacco, and at Machu Picchu in the Royal Mausoleum and Temple of the Moon.

1.2 Mytho-Historic Traditions

Carved *huacas* may express mytho-historic traditions of the Incas, such as creation mythologies dealing with water and caves, animism, and shamanistic ritual. Origin myths of the Incas involve emergence of the creator, Viracocha, from the waters of Lake Titicaca. The Sun, Moon and stars were evoked from an island in Lake Titicaca, traditionally the Island of the Sun, where there was a major Incan shrine and pilgrimage destination point. Some of the human creations of Viracocha were sent underground from the place of origin to emerge as ancestors out of springs, caves and snow covered mountain tops (Urton 1999). The meaning of caves, springs and water channels at *huacas* may be derived from such origin myths. Ritual stairs are a dominant motif of *huacas*, expressing movement of the ancestors up from the Earth, shamanic travel between words, and transformative acts (Eliade 1964). Some of the stairs are stunning in their lack of functional purpose, often emerging from nowhere and leading nowhere. A fascinating aspect of certain sets of stairways is their fractal nature, duplicated with smaller and smaller scale, perhaps expressive of a perceived continuity of nature across all dimensions. There are many inaccessible portions of stairways on the sides of cliffs at Ollantaytambo; stairs that pass through caves at Chinchero; steps within caves such as the Royal Mausoleum at Machu Picchu.

1.3 Camay

Running water was understood in the Incan world as a vitalizing life force, known by the Quechua verb, *camay*. In the complex cosmology described in the Huarochirí manuscript, life is born from the ‘embrace’ of feminine Earth by masculine water, homologous to the growth of plants from soil when moistened by water (Salomon 1991; Taylor 1974).

Places, objects, stones and mummies could be similarly animated by the circulation of running water and the pouring of libations and offertory liquids (Bray 2009; Malville 2009). Once animated these objects and places could become sentient beings with superhuman powers. The *huacas* associated with water or other ceremonial liquids combine origin myths, practical needs of agriculture, and ritual involving 'sympathetic magic' intended to bring on rain and harmony in the land. The act by which *huacas* are brought into being is expressed by the verb *camay*. The meaning of *camay* is carefully distinguished from that of 'create', which suggests creation out of nothing, *ex nihilo*. Also it is distinguished from 'fashion', which suggests an initial shaping of inert matter and nothing thereafter. Consistent with the metaphor of the cultivation and nurturing of plants, *camay* is intended to describe a continuous act (Salomon 1991).

At Tiwanaku drainage canals may have served a ritual as well as a hygienic function. Couture (2004) suggests that circulation of water through these large canals may have been intended to imbue the area and its inhabitants with *camay*.

Water in the form of rain, snow and glacial runoff, irrigation canals and rivers, and the Milky Way was the kinetic part of the world and moved over the Earth rising up from the ocean into the sky via the Milky Way. Water is carried upward by the celestial llama, which then washes down from the mountains, bathing and fecundating the Earth as it descends to the oceans.

Offerings to *huacas* were also meant to encourage the flow of energies necessary to maintain harmonious relations. Forces of flow in nature are stimulated by pouring liquid offering in channels. Liquid offerings encourage the flow of energy necessary to maintain harmonious relations on the Earth. Such harmony and balance is associated with a reciprocal exchange between humans and ancestral powers. A common motif of carved *huacas* is a straight or zigzag channel (Quechua: *qénqo*) through which liquids, water, corn beer (*chicha*) or blood could flow. Examples of such ceremonial zigzag channels are found at Kenko Grande, Saihuite, Chinchero and Vilcashuman (see Figure 1). Local informants at Chinchero have indicated that its *qénqo* may be a modern construct (Jessica Christie, personal communication), which is itself an interesting revelation since the women of Chinchero frequently incorporate the *qénqo* pattern in their weaving (Alvarez 2007).

A paradigmatic example of *camay* is found at Saihuite where the extravagantly carved, egg-shaped principal stone is threaded with channels into which liquids could be poured. The rock contains images of pumas, reptiles, frogs, shellfish and humans, intricately threaded with channels. Liquids, poured into the rectangular basin at the top of the rock, would have circulated though this microcosm, thereby animating, perhaps, the entire Incan cosmos. Saihuite contains a niche opening to June solstice sunrise, which may thereby identify one of the dates when this ceremony of *camay* was performed. Elsewhere at Saihuite one finds cardinally-oriented platforms and stairways (Zawaski 2007). Other offertory channels were present at Llactapata, Corichancha and the Sanctuary of the Island of the Sun, all of which are also associated with June solstice sunrise. The first Europeans to visit Lake Titicaca reported the presence of

Fig. 1 *Qénqo* at Chinchero. This pattern is used by the weavers of Chinchero (Callañaupa Alvarez, 2007); the carved channel may be a modern construct.

large numbers of "… women who make *chicha* in order to throw it upon that stone …" and pour *chicha* into a large stone basin (Bauer and Stanish 2001: 206). Natural water channels are found at Ollantaytambo, Quespiwanka, Machu Picchu, Pisac, Choquequirao and Tipon. Dearborn and Schreiber (1986) report a carved edge on the Intiwatana of Pisac, which is oriented to June solstice, similar to that of the Torreon of Machu Picchu (Dearborn and White 1983). Most of the Incan *huacas* that display astronomy are associated with June solstice and water channels (see Table 1).

1.4 Endogenous Power

The Incas apparently believed that rock could also be empowered and energized by elaborate carving. Such carving, which is represented in *huacas* in the vicinity of Cusco, may have been attempts to express, manifest and bring into being inherent meaning contained in a unique rock, its 'endogenous' meaning (Paternosto 1989: 94). The chthonic power of rocks, with deep roots in the ground, emerging from the Earth, seems manifest in many of these carved stones, providing contact with the primordial powers of Pachamama. Stones that were unusual in shape or in location seem to have been especially venerated. If nature had marked out such a stone, it may have been viewed as something miraculous, an entry of the divine into the ordinary, a hierophany (Eliade 1964). Niles (1987: 204–205) suggests that the Incan

Table 1 Incan *Huacas* with astronomical features

Huacas	June solstice sunrise/sunset	December solstice sunrise	Pleiades rising	Cardinal or EW orientations	Natural water channels	Poured liquids	Caves	References
Urubamba: Quespiwanka	X	X			X			1,6,8
Llactapata	X		X	X		X		2,8
Machu Picchu	X	X	X		X		X	3,4
Sanctuary Isla del Sol	X					X		5
Saihuite	X			X		X		6
Urubamba Intiwatana	X[a]			X	X		X	8
Coricancha	X		X			X		7
Vilcashuman				X		X		6
Ollantaytambo	X	X			X			6
Kenko	X					X	X	8
Lacco	X						X	8
Pisac	X				X			3

Key:
1. Malville et al. (2008)
2. Malville et al. (2004, 2006)
3. Dearborn et al. (1987), Dearborn and Schreiber (1986), Dearborn and White (1983)
4. Dearborn et al. (1987)
5. Dearborn et al. (1998), Seddon and Bauer (2004), Bauer and Stanish (2001)
6. Zawaski (2007)
7. Zuidema (1982)
8. This paper

[a] The Urubamba Intiwatana lies on the line toward the Sacred Plaza of Machu Picchu and June solstice sunrise as viewed from Llactapata

emperor Pachacuti saw himself ‘improving’ upon the work of his ‘co-creator’ by the shaping of rocks. Niles also suggests that a fairly limited number of motifs were used in the shaping of *huacas*:

> The pattern does not suggest a tolerance of innovation. It is unlikely that the Incas would encourage individual graffiti artists to practice their skills on sacred rocks. Certainly, the improvements on nature seen in Inca shrines … must have been officially controlled.

This process of *fashioning* rocks seems formally different from that of *camay*, which was understood to be a continuing process, but the presence of water channels associated with many of the carved *huacas* may have provided ongoing nurturing.

Pachacuti incorporated carefully-fitted stone masonry into natural outcrops such as at the Intihautana of Pisac and at Machu Picchu where “… buildings seem to grow organically out of the bedrock … and the boundary between the work of the architect and the Creator is blurred.” (Niles 2004: 62). Stone *huacas* in the *ceque* system of Cusco, the Royal estate of Pachacuti at Ollantaytambo, and those in the estate of Topa Inca at Chinchero appear to reveal a common interest in the empowerment of large rocks by carving and shaping. The great circular structures of Moray seem to be another example of bringing inherent meaning into being through modification of nature. These great slump holes meant little in their original form, but with elaborate terracing, they became very special, perhaps intended as ‘inverted’ *huacas* to Pachamama. They also would have been dramatic theatres for celebrating the zenith Sun. The large granite boulder in the center of the courtyard of the palace of Huayna Capac in Urubamba is uncarved, revealing a different approach to the natural world than that of his father and grandfather.

2 Llactapata and Machu Picchu

Machu Picchu appears to have served as both a sacred center (Reinhard 2007) and a Royal estate (Niles 2004; Salazar 2004). It is possible that before Pachacuti adopted the dramatic location above the Urubamba River it was already recognized in pre-Incan times as a site of power because of its granite outcrops and caves, the peak of Huayna Picchu and the cardinality of the surrounding sacred mountains. Salazar (2004: 41) suggests that Pachacuti established shrines at Machu Picchu because of the special association that he felt existed between him and the “… supernatural forces imminent in the landscape and the celestial sphere …”, and that his connection with these forces needed to be “… actively reaffirmed through daily ritual.” The major astronomical *huacas* of Machu Picchu are the Torreon-Royal Mortuary (June solstice sunrise), Intimachay (December solstice sunrise) and the Sacred Plaza, which is crossed by an axis established by June solstice sunrise and December solstice sunset.

The 2003 re-discovery of Llactapata, which overlooks Machu Picchu from a distance of 5 km, revealed a structure that has an orientation and architectural design remarkably similar to that of the Coricancha of Cusco (Malville et al. 2004, 2006;

Fig. 2 Stone-lined channel in front of double-jambed doorway of Sector I at Llactapata.

Zawaski and Malville 2009). The courtyard in front of the double-jambed doorway of Sector I contains a stone-lined channel (see Figure 2) leading from the doorway toward the Sacred Plaza of Machu Picchu, which is also in the approximate direction of the June solstice sunrise and the rise of the Pleiades (Gullberg 2010). The point of sunrise occurs in a recess on the jagged horizon (see Figure 3).

Llactapata was most likely an integral part of the ceremonial complex of Machu Picchu. Llactapata's Sun Temple is located on a nearby ridge and is surrounded by more than a hundred other structures still currently engulfed by the cloud forest. The temple is presently visible from Machu Picchu's Sacred Plaza due to clearing performed by the Instituto National de Cultura-Cusco (see Figure 4).

We examined solar reflections from Llactapata to Machu Picchu in June 2007 during our documentation of the solstice-oriented sunrise. One assistant remained behind with a mirror as we descended to the Urubamba River valley and Aguas Calientes. The next morning we positioned ourselves at Machu Picchu's Sacred Plaza, well before the rise of the Sun. The reflections of sunlight from our assistant began at 06:41, the time of the previous day's Llactapata dawn. The reflections were prominent and observed by many visitors. They continued through the Sacred Plaza sunrise at 07:17 and beyond. The 36 min period between the Llactapata and Machu Picchu sunrises would have afforded ample time for special ceremony celebrating the morning solstice Sun. Our demonstration shows only the reflection from one hand-held mirror (see Figure 4). Large gold medallions worn by the ruling Inca, or perhaps plates mounted on the temple would have produced an even more brilliant effect.

Fig. 3 Llactapata solstice sunrise June 2007.

Fig. 4 Reflection of June solstice sunrise from double-jambed doorway viewed from Machu Picchu.

2.1 June Solstice Sunrise

The rugged Andean peaks surrounding Machu Picchu and Llactapata provide ample reference for marking solar horizon events and natural features that may have been used to identify sunrises or sunsets from either location (Zawaski 2007). In June 2007 Gullberg documented the Llactapata solstice sunrise over Machu Picchu and its close alignment with the water channel extending from the Sun Temple. Both the temple and the nearby corridor exhibit astronomical alignments similar to those found in the Coricancha of Cusco (Malville et al. 2004, 2006).

Water could have been carried from a nearby spring up to the double-jambed doorway at the Llactapata Sun Temple to be poured into the channel as an offering to the solstice Sun. A similar ritual may have occurred in the Coricancha, as suggested by the three small openings in the wall to Ahuacpinta Street. Artificially-fed channels also face June solstice sunrise at Saihuite. At June solstice, the pouring of water into the Llactapata channel may have represented the feeding of the Sun during the dry season (Urton 1981). The mythic and ritual connections between the Sun, sacred mountains, the Urubamba River and the Milky Way (Urton 1981) may have been especially powerful on this *ceque* connecting Machu Picchu and Llactapata. As we have noted, *chicha* may also have been poured into these channels (Bauer and Stanish 2001).

2.2 Pleiades Rise

The long corridor of Sector I is orientated toward both the June solstice sunrise as well as the nearby rising point of the Pleiades.

The Pleiades were of great importance in Incan astronomy as the Incas found them useful in predicting and planning for harvests. The stars in this prominent grouping were viewed with regard to their relative brilliance. A bright appearance by the cluster indicated a future of ample rain with a correspondingly good harvest. A dull appearance (caused by atmospheric obscuration) indicated that there would be drought in the months to come (Orlov et al. 2000). In actuality, the Incas had discovered a method of anticipating the arrival of El Niño in a manner still used by Andean farmers today.

The Pleiades disappear behind the Sun for 37 days and first return to view at Llactapata about 9 June, 12 days before the solstice sunrise. This corridor was aimed at points on the horizon for the two astronomical events and likely served as guide in their observation, especially that of the first fleeting heliacal sighting of the Pleiades.

3 The Urubamba River *Huaca*

Deep in the Urubamba River canyon between Machu Picchu and Llactapata lies the little known carved granite *huaca* that was identified by Bingham as another *intiwatana*. The shrine, which consists of multiple carved stones, fountains, caves,

Fig. 5 The Urubamba River *Huaca.*

terraces and structures lies along more than 25 m on the side of a hill between the Peru Rail switchbacks above the hydroelectric plant located west of Aguas Calientes. The major carved granite stone measures 344 cm by 427 cm and contains carved steps and a vertical gnomon (see Figure 5). Below it is a large platform carved into the same granite boulder, which provides a view to the northeast of the Intiwatana of Machu Picchu and to the west of the Overlook Temple on the Llactapata ridge. Above the major stone are two oval basins aligned east-west and an elaborately-engineered water fountain with four spouts that is located above a small cave (see Figure 6). Further to the east of these rock carvings are the remains of several rectangular structures likely used by the *huaca*'s attendants, a tower and a second cave. The majority of the structures have east-west alignments, in parallel with the east-west orientation of the Overlook Temple (Malville et al. 2006). Another line or *ceque* that contains the *huaca* is that between the Llactapata Sun temple and the Sacred Plaza of Machu Picchu.

4 Kenko Grande

One of the most significant *huacas* in the Cusco region, Kenko Grande (Q'Enqo) is situated on a visual sightline 1,600 m north of the Coricancha. Kenko is also 1,300 m east of Sacsahuaman and lies at an altitude of 3,594 m above mean sealevel. The limestone outcropping was carved in situ by Incan masons and includes many features such as altars, thrones, water channels and basins. On its upper surface are

Fig. 6 Fountain at the Urubamba Intiwatana; note the cave beneath, to the left.

two sucancas, or bollards, that feature purposeful effects of light and shadow at the time of the June solstice. Stairways figure prominently; some are functional while others are merely symbolic (see Figure 7).

The northern section of the shrine reveals many carvings while the southern side has relatively few. A natural passage leads through the rock's interior with carvings found on the walls of both sides. Just north of the *huaca* there is a 5.5 m tall monolith thought by some to represent a puma (see Figure 8). Across from the monolith is an arced wall that contains 19 nich. (see Figure 9). While shorter at present, the wall and niches are believed to originally have been tall enough to display erect mummies. Within the *huaca* exists astronomical alignments, a cave with altars and, for the Incas, shamanic connections with the underworld.

4.1 "The Awakening of the Puma"

Kenko Grande exhibits a dramatic phenomenon at the time of the June solstice called by locals "… the awakening of the puma." The Incas venerated the condor, puma and snake with regard to their respective sacred correlations with the sky, Earth and underworld. They believed that light and shadow could transform into the shape of a living being.

Located atop the *huaca* and carved into the stone are two circular knob-like bollards called *sucancas* set there to gauge the Sun (see Figure 10). They are 25 cm high and 35 cm apart. In close proximity is a small wall with a fissure oriented for the

Fig. 7 The western face of Kenko Grande.

Fig. 8 The monolith and Kenko Grande’s north face.

Fig. 9 The semicircular wall with niches opposite Kenko Grande's north face.

Fig. 10 Bollards carved on top of Kenko Grande.

sunrise at the June solstice. Light from the morning Sun passes through the fissure and first touches the left side of the smaller *sucanca*. As the Sun continues to rise its rays move across the *sucanc*a and then illuminate the opposite one as well. The *sucancas* are situated in such a way that the glowing pair and the relative shadows will resemble a puma's face (see Figure 11). When both *sucancas* are fully illuminated the puma will have been 'awakened' according to local tradition (Gullberg 2010).

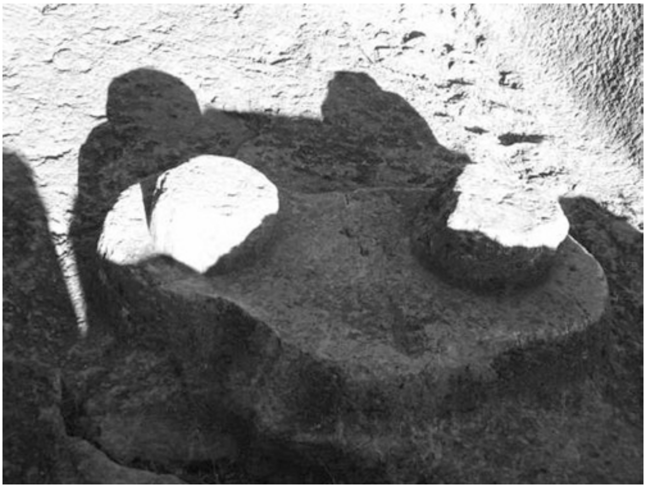

Fig. 11 Illumination of bollards at June solstice sunrise.

Fig. 12 Kenko's bollards are half-illuminated on the equinoxes.

The lore of these Incan carvings continues at times of the equinoxes. In September and March on the day of the equinox the light and shadow at sunrise split the Puma *sucancas*. The left half of the puma's face is illuminated while the right half remains in shadow, which local legend says signifies day and night as being equal (see Figure 12).

4.2 Zigzag Channel

Several rock huacas have been found to exhibit straight or zigzag channels through which liquids could flow. The current of energy necessary to establish harmony and maintain equilibrium in the world was stimulated by the pouring of such offerings, most commonly *chicha*, or corn beer, into these carved waterways. An outstanding example of such a ceremonial channel is found at Kenko Grande (see Figure 13).

Kenko Grande appears to have been named with regard to its ceremonial conduit. The channel was carved atop the huaca and within it liquids flowed to a point where they may have fallen into the cave below. Nearby, also cut into the stone, are a condor and a puma. Water, chicha or blood would run the 3.55 m course of the Q'Enqo for purposes of divination. The channel begins with a small basin and then flows 130 cm before turning slightly to the right. It continues for another 145 cm and then splits into two channels, each continuing for approximately another 80 cm (Van de Guchte 1990).

Cachot links the Q'Enqo with a very ancient Andean water cult. Zigzagging lines and cups first appear during the Lower Paleolithic and are found to flourish during the Neolithic. Paternosto (1989) states that these carvings place Kenko Grande at the beginning of Inca settlement in the Cusco area.

4.3 Interior Cave and Altars

Located within Kenko Grande is a cave sculpted from the limestone that contains two ceremonial altars (see Figure 14). The cave lies on a natural SE-NW intercardinal

Fig. 13 Zigzag channel (Quechua: *qénqo*) atop Kenko Grande.

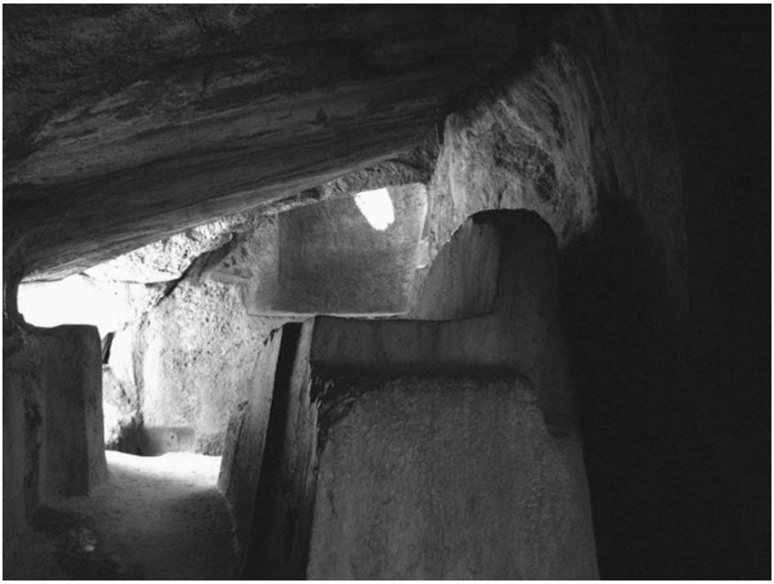

Fig. 14 Primary altar and cave within Kenko, including the niche for the illumination at the cave's northwest end.

axis and is paralleled by a similarly oriented crevasse. This bearing is of special significance to the Inca as it is the direction traveled by the god Viracocha on his journey from Lake Titicaca to the sea. The interior chamber is finely crafted, and the primary altar was carved and polished from a rectangular block. The cave has a rear entrance and thus forms a passageway within Kenko. Near the back opening is a secondary altar. Alongside the primary altar are three ritual stairs and between the two altars there is a great niche, perhaps carved for a mummy (Paternosto 1989). Locals maintain that light entering the cave through another niche located at its northwestern end was reflected with gold or silver plates in order to illuminate the entire chamber.

Three ritual stairs lie at the northern end of the primary altar (see Figure 15). During the time nearing the June solstice sunlight enters the cave, approaches the altar, and climbs the three stairs providing an additional illumination effect that was perhaps a component part of the ceremony and sacrifice (see Figure 16). Ritual stairs symbolize shamanic movement between the three worlds of the Incan cosmos. Within caves they often facilitated movement between the underworld, Ucu Pacha, and the here and now, Kay Pacha. These particular stairs, as situated, however, may symbolize ascent to Hanan Pacha, the world above. Sculpting of the cave enhanced its presence as a portal to the underworld.

At times surrounding the March and September equinoxes we found the cave's secondary altar to be illuminated at sunrise (see Figure 17). This altar is located at the rear of Kenko's interior passage and is oriented toward 90° as it looks out to the horizon. The primary and secondary altars are 2.5 m apart on opposite sides of the narrow cave.

Fig. 15 Ritual stairs at the primary altar's northwest end.

Fig. 16 Illumination of ritual stairs on 5 June 2008.

5 Lacco

Three kilometers northeast of Sacsahuaman at an altitude of 3,655 m lies the *huaca* known as Lacco (Laqo), the largest in situ limestone carving north of Cusco (see Figure 18). Bauer (1998) suggests that Lacco is the *huaca* known as Mantocalla, while Zuidema (1997) and Aveni (1981) suggest it was adjacent to a temple of the Sun known as Chuquimarca. Sometimes known as Solonpuncu (Temple of the Moon), Lacco is the largest among seven nearby outcrops (at 1,672 square meters).

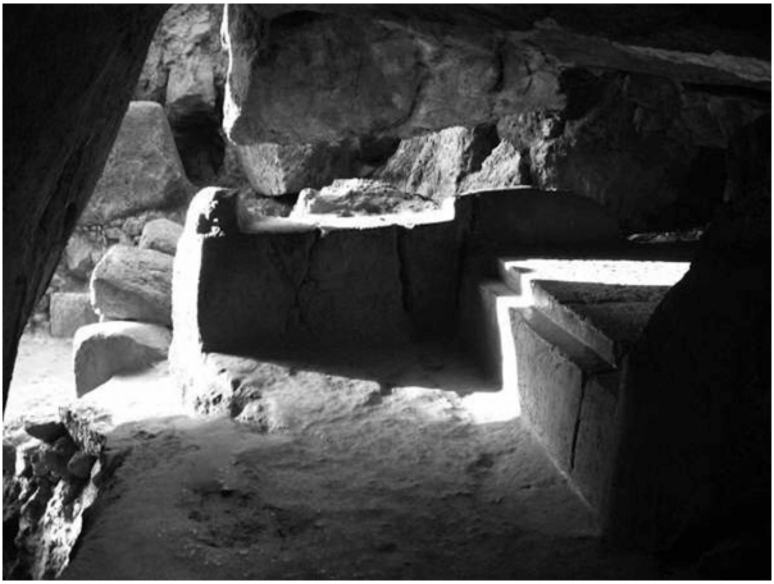

Fig. 17 Illumination of the secondary altar at sunrise on 22 March 2008.

Fig. 18 The northern half of Lacco with the sacred Mount Ausengate in the distance.

The sacred mountains Salcantay and Ausengate can be seen in the distance and colonial reports tell of a pair of pillars, no longer extant, that marked the June solstice sunset on the horizon.

The upper surface of Lacco displays many individual carvings. Found there are several seats, platforms and sculpted condors, pumas and serpents. Lacco features the only extant example of all three sacred animals sculpted together (Van de Guchte 1990). A large, primarily symbolic staircase ascends the *huaca*'s northwest face (see Figure 19) and a small gnomon is located to the southeast (see Figure 20). Within Lacco are three ceremonial caves that we found to display astronomical orientations.

A fault runs through Lacco forming a corridor connecting the northeast and southeast faces. The crevasse effectively divides the outcrop into two sections, the western one being the larger. The southeast cave is located in the eastern section, while the northeast and southwest caves lie on the west side of the divide.

The Incas apparently believed rock could be empowered by elaborate carving as well as through the movement of water. Water channels are associated with most of the astronomical *huacas* we have found and Lacco is no exception. A canal, originating at Ucu Ucu some 3 km distant, runs along the southern base of the rock, and the Inca road to Pisac is nearby. This area is rich in symbolism important to the Inca: sun, water and earth.

Fig. 19 Large stairs on Lacco's northwest face.

Fig. 20 Small gnomon atop Lacco to the Southeast.

5.1 Northeast Cave

On its northeast face, just west of the fault corridor, Lacco has an opening which is oriented 65° for the June solstice sunrise. The maximum angle through the cave's entrance toward the Sun's path on the horizon is 78°, therefore at least some light is admitted to part of the interior for a number of days before and after the solar standstill. The sunrise on the horizon centers on the cave opening at the time of the June solstice (see Figure 21). During this period sunlight enters the portal and illuminates the altar and cave interior. The altar is lighted directly and the cave walls receive mostly reflected light (see Figure 22). We calculated this phenomenon during 2006 field research and observed it at the June 2007 solsticial sunrise. The process began very quickly at 06:25 and persisted until the last vestiges of light disappeared from the altar's stone surface at 08:24. The altar's positioning appears to have been intentionally designed for illumination of ceremonies at the time of the festival of Inti Raymi during the Incas' winter solstice.

The cave was formed from a small natural crevasse that was cut and worked by the Incas into its present size and shape. A 3.97 m altar was carved along the eastern wall of the narrow fissure, 1.28 m of its left end being 27 cm below the main section. The main platform is 1.77 m at its widest and stands 1.35 m above the cave's floor. Carved in front of the cave are two ceremonial thrones and behind them are two large steps at the entrance. Four steps descend into the cave from this platform.

Fig. 21 Sunrise 22 June 2007 centered on horizon as viewed from northeast cave opening.

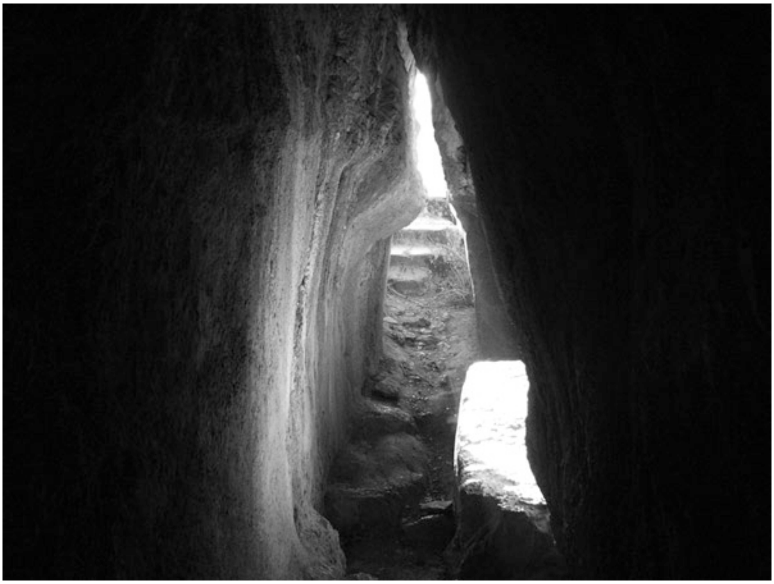

Fig. 22 Direct illumination of altar and reflected illumination of cave interior.

5.2 The Southwest Cave

Lacco contains two other caves, each with a light-tube oriented upward to the sky. The first we examined is a ceremonial cave with a small altar lying below an opening pointing at times toward the ecliptic. The southwest cave's light-tube is not perfectly vertical, but is oriented with its opening pointing between 70 and 75° above the horizon. When properly positioned either the Sun or a full Moon at night can illuminate the altar within. We observed a waxing crescent Moon through the light-tube in October 2006, giving graphic demonstration of this type of astronomical alignment (see Figure 23).

The altar is set 5 m back from the cave's opening on a 55° axis. The light-tube extends from the ceiling of the cave's interior to a terrace above. The angle of elevation from the altar through the center of the opening is 72° at an azimuth of 211°. The chamber is 7.2 m long and 1.7 m wide. Two niches are cut into the west wall.

The southwest cave may have been used for meditation and preparation prior to ceremonies conducted in the larger, more elaborate southeast cave.

5.3 The Southeast Cave

The second cave with light-tube illumination is known both as the Temple of the Moon and the Temple of the Sun. This cavern is the most elaborate found within the *huaca* and the remains of carvings of both a puma and a snake adorn its entrance.

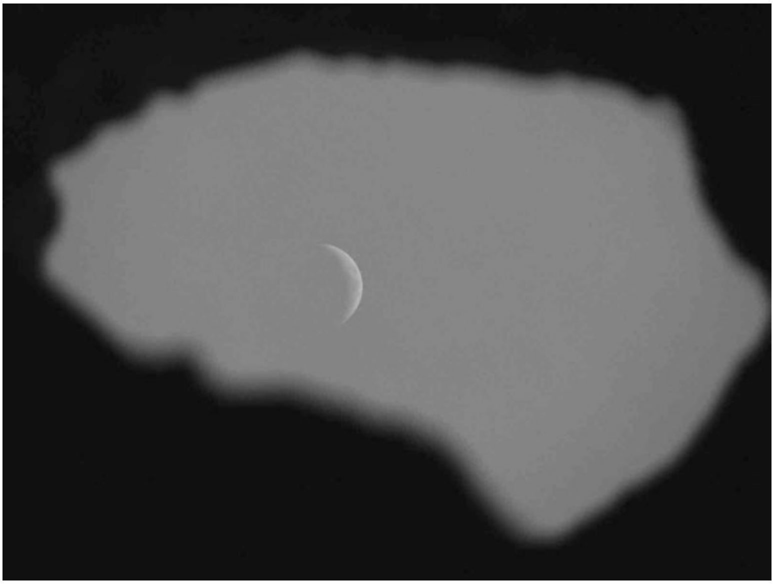

Fig. 23 Crescent Moon visible through the southwest cave light-tube at 15:50 on 26 October 2006.

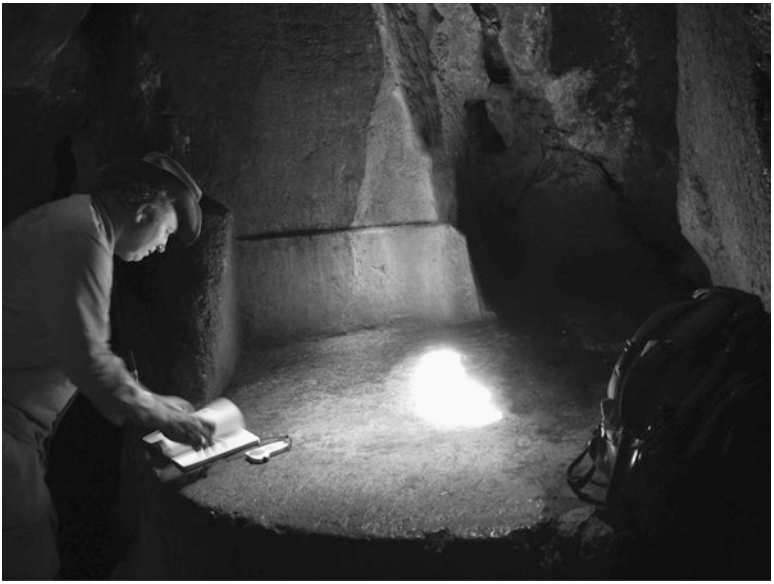

Fig. 24 Illumination of the southeast cave's altar at 11:55 on 26 October 2007.

Within is a finely carved altar we observed to be brilliantly illuminated near the time of the zenith Sun. Such sunlight could have greatly enhanced a variety of Incan ceremonies and sacrifices.

We found sunlight to be admitted through the cave's light-tube near solar noon on 26 October 2007. The zenith Sun occurs on 30 October at this latitude. The photograph reproduced in Figure 24 was taken when the Sun was at an elevation of 89° on an azimuth of 55°. The high aspect of this opening makes illumination possible only from September through March when the Sun's altitude is greatest in the Southern Hemisphere. The altar will also be lighted by an appropriately aligned moon at night, thus the name 'Temple of the Moon'.

The cave is accessed by a monumental staircase leading up to its entrance. This is then followed by a small, narrow set of steps that descend into the chamber. On either side of the entranceway are carvings of snakes, a condor and a llama. The snake along the right side of the passage was finely crafted with its head pointing into the cavern (see Figure 25). The cave has both an outer and an inner chamber that connected the Incas with the chthonic underworld. Located 2.5 m deep in the inner chamber is the finely polished altar beneath the illuminating light tube. The altar is 2 m wide, 1.2 m deep and its platform stands 66 cm above the floor. The light tube is on an axis of 55° and the elevation of its opening ranges from 80 to 92°.

Fig. 25 Serpent carved along wall of entrance to southeast cave.

6 Urubamba

Although known to the local community, the astronomical functions of the pillars on the northeastern horizon of the town of Urubamba had not been identified until recently. In 2005 Michael Zawaski (2007) established that the Urubamba pillars mark the June solstice sunrise and we found in June 2007 that a large granite boulder in the courtyard of Quespiwanka, the palace of Huayna Capac, is the properly-aligned point for viewing this phenomenon. The granite boulder appears to be responsible for the Quechua name of the palace, Quespiwanka: *quespi* = ‘crystal’ or ‘shimmering’ and *wanka* = ‘standing rock’ (Farrington 1995). Stone-lined channels in the courtyard of Quespiwanka could have surrounded the boulder with water (Niles 1999). A modern chapel lies adjacent to the boulder (see Figure 26) on a spot thought to have originally been the site of a ceremonial platform used during the time of the Incas. Today a modern channel carries water toward the boulder. Quespiwanka was built in a previously-uninhabited area of the Urubamba River valley during the last decade of the fifteenth century and the boulder at the palace appears to be the only Incan site in the area for observing June solstice sunrise between the pillars. A search of the surrounding hillsides revealed no additional marked site for observing sunrise or sunset between the pillars. The photograph reproduced here as Figure 27 was taken from the granite boulder shows the Sun rising along the eastern pillar on 8 June 2008.

Fig. 26 The granite boulder and modern chapel of Quespiwanka.

Fig. 27 Sunrise on 8 June 2008 along the eastern solar pillar as viewed from Quespiwanka's granite boulder; the western pillar is visible to the left.

6.1 Solar Pillars

Natural features on the ridgeline alone might have been sufficient for priests to determine the time of the approaching solstice. Construction of the towers underscores the importance that the Incas placed on the June solar event and the significant role that this site played in their ritual ceremonies.

Measurements of the pillars and palace were enhanced by multiple sunsights made with a T2 theodolite as well as GPS positioning. As viewed from the granite boulder, the azimuth of the mid-point of the pillars is 56° 14'; their mean altitude is 22° 59'. The pillars are 35.3 m apart on either end of a level terrace and are constructed out of sandstone in contrast to the granite of the palace (see Figure 28). They are located along an azimuth of 100° at an elevation of approximately 3,860 m above sea level. When viewed from Quespiwanka, the separation of the pillars is

Fig. 28 The solar pillars of Urubamba.

0.59°. The easternmost pillar has a height of 4.3 m and a base 1.5 m by 3.3 m; the base of the partially restored western pillar is similar.

Solar pillars on the horizons of Cusco were described by sixteenth and seventeenth century chroniclers (Bauer and Dearborn 1995). As many as 16 towers reportedly marked the dates of significant astronomical and agricultural events. No evidence of these pillars remains in the archaeological record (Bauer 1998). During the purge following their 1532 invasion of the Incan Empire, the Spaniards proceeded to destroy many shrines. Those that were large carved rocks could not be obliterated and remain to this day, but the solar pillars of Cusco did not survive. How did the Urubamba pillars escape the ravages of colonial politics that destroyed the pillars of Cusco? They are relatively modest features on the high horizon and can easily escape detection from below. Furthermore, Quespiwanka was remote from the political center of Cusco, so remote that the mummy of Huayna Capac, ardently sought after by the Spanish, was successfully concealed in the palace for several decades (Farrington 1995). In his retreat down the Urubamba River valley in A.D. 1536, Manco Inca torched the palace to prevent the Spanish from utilizing the buildings, thereby keeping the hiding place of his father's mummy as well as the presence of the pillars unknown to the Spanish invaders.

6.2 The South Wall of Palace

Although the courtyard of the palace is greater than two hectares in area, it may not have been the scene of *public* ceremonies. Its eastern wall contains a massive triple-jambed doorway (see Figure 29) surrounded by two double-jambed doorways. Incan doorways with multiple jambs typically marked entry into a space of special importance to be used only by elites. The courtyard may thus have been similar to the Corichancha of Cusco and the Sanctuary of the Island of the Sun in that non-elites were barred from entry and participation in ceremonies (Dearborn et al. 1998; Seddon and Bauer 2004).

June solstice sunrise, however, may also be viewed from outside the southern wall of the palace. Niles (1999) suggests that there were 40 double-jambed niches along its 190 m length (see Figure 30) and that the wall faced an artificial lake and large granite boulders. This area may have been for public viewing where pilgrims and non-elites were allowed to observe solstice sunrise between the pillars, in a manner similar to ceremonies on the Island of the Sun (Dearborn et al. 1998; Seddon and Bauer 2004). Niles (1999) proposes that a platform existed at the center of the palace plaza, next to the white granite boulder. As with platform alignments at the Island of the Sun, the public viewing area for the June solstice sunrise outside of Quespiwanka might have been designed to feature the Sun rising over Huayna Capac, the ruling Inca and Son of the Sun, perhaps on just such a platform located on the higher courtyard. Water appears to be associated with ceremonies, both inside the courtyard where channels could have carried water to the boulder and beyond the southern wall of niches. In both places, viewing reflections of the rising Sun from pooled water may have been part of the ceremony.

Fig. 29 Triple-jambed entranceway to Quespiwanka from the East.

Fig. 30 Niches in Quespiwanka's south wall.

A third solar ceremonial site is the 40 m-long terraced platform built between and around the pillars. Retaining walls, which are approximately 1 m high, are on its northern and southern sides. Interestingly, the pillars are not co-linear, but rotated such that their long sides with azimuths of 286° and 298° approximately bracket sunset on June solstice on the 3° northwestern horizon. Chroniclers noted that sacrifices to the Sun were often made at the pillars of Cusco. Steps to a platform at the upper structure of the Island of the Sun suggest that sacrifices were made there as well. The platform between the Urubamba pillars and the orientation of the pillars suggest that this, too, was a place for ceremony. The center of the platform contains a pit, apparently dug by *huacaros* (looters), who probably found nothing of value. The pit may have been an original feature into which offerings were poured, suggesting that the platform served as an *ushnu*. Offerings may have been made not only to the Sun but also to the great snow peak of Chicon. The insight provided by the Urubamba pillars is that both ends of the sightline connecting the palace and the pillars appear to have been ritual loci. Real and symbolic ascent would have occurred when a procession of celebrants climbed 950 m from the valley to the platform, where they could make sacrifices, place offerings and celebrate the passage of the Sun across the sky from dawn to dusk.

7 Cerro Unoraqui

Cerro Unoraqui, with an altitude of 4,377 m, is a major feature of the southeastern horizon as viewed from the eastern façade of Quespiwanka. Although the peak has a distance of 11 km, good eyes can detect pillars on its summit, which have an azimuth of 110.7°, approximately 2° north of the rising point of December solstice sunrise. The three rock pillars on its summit are encircled by a low stone wall and are aligned approximately north-south (see Figures 31 and 32). The pillars are built of un-shaped stone and with interstices filled with soil, very different from the pillars of Cerro Saywah. Local villagers claim these date back to Incan times. A local informant told us of three similar structures, destroyed by looters, that had existed further east on the ridge. We found evidence that may be the base of one of the missing pillars. The site provides a commanding view of the Cordillera Urubamba, including the 5,818 m snow peak, Nevado Sahuasiray (see Figure 33). The full significance of these pillars is the subject of our continuing research.

8 Concluding Remarks

We view these *huacas* with astronomical features as part of a long-standing Andean tradition. There is such depth of meaning that we are reluctant to use the western ethnocentric term ‘observatory’ to describe them. The Incas considered the Sun a preeminent ancestor, and each of the sites we present involves attention to the solstices. As the Incas had no written language, their methods used to make these observations remain elusive. Smooth horizons presented a challenge that apparently was solved by pillars built to mark annual solar positions when significant natural features were not available. We observed that the two Sun pillars located on a ridge

Fig. 31 Three pillars on top of Cerro Unoraqui.

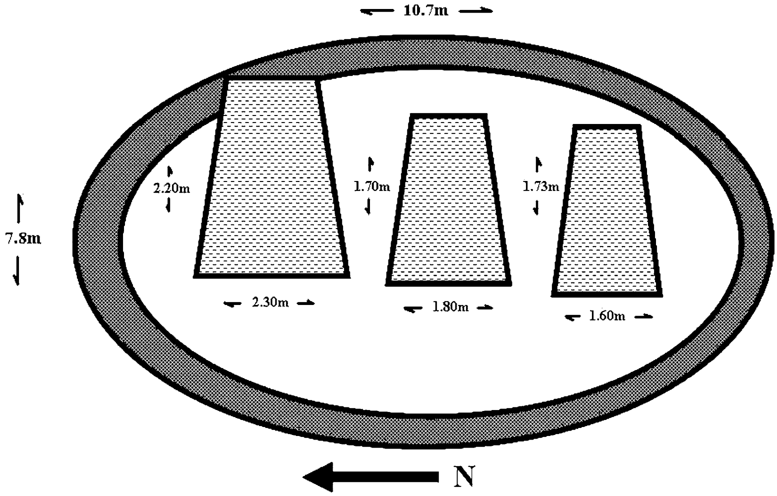

Fig. 32 The three stone pillars and the encircling low stone wall.

above the palace of Huayna Capac are aligned to mark the rising of the June solstice Sun when viewed from the large boulder located in the center of the palace courtyard. We suspect the observation of the solstice Sun rising between the towers was more a demonstration of the power and skill of the Incan ruler and worship of the Sun than a calendrical marker.

Fig. 33 Pillars oriented north and south with Nevado Sahuasiray to the right in the distance; the enclosing wall is in the foreground.

There is much ethno-historical description by Spanish chroniclers of similar pillars surrounding the city of Cusco, but none remains to this day. These towers provide the first direct evidence of this type of Incan celestial alignment. Our results demonstrate that such solar pillars did exist for the purpose of marking significant Incan astronomical events and add credibility to the colonial reports of these structures on the horizons of Cusco.

Alternate methods of establishing sunrise positions appear to have been practiced at Machu Picchu and the neighboring ceremonial center of Llactapata where the irregularities of the horizon provide natural calendrical markers for the June solstice. On the day of the June solstice the Sun as viewed from the Llactapata Sun Temple rises over the Sacred Plaza of Machu Picchu. The specific position of this yearly event is indicated by both horizon features and a purposefully-aligned water channel. Water offerings to the solstice Sun could have been made through this channel originating at the double-jambed doorway of the temple. In addition, a 33 m long corridor at Llactapata establishes a 4.3° window along the horizon that includes the rising position of the June solstice Sun as well as the heliacal rise of the Pleiades. A similar sighting device may have been established at the Coricancha of Cusco.

Ancestor veneration, shamanism and origin mythologies are intertwined themes in the *huacas* we have considered in this paper. While the Urubamba pillars and the palace of Huayna Capac lie on the sightline to June solstice sunrise, in December the solstice sunrise as seen from the palace occurs close to the pillars atop Cerro Unoraqui. The Sacred Plaza of Machu Picchu, the River Intiwatana and the Llactapata Sun Temple lie approximately along a line established by the June solstice sunrise and December solstice sunset. The Urubamba River Intiwatana is an archetypal *huaca* containing caves, fountains, steps and platforms. The carved-rock *huaca* at Kenko is rich with astronomical orientation, but even more impressive are the June solstice and light-tube effects in the caves of its neighbor at Lacco.

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Part III
Astronomers, Books, Manuscripts, and Star Charts

Ábdul-Raḥmān al-Şūfī and His *Book of the Fixed Stars*: A Journey of Re-discovery

Ihsan Hafez, F. Richard Stephenson, and Wayne Orchiston

Abstract The *Book of the Fixed Stars* was written by the Persian astronomer Ábdul-Raḥmān al-Şūfī around AD 964, and is one of the most important medieval Arabic treatises on astronomy. al-Şūfī's work contains an extensive star catalog as well as detailed star charts for the 48 classical constellations, and draws on material in Ptolemy's *Almagest*. At present no English translation of al-Şūfī's treatise exists. This paper summarizes a detailed study by the first author for a Ph.D. degree in the Centre of Astronomy at James Cook University (Townsville, Australia) which will include for the first time a complete English translation of the main parts of al-Şūfī's major work.

This paper includes a brief biography of al-Şūfī, along with information on the extant manuscripts of the *Book of the Fixed Stars*, the structure of the book and star catalogue, and the star maps and charts. A major finding which we highlight in this paper is al-Şūfī's stellar magnitude estimates which were based upon a unique three-step intermediate magnitude system that he developed. al-Şūfī also identified and commented on more than 100 new stars that were not listed in the *Almagest* or other early star catalogs. al-Şūfī's contribution to astronomy reverberated throughout history, extending to recent times.

1 Introduction

al-Şūfī's *Book of the Fixed Stars*, dating from around AD 964, is one of the most important medieval Arabic treatises on astronomy. This major work contains detailed star charts and an extensive star catalogue, which lists star co-ordinates and magnitude estimates. Other topics include descriptions of nebulae and Arabic folk astronomy.

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Thus it is surprising that at present no English translation of al-Ṣūfī's treatise exists. In order to remedy this, one of us (IH) is currently conducting a detailed study of this book for a Ph.D. in the Centre for Astronomy at James Cook University, and this will include the preparation of what will eventually be a complete English translation.

Topics to be discussed in the present paper include a brief biography of al-Ṣūfī, the extant manuscripts of al-Ṣūfī's treatise, the structure of the book, the star catalogue, and the star maps and charts. This paper also includes some of the major findings of this doctoral research, such as the magnitude estimates and the unique three-step intermediate magnitude estimate adopted by al-Ṣūfī, as well as the identification of more than 100 new stars which were mentioned by al-Ṣūfī in his constellation commentaries but were not included in the *Almagest* or any other ancient star catalogues that preceded al-Ṣūfī's treatise.

The subtitle chosen for this paper and for the doctoral thesis at James Cook University is "A Journey of Re-discovery", as this is a journey to re-discover the man, and the book which had an important influence on astronomy and helped mould our understanding of the celestial sphere.

2 al-Ṣūfī: A Biography

Surprisingly, we know relatively little about al-Ṣūfī's life and career. However, we do know that his full name was ʹAbdul Raḥmān, Abuʹl Ḥusayn, Ibn ʹUmar, Ibn Moḥammad, al-Rāzī, al-Ṣūfī.

al-Ṣūfī was born in AD 903 in the city of Rayy, south east of what is now called Tehran, the capital of Iran. He died in AD 986 but we do not know where, most probably in Shiraz or maybe in Baghdad (which was the political capital as well as the cultural center of that period). From his name we can deduce that al-Ṣūfī's father's name was ʹUmar, signifying that he was a Sunni Muslim rather than a Shiite Muslim – which was the dominant sect of the Buwayhid Dynasty at that time. al-Rāzī indicates that he came from the town of Rayy, while al-Ṣūfī signifies that he or his family was part of a Ṣūfī religious sect.

From the introductory chapter of his book we know that al-Ṣūfī lived most of his life between the provinces of Isfahan and Fars in Iran. He also wrote that he visited Dainaour, which is the home of the famous scholar and astronomer Abu Ḣanifa al-Dainaouri. He also visited Isfahan to research a celestial globe constructed by another important astronomer of that period. In his book, al-Ṣūfī explains the reasons why he wrote *The Book of the Fixed Stars*. He mentions that his book was dedicated to the Buwayhid ruler, ʹAḍud al-Dawla, who was a great patron of astronomy and was himself an accomplished scholar and astronomer. In his book al-Ṣūfī also comments upon several other works, such as al-Battāni's star catalog which was written in AD 880, as well as al-Dainaouri's book on old Arabic astronomical traditions, and of course Ptolemy's *Almagest*.

From other historical records we learn that al-Şūfī also wrote a *Zīj*, which is an astronomical handbook (Kennedy 1956). Unfortunately it no longer exists. He also wrote several treatises on astrology, which we also know very little about. Available treatises on the astrolabe and celestial globes reveal that al-Şūfī was an accomplished instrument-maker (Kennedy et al. 1983) and that a celestial globe which he constructed existed in Cairo in AD 1043 but can no longer be located. Historical records (Sayili 1960) also show that al-Şūfī built an observatory at Shiraz, in Iran.

Many influential astronomers in the past based their astronomical tables on al-Şūfī's work, including al-Bīrūnī in AD 1030, the authors of the Alfonsine tables in AD 1252 and the famous prince and astronomer, Ulugh Bēg in AD 1437. In more recent times, al-Şūfī's work has been discussed by Ideler (1809), Argelander (1843), Knobel (1917) and Fujiwara and Yamaoka (2005). However, al-Şūfī's name was sometimes mis-spelled or mis-written. Thus, he has been referred to as *Abolfazen* (which we find in an Italian translation of the Alfonsine Tables), *Esophi* by Leo Africanus and *Azophi* by the Spanish Jewish astronomer Ibn 'Ezra (see Kunitzsch 1989).

3 The *Book of the Fixed Stars*

al-Şūfī's star catalog was based on Ptolemy's classical work, the *Mathematike Syntaxis*, which was written in AD 125 and was later called the *Almagest* by the Arabs. al-Şūfī updated Ptolemy's stellar longitudes from AD 125 to AD 964 by adjusting for precession. In his book he described the methods he used in constructing his catalog and especially in calculating precession. For his epoch of AD 964 he applied the most accurate Arabic precession constant available at that time of 1° in 66 years rather than the correct value of 1° in 71.2 years, thereby adding 12° 42′ to Ptolemy's longitudes. Over the 839 years between the tables of Ptolemy and al-Şūfī, precession would actually amount to 11° 47′. Hence by using 12° 42′ al-Şūfī over-corrected Ptolemy's stellar longitudes by 55′. al-Şūfī would not have been aware of this over-correction because his calculations were based on the *Almagest*.

The original Arabic name for al-Şūfī's book was *Şuwar al-Kawākib al-Thamāniyah wa al-Ārba'een*, which is simply translated as *The Forty-eight Constellations*. However, it was later known by other names, the most famous of which was *Kitāb al-Kawākib al-Thābita*, or *The Book of the Fixed Stars*. al-Şūfī's original Arabic text contained 55 astronomical tables, plus star charts for 48 constellations. al-Şūfī commented in detail on each constellation, and supplemented this material with star charts. These tables and charts were written in the same order as in the *Almagest*, and were divided into three main groups. The first group contained 21 northern constellations: Ursa Minor, Ursa Major, Draco, Cepheus, Bootes, Corona Borealis, Hercules, Lyra, Cygnus, Cassiopeia, Perseus, Auriga, Ophiuchus, Serpens, Sagitta, Aquila, Delphinus, Equuleus, Pegasus, Andromeda and Triangulum. The second group contained the 12 constellations of the zodiac: Aries, Taurus, Gemini, Cancer,

Fig. 1 The constellation “Lepus” (The Hare). At the *top of the figure* is an image of the constellation (in duplicate). In the *lower part* is the table of stars in this constellation, including their ecliptical coordinates and estimated magnitudes.

Leo, Virgo, Libra, Scorpio, Sagittarius, Capricorn, Aquarius and Pisces. The last group contained 15 southern constellations: Cetus, Orion, Eridanus, Lepus, Canis Major, Canis Minor, Argo Navis, Hydra, Crater, Corvus, Centaurus, Lupus, Ara, Corona Australis and Piscis Austrinus. By way of illustration, Figure 1 shows the constellation Lepus (The Hare). At the top of the figure we can see two images of the constellation, and below these is a table of the stars in this constellation.

3.1 The Structure of al-Şūfī's Book and Star Catalog

Since al-Şūfī's work was based on the *Almagest,* al-Şūfī used the same structure and layout. Thus, his book was divided into four main sections:

1. An Introductory Chapter
2. The Northern Constellations (of which there are 21).
3. The Constellations of the Zodiac (of which there were 12).
4. The Southern Constellations (of which there are 15).

The description of each constellation is divided into three parts. The first part is a detailed written commentary describing the position of the stars, their numbers and magnitudes, as well as many other details. al-Şūfī also tried to identify the stars or groups of stars according to the old Arabic tradition, by giving their old Arabic names and what the Arabs said about them. The Arabic text in Figure 2 is from a copy of al-Şūfī's book which was produced by Ulugh Bēg in the fifteenth century, and is a very well-written and clear manuscript. This was one of the

يكون درجاته أكثر فهو التالي لذلك المتقدم وهو الى المشرق
أقرب فليحفظ هذه الأشياء إن شاء الله تعالى

كوكبة الدب الأصغر

وأقرب كوكب إلى القطب الظاهر الشمالي كوكبة الدب الأصغر
وكواكبها من نفس الصورة سبعة منها ثلاثة على ذنبه وهي
الأول والثاني والثالث وأنورها الأول وهو على طرف الذنب
من القدر الثالث والاثنان الباقيان من القدر الرابع والأربعة
الباقية على مربع مستطيل على بدنه اثنان منها اللذان يليان
الذنب أخفى وهما الرابع والخامس والاثنان التاليان لهما وهما ال
والسابع أنور وذكر بطلميوس أن الرابع والخامس جميعا من القدر
الرابع وأن السادس والسابع جميعا من القدر الثاني فأما الرابع
فهو من القدر الرابع لأنه مثل الاثنين اللذين على الذنب ولما

Fig. 2 The detailed written commentary on the constellation Ursa Minor describing the position of the stars, their numbers, and magnitude as well as many other details.

Fig. 3 The table showing the coordinate and magnitude values for the constellation Ursa Minor.

main manuscripts that we used for the English translation. The second part of each constellation chapter is a table showing the coordinates and magnitudes of the stars (see Figure 3). al-Şūfī used ecliptical coordinates, as did Ptolemy before him. The last part of each constellation chapter contains the star charts (e.g. see Figure 4). There were two charts, depicting the stars as they actually appeared in the sky and – in reverse – as they were drawn on a celestial globe.

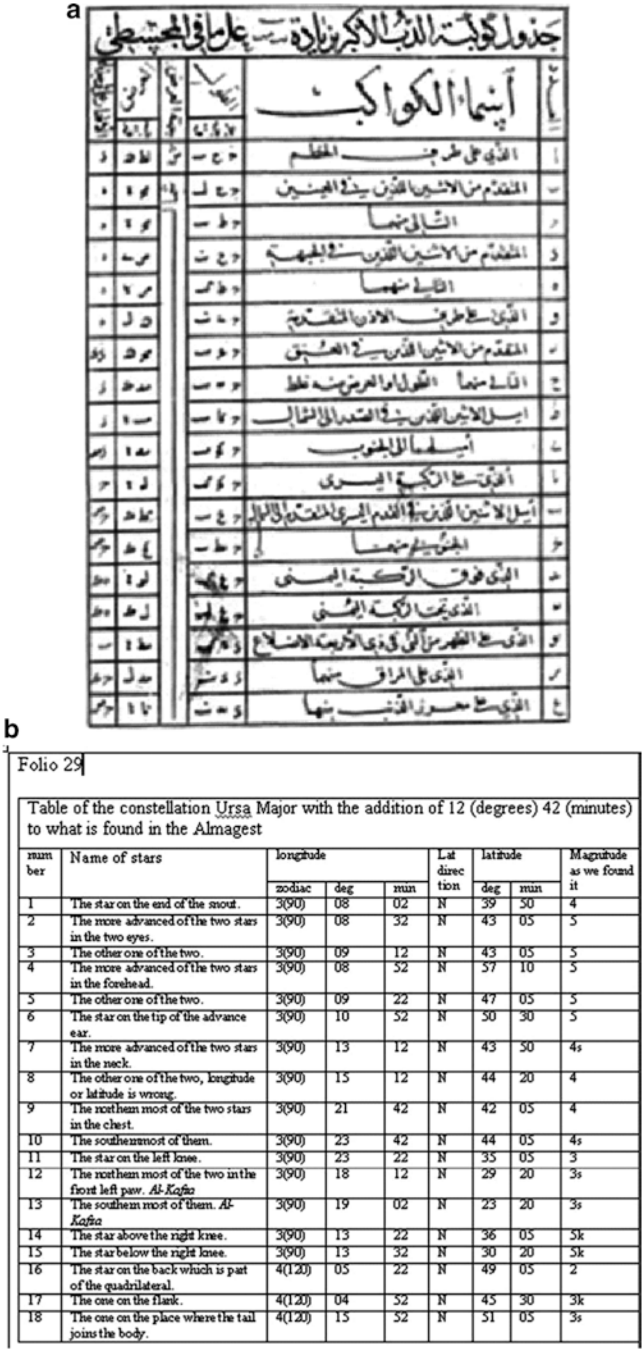
4 Translating *The Book of the Fixed Stars*

The main effort to search for the hidden astronomical treasures in al-Şūfī's book started with the translation of this work from Arabic to English, and especially the constellation commentaries. For every constellation al-Şūfī wrote a commentary which describes in detail the number of stars, their locations and their magnitudes.

The layout of this translation is depicted in Figure 5, which shows in Figure 5a the star catalog for the constellation of Ursa Major. Next to it, in Figure 5b, is the

Fig. 4 The dual charts depicting the stars as they appear in the sky and as they are drawn on a globe for the constellation Ursa Minor.

corresponding English translation. At the top of this table al-Ṣūfī noted that he added 12° 42′ to Ptolemy's longitude to allow for precession. The first column in Fig. 5b lists the number of the star in the constellation. The second gives the description or name of the star. This sometimes includes the star's color, Arabic name and explanation of the position of the star in the constellation. The third group of columns lists the ecliptical longitude coordinates. It was also customary to divide the ecliptic into twelve 30° divisions. Therefore, when describing the longitude, al-Ṣūfī first wrote the number of that division then the remaining degrees and minutes in



جدول كوكبة الدب الأكبر بزيادة يب مب على ما في المجسطي

أسماء الكواكب

Folio 29

Table of the constellation Ursa Major with the addition of 12 (degrees) 42 (minutes) to what is found in the Almagest

num ber	Name of stars	longitude			Lat direc tion	latitude		Magnitude as we found it
		zodiac	deg	min		deg	min	
1	The star on the end of the snout.	3(90)	08	02	N	39	50	4
2	The more advanced of the two stars in the two eyes.	3(90)	08	32	N	43	05	5
3	The other one of the two.	3(90)	09	12	N	43	05	5
4	The more advanced of the two stars in the forehead.	3(90)	08	52	N	57	10	5
5	The other one of the two.	3(90)	09	22	N	47	05	5
6	The star on the tip of the advance ear.	3(90)	10	52	N	50	30	5
7	The more advanced of the two stars in the neck.	3(90)	13	12	N	43	50	4s
8	The other one of the two, longitude or latitude is wrong.	3(90)	15	12	N	44	20	4
9	The northern most of the two stars in the chest.	3(90)	21	42	N	42	05	4
10	The southernmost of them.	3(90)	23	42	N	44	05	4s
11	The star on the left knee.	3(90)	23	22	N	35	05	3
12	The northern most of the two in the front left paw. *Al-Kafza*	3(90)	18	12	N	29	20	3s
13	The southern most of them. *Al-Kafza*	3(90)	19	02	N	23	20	3s
14	The star above the right knee.	3(90)	13	22	N	36	05	5k
15	The star below the right knee.	3(90)	13	32	N	30	20	5k
16	The star on the back which is part of the quadrilateral.	4(120)	05	22	N	49	05	2
17	The one on the flank.	4(120)	04	52	N	45	30	3k
18	The one on the place where the tail joins the body.	4(120)	15	52	N	51	05	3s

Fig. 5 The table or star catalog for the constellation Ursa Major (*left*) (**a**) along with the corresponding English translation (**b**).

order to depict the complete longitude value. The fourth column gives the latitude, and also specifies the direction of the star north or south of the ecliptic. The fifth group of columns lists the latitude coordinates, and the final column records al-Ṣūfī's estimate of the apparent magnitude of each star.

5 Extant Manuscripts of al-Ṣūfī's Book

Before a detailed study of al-Ṣūfī's book and the English translation could begin, the extant manuscript copies of the *Book of the Fixed Star*s had to be located, and examined. It is a measure of the popularity of this book that many manuscripts are still preserved in libraries throughout the world. However, the tracking down of some of these involved extensive worldwide travel and much library research. This resulted in a total of 35 different manuscripts being located, and copies of the major ones, needed for this study, were acquired. Table 1 lists the existing manuscripts of al-Ṣūfī's book known at the time of this study, and the 35 copies are distributed among 20 libraries in 15 different countries.

These 35 extant copies merely represent the 'tip of the iceberg'. As might be imagined, various copies of the *Book of the Fixed Stars* were written by hand, time and time again, and were passed down from one generation to the next. So there may

Table 1 Geographical distribution of extant copies of al-Ṣūfī's *Book of the Fixed Stars*

Country	City	Library	No. of copies of the *Book of the Fixed Stars*
Denmark	Copenhagen	Royal Library	1
Egypt	Cairo	The Egyptian Dar books	1
England	London	British Library	5
	Oxford	Bodleian Library	3
France	Paris	Bibliotheque Nationale	4
Germany	Berlin	Ahlwardt	1
India	Hyderabad	Asafiya	1
Iran	Tehran	Majles	2
Italy	Bologna	Collection Marsigli	1
	Vatican	Rossi	1
Lebanon	Beirut	American University of Beirut	1
Qatar	Doha	Museum of Islamic Art	1
Russia	St. Petersburg	Bibliotheque Imperiale	3
Spain	Madrid	Library Escurial	1
Tunisia	Tunisia	Bibliotheque Nationale	1
Turkey	Istanbul	Topkapi Sarayi	3
	Istanbul	Sulaymania Library	1
USA	New York	Metropolitan Museum of Art	2
	Princeton	Princeton University Library	1
	Washington	Library of Congress	1

have been hundreds of copies in existence at any one time. Unfortunately the original manuscript, written by al-Ṣūfī, has not survived, but we do have the next best thing – a copy made by his son.

6 Identifying the Manuscript for Translation

Unfortunately not many of the manuscripts listed in Table 1 could be used for this study once the following criteria were considered: manuscript age, legibility, correctness of the information contained and completeness. As a result of this analysis, two manuscripts were selected to form the basis of the translation and discussion: 'Marsh144' in the Bodleian Library in Oxford and manuscript 'MS5036' in the Bibliotheque Nationale in Paris. The Marsh144 manuscript is the oldest surviving copy of the *Book of the Fixed Stars* and dates to AD 1009, just 23 years after al-Ṣūfī's death. This manuscript was actually written by al-Ṣūfī's son. A facsimile of this manuscript was acquired for this study and was used as the basis for the English translation. Meanwhile, MS5036 in Paris was copied much later, in AD 1430, but it is much better written and is a more complete version. Various differences were found in the specific contents of these two manuscripts, which were probably due to scribal errors at the time the manuscripts were copied. Where differences in listed stellar coordinates and magnitudes were found, the values in Marsh144 were used in the preparing the English translation. Since this manuscript was older than the Paris manuscript and was scribed by al-Ṣūfī's son it was presumed to be more accurate.

Although there has been no English translation of the *Book of the Fixed Stars*, a French translation was published by the Danish astronomer Hans Karl Frederik Schjellerup in 1874. Schjellerup used the Copenhagen manuscript, 'MS83', which dates to AD 1601 for this translation. In 1956 an Arabic copy of al-Ṣūfī's book was published in Hyderabad (India) by Dār al-Āthār al-´Uthmāniyah, who made use of several different manuscripts. This version contains many mistakes and is of limited usefulness.

7 The Maps in al-Ṣūfī's Catalog

One of al-Ṣūfī's innovations in charting the stars was the production of dual illustrations of each of Ptolemy's constellations. One illustration was as portrayed on a celestial globe, and the other as viewed directly in the night sky. By way of example, Figure 6 is a picture of the constellation Cancer. The upper figure shows the constellation as seen on a celestial globe and the lower figure as it is seen in the sky. In this Figure the stars drawn in gold are considered part of the constellation while stars drawn in red are bright enough to be noticed but lie outside the constellation. The stars in every constellation were divided into two groups. Stars in the first group formed the main image of the constellation, while stars in the other group were outside that image.

Fig. 6 The constellation cancer. The *upper figure* shows the constellation as seen on a celestial globe. The *lower figure* shows the constellation as it is seen in the sky.

At the end of the chapter on Ursa Minor, al-Şūfī explains why he provided two different star maps and how these should be used:

> For every constellation we have drawn two pictures: one as it is projected on the globe and the other as it is seen in the heavens. Hence we have covered both of the different cases, so there is no confusion for anyone who sees that what is viewed on the globe is different from what is in the heavens. When we want to see the constellation as it [really] is we lift the book over our heads and we look at the second picture [in the book]. From beneath [the book] we are viewing [the constellation] as it is seen in the heavens.

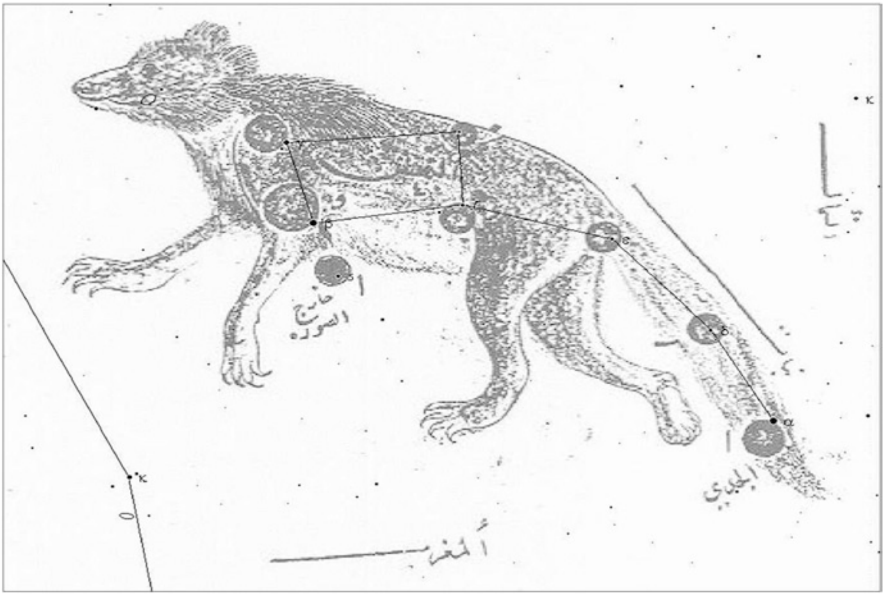


Fig. 7 An image of the constellation Ursa Minor taken from the *Book of the Fixed Stars*, and projected onto a modern chart, showing the true locations of the stars for comparison.

An important issue concerns the accuracy of these maps. Also, were they really used as intended by al-Şūfī? It is apparent that as an observational astronomer and an instrument-maker al-Şūfī was very concerned about the accuracy of the data he had and that they should be used correctly when constructing a celestial globe. Therefore, in order to investigate these questions one of al-Şūfī's star charts for Ursa Minor is reproduced here in Figure 7 projected onto a modern chart. As can be seen, the constellation chart in the MS5063 manuscript is fairly precise, indicating that the star charts in the *Book of the Fixed Stars* could have been used as al-Şūfī intended.

8 Star Names and Modern Designation of Stars

In another section of this doctoral study, a complete list of all the stars in the constellations in the *Book of the Fixed Stars* was compiled. This included a description of each star, as listed in al-Şūfī's star tables, and their HR, Bayer and Flamsteed numbers, so that each star could be correctly identified. This list also includes the name of the stars according to the old Arabic tradition as mentioned in al-Şūfī's book, as well as the various names which have been given to these stars throughout history.

9 Magnitudes of the Stars in the *Book of the Fixed Stars*

9.1 Comparison Between al-Şūfī and Ptolemy

The next analysis was to compare al-Şūfī's stellar magnitudes with those found in the *Almagest.* All stars which showed a difference in magnitude or coordinate values were identified so that an investigation of the reasons for these discrepancies could be made. This study was mainly to confirm that al-Şūfī actually made the measurements himself.

The results showed that al-Şūfī's magnitude values for 520 stars out of the total of 1,019 stars (i.e. 51%) were identical to those provided by Ptolemy. Therefore one might wonder whether al-Şūfī only re-estimated the magnitudes of about half of the stars observed by Ptolemy. However, upon detailed comparison we found that out of these 520 stars only 206 stars differed in value from the modern visual magnitudes by ≥0.5 magnitude and 56 stars differed by >1 magnitude. The results also showed that of these 56 stars, 22 had magnitudes of either 5 or 6. This discrepancy can be understood given how difficult it is to visually estimate the visual magnitudes of faint stars. Therefore, a level of accuracy of no better than ±0.5 magnitude can be expected for al-Şūfī and Ptolemy. This conclusion is confirmed by our calculation of the standard error (see below). However, this does not prove that al-Şūfī personally re-estimated the magnitudes of all of the stars in his *Book of the Fixed Stars*.

9.2 al-Şūfī's Three-Step Intermediate Magnitude System

al-Şūfī and Ptolemy both added intermediate values to the magnitudes of some stars. Ptolemy mentioned the words "more-bright" and "less-bright" for certain stars, while al-Şūfī expressed these intermediate magnitude values by the words "*Aṡghareh*", which means "less", or "*Akbareh*" which means "greater", or "*A'ẓameh*" which means "much-greater".

Therefore, in this part of the study a complete magnitude analysis was made in which al-Şūfī's magnitude values were numerically interpreted by constant differences of 0.25 magnitudes: that is, "+0.25" for "less", "−0.25" for "greater" and "−0.5" for "much-greater". Ptolemy's two-step intermediate magnitude difference was interpreted by a difference of −0.3 or +0.3 magnitude. In the translation of the charts the letters (s) for "less", (k) for "greater" and (m) for "much greater" were added. For example, the magnitude of the star 19 Ursa Major was expressed by al-Şūfī as "much greater than 3rd magnitude". This can be interpreted on the three step scale as 3 minus 0.5, which is equal to magnitude 2.5. The modern magnitude of this star is 2.44 which is very similar. However, if we are to interpret the magnitude estimate on a two-step scale – as Ptolemy did – then we end up with a magnitude of 2.7. Therefore, we believe that al-Şūfī used what we have termed a three-step intermediate magnitude system, which was more accurate than Ptolemy's two-step system. We think that with this system al-Ṣūfī was able to express all magnitude values by a constant difference of 0.25.

One of the main topics in this study was to research this three-step intermediate magnitude system which would shed new light on the accuracy and independence of al-Ṣūfī's work. However, in order to analyze this topic further, all the data and information from al-Ṣūfī's book were collected according to the example shown in Table 2. The first three columns show the number and the number sequence of the stars and constellations. The fourth column shows the magnitudes of the stars according to al-Ṣūfī. We used the letters (s) for "less", (k) for "greater" and (m) for "much-greater". The fifth column shows the magnitudes after adjustment for the three-step system and the sixth column for the two-step system. As explained above, this was done by adding the values +0.25 for "less", −0.25 for "greater" and −0.5 for "much-greater" for the three-step system while we added the values +0.3 or −0.3 for the two-step system. The seventh column shows the magnitude according to Ptolemy. Here we used the magnitudes which al-Ṣūfī attributed to Ptolemy. The eighth column shows Ptolemy's magnitudes after adjustment for the two-step system. The ninth and tenth columns show the modern visual magnitude and the HR number for each star. Then in columns 11 to 13 we made an accuracy analysis for the magnitudes of al-Ṣūfī and Ptolemy by calculating the difference (Δ) between those values and the visual magnitudes. We made two kinds of analysis to see if al-Ṣūfī had in mind a two step or three step magnitude system (Δ al-Ṣūfī-1 and Δ al-Ṣūfī-2). The results of this statistical analysis of all 1,019 stars are summarized in Table 3. From the values listed in this table it would seem that the mean for the three-step system is slightly better. The standard deviation is the same whether we apply the three-or two-step system, whereas it is higher with Ptolemy. The dispersion in al-Ṣūfī's data is thus significantly less than in that found for Ptolemy's data.

Given the above values, we cannot prove conclusively that al-Ṣūfī chose to use the three-step system in lieu of the two-step systems, although we believe that was his intention. The main reason for this is the way al-Ṣūfī expressed or described the values of the stellar magnitudes in his book. Most scholars who have studied al-Ṣūfī's work used the Schjellerup (1874) translation, which does not differentiate between the two words "*Akbareh*" and "*Athami*". In Schjellerup's translation the magnitude was always written as the middle value; for example 4–5 (i.e. between 4 and 5 magnitude). In their work on Ptolemy, Knobel and Peters (1915) and later Toomer (1998) and Grasshoff (1990) all relied on Schjellerup's translation of al-Ṣūfī's data. They categorised Ptolemy's magnitudes by the word "greater" and "less", and expressed these magnitudes in a two-step system. This two-step intermediate magnitude was later numerically interpreted by a constant difference of 0.33 magnitude, especially by Grasshoff. However, when we look at al-Ṣūfī's text in detail it is evident that he made a clear distinction between three intermediate magnitudes. For example, if we look at magnitude values in the constellation Gemini, we see that he made the distinction between (m) and (k), and he really was not concerned with word repetition or correct sentence

Table 2 Analysis of magnitudes of stars in the *Book of the Fixed Stars*

Seq	Recno	Constallation	al-Ṣūfī magni-tude	al-Ṣūfī magnitude adjusted-1	al-Ṣūfī magnitude adjusted-2	Ptolemy magni-tude	Ptolemy magnitude (adjusted)	Visual magni-tude	HR number	Δ al-Ṣūfī-1	Δ al-Ṣūfī-2	Δ Ptolemy	Δ al-Ṣūfī-3	Δ al-Ṣūfī-4
1	1	Ursa Minor	3	3.00	3.00	3	3.00	2.02	424	–0.98	–0.98	–0.98		
2	2	Ursa Minor	4	4.00	4.00	4	4.00	4.36	6,789	0.36	0.36	0.36		
3	3	Ursa Minor	4	4.00	4.00	4	4.00	4.23	6,322	0.23	0.23	0.23		
4	4	Ursa Minor	4	4.00	4.00	4	4.00	4.32	5,903	0.32	0.32	0.32		
5	5	Ursa Minor	5(k)	4.75	4.70	4	4.00	4.95	6,116	0.20	0.25	0.95	0.20	0.25
6	6	Ursa Minor	2	2.00	2.00	2	2.00	2.08	5,563	0.08	0.08	0.08		
7	7	Ursa Minor	3	3.00	3.00	2	2.00	3.05	5,735	0.05	0.05	1.05		
8	8	Ursa Minor	4	4.00	4.00	4	4.00	4.25	5,430	0.25	0.25	0.25		
1	9	Ursa Major	4	4.00	4.00	4	4.00	3.36	3,323	–0.64	–0.64	–0.64		
2	10	Ursa Major	5	5.00	5.00	5	5.00	5.47	3,354	0.47	0.47	0.47		
3	11	Ursa Major	5	5.00	5.00	5	5.00	4.60	3,403	–0.40	–0.40	–0.40		
4	12	Ursa Major	5	5.00	5.00	5	5.00	4.76	3,576	–0.24	–0.24	–0.24		
5	13	Ursa Major	5	5.00	5.00	5	5.00	4.80	3,616	–0.20	–0.20	–0.20		
6	14	Ursa Major	5	5.00	5.00	5	5.00	4.56	3,771	–0.44	–0.44	–0.44		
7	15	Ursa Major	4(s)	4.25	4.30	4	4.00	4.67	3,624	0.42	0.37	0.67	0.42	0.37

Table 3 Statistical comparison of the magnitude systems of al-Şūfī and Ptolemy

Astronomer	Mean	Standard deviation
al-Şūfī three-step	–0.06	0.59
al-Şūfī two-step	–0.09	0.59
Ptolemy	+0.07	0.71

structure. This example shows that he expressed 4(m) and 4(k) consecutively then 4(k) twice. He also mentioned several successive examples of (s). Therefore, the assumption of word repetition is not valid in this case because if al-Şūfī was concerned with correct grammatical structure then why did he not use other words for (s) "*Asgharih*". He repeated the word "*Asgharih*" (s) many times in many locations throughout his book.

10 Stars Mentioned by al-Şūfī that Are Not in the *Almagest*

In his written comments on the constellations al-Şūfī mentioned some additional stars that were not included in Ptolemy's star catalog, but surprisingly he did not include these stars in his tables even though he identified many of them in detail, describing their locations and estimating their magnitudes. One reason why al-Şūfī did not include these additional stars may have been out of respect for Ptolemy, whose catalogue had long been a standard reference work in this field. In his introductory chapter, al-Şūfī clearly stated that the tables he produced were based upon Ptolemy's work.

In our study we have identified 128 of these 'missing' stars, 59 in the Northern constellations, 41 in the Zodiac constellations and 28 in the Southern constellations. al-Şūfī specifically mentioned these stars in his constellation commentaries but not in the tables, and he clearly said that these stars were not included in the *Almagest*. For identification of these stars we included their HR numbers, along with their magnitudes as derived by al-Şūfī and their modern magnitudes.

11 Nebulae in al-Şūfī's Book

We find many references in modern history of astronomy books to al-Şūfī and those few nebulae which he identified. Therefore in this study all of these nebulous objects were located and all the commentaries which were written by al-Şūfī were summarized. Just to give an example of the importance of al-Şūfī's comments about nebulae, we would like to quote here a remark which he made more than 1,000 years ago: "The two lines (of stars) begin from the nebula which is close to the 14th star [in the constellation of Andromeda] …". Here he is describing the constellation of Andromeda, and for the first time in recorded history he mentions the location of a nebula which is now identified as M31, the spiral galaxy in Andromeda. The location of this is shown in Figure 8.

Fig. 8 al-Ṣūfī's image of the constellation Andromeda. The 'Great Nebula in Andromeda' is close to the 14th star, which is marked by the *arrow*.

12 Old Arabic Astronomical Traditions in al-Ṣūfī's Book

Finally, in the last section of this doctoral study the old Arabic astronomical traditions mentioned in al-Ṣūfī's book were examined. We tried to summarize the names of the stars and/or asterisms for the constellations that were used in Arabic folk astronomy as per the explanations provided by al-Ṣūfī. For example, the Arabs located the star Alcor which they named *al-Suhā*. However, this star was not mentioned by Ptolemy or any of the other ancient Greek astronomers. The Arabs considered this star to be a faint star which they used to test their eyesight. The study of old Arabic astronomical traditions is a fascinating work in its own right, and shows the level of sophistication of the ancient Arabs and how the stars were considered a part of their everyday lives.

13 Concluding Remarks and Publishing

al-Ṣūfī and his *Book of the Fixed Stars* have a very important place in the history of Arabic observational astronomy. al-Ṣūfī not only corrected observational errors in the works of his predecessors, such as the famous Arab astronomer al-Battāni, but he also exposed many of the faulty observations found in the various versions of the *Almagest.* He carefully defined the boundaries of each constellation, and recorded magnitudes and positions of stars using new and independent observations which he made.

After this doctoral project is completed (see Hafez 2010) the first author plans to publish this study along with a full English translation of al-Şūfī's famous book.

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Japanese Astronomy in the Seventh Century

Mitsuru Sôma and Kiyotaka Tanikawa

Abstract There are astronomical records in both the α and β volumes of the *Nihongi*, and we have already shown that the reliability of these records depends on which particular volumes they appeared in. In order to strengthen and extend our previous conclusion, we study more thoroughly the astronomical data in the *Nihongi* and analyze the reliability more precisely with reference to Chinese and Korean history books. There are only three astronomical records in the volumes of the α group, and none of these can be said to be observational. In the volumes of the β group, there is, in each of the three volumes, one record, which was surely based on actual observations. Five records of comets are common to Chinese records, but wording and the form of the records are different in Japanese and in the continental records, so the records are judged not to have been transported from China or Korea. Most of the remaining records represent local phenomena, which we believe are all based on observation. In the case of eclipse records, we not only analyze the reliability of each event but also apply elementary statistics to weather records in order to examine the completeness of the records. We conclude that there were major changes in observational astronomy in Japan during the seventh century. Specifically, observations were made during AD 620–641 and AD 672–686 (in the β group of the *Nihongi*), but no observations were made between AD 642 and 671 (in the α group). After AD 686 (during the Jitô era), no observations were made except for one appulse observation of Mars and Jupiter.

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1 Introduction

Ancient Japanese astronomical observations of aurorae, eclipses, comets, meteors, occultations and appulses of planets were recorded in *Rikkokushi* (六国史, *Six Formal Japanese History Books*, see Table 1). Further astronomical records were also given in other history books, like *Nihon-Kiryaku* (日本紀略, *Brief History of Japan*), and in many personal diaries. Astronomical records from these various sources were assembled by Kanda (1934, 1935).

The Japanese astronomical records begin in AD 620 in the *Nihongi* (*Chronicle of Japan*). This paper deals with Japanese seventh century astronomical records, and discusses them in the context of the astronomy that was carried out in Japan during that century. The *Nihongi* was written in Chinese characters. Mori (1991, 1999) classified the volumes of the *Nihongi* into α and β groups according to the usage of Chinese characters. The volumes in the α group were written using correct Chinese characters whereas those in the β group had improper Chinese characters. This implies that the volumes in the α group were written by people from China and those in the β group were written by Japanese scholars. The chronological intervals of the two *Nihongi* groups are shown in Table 2. Kawabata et al. (2002) assigned a γ group to the volume of the Jitô era because the volume could not be classified into either α or β.

Tanikawa and Sôma (2002, 2004) have shown that the records of the solar eclipse in AD 628 and the lunar occultation of Mars in AD 681 were based on actual observations. Kawabata et al. (2002) pointed out that both of them were in the β group, and showed that all of the eclipses and occultations recorded in the β group were

Table 1 Six Formal Japanese History Books

Name	Period	Completed
日本紀(日本書紀) *Nihongi*	–697	720
続日本紀 *Shoku-Nihongi*	697–791	797
日本後紀 *Nihon-Kôki*	792–833	840
続日本後紀 *Shoku-Nihon-Kôki*	833–850	869
日本文徳天皇実録 *Nihon-Buntoku-Tennô-Jitsuroku*	850–858	879
日本三代実録 *Nihon-Sandai-Jitsuroku*	858–887	901

Table 2 Numbers of astronomical records according to the eras in the *Nihongi*

Group	Years	Emperor and number
β	593–628	Suiko[a] 2
	629–641	Jomei 7
α	642–645	Kôgyokua[a] 2
	645–654	Kôtoku 0
	655–661	Saimei[a] 0
	661–671	Tenji 1
β	672–686	Tenmu 12
γ	686–697	Jitô 7

[a] These were empresses. Kôgyoku and Saimei were the same empress with different names

considered to be observationally-based, while there were no reliable astronomical records in the α group. In addition, Kawabata et al. argued that the records of natural phenomena such as earthquakes, tsunami, and volcanic eruptions in the β group were also reliable. They also showed that all of the solar eclipse records in the Jitô period were the predicted ones. On the other hand, Hosoi (2007) criticized this research and insisted that the astronomical records in the α and β groups were equally unreliable.

Hosoi dealt with recording principles of astronomical records in the *Six Formal Japanese History Books*, discussed if those records were true, and argued over the political environment of that time. However, concerning the astronomical records in the *Nihongi*, he only described them by denying our assertion.

This paper deals with astronomical records in the α and β groups of the *Nihongi* separately, and discusses whether they were based on real observations of the phenomena by estimating fine weather rates, using statistics of the numbers of observations and examining Chinese and Korean records. As a result, this paper strengthens our former assertions:

1. In the α group there were only a few astronomical records and none of them was based on actual observations.
2. In the β group there were many astronomical records, about half of which could have been based upon observations made in Japan. The observational basis of the remaining records could not be ascertained because they involved local phenomena such as meteors and aurorae.
3. The solar eclipses recorded in the Jitô era were not based on observations. There was a record of an appulse of planets in the Jitô era which may have been based on observations, but this is somewhat questionable because the recorded date was far from the date of the closest approach.

Note that ΔT in this paper denotes TT–UT, where TT is Terrestrial Time, which is a uniform time used in dynamical theories, and UT is Universal Time, which indicates the rotation angle of the Earth. We need the value of ΔT to calculate local predictions of astronomical phenomena, and the value in the seventh century can be assumed to be between 2,000 and 4,000 s. Also note that the AD dates in this paper are according to the Julian Calendar.

2 Astronomical Records in the Nihongi

2.1 Statistics

Astronomical records in the *Nihongi* begin in AD 620 and the number of astronomical records in the *Nihongi* is 31. Their numbers according to the volumes are shown in Tables 2 and 3. The annual mean number of astronomical records in the α group in the seventh century is 0.10 because the interval of the α group in this century is just 30 years and the number of astronomical records is 3. On the other hand, the

Table 3 Records in the β group (AD 593–641, 672–686)

2 in Suiko: 1 aurora, 1 total solar eclipse
7 in Jomei: 3 comets, 2 solar eclipses, 1 meteor, 1 occultation
12 in Tenmu: 4 comets, 2 solar eclipses, 1 lunar eclipse, 1 occultation of Mars, 3 meteors, 1 aurora

Table 4 Astronomical records in the α group

Date	Phenomenon	Era	Record in China
9 August 642	Lunar occultation of a star	Kôgyoku	None
8 June 643	Lunar eclipse	Kôgyoku	None
April–May 664	Meteorite fall	Tenji	None

annual mean number of astronomical records in the β group is 0.55 because the total interval of the β group in the seventh century after AD 620 is 38 years and the number of astronomical records during this period is 21. We counted the number of years from the year AD 620 because astronomical records began in that year, but if we count the number of the years from the beginning of the Suiko era (AD 593), the annual mean number of astronomical records in the β group becomes 0.32 because the total number of the years becomes 65. In any case, the annual mean number of astronomical records in the β group is significantly higher than that in the α group. It was also noticed that the annual mean number of astronomical records in the β group increased gradually as time progressed from the Suiko era to the Tenmu era.

2.2 Records in the α Group

In the α group there are three astronomical events (see Table 4), but none of them can be based on actual observations. Details of these three records are presented below.

2.2.1 Lunar Occultation of a Star

This lunar occultation involved a ‘visiting star’ (kyaku-sei, 客星) on 9 August 642. Kanda (1935) classified this object as a comet, but the term ‘visiting star’ can also mean a nova or a supernova. Saito (1986) assumed that the star was the 4.4 magnitude star χ Ophiuchi. This occultation occurred during daylight hours in Japan and therefore could not have been observed, but he assumed that people saw the star near the Moon in the evening and recorded an occultation. The star, however, was too faint to be seen near the Moon. There is little possibility that the occulted star was a comet, because if it was bright enough to be seen with the naked eye it should have had a tail, and would surely have been recorded in China, but a comet was only recorded there in the previous year (i.e. 641) and the next one was in 663. The star might have been a nova or a supernova. In China a visiting star was recorded in 561 but the next one was not until 829, raising the possibility that Chinese astronomers were not interested in recording visiting stars during the seventh and eighth centuries.

We can therefore conclude that there is no firm evidence that this reported lunar occultation of 9 August 642 was an observed event.

2.2.2 Lunar Eclipse

We have already discussed this eclipse of 8 June 643 in Kawabata et al. (2002), and Figure 1 here is a reproduction of Figure 1 in that paper. As shown in this figure, this eclipse was not seen in the area surrounding Chang'an (長安), the capital of China at the time, and nor was it seen in Korea either. Naturally there are no records of this event in China or in Korea. Kanda (1935) mentioned the

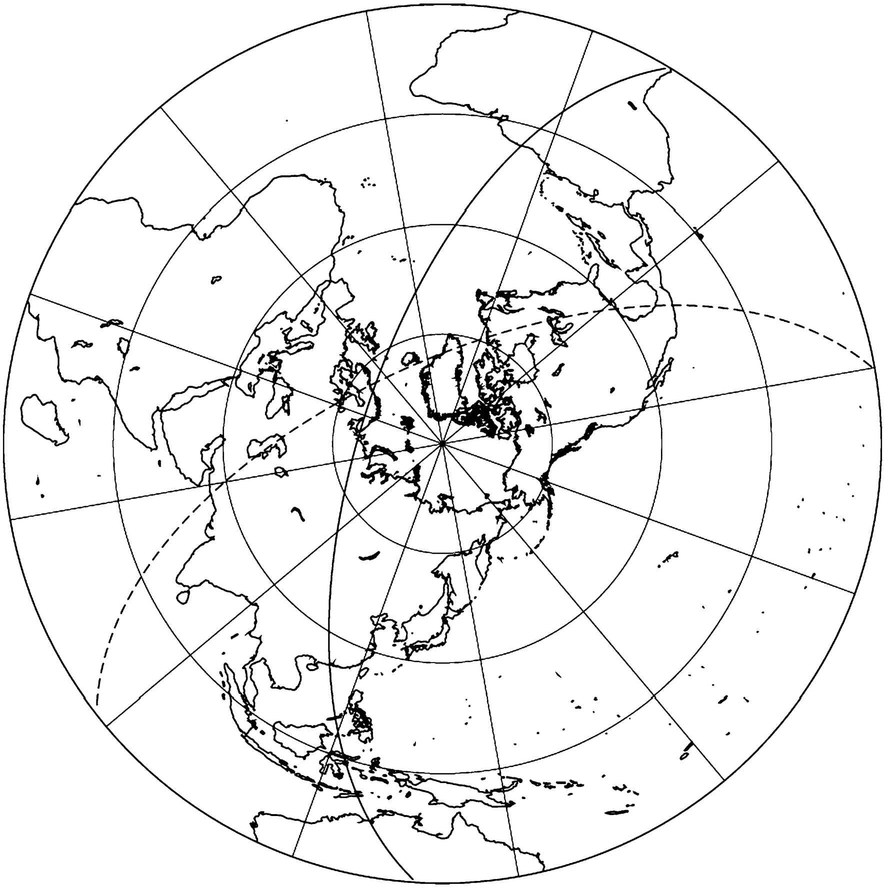

Fig. 1 Visible area of the lunar eclipse of 8 June 643. The beginning of the eclipse was seen in the area to the *left* of the *solid line*, and the *end of the eclipse* in the area above the *broken line*. Therefore, the eclipse was not visible at all in Japan and its surrounding areas (after Kawabata et al. 2002: Figure 1).

possibility that a prediction of this event was brought by a messenger from Baekje (Paekche, 百済) in Korea and Hosoi (2007) gave his assent to it, but we would like to emphasize that it was only a guess: it would be very unlikely that all of the facts relating to a false prediction of a lunar eclipse were given in an almanac in Baekje, that a messenger brought it to Japan, and that it was recorded as an actual observation in Japan.

2.2.3 Meteorite Fall

The article says that a star fell to the north of the capital in the third month (of the Japanese calendar) of the third year of the Tenji era (i.e. AD 664), but we cannot find any evidence for it. It is also suspicious because the precise date of the event was not given.

2.3 Records in the β Group

There are three kinds of astronomical records in the β group: records of phenomena that are confirmed to have been observed in Japan; those that were also observed in China but can be assumed to have been observed in Japan from the wording and the form of the records; and those that cannot be confirmed to have been observed because they were local phenomena. These are examined in detail below.

2.3.1 Records of Phenomena Observed in Japan

There were three eras in the β group: Suiko, Jomei, and Tenmu. Interestingly, in each era there was one record of a phenomenon that can be confirmed to have been observed in Japan.

Total Solar Eclipse on 10 April 628

The record indicates that a total solar eclipse (or at least very close to total) was seen on 628 April 10. As seen in Figure 2, it cannot have been recorded as total in China because the magnitude of the eclipse at the capital, Chang'an, was between 0.5 and 0.7. Therefore we can conclude that this was the original observation as recorded in Japan.

Lunar Occultation of a Star on 4 March 640

It can be shown that the star was the first magnitude star Aldebaran. As shown in Figure 3, it should have been also observed in China and in Korea but there was no record in either country, presumably because of bad weather. Therefore, we can infer that this event was recorded in Japan.

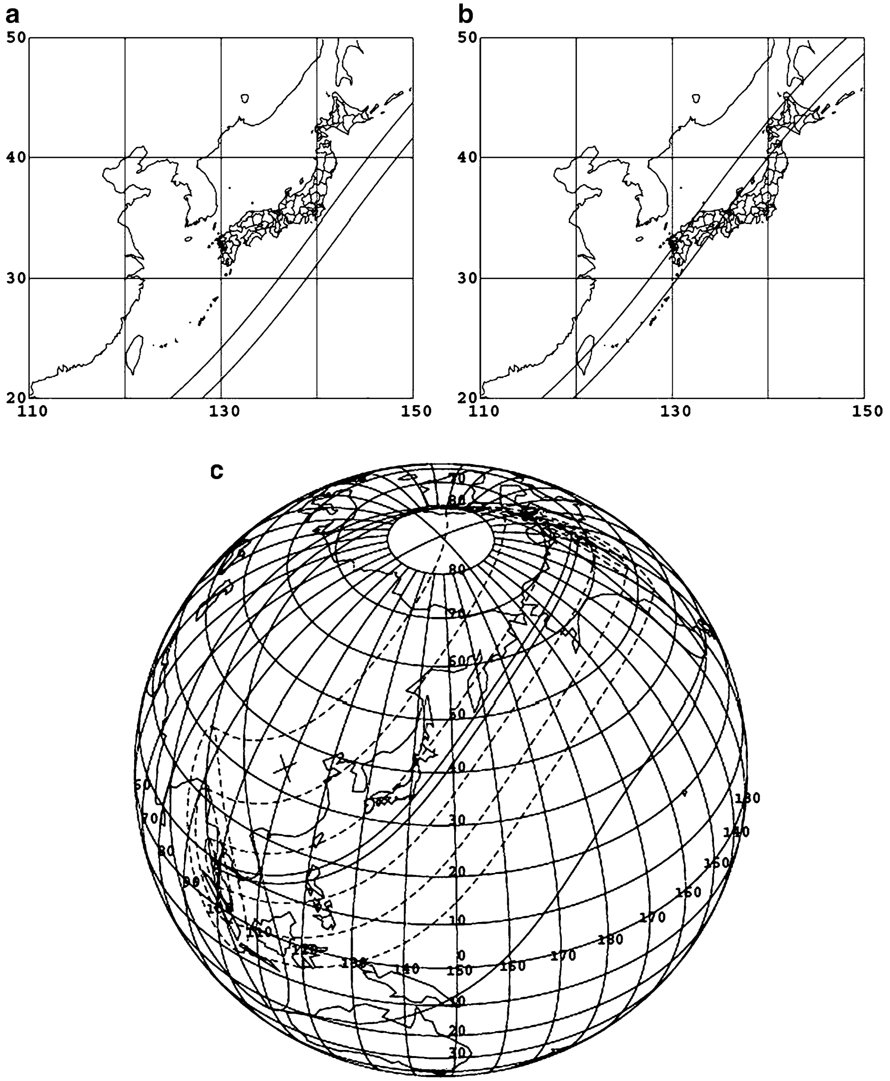

Fig. 2 Solar eclipse on 10 April 628 according to different ΔT values. (**a**) Visible area of the total eclipse with $\Delta T = 4{,}000$ s. (**b**) Visible area of the total eclipse with $\Delta T = 2{,}000$ s. (**c**) Visible area of the eclipse with $\Delta T = 4{,}000$ s, with the *broken lines* of equal eclipse magnitudes of 0.5, 0.7, and 0.9. Chang'an, the capital of China at that time, is indicated by the *cross*.

Lunar Occultation of Mars on 3 November 681

Saito (1986) wrote that, although Mars was not occulted at Asuka (the capital of Japan at the time) the Moon was so brilliant that the observer would have lost sight of Mars near the Moon. However, as was shown by Tanikawa and Sôma (2002, 2004) and Sôma et al. (2004), this was a grazing occultation as seen from Asuka

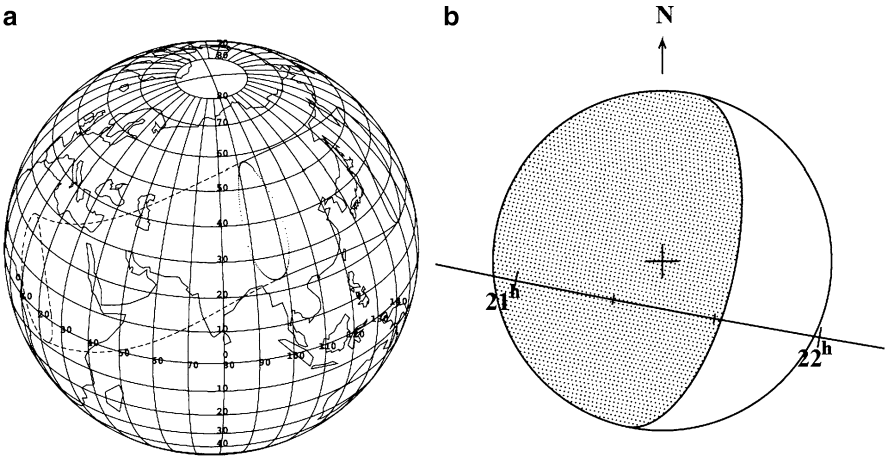

Fig. 3 Lunar occultation of Aldebaran on 4 March 640. (**a**) Visible area of the occultation, (**b**) Occultation seen at Asuka, the capital of Japan at that time.

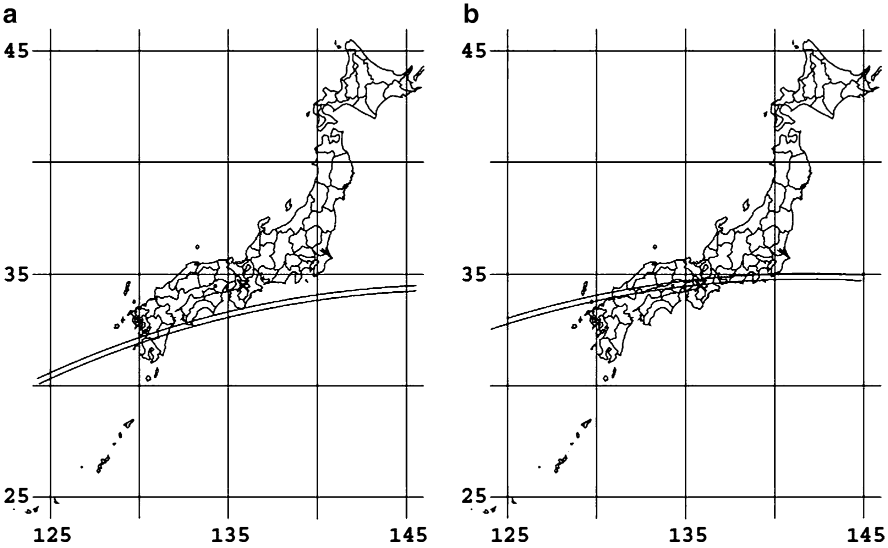

Fig. 4 Northern limits of the lunar occultation on 3 November 681. Mars was occulted in the area south of the lines, and Mars was partially occulted in the area between the two lines. Asuka, the capital of Japan at that time, is indicated by a *cross*. (**a**) Calculated with $\Delta T = 4{,}000$ s, (**b**) Calculated with $\Delta T = 2{,}000$ s.

(see Figure 4). This occultation was not seen at the capital of China although Mars was seen near the Moon there. Nor was it seen in Korea. Therefore, we can conclude that this event was recorded in Japan.

2.3.2 Records of Comets

Records of comets are characterized as follows:

1. Comets can be seen from almost everywhere on the Earth, which is not at all the case for meteors. Hosoi (2007: 314) had a misunderstanding about this fact when he classified comets as a kind of meteor and explained that comets are meteors with clear trains, which is clearly wrong.
2. Seven comets were recorded in the β group. Three were in the Jomei era and the four in the Tenmu era, and their years were 634, 635, 639, 676, 681, 684 (with two in 684). Five of the seven (i.e. all but the comet of 635 and the later one in 684) were also recorded in China).
3. In the α group period (642–671) there were three comets recorded in China, but none of these was recorded in Japan. In this respect the difference between the α and β groups is clear.

Since comets can be seen from almost everywhere on the Earth, one may suspect that the Japanese records of comets came from China or Korea. In the following account it is shown that we can infer that those records were not the ones from China or Korea.

As for the Silla (新羅) Kingdom in Korea, from the last half of the 640s the Koreans followed the system of the Tang (唐) Dynasty in China and therefore they probably did not have their own original records at that time (or if they did, these were not shown to foreigners). The Baekje (Paekche, 百済) Kingdom fell in 660 and the Goguryeo (Koguryo, 高句麗) Kingdom in 668, so the Koreans did not have astronomical records after those years. Hence the records in 676, 681, and 684 are not ones that came from Korea.

As for the comets in 634, 635, and 639, no records of comets were given in those years in Silla. There was a record of a comet in 640 in Baekje, but the Chinese characters "星孛" indicating a comet used in Baekje at that time were different from the characters "長星" in Japan. In Goguryeo there were no records of comets. Accordingly, it can be inferred that all of the Japanese records of comets were not ones that came from Korea.

Next let us compare the Japanese records of comets with the Chinese ones. The three Japanese records in the Jomei era used "長星" (long star) to denote a comet. In China this term was seldom used: there were only four records using this term out of more than 50 records of comets in total in Hanshu (漢書), one in Houhanshu (後漢書), one in Weishu (魏書) and two in Suishu (隋書), and they were all in earlier records; this term was never used in the records after AD 608. The four Japanese records in the Tenmu era used "彗星" to denote comets, which were the same as the Chinese records at the time. However, while names of the Chinese constellations in which comets appeared were usually given in Chinese records, they were not given in the Japanese records.

Accordingly, from the different wording or the different form of records we can infer that the records of comets were not the ones from China or Korea. And from the fact that five of the seven comets recorded in Japan were also recorded in China, we can see that they were surely based upon actual observations.

2.3.3 Other Astronomical Records

A lunar eclipse on 12 December 680 in the Tenmu era was recorded in Japan. It was also recorded in China, but interestingly, the gānzhī (干支) indicating the date of the lunar eclipse given in the Chinese record was erroneous while that in the Japanese record was correct. Therefore, it can be inferred that this Japanese record was the original one.

There were other records of local astronomical phenomena in the β group as shown in Table 5. Since these were local ones, we cannot make a comparison with those in China or Korea, but since we can confirm that Japanese records of eclipses and comets in the β group were based on actual observations, it would be natural to assume that these records of local phenomena were also real. Indeed, as will be shown in the next Section, the ratio of the number of recorded solar eclipses in the β group to the total number of solar eclipses that should have been observable in Japan corresponds to the ratio of fine weather, and therefore we can infer that there existed astronomers who carefully observed astronomical phenomena during the period covered by the β group. They observed solar eclipses during the day time, and lunar eclipses, comets, occultations, etc. at night.

2.4 Astronomical Records in the Jitô Era

2.4.1 An Appulse of Mars and Jupiter on 14 September 692

The date was denoted as the 28th day of the seventh month of the 6th year of the Jitô era according to the Japanese calendar. The apparent angular distance of Mars and Jupiter on that day (14 September 692) was 5.5°, but the two planets should have been seen closer 10 days later on 24 September 692 at 2.4° apart. In addition, the Moon was seen near the two planets on 24 September 692 (the Moon was 8°

Table 5 Other astronomical records in the β group

Date	Phenomenon	Date in the Japanese calendar
30 December 620	Aurora	1st day of 12th month in Suiko 28th year
24 March 637	Meteor	23rd day of 2nd month in Jomei 9th year
29 November 680	Bright eastern sky	3rd day of 11th month in Tenmu 9th year
10 September 682	Meteor	3rd day of 8th month in Tenmu 11th year
18 September 682	Aurora	11th day of 8th month in Tenmu 11th year
1 January 685	Meteor	21st day of 11th month in Tenmu 13th year
3 January 685	Meteoric shower	23rd day of 11th month in Tenmu 13th year

Table 6 Appulses of planets from Mercury through Saturn during 690–693[a]

Planets		Date	TT (h m)	Distance	Elongation
Jupiter	Saturn	10 March 690	15 47	1.59°	122.04° W
Mercury	Venus	25 April 690	17 51	4.80°	18.52° W
Mars	Jupiter	25 July 690	17 49	3.02°	97.00° E
Mars	Saturn	2 August 690	06 14	4.23°	93.83° E
Jupiter	Saturn	17 September 690	13 21	1.19°	51.29° E
Mercury	Jupiter	23 October 690	08 54	4.30°	19.60° E
Mercury	Venus	14 November 690	05 37	1.41°	18.88° W
Mercury	Saturn	3 December 690	16 05	0.83°	18.15° W
Mercury	Jupiter	10 December 690	06 41	0.42°	15.28° W
Venus	Mars	20 April 691	04 54	0.09°	19.82° E
Mercury	Venus	26 May 691	02 48	4.49°	24.51° E
Venus	Saturn	14 January 692	20 02	2.80°	46.29° W
Venus	Jupiter	19 February 692	06 46	1.89°	45.26° W
Mars	Saturn	9 March 692	15 41	1.16°	98.00° W
Mercury	Venus	23 June 692	18 54	3.16°	19.23° W
Mars	Jupiter	24 September 692	02 08	2.37°	103.82° E
Venus	Saturn	14 November 692	01 23	1.92°	18.99° E
Venus	Jupiter	21 December 692	19 46	0.95°	27.57° E
Mercury	Jupiter	1 January 693	20 56	1.01°	18.38° E
Mercury	Jupiter	25 February 693	11 50	1.14°	23.32° W
Venus	Mars	17 March 693	08 31	1.43°	43.64° E
Venus	Mars	9 June 693	12 16	2.30°	17.80° E
Mercury	Mars	28 September 693	00 55	1.48°	17.80° W
Venus	Mars	14 November 693	11 11	1.11°	35.93° W

[a] This list gives those with the angular distance of less than 5° and the elongation from the Sun of more than 15°. The times are given in Terrestrial Time. 'Distance' means the apparent angular distance between the two planets, and 'Elongation' means the elongation from the Sun

from Mars and 6° from Jupiter). Accordingly, the event should have been more prominent on or near 24 September 692, and, therefore, the record is somewhat questionable because the recorded date was 10 days earlier than the date of the closest approach.

Table 6 lists observable appulses of planets during 690–693, where it can be seen that such events occurred rather frequently. It is not known why only the event of 692 involving Mars and Jupiter was recorded.

2.4.2 Solar Eclipses

There were six solar eclipses given in the Jitô era. It is well known that none of them was observable in Japan and, therefore, that they were predicted ones (see Kawabata et al. 2002). The issue of how they were predicted should be resolved in the future.

3 Solar Eclipse Records in the β Group and Incidence of Fine Days

As already explained, solar eclipses were observed and recorded in the β group of the *Nihongi*. Now we will examine whether all of the observed eclipses were recorded.

Nowadays the number of sunshine hours for each day are observed at various places in Japan by the Meteorological Agency, and their mean values for 1971–2000 are given in the annual *Chronological Scientific Tables* (理科年表) edited by the National Astronomical Observatory of Japan (2007). Meanwhile, the total number of day time hours can be calculated from astronomical ephemerides.

Table 7 shows monthly data for the ratio of total sunshine hours versus total day time hours, together with its year mean value for Nara (which is close to Asuka, the capital of Japan in the seventh century). The mean ratio was found to be 41.1%. The corresponding values for Morioka in northern Japan and for Fukuoka in western Japan were also calculated, and were 38.8% and 41.5% respectively. Therefore, we can say that two solar eclipses out of five were observed in Japan, while three out of five were missed due to bad weather. There were 15 solar eclipses that should have been observable during the β group period in Japan. Therefore, the expected number of observed eclipses is six, while the number of the recorded solar eclipses was five. Consequently, we can say that it is highly probable that all of the observed solar eclipses in the β group were recorded in the *Nihongi*. On the other hand, there were at least 13 solar eclipses that should have been observable in the α group period in Japan, but none of them was recorded. Therefore, it is clear that solar eclipses were not observed during the α group period.

Table 7 The ratio of the sunshine hours to the daytime hours at Nara

Month	Sunshine (h)	Daytime (h)	Ratio (%)
1	119.8	315.9	37.9
2	113.5	310.5	36.6
3	148.6	372.9	39.8
4	177.9	393.5	45.2
5	193.4	435.2	44.4
6	142.3	435.3	32.7
7	173.1	443.1	39.1
8	204.6	418.4	48.9
9	146.0	373.8	39.1
10	154.7	352.8	43.8
11	135.6	313.2	43.3
12	128.0	308.4	41.5
Total	1,837.6	4,473.1	41.1

4 Conclusion

From the study of the astronomical records in the *Nihongi*, it is found that progression and retrogression alternated in observational astronomy during the seventh century in Japan. Specifically, observations were made during 620–641 (in the β group of the *Nihongi*), then no observations were made during 642–671 (in the α group), and observations were again made during 672–686 (in the β group), and again no observations – other than one planetary appulse – were made during the Jitô era, between 686 and 697. The issue of why these variations occurred in Japanese observational astronomy during the seventh century will be the subject of future research.

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An Astronomical Problem in a Japanese Traditional Mathematical Text: The 49th Problem of the Kenki-sanpo of Takebe Katahiro

Yukio Ôhashi

Abstract During the Edo period (Tokugawa-shogunate period) (1603–1867), there was a mathematical tradition now called *"Wasan"* which was primarily based on Chinese mathematics, but Japanese mathematicians also created new devices. It was quite popular, and common people could enjoy solving mathematical problems through *Wasan* regardless of their social status. Some astronomical problems were also treated there.

In this paper, I would like to explain one problem solved by Takebe Katahiro (1664–1739), who was one of the leading disciples of the celebrated mathematician Seki Takakazu (ca.1640–1708). The problem is to obtain the grand epoch from some fragmental data of a draft of an annual calendar from an astronomical point of view, and is the process of solving simultaneous congruence expressions from a mathematical point of view. This is not so difficult to understand astronomically, but it was extremely hard to make the necessary numerical calculations (without access to an electronic computer, of course).

Here, we can see that astronomy offered interesting problems for mathematicians. Although certain areas of calendrical astronomy might have been monopolized by Government officials, others could enjoy making astronomical calculations through *Wasan*, which was basically open to the public.

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1 Introduction

1.1 Method of Transliteration

In this paper, words which are used in both Japan and China are basically transliterated in the Japanese ("Hepburn") system first, and its corresponding Chinese ("Pinyin") system of transliteration is only added when necessary. Proper names are basically transliterated in Japanese, Chinese or Korean according to their place of origin, but are transliterated in Japanese in my translation of the *Kenki-sanpō*, because this text was produced in Japan (even if written in Classical Chinese language). Note, also, that as the terminology of denominations largely changes by multiples of 104 in Chinese and Japanese, throughout this paper commas are used between four digits in large numbers in order to make it easy to compare these with the original sources.

1.2 Japanese Astronomy and Mathematics

From the available written evidence, the beginning of Japanese mathematical astronomy was marked by the introduction of the Chinese calendar into Japan in AD 554 by a Korean calendar specialist invited from the Paekche (百済) Kingdom in Korea. This fact is recorded in the *Nihon-shoki* (日本書紀), an official history of ancient Japan. Subsequently, some calendrical knowledge was introduced into Japan from Korea and China. Thereafter the Chinese calendar was used in Japan from around the beginning of the seventh century AD.

At the beginning of the eighth century, a legal and administrative system called *"ritsuryō"* (律令), which was based on a Chinese model, was adopted in Japan, and the *Onmyō-ryō* (陰陽寮, Bureau of Astronomy and Astrology) was established. In this Bureau, astronomical observations (including for astrology), calendar-making, time-keeping (using water clocks) and divination were carried out.

Until the second half of the seventeenth century annual calendars were produced by this Bureau. They used the theories of calendrical system which were exclusively imported from China, but the actual calculations for each year were done in Japan. There were five systems of Chinese calendar which were officially used in Japan, and the last of these was the *Xuanming-li* (宣明暦, *Senmyō-reki* in Japanese, where Chinese *li* and Japanese *reki* stand for "calendar" or "ephemeris"), which was used from AD 862 to 1684 in Japan.

By the beginning of the Edo (江戸) Period (AD 1603–1867),[1] some Japanese scholars noticed the inaccuracy of the old *Xuanming-li* and tried to study the more

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[1] This was the Tokugawa (徳川)-shogunate period, during which Edo (present-day Tokyo) was the headquarters of the Shōgun (which literally means "general," but in reality is something like the king, although the nominal emperor existed in Kyoto).

accurate *Shoushi-li* (授時暦, *Juji-reki* in Japanese). This excellent traditional Chinese calendrical system was made by Guo Shoujing (郭守敬) and others at the time of the Yuan (元) Dynasty in China, and was used in China from AD 1281 but was never used officially in Japan.

Also from the beginning of the Edo Period, traditional Japanese mathematics, which was based on Chinese traditional mathematics, became quite popular and developed rapidly. Later Japanese mathematicians also made new devices. This system of traditional Japanese mathematics, mainly developed during the Edo Period, is now called "*Wasan*" (和算).

One very famous book published at the beginning of the main period of *Wasan* is the *Jinkōki* (塵劫記) (AD 1627) of Yoshida Mitsuyoshi (吉田光由, AD 1598–1672). It explained the method of using the *"soroban"* (the East Asian abacus) and its application in a lucid manner, became a kind of best seller, and was reissued several times. At the end of the AD 1641 edition, Yoshida added twelve unsolved problems, which were meant to be a kind of challenge to readers. These sorts of unsolved problems are called "*idai*" (遺題). Since then, the tradition of *idai-keishō* (遺題継承, succession of "*idai*") has developed, and after one author published some questions at the end of his mathematical book other author(s) would publish the solutions. The tradition of *idai-keishō*, started by Yoshida, continued until the time of Seki Takakazu (関孝和, ca.AD 1640–1708), who did not add unsolved problems in his book. From that time, some "schools" of mathematics were created, and the Seki school (関流) was the largest of these. Seki had some disciples, and Takebe Katahiro (建部賢弘, AD 1664–1739) was one of the most prominent of these. Subsequently, *Wasan* was rapidly developed in these schools, right through to the end of the Edo Period.

In AD 1683 Shibukawa Harumi (渋川春海, AD 1639–1715) developed a new calendrical system, which was named *Jōkyō-reki* (貞享暦) the following year, and was officially used in Japan from AD 1685. It was the first new calendrical system produced in Japan. While based mainly on the *Shoushi-li*, it considered the time difference between China and Japan, and also the change in the position of the apogee or perigee of the solar orbit (in a geocengtric model) since the time of the *Shoushi-li*. Shibukawa obtained the necesary astronomical knowledge through information on Western astronomy mentioned in a book titled *Tianjing-huowen* (天経或問, *Tenkei-wakumon* in Japanese). This was a popular Chinese astronomical book.

Although Shibukawa accepted some Western elements like this, he basically followed the traditional Chinese system of astronomy. Later the Japanese astronomers Takahashi Yoshitoki (高橋至時, AD 1764–1804) and Hazama Shigetomi (間重富, AD 1756–1816) adopted more Western astronomical elements when they developed the calendrical system *Kansei-reki* (寛政暦), and they were followed by Shibukawa Kagesuke (渋川景佑, AD 1787–1856) who developed the calendrical system *Tenpō-reki* (天保暦). This was the last traditional calendrical system developed by Japanese scholars.[2]

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[2] For the history of astronomy in China in general, Chen (1983) or Chen (2003) may be consulted. The former reference provides an English language introduction to the calendrical systems of China (although the *Xuanming-li* is not mentioned there), while the second Chen reference, in Chinese

1.3 The 49th Problem of the Kenki-sanpō

In 1674, the *Sūgaku-jōjo-ōrai* (数学乗除往来), which is an anonymous mathematical work but is attributed to Ikeda Masaoki (池田昌意), was published, and at the end there were some unsolved problems. The *Kenki-sanpō* (研幾算法) of Takebe Katahiro, published in 1683, contained the solutions to those *"idai"* (unsolved problems). The final problem, number 49, is about calendrical calculations. At that time, the *Xuanming-li* was still in use in Japan, and calculation of the problem is based on this system.

In this paper, I would like to explain the astronomical meaning of this problem. Here, we will see that a calendrical system can provide an interesting problem for mathematicians. This problem is to obtain the number of years that have elapsed since the grand epoch of the calendar[3] using fragmentary data contained in the draft of an annual calendar. This kind of exercise involves solving simultaneous congruence expressions.

This paper has been developed from an unpublished paper that I presented at The 6th International Symposium on the History of Mathematics and Mathematical Education using Chinese Characters (ISHME), which was held in Tokyo in 2005.

2 An English Translation of the 49th Problem of the Kenki-sanpō

A copy of the original text is shown in Figure 1. An English translation follows.

> No.49: Let a *kengyōsō* (見行草, annual draft to make a calendar for a particular year) of the *Senmyō-reki* (宣明暦 = Chinese calendar "*Xuanming-li*") be presented, where *sekinen*

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language, is probably the most comprehensive history of Chinese astronomy in a single volume that is currently available. There is no comparable work written in English, as Needham's monumental work (1959) does not provide enough detailed information on Chinese calendars. There is also a collection of detailed monographs on the history of Chinese astronomy in Chinese by Bo (2008–2009). For earlier developments in Chinese astronomy, in English language, see Ôhashi (2007; 2008).

For the history of astronomy in Korea the English language book by Jeon (1974) may be consulted, but there are many other works written in Korean.

For the history of astronomy and mathematics in Japan in general, the English language books by Nakayama (1969) and Smith et al. (1914) may respectively be consulted, but there are many other works in Japanese. An English translation of the *Jinkōki* of Yoshida Mitsuyoshi has been published by the Wasan Institute (2000), and some of the works of Takebe Katahiro, including a rough translation of his *Kenki-sanpō*, have been published in English by Takenouchi and Morimoto (2004). For some aspects of the calendrical system of Shibukawa Harumi see Ôhashi (2009).

[3] The "grand epoch" is defined as some specified time in the remote past, and varied from one calender system to another. The grand epoch in reality was a kind of artificial epoch that was used for the sake of convenience rather than a time when specific astronomical events actually took place. In the case of the *Xuanming-li* calendar, the date of the grand epoch was 7,069,317 BC.

四十九　今有宣明暦見行草不知積年只云
天正冬至大餘小餘（若干）經朔大餘小餘（若干）入暦
進退大餘小餘秒（若干）入交汎日小餘秒（若干）問積
年幾何（本書云没日・土用・滅日・入定氣・同朓朒・進退朓朒・合朔此七辞多故併削之）
○答曰得積年
術曰置冬至大小餘通分内子（乃置大餘以統法乘之加入小
餘數也後倣之）如四十五分而一得數以一京一千六
百一十二萬零三百四十八兆零三百三十九
萬一千四百四十一億零四百一十九萬七千
零一十九乘之得數○置冬至大小餘内減經
朔大小餘（不足減者大餘加紀法小餘解統法而後減之）餘通分内子
爲閏餘分以二京八千四百六十九萬七千六
百七十五兆八千三百五十四萬五千五百四
十九億四千三百四十五萬四千四百乘之得
數○置入暦進退大小餘秒大餘内減一筭餘
（若退者加暦中）通分内子加入閏餘分（若加之滿暦周者去之）如
三秒（百秒爲分）而一得數以一京六千二百八十三
萬一千三百七十八兆九千零二十六萬三千

研幾算法　卅九

二百四十八億六千零一十萬零七千二百乘
之得數○置入交汎日小餘秒通分内子加入
閏餘分（若加之滿終率者去之）如一十六秒（千秒爲分）而一得
數以一京九千二百九十八萬五千一百一十
二兆五千二百三十二萬零三百零二億四千
二百六十四萬八千乘之得數○右四位相併
共得數滿三京零六百二十二萬七千四百三
十兆零六千五百二十一萬八千七百七十五
億五千二百八十六萬二千四百去之餘得積
年合問

Fig. 1 Original text of the 49th problem in the *Kenki-sanpō*.

(積年, the number of years elapsed since the grand epoch) is the unknown. Only given are the *daiyo* (大余, day-number expressed in 60-day cycle) and *shōyo* (小余, numerator of its fraction) of the *tensei-tōji* (天正冬至, winter solstice of the preceding year); the *daiyo* (day-number expressed in 60-day cycle) and *shōyo* (numerator of its fraction) of the *keisaku* (経朔, mean new moon, immediately before the winter solstice); the *daiyo* (number of days), *shōyo* (numerator of its fraction) and *byō* (秒, numerator of its sub-fraction) of the *nyūreki-shintai* (入暦進退, time elapsed since the moon's passage of the apogee or perigee, at the time of the new moon immediately before the winter solstice); and the elapsed days, *shōyo* (numerator of its fraction) and *byō* (numerator of its sub-fraction) of the *nyūkō-han* (入交汎, time elapsed since the moon's passage of the descending node, at the time of the new moon immediately before the winter solstice). Find a value for *sekinen*. (Original commentary: The book [*Sūgaku-jōjo-ōrai*] also gives the *botsujitsu* (没日, a kind of special day), *doyō* (土用, duration of one fifth of a season (quarter of a solar year) placed at the end of each season), *metsujitsu* (滅日, a kind of special day), *nyū-teiki* (入定気, the amount which may be considered to correspond to the true Sun's longitude) and its *chōjiku* (朓朒, correction of solar motion), *shintai*'s *chōjiku* (進退朓朒, a correction for lunar motion) and *gassaku* (合朔, the true new Moon), but these seven items are not required (in order to solve the problem). Therefore, they have been omitted here). [For information on the *botsujitsu* (*mori* in Chinese) and *metsujitsu* (*mieri* in Chinese), see Ôhashi (2000) or Ôhashi (2001).]

As the result, a value for *sekinen* (積年) can be derived.

The procedure used in order to solve this problem is as follows. Take the *daiyo* (大余, day-number expressed in 60-day cycle) and *shōyo* (小余, numerator of its fraction) of the *tōji* (冬至, winter solstice), convert them into an improper fraction (whose denominator is *tōhō* (統法, 8,400) as the *shōyo*), and use its numerator. (Original commentary: The method of the conversion is that the *daiyo* is multiplied by the *tōhō* (8,400, the number used as the denominator of the fraction), and the result is added to the *shōyo*. The following conversions are also to be done similarly). Divide the numerator by 45, and multiply the result by 1,1612,0348,0339,1441,0419,7019. Record the result.

Take the *daiyo* (day-number expressed in 60-day cycle) and *shōyo* (numerator of its fraction) of the *tōji* (winter solstice), and subtract the *daiyo* (day-number expressed in 60-day cycle) and *shōyo* (numerator of its fraction) of the *keisaku* (経朔, mean new moon) respectively from them. (Original commentary: If the amount is not enough to be subtracted, add *kihō* (紀法, 60, the amount of the days in the 60-day cycle) to the *daiyo*, and add *tōhō* (8,400, the number used as the denominator of the fraction) to the *shōyo*, then make the subtraction). Convert the results into an improper fraction (whose denominator is *tōhō* (8,400) as the *shōyo*), and denominate its numerator *junyo-fun* (閏余分). Multiply it by 2,8469,7675,835 4,5549,4345,4400. Record the result.

Take the *daiyo* (number of days), *shōyo* (numerator of its fraction), and *byō* (秒, numerator of its sub-fraction) of the *nyūreki-shintai* (入暦進退, time counted from the time of the Moon's passage of the apogee or perigee), and subtract one from the *daiyo*. (Original commentary: If the Moon's anomaly is in the second half (from the perigee to apogee) of an anomalistic month (from the apogee to apogee), add *rekichū* (暦中, a half of the length of an anomalistic month) [in order to count from the apogee]). Convert the results into an improper fraction (whose denominator is *tōhō* (8,400) as the *shōyo*), and add its numerator to the *junyo-fun*. (Original commentary: If the result exceeds a *rekishū* (暦周, length of an anomalistic month expressed in terms of 1/8,400 of a day), subtract a *rekishū*). [Multiply the result by 100 in order to convert its unit (or denominator of the fraction) into *byō*, and] divide it by 3. (Original commentary: One hundred *byō*s are equal to one *fun* (unit of *shōyo*) [in the case of the *nyūreki-shintai*]). Multiply the result by 1,6283,1378,9026,3248,6010, 7200. Record the result.

Take the days, *shōyo* (numerator of its fraction), and *byō* (numerator of its sub-fraction) of the *nyūkō-han* (入交汎, time elapsed since the Moon's passage of the descending node), and convert the results into an improper fraction (whose denominator is *tōhō* (8,400) as the *shōyo*), and add its numerator to the *junyo-fun*. (Original commentary: If the result exceeds a *shūritsu* (終率, length of a nodical month expressed in terms of 1/8,400 of a day), subtract a *shūritsu*). [Multiply the result by 10,000 in order to convert its unit (or denominator of the fraction) into *byō*, and] divide it by 16. (Original commentary: One thousand *byō*s [*sic.*: the amount should actually be ten thousand *byō*s] are equal to one *fun* (unit of *shōyo*) [in the case of the *nyūkō-han*]). Multiply the result by 1,9298,5112,5232,0302,4264,8000. Record the result.

Add up the above four results. If the obtained amount exceeds 3,0622,7430,6521,8775, 5286,2400, subtract this amount (as many as possible). The remainder is the *sekinen* (積年, number of years elapsed since the grand epoch). Thus the problem is solved.

3 Exposition of the Problem

3.1 Introduction

This problem is to obtain the *sekinen*, the number of years that have elapsed since the grand epoch, when some calendrical data for the year, based on the *Xuanming-li*, are given.

The *Kenki-sanpō* of Takebe Katahiro gives solutions for the problems presented in the *Sūgaku jōjo ōrai*. In the original problem in the *Sūgaku jōjo ōrai*, the values of the *tensei-tōji* etc. for a particular year are given, and five calendrical systems (one of which is the *Xuanming-li*) are suggested to be used. However, in the *Kenki-sanpō*, the year is not specified, and a general method which can be used for any year is given. And also, only the *Xuanming-li*, which was the current calendar at the time of its publication, is used in the *Kenki-sanpō*. As my exposition is for the *Kenki-sanpō*, the general method is explained below. There is a commentary for the 49th problem of the *Kenki-sanpō*, entitled *Kenki-sanpō dai-shijūku kaijutsu*

(研幾算法第四十九解術, The method of solving the 49th problem of the *Kenki-sanpō*),[4] and this work gives the solution for the particular year which was suggested in the *Sūgaku jōjo ōrai* as well as an exposition of the general method.

The *Xuanming-li* is a calendrical system compiled by the Chinese astronomer Xu Ang (徐昂) at the time of the Tang (唐) Dynasty, and was used from AD 822 to 892 in China. It was also used in the Koryo (高麗) Kingdom in Korea, and in Japan. In Japan, it was used for a long period, from AD 862 to 1684. Therefore, the *Xuanming-li* was still in use when Takebe Katahiro published his *Kenki-sanpō* in 1683. At about the same time, the *Jōkyō-reki* was developed by Shibukawa Harumi, and this was used in Japan from 1685 to 1754.

The *Xuanming-li* is recorded in a Chinese official dynastic history *Xin-tang-shu* (新唐書) (AD 1060), but its description is too brief. A more detailed description is recorded in a Korean official history *Koryo-sa* (高麗史) (AD 1451). And also, there is a detailed monograph entitled *Senmyō-reki*, published in AD 1644 in Japan. There is also a detailed exposition published in Japan, that is the *Chōkei Senmyō-reki Sanpō* (長慶宣明暦算法) (AD 1676) written by Andō Yūeki (安藤有益).

A *Kengyōsō* is an annual draft in order to make a calendar for a particular year, and where necessary astronomical data calculated by the current calendrical system (the *Xuanming-li* in this case) are given. For a discussion of the *Kengyōsō* see Momo (1990).

In order to write the following commentary, I consulted Fujii (2000; 2002–2003) and drafts written by Fujii Yasuo (藤井康生) and Yokotsuka Hiroyuki (横塚啓之), which were kindly made available to me.

3.2 Chinese Luni-solar Calendars

Since this section is to explain Chinese calendars, Chinese words are transliterated in the Chinese ("Pinyin") system first, and the Japanese ("Hepburn") transliteration is only added when necessary.

Chinese traditional calendars are classified as luni-solar calendar, where a month is a synodic month, and a year is basically a tropical year. As the duration of 12 synodic months is slightly shorter than a tropical year, intercalary months are inserted regularly in order to adjust the relationship between months and seasons.

A month begins from the new Moon. At the time of the *Xuanming-li*, the inequality of lunar motion (equation of centre of the Moon) and that of solar motion (equation of centre of the Sun, in geocentric theory) were already known. Applying the lunar and solar inequalities, a mean new Moon is converted into a true new Moon. In the *Xuanming-li*, the true new Moon was used for the civil calendar. The mean new Moon is called *jingshuo* (経朔, *keisaku* in Japanese) or *pingshuo* (平朔, *heisaku* in Japanese), and the true new Moon is called *dingshuo* (定朔, *teisaku* in Japanese).

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[4] The *Kenki-sanpō dai-shijūku kaijutsu* is included in a manuscript *Sekisan-kōden* (関算後伝) volume 69, and is preserved in the Miyagi Prefectural Library (宮城県図書館; accession number: KD090, se5, 474–245). A facsimile of this work is included in Higashi-Ajia Sūgakushi Kenkyūkai (2010).

A tropical year is considered to start from the winter solstice. However, the winter solstice is included in the 11th month of Chinese year, and the 1st month is 2 months later than the month which includes the winter solstice, if there is no intercalary month in between. The winter solstice immediately before a certain year is called *tianzheng-dongzhi* (天正冬至, *tensei-tōji* in Japanese) of the year. Here, *tianzheng* (*tensei* in Japanese) corresponds to the 11th month, and *dongzhi* (*tōji* in Japanese) stands for winter solstice. One tropical year is divided into 24 segments, and their initial points of time are called 24 *jieqi*s (節気, *sekki* in Japanese).

In Chinese calendars, the cycle of *ganzhi* (干支, *kanshi* in Japanese), which is made as a combination of 10 *gan*s (*kan* in Japanese) and 12 *zhi*s (*shi* in Japanese), is used. Both the *gan*s and *zhi*s change serially, and there are 60 combinations. This cycle is used to count (or denominate) days and years. Therefore, the 60-day cycle is frequently used in calculations of Chinese calendars.

In each Chinese luni-solar calendar, a certain epoch is used, at which the winter solstice and the new Moon occur at the beginning (midnight) of the day which is the beginning of 60-day cycle. The epoch is also assumed to be the beginning of the anomalistic month, nodical month, and also synodic period of planets, etc. Usually, the epoch was placed in the remote past. One may doubt the ability of ancient astronomers to calculate astronomical phenomena in the remote past correctly with their inaccurate astronomical constants even though they must have used careful observational data. But for the practical construction of the calendar, however, it does not matter. If the epoch is remote enough, the calendar can be constructed with the required accuracy, whether or not the assumed astronomical phenomena actually occurred at the time of the epoch. It should be considered that a remote epoch is a kind of artificial epoch for the sake of convenience rather than a point when astronomical events really took place. Probably Chinese astronomers knew this, because they were aware that calendars with inaccurate astronomical constants could not be used for long periods. This kind of remote epoch is called *shangyuan* (上元, *jōgen* in Japanese), which may be translated as "grand epoch." In the case of the *Xuanming-li*, the grand epoch is assumed to be 7,069,317 BC.

3.3 Exposition of the Problem

From now on, terms are basically transliterated in the Japanese ("Hepburn") system.

3.3.1 Tensei-tōji

The *tensei-tōji* (天正冬至, *tianzheng-dongzhi* in Chinese) is the winter solstice immediately before the required year. It is the reference point of time for the calculation of the required year. Its *daiyo* (大余, *dayu* in Chinese) is its day-number expressed by the 60-day cycle, where its initial component, *kōshi* (甲子, *jiazi* in Chinese), is counted as the number zero. Its *shōyo* (小余, *xiaoyu* in Chinese) is the numerator of its fraction whose denominator is *tōhō* (統法, *tongfa* in Chinese) (8,400). Therefore, the *shōyo* corresponds to the time of the winter solstice in the day. Now the period a (in terms of 1/8,400 of a day) from the beginning of the 60-day cycle immediately before the winter solstice to the winter solstice is expressed by the following equation:

$$\text{(The } \textit{tensei} - \textit{tōji}\text{'s)} \textit{daiyo} \times 8400 + \textit{shōyo} = a \tag{1}$$

Now, 60 multiplied by 8,400 (*tōhō*) is called *junshū* (旬周, *xunzhou* in Chinese) (50,4000), which is a period of 60-day cycle expressed in terms of 1/8,400 of a day. The length of a tropical year (in terms of days) multiplied by 8,400 (*tōhō*) is called *shōsai* (章歳, *zhangsui* in Chinese) (306,8055). The remainder of the *shōsai* diminished by *junshū*s as many times as possible is called *tsūyo* (通余, *tongyu* in Chinese) (4,4055). So, the day-number (with fraction) of the winter solstice increases by *tsūyo/tōhō* (4,4055/8,400) per year. Therefore, the following congruence equation for the *sekinen* (積年, *jinian* in Chinese, number of years elapsed since the grand epoch), n, is obtained:

$$4{,}4055n \equiv a (\text{mod.} 50{,}4000) \tag{2}$$

Here, 4,4055 and 50,4000 have the greatest common measure 45. Therefore, (2) can be converted into the following equation:

$$979n \equiv a/45 (\text{mod.} 1{,}1200) \tag{3}$$

3.3.2 Keisaku

A *keisaku* (経朔, *jingshuo* in Chinese) is a mean new Moon. In this problem, the mean new Moon immediately before the winter solstice is used. The *daiyo* and *shōyo* of the winter solstice diminished by the *daiyo* and *shōyo* of the new Moon immediately before the winter solstice are called the *daiyo* and *shōyo* of the *junyo* (閏余, *runyu* in Chinese). The *junyo* corresponds to the period from the new Moon to the winter solstice, and this period (in terms of 1/8400 of a day) b can be expressed by the following equation:

$$\text{(The } \textit{junyo}\text{'s) } \textit{daiyo} \times 8400 + \textit{shōyo} = b \tag{4}$$

This amount b is called *junyo-fun* (閏余分) in the text, where *fun* stands for a unit which is 1/8400 of a day. The length of a synodic month (in terms of days) multiplied by 8400 (*tōhō*) is called *shōgetsu* (章月, *zhangyue* in Chinese) (24,8057). The remainder of the *shōsai* (306,8055) diminished by *shōgetsu*s as many times as possible is called *shōjun* (章閏, *zhangrun* in Chinese) (9,1371). So, the *junyo-fun* increases by *shōjun* per year. Therefore, the following congruence expression for the *sekinen n* is obtained:

$$9{,}1371n \equiv b\,(\text{mod. } 24{,}8057) \tag{5}$$

3.3.3 Nyūreki-shintai

The *nyūreki-shintai* (入暦進退) corresponds to the time counted from the time of the Moon's passage of the apogee or perigee. Its *daiyo* expresses the number of days. Its *shōyo* is the numerator of its fraction whose denominator is *tōhō* (8400). Its *byō* is the numerator of its sub-fraction whose denominator is 100. As the *daiyo* of the first day of the passage is defined to be one and not zero, one is subtracted from the *daiyo*, so that the result expresses the time elapsed from the passage. The Moon is assumed to be at the apogee at the grand epoch, and the period from the Moon's passage of the apogee to the next passage of the apogee is an anomalistic month. The Moon's speed changes in this cycle. As an anomalistic month is divided into two halves (*shin* and *tai*), and the *nyūreki-shintai* is counted from the apogee and perigee, the amount of *rekichū* (暦中, *lizhong* in Chinese, a half of the anomalistic month in terms of 1/8400 of a day) is added to the *nyūreki-shintai* for the second half, so that the result corresponds to the time from the passage of the apogee.

In this problem, the *nyūreki-shintai* of the mean new Moon immediately before the winter solstice is used. If this is added to the *junyo(−fun)*, the *nyūreki-shintai* at the time of the winter solstice is obtained. Therefore, the *nyūreki-shintai* at the time of the winter solstice (in terms of *byō*s or 1/84,0000 of a day) *c* can be expressed by the following equation:

$$(\text{The } ny\bar{u}reki-shintai\text{'s})daiyo \times 8400 + sh\bar{o}yo + by\bar{o}\,/\,100 + b = c\,/\,100 \tag{6}$$

Now, the length of a tropical year (in terms of 1/8400 of a day) is the *shōsai* (章歳, *zhangsui* in Chinese) (306,8055), and the length of an anomalistic month (in terms of 1/8,400 of a day) is the *rekishū* (暦周, *lizhou* in Chinese) (23,1458$^{19}/_{100}$). Therefore, the following congruence expression for the *sekinen n* is obtained:

$$306{,}8055 \times 100n \equiv c\ (\text{mod. } 2314{,}5819) \tag{7}$$

Here, 3,0680,5500 and 2314,5819 have the greatest common measure 3. Therefore, (7) can be converted into the following expression:

$$1{,}0226{,}8500n \equiv c\,/\,3(\text{mod. } 771{,}5273) \tag{8}$$

3.3.4 Nyūkōhan

The *nyūkōhan* (入交汎) corresponds to the time elapsed from the time of the Moon's passage of the descending node. Besides its days, its *shōyo* is the numerator of its fraction whose denominator is *tōhō* (統法, *tongfa* in Chinese) (8400). Its *byō* is the numerator of its sub-fraction whose denominator is 10,000. The Moon is assumed to be at the descending node at the grand epoch, and the period from the Moon's passage of the descending node to the next passage of the descending node is a nodal month (also called draconic month). This is used to predict eclipses, because an eclipse occurs when the Sun and the Moon are situated near the nodes.

In this problem, the *nyūkōhan* of the mean new Moon immediately before the winter solstice is used. If this is added to the *junyo(−fun)*, the *nyūkōhan* at the time of the winter solstice is obtained. The *nyūkōhan* at the time of the winter solstice (in terms of *byō*s or 1/8400,0000 of a day) d can be expressed by the following equation:

$$\text{(The } nyūkōhan\text{'s)} daiyo \times 8400 + shōyo + byō / 1{,}0000 + b = d / 1{,}0000 \qquad (9)$$

Now, the length of a nodal month (in terms of 1/8400 of a day) is the *shūritsu* (終率, *zhonglü* in Chinese) ($228{,}582^{6{,}512}/_{10{,}000}$). Therefore, the following congruence expression for the *sekinen*, n, is obtained:

$$306{,}8055 \times 1{,}0000n \equiv d \ (\text{mod. } 22{,}8582{,}6512) \qquad (10)$$

Here, 306,8055,0000 and 22,8582,6512 have the greatest common measure 16. Therefore, expression (10) can be converted into the following equation:

$$19{,}1753{,}4375n \equiv d / 16 (\text{mod. } 1{,}4286{,}4157) \qquad (11)$$

3.3.5 The Simultaneous Congruence Expressions to be Solved

Now the following four simultaneous congruence equations have been obtained, and the problem is to solve these expressions:

$$979n \equiv a / 45 (\text{mod. } 1{,}1200) \qquad (3)$$

$$9{,}1371n \equiv b (\text{mod. } 24{,}8057) \qquad (5)$$

$$1{,}0226{,}8500n \equiv c / 3 (\text{mod. } 771{,}5273) \qquad (8)$$

$$19{,}1753{,}4375n \equiv d / 16 (\text{mod. } 1{,}4286{,}4157) \qquad (11)$$

In (8) and (11), the coefficients of n are greater than respective moduli, and the following equations are obtained:

$$1,0226,8500 = 771,5273 \times 13 + 196,9951$$
$$19,1753,4375 = 1,4286,4157 \times 13 + 6030,0334$$

Therefore, (8) and (11) can be converted into the following expressions:

$$196,9951n \equiv c/3(\text{mod. } 771,5273) \tag{12}$$

$$6030,0334n \equiv d/16\,(\text{mod. } 1,4286,4157) \tag{13}$$

Now, let us define A, B, C and D as follows:

$$A = a/45 \tag{14}$$

$$B = b \tag{15}$$

$$C = c/3 \tag{16}$$

$$D = d/16 \tag{17}$$

Using there definitions, (3), (5), (12) and (13) are expressed as follows:

$$979n \equiv A(\text{mod. } 1,1200) \tag{18}$$

$$9,1371n \equiv B(\text{mod. } 24,8057) \tag{19}$$

$$196,9951n \equiv C(\text{mod. } 771,5273) \tag{20}$$

$$6030,0334n \equiv D(\text{mod. } 1,4286,4157) \tag{21}$$

3.4 Method of Solving the Simultaneous Congruence Expressions

3.4.1 Introduction

In China, a problem to solve simultaneous congruence expressions (or indeterminate equations) first appeared in the *Sunzi-suanjing* (孫子算経, ca. fourth to fifth century AD). This problem is also mentioned in the *Yanghui-suanfa* (楊輝算法) of Yang Hui (楊輝, thirteenth century AD) in China. In Japan, Seki Takakazu, the master of Takebe Katahiro, was inspired by the *Yanghui-suanfa*, and developed the method of solving simultaneous congruence expressions (or indeterminate equations). Takebe followed Seki's method, which is similar to the Chinese method called *dayan-qiuyi-shu* (大衍求一術) of Qin Jiushao (秦九韶, thirteenth century AD) and is mentioned in his *Shushu-jiuzhang* (数書九章, 1247 AD). Fujiwara Matsusaburō, a modern Japanese historian of mathematics, wrote that Seki's method is independent of Qin's method, and that it was developed by Seki himself, because there was no record that Qin's work *Shushu-jiuzhang* had been introduced into Japan in Seki's time. Seki's method is explained in Nihon-gakushi'in (1956), and Qin's method is explained in English by Li et al. (1983).

3.4.2 Procedure to Solve Each Congruence Expression

When simultaneous congruence expressions, such as (18)–(21), are given, each equation should be solved first, so that they are expressed in the form of "$n \equiv e$ (mod. M)", where n is an unknown quantity.

Let us suppose that the following equation, where n is an unknown quantity, is given:

$$fn \equiv g \text{ (mod. } M) \tag{22}$$

In order to solve this equation, the amount H which satisfies the following equation should be obtained:

$$fH \equiv 1 \text{ (mod. } M) \tag{23}$$

From (22) and (23), the following equation is obtained:

$$n \equiv fHn \equiv Hg \text{ (mod. } M\text{), hence}$$
$$n \equiv Hg \text{ (mod. } M) \tag{24}$$

Equation (24) is the solution of (22).

The procedure to obtain H which satisfies (23) is as follows. Firstly, divide the amount M by the amount f, and obtain the quotient q_1 and remainder r_1. Then, calculate h_1 as follows. Continue to calculate as follows:

	Quotient	Remainder	Calculation
M/f	q_1	r_1	$h_1 = q_1$
f/r_1	q_2	r_2	$h_2 = q_2 h_1 + 1$
r_1/r_2	q_3	r_3	$h_3 = q_3 h_2 + h_1$
r_2/r_3	q_4	r_4	$h_4 = q_4 h_3 + h_2$
r_{m-2}/r_{m-1}	q_m	r_m	$h_m = q_m h_{m-1} + h_{m-2}$

Continue this procedure until r_m becomes 1, when its suffix m is an even number. Then, h_m is the H which was to be obtained. Using this amount H, (24) is obtained.

3.4.3 Procedure to Solve Simultaneous Congruence Expressions

Let the following simultaneous congruence expressions, where n is an unknown quantity, be given:

$$n \equiv S_i \ (\mathrm{mod.}\ M_i), i = 1, 2, 3, ---m \tag{25}$$

Let us define N_i as follows:

$$N_i = T/M_i, T = M_1 M_2 M_3 --- M_m \tag{26}$$

Now, the following equations should be solved in order to obtain H_i:

$$N_i H_i \equiv 1 \ (\mathrm{mod.}\ M_i) \tag{27}$$

If H_i is obtained, (25) can be solved as follows:

$$n \equiv \sum N_i H_i S_i (\mathrm{mod.}\ T) \tag{28}$$

The method of solving (27) is as follows. If N_i is greater than M_i, subtract M_i from N_i as many times as possible, and use the remainder F_i. Then, solve the following equation just like in the previous section:

$$F_i H_i \equiv 1 \ (\mathrm{mod.}\ M_i) \tag{29}$$

Now, using H_i, (28) is obtained.

3.4.4 Method of Solving the Problem

Now, what we have to do is to solve the following simultaneous congruence expressions:

$$979n \equiv A (\mathrm{mod.}\ 1{,}1200) \tag{18}$$

$$9{,}1371n \equiv B (\mathrm{mod.}\ 24{,}8057) \tag{19}$$

$$196{,}9951n \equiv C (\mathrm{mod.}\ 771{,}5273) \tag{20}$$

$$6030{,}0334n \equiv D (\mathrm{mod.}\ 1{,}4286{,}4157) \tag{21}$$

The *Kenki-sanpō* itself does not give the method of solving these equations, but there is another work entitled *Kenki-sanpō dai-shijūku kaijutsu* (hereafter *Kaijutsu*) where the method is explained. The *Kaijutsu* is included in a manuscript entitled *Sekisan-kōden*. It was examined by the modern historian of mathematics Hirayama Akira (平山諦) in 1953, and he concluded in a slip written in 1953 which is attached to the manuscript, that the *Kaijutsu* must be the work of Takebe Katahiro.

I shall review the procedure explained in the *Kaijutsu* just briefly. There are some incorrect figures in the *Kaijutsu* manuscript. The figures have been checked by Fujii Yasuo, and the correct figures are mentioned in his unpublished draft. I also have checked that Fujii's correction is correct. In the following review, I have retained the original figures in the *Kaijutsu* manuscript and supplied the correct figures in square brackets. As these mistakes are not repeated in subsequent calculations etc., these are just scribal errors and the original calculations must have been done correctly.

Firstly, applying the method which I summarized in Sect. 3.4.2, the four equations (18)–(21) are solved. The method of solving (18) is, for example, as follows:

	Quotient:	Remainder:	Calculation:
11,200/979	11	431	($h_1=11$)
979/431	2	117	$h_2=2\times 11+1=23$
431/117	3	80	$h_3=3\times 23+11=80$
117/80	1	37	$h_4=1\times 80+23=103$
80/37	2	6	$h_5=2\times 103+80=286$
37/6	6	1	$h_6=6\times 286+103=1{,}819$

Here, the amount h_6 (1819) is the H to be obtained. Therefore, (18) is solved as follows:

$$n \equiv 1819A \text{ (mod. 1,1200)} \tag{30}$$

Similarly, the following equations are obtained:

$$n \equiv 18{,}9232B \text{ (mod. 24,8057)} \tag{31}$$

$$n \equiv 33{,}1577C \text{ (mod. 771,5273)} \tag{32}$$

$$n \equiv 8703{,}2976D \text{ (mod. 1,4286,4157)} \tag{33}$$

Now, using the method which I summarized in Sect. 3.4.3, the simultaneous congruence expressions (30–33) are solved.

The amounts corresponding to H_i (in (29)), N_iH_i (in (27)) and T (in (26)) are given in the *Kaijutsu* as follows:

$H_1=2{,}613$
$H_2=7{,}928$
$H_3=702{,}4795$
$H_4=1{,}1775{,}3065$
$N_1H_1=7144{,}3953{,}2405{,}5058{,}98$[*sic*, the correct figure is 6]93,1201
$N_2H_2=978{,}7150{,}0107{,}1$[*sic*, the correct figure is 2]553,6968,9600
$N_3H_3=2{,}7882{,}1620{,}9210{,}4003{,}0909{,}6000$
$N_4H_4=2{,}5240{,}2137{,}1320{,}5935{,}3000{,}8000$
$T=3{,}0622{,}7430{,}6521{,}8775{,}5286{,}2400$

Now, using the coefficients in (30–33), the following amounts are calculated:

$1819\ N_1H_1 = 1299{,}5655{,}0944{,}5615{,}2265{,}1785{,}4619$
$189232\ N_2H_2 = 1{,}8520{,}4197{,}0829{,}6148{,}1171{,}0238{,}7200$
$331577\ N_3H_3 = 92{,}4508{,}3660{,}0135{,}6903{,}2891{,}2439{,}2000$
$87032976\ N_4H_4 =$ 1[*sic*, the correct figure is 2],1967,3091,4336,3230,5002,9415,4380,8000

Finally, the amount T is subtracted from these four amounts as many times as possible. Let us denominate the results U_i as follows:

$U_1 = 1{,}1612{,}0348{,}0339{,}1441{,}0419{,}7019$
$U_2 =$ 2,8469,7675,8354,53[*sic*, the correct figure is 5]49,4345,4400
$U_3 = 1{,}6283{,}1378{,}9026{,}3248{,}6010{,}7200$
$U_4 =$ 1,9298,5112,5230[*sic*, the correct figure is 2],0302,4264,8000

Now, the final answer is as follows.

$$n \equiv U_1A + U_2B + U_3C + U_4D \ (\mathrm{mod.}T), \text{hence}$$
$$n \equiv U_1(a/45) + U_2b + U_3(c/3) + U_4(d/16) \ (\mathrm{mod.}T)$$
$$(T = 3{,}0622{,}7430{,}6521{,}8775{,}5286{,}2400) \tag{34}$$

Equation (34) is the answer to the 49th problem in the *Kenkisanpō*.

4 Conclusion

The 49th problem of the *Kenkisanpō* is astronomically quite simple, and is easy to understand as I have shown. However, it is extremely hard to make the numerical calculations in order to solve the simultaneous congruence expressions. So, this problem must have been a high-grade problem for advanced students of *Wasan*.

During the Edo period in Japan certain areas of astronomy were monopolized by government officials, but mathematical astronomy provided interesting problems for students of *Wasan*, some of whom were amateur astronomers. *Wasan* could be enjoyed by ordinary people and several *Wasan* books were published openly, although some advanced knowledge might have been taught only to high-grade students in *Wasan* schools.

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Hirayama Kiyotsugu: Discoverer of Asteroid Families

Seiko Yoshida and Tsuko Nakamura

Abstract Currently ‘asteroid families’ are considered to be one of the most basic concepts in planetary sciences, relating to planetary formation, impact evolution and spacecraft exploration. And this trend will be even more important in the near future. The asteroid families were first discovered in 1918 by Hirayama Kiyotsugu, an astronomer at the Tokyo Imperial University, and this was one of the earliest internationally-recognized scientific achievements by a Japanese scientist following the Meiji Restoration of 1868. Since then, research on the precise orbital elements proving the existence of asteroid families, and on their photometric and spectral characteristics, has continued through to the present day.

This paper overviews the lifetime and scientific career of Hirayama. We first mention his motivation and clues that led him to the discovery of asteroid families and then discuss the ideas he had in mind about their formation. In our paper we also introduce his other research activities, such as latitude observations, analysis of latitude variation, geodetic measurements of the Japan–Russia border on Sakhalin island after the Russo-Japanese War of 1904–1905, overseas solar eclipse expeditions, the explanation of the Kirkwood gaps and the resisting medium in the Solar System, motion theories of Hilda and Hecuba asteroids, light-curve interpretation of a certain type of variable stars, and surveys of archival astronomical records in China and Korea, as well as in Japan.

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1 Introduction

According to the history of astronomy in Japan after the Meiji Restoration Japanese observational and theoretical researches received an international boost with two discoveries. One was the Z-term in latitude variation (1902) discovered by Kimura Hisashi (1870–1943), and the other was the existence of families of asteroids (1918) by Hirayama Kiyotsugu (1874–1943; Figure 1), which is the main theme of this paper. The Z-term has now passed into the realm of classical history, although it played an important role during the early development stage of Japanese astronomical studies (Wako 1967). On the other hand, the Hirayama families have continued to attract the interest of the international astronomical community through to the present day (e.g. see Bottke et al. 2002; Fujiwara 1982; Gehrels 1979; Kozai et al. 1994).

When modern Western astronomy was introduced into Japan, we Japanese met for the first time not only the high skills of positional astronomy but also celestial mechanics and early developing astrophysics. Kimura and Hirayama were both students of Terao Hisashi (1855–1923), who was the first Director of the Tokyo Astronomical Observatory at Azabu (TAO) and the first Professor of Astronomy at the Tokyo Imperial University (TIU). Terao taught them classical astronomy and introductory celestial mechanics.

Hirayama opened up a new field in Japanese astronomical studies, research on the motion of asteroids using advanced techniques of celestial mechanics such as secular perturbation theories. On the other hand, his later studies in astrophysics eventually resulted in failure in spite of his eagerness. In this paper, we will explain his early interests and investigations in astronomy, detail his discovery of the asteroid families, relate subsequent changes in his astronomical interests, and finally overview his other research achievements.

2 The Hirayama Families of Asteroids

Prior to the discovery of 1918, Hirayama's approach to the families of asteroids was basically statistical, but when he began investigating unusual characteristics noticed in asteroidal data his focus shifted to advanced dynamics of secular perturbations.

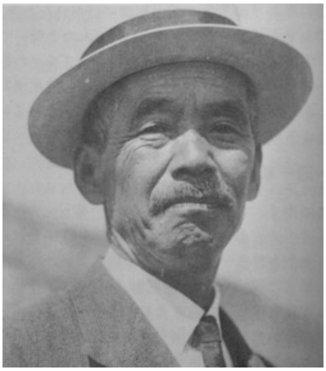

Fig. 1 Portrait of Hirayama Kiyotsugu (after Hirose Hideo 1979; courtesy: Abe Akira).

2.1 A Statistical Approach as the First Step of Discovery

In the opening paragraph of his hallmark 1918 paper which was published in the *Astronomical Journal*, Hirayama (1918: 185; our italics) gives us a clue about the discovery:

> On examining the distributions of the asteroids with respect to their orbital elements, particularly to the mean motion (n), the inclination (i) and the eccentricity (e), we notice condensations here and there. In general, they seem to be due to chance. *But there are some which are too conspicuous to be accounted for by the laws of probability alone*.

Upon classifying 37 asteroids with daily mean motions between $720''$ and $740''$ into six regions of inclination (i), Hirayama (ibid.) noticed that 16 of the orbits in the $i = 0^\circ$–4° region were surely "… out of proportion."

He first assumed the existence of a physically-connected asteroid group, and tentatively excluded those objects in that region. Computing the proportional number (the number calculated under the assumption of a flat distribution) using the remaining asteroids (37−16=21), which was called the 'corrected proportional number' in the column of Table 1, he found that the number of the asteroids belonging to the group should probably be 11. Next, he classified these 16 asteroids by eccentricity, and again saw a non-proportionality between 0° and 4° of the angle of eccentricity. In all, 10 orbits were out of proportion. He was then convinced of the existence of a group of asteroids, which differed from the already-established Trojan Group (Hirayama 1918).

2.2 Discovery of the Asteroid Families

Furthermore, taking the 16 asteroids which were out of proportion in the region near $n = 730''$, he plotted the poles of their orbital planes on the p–q plane, and noticed that 15 asteroids were located on the circumference of a circle (see the left graph in Figure 2). At the same time, 13 objects were distributed on another circumference of the u–v plane relating to the eccentricity (the right graph in Figure 2).

Table 1 Classification table of orbits with respect to the inclination (after Hirayama 1918: 185)

i	Actual number	Total	Proportional number	Diff.	Corr. prop. no.	Diff.
0º–4º	16	149	7	+9	5	+11
4–8	6	213	10	−4	7	−1
8–12	6	191	9	−3	6	0
12–16	6	131	6	0	4	+ 2
16–20	3	55	3	0	2	+ 1
20–	0	48	2	−2	2	−2
Sum	37	790	37	0	26	+11

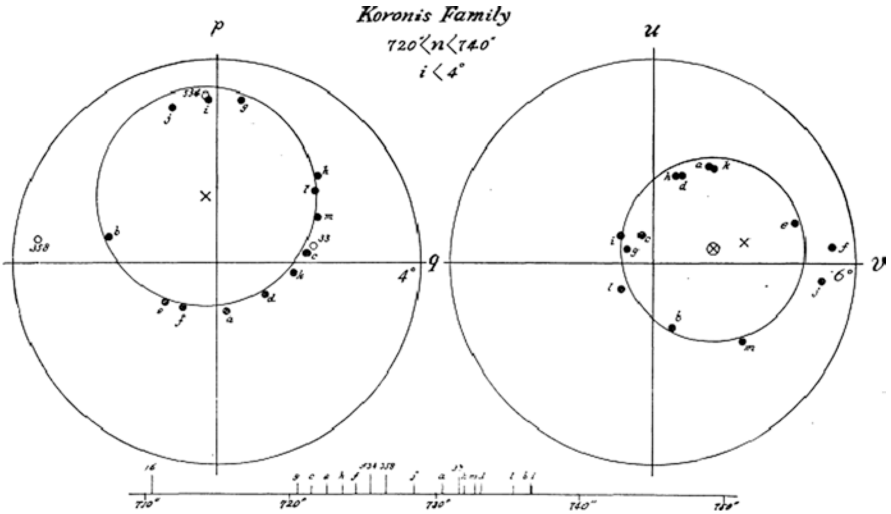

Fig. 2 Inclination and eccentricity diagrams showing the grouping of asteroids as a family (after Hirayama 1918: 186).

Here are given the definitions of p, q as functions of inclination (i) and nodal longitude (Ω), and u, v as those of eccentricity (e) and longitude of perihelion (ϖ):

$$p = \tan i \sin\Omega = p' + N\sin(ht + \beta) \quad u = e\sin\varpi = ku' + M\sin(gt + \alpha)$$
$$q = \tan i \cos\Omega = q' + N\cos(ht + \beta) \quad v = e\cos\varpi = kv' + M\cos(gt + \alpha)$$

where the rightmost terms of p, q represent a constant-velocity (h) circular motion with its radius of N and center at p', q', and the u and v equations are for a similar circular motion on the u–v plane. These equations can be derived from a general theory of planetary secular perturbations, and N and M are obtained as arbitrary constants in the solution of the relevant differential equations. Hirayama applied these equations to asteroid motions, with Jupiter as the main perturbing body, and for the first time was able to explain theoretically the circular distributions of the observed asteroids on the p–q and u–v planes from a dynamical viewpoint.

As to the formation process of the asteroid families, Hirayama imagined as follows: an asteroid was broken into a number of fragments at a time in the past. Since the additional velocities given to the fragments were small compared with that of the original body, each of the fragments initially stayed close each other. But after a long elapse of time, under the perturbation by Jupiter, the points p and q of the fragments were scattered irregularly, due to the term of $ht+\beta$, along the whole circumference of a circle with a radius approximately equal to N (Hirayama 1918).

Hirayama had little doubt that there was a physical relationship between those fragmentary asteroids, so he named the asteroids in such a group a *family*. In his 1918 paper he announced three families (Koronis, Eos, Themis) from 790 asteroids.

At this point, he did not yet call N and M the proper inclination and the proper eccentricity respectively, but recognized the importance of those quantities (Figure 2). This indicates that he directed his attention not to the osculating (i.e. observed) orbital elements but to the proper elements (Hirayama 1918, 1919, 1920).

At that time, it was not easy to judge whether or not a particular asteroid belonged to a family (and the situation is more or less the same even today), so Hirayama needed some systematic criteria of judgment. He did not use the terminology "… the invariable elements …" (meaning, the proper elements) until the appearance of his 1922 paper, titled "Families of Asteroids". This was a theoretical paper based upon secular perturbations, and among 950 asteroids he found the following five families, all with small inclinations and eccentricities: Koronis, Eos, Themis, Maria and Flora.

At this stage, Hirayama avoided including some groups of asteroids with large inclinations and eccentricities as families, but in 1927, after careful examination, he added two new families, Phocaea and Pallas, both characterized by large inclinations and eccentricities (Hirayama 1927b).

Initially, Hirayama (1922) only mentioned that the asteroids belonging to a group were disrupted by some unknown cause. Then, to explain the destruction of the original asteroid, he adopted an explosion theory whereby the parent body was broken into individual asteroids belonging to the one family (Hirayama 1927b). However, in a later paper (Hirayama 1935a), he also added as a possible cause collisions between asteroids (see Yoshida and Sugiyama 1997, 2001).

2.3 Responses to and Evaluations of Hirayama's Discovery

Hirayama devised a method of finding the asteroids belonging to a single family by using invariable elements, that is, their proper inclination and eccentricities. His discovery of asteroid families was warmly received by the international astronomical community, although it took some time before papers by other authors began to appear that made reference to the 'Hirayama families' (e.g. Barton 1924; Recht 1934).

Dirk Brouwer (1902–1966),[1] a leading astronomer who specialized in celestial mechanics, mentioned that his work was a modification of Hirayama's research. Specifically, what he did (Brouwer 1951) was to develop the secular variation theory of the orbital elements of asteroids based upon Hirayama's papers. Boosted by Brouwer's investigation, many planetary astronomers then directed

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[1] Hirayama (1933b) remembers that he first met Dirk Brouwer in 1932 at the 4th IAU Meeting, and that he also met W.W. Campbell again at this meeting (Hirayama 1933a). When they first met, around 1916, Campbell told him about the abnormal variable star SS Cygni (Hirayama 1917b). This star had a strong impact on him and subsequently motivated him to launch research on variable stars (Hirayama 1933b).

their attention to asteroid families. In 1993, an international conference was held in Tokyo to commemorate the 75th anniversary of the discovery of the Hirayama Families and the proceedings was published by the Astronomical Society of the Pacific (Kozai et al. 1994).

Hagihara Yusuke (1897–1979), well known as an authority on theoretical celestial mechanics, reviewed Hirayama's work in the obituary that he published in *Monthly Notices of the Royal Astronomical Society* in 1947. He emphasized the excellence of Hirayama's technique of celestial mechanics. Nakayama Shigeru (1981) wrote a short article in *the Dictionary of Scientific Biography*, saying that "Based on statistics as well as on the known principles of celestial mechanics, Hirayama's hypothesis was a rare accomplishment, considering the level of research in astronomy in Japan at that time." In an attempt to correct the wrong understanding by some overseas astronomers that Hirayama found groupings of asteroids simply by plotting the *osculating* orbital elements on the *p*–*q* and *u*–*v* diagrams, Kozai (1994) showed that Hirayama actually discovered the asteroid families by using proper elements earlier than Brouwer did.

3 Why Could Hirayama Discover the Families of Asteroids?

In this section we analyze in more detail the discovery situation of the asteroid families, relating it to Hirayama's life and academic circumstances. We explain why he could find the condensations of asteroids in the data. After reviewing the academic milieu of that era we mention three background circumstances to his discovery, and try to reconstruct the early stage when he first noticed unusual characteristics in the orbital elements of the asteroids.

3.1 Academic Milieu of that Era

Hirayama was born on 13 October 1874, in the city of Sendai in northern Japan. He was the only son of a civil engineer and was educated at Sendai High School under the old educational system up to the age of 20 (Figure 3). In 1894 he entered the Tokyo Imperial University (henceforth TIU). Further biographical details are supplied in Appendix 1.

Around that time, a new phenomenon called latitude variation was discovered in Germany and the USA, and in 1894 the International Association of Geodesy asked Japan to found a latitude observatory as part of an international geodetic collaboration, in order to study and reveal the worldwide nature of latitude variation. Responding to this movement, the Mizusawa Latitude Observatory was established in 1899, headed by the young director, Kimura Hisashi, who was just 29 years of age. Subsequently, Kimura discovered the Z-term in latitude variation. Hence we may say that Japanese astronomy was much influenced by geodesic interests in those days. Observations of latitude variation then started at the Tokyo Astronomical

Fig. 3 *Sendai Nikou* (The Second High School – the name used under the old educational system). This photograph was probably taken in the early 1890s, and Hirayama is in the second row from the *bottom* and third from the *left* (coutesry: Tomita Yoshio).

Observatory (henceforth TAO) in order to check Mizusawa's results, and 25 year old Hirayama was one of the observers.

Towards the end of the nineteenth century, the level of astronomical research in Japan was catching up with that of the leading European countries: courses in astronomy were first established at the TIU in 1877, and the TAO was founded in 1888. Early astronomical research at the University and at the TAO was heavily biased towards positional astronomy and geodesy. Since the Department of Astronomy in the Science College at the TIU maintained close relations with the Departments of Physics and Mathematics, staff and students in astronomy could share lectures and share a common cultural background with people in these latter departments.

When the curriculum was reformed in 1897, Hirayama Shin (1867–1945) lectured on astrophysics,[2] while TAO Director, Terao, taught celestial mechanics. In addition, Kimura and Hirayama were taught by Tanakadate Aikitsu (1856–1952) and Nagaoka Hantaro (1865–1950), who were respectively an experimental physicist and a theoretical physicist in the Department of Physics. Tanakadate was

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[2] Although T. Nakamura detailed the emergence of astrophysics in Japan at this conference, his paper has been published elsewhere (see Nakamura 2008).

one of Kimura's academic superintendents. Details of subsequent curriculum reforms in astronomy during the early twentieth century are presented in Appendix 2.

3.2 Why Did Hirayama Notice Concentrations of Asteroids?

Here we discuss three aspects of the likely background that led Hirayama to the discovery of the asteroid families. First, he had mastered the famous textbook *Traité de Mécanique Céleste* (Tisserand 1889–1896) before he went to the USA. Secondly, he was able to study there as E.W. Brown's research assistant. Thirdly, he first noticed unusual characteristics in the orbital elements of asteroids in the course of elucidating the nature of the Kirkwood gaps. In the following subsections we will examine these three points more closely.

3.2.1 Early Background in Mathematical and Astronomical Training

We would say that if Hirayama had not reached an advanced level of knowledge of celestial mechanics (including secular perturbation theory) before he went to the USA, he could not have developed his theory of asteroid families; it was obviously insufficient only to work under a famous astronomer like E.W. Brown. We stress the importance of his encounter with the famous text book on celestial mechanics, *Traité de Mécanique Céleste*, after his graduation from TIU in 1897. This masterpiece by the reputable French astronomer F.F. Tisserand was published between 1889 and 1896, and Hirayama would quickly have learnt a lot from its careful reading.

In addition to theoretical studies, Hirayama received practical training in both astronomy and astrometry. Entering the graduate school at the TIU in 1897, he began his scientific career as an observer of the latitude observation, and then went to Sumatra (Indonesia) as a member of the 1901 Japanese solar eclipse expedition. Because the TAO library lacked some important star catalogues, Hirayama determined the declinations and proper motions of 246 stars himself, and published his results in the form of a catalogue (Hirayama 1907b).

3.2.2 New Interests Motivated by E.W. Brown

From 1907 onward, Hirayama's interests gradually changed from observational astronomy to theoretical astronomy, and as Kimura's successor he obtained a position as a teacher in the Engineering School attached to the General Staff Office of the Japanese Army where he taught practical astronomy from 1897 to 1901. In 1906 he was appointed an Associate Professor in the Department of Astronomy at the TIU, where he lectured students on observational and practical astronomy. Two years later, he was appointed for a further period at the TAO, where he assisted the Director, Terao, in computing the ephemerides of the Sun, Moon and the planets, for which the TAO had a responsibility to the Government. This led him to take an interest in the historical calendars of East Asia later in his career.

For Hirayama, this new tour of duty proved a turning point, and in 1915 he arranged through the U.S. Naval Observatory to go to Yale University in order to study celestial mechanics for calendar-making under Brown who had already published his famous lunar theory (in 1908) and his libration theory (in 1912). When Hirayama arrived Brown was busy computing tables of the motion of the Moon and Hirayama helped with the tedious calculations and was acknowledged by Brown (1919: 140) when this three volume work finally was published.

Hirayama was at Yale University from 1915 to 1917, and according to his reminiscences Brown suggested to him that one of the most interesting research topics in Solar System astronomy would be to research the distribution of the mean motion of the asteroids (Brown et al. 1922).[3] Therefore, it was Brown's suggestion that led Hirayama to direct his attention to the study of asteroids.

But we must not forget another factor: in Japan, Hirayama was regarded as a member of an educated research elite, so he did not have to be deeply involved in administration of the TIU or the TAO. By around 1915, the educational system at these two organizations had been established and fundamental research environments had been much improved, so when Hirayama returned to Tokyo he was able to continue to study this new research topic.

3.2.3 The Kirkwood Gaps as a Clue to the Discovery of Asteroid Families

After returning to Japan, Hirayama (1917a) published his first theoretical paper on asteroid motions. Some asteroids show a special type of motion called 'libration', in which a certain orbital parameter does not circulate but swings just like the motion of a pendulum. Using a modified and simplified version of the libration theory studied by Brown, Hirayama classified the types of the asteroid motions and thereby tried to explain the formation of the Kirkwood gaps. The gaps, discovered by the American astronomer D. Kirkwood, are the regions of mean motion (or the semi-major axis) distribution where very few asteroids exist, and the position of a mean motion gap had a simple integer ratio with that of Jupiter, such as 3/1 (called commensurability), due to the dynamical resonance with Jupiter.

First, assuming that resisting materials in the Solar System move around the Sun in circular orbits, Hirayama examined their effects on the elliptic motion of the planets. Second, he investigated the motions of the asteroids whose mean motions are nearly

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[3] According to the *Bulletin of the National Research Council* (Brown et al. 1922), the report of the Committee on Celestial Mechanics consisted of three general divisions: (1) the Solar System (the Moon, the eight major planets, their satellites other than the Moon, the asteroids or minor planets and comets); (2) celestial mechanics as applied to the stars (the problems of the orbit determination for cases of visual, spectroscopic or eclipsing binaries; the internal constitution of stars; the oscillations of a gaseous star about its normal equilibrium (Cepheids), the origin and evolution of binary stars); and (3) the theory of the problem of three or more bodies. This report did not refer to the Hirayama families.

commensurable with that of Jupiter. Third, he estimated theoretically the effects of the resistance on the motion of the asteroids. Regarding a specific angular orbital element called ‘critical argument’, he considered its transition mechanism from the librational (vibrational) motion to the revolutional one, and vice versa. Fourth, he investigated the two peculiarities seen in the distribution of the mean motions of asteroids, namely, the gaps found by Kirkwood and the three concentrated regions of asteroids (the Trojan, Thule and Hilda groups); these opposing peculiarities had been a very difficult theme to tackle within the framework of pure Newtonian dynamics of gravity. Finally, based upon the types of the motion that Hirayama had studied, he tried to give possible explanations for the Kirkwood gaps.

In the next subsection, more concrete explanation will be given about Hirayama’s line of thought towards a better understanding of the asteroid gaps.

3.3 Discovery Processes of the Hirayama Families

When he attempted to solve the problem of Kirkwood gaps using a modified version of Brown’s libration theory, Hirayama came across some strange features in the distribution of asteroidal orbital elements. In short, he noticed that there were too many asteroids with small inclinations and eccentricities between the mean motions of 700″ and 750″, sandwiched by the two void regions (see Figure 4).

Table 2 lists nearly all the asteroids examined by Hirayama in his 1917 paper. In order to know the behavior of asteroids around the class $n_0/n' = 12/5$, Hirayama needed to calculate orbital elements of asteroids on both sides of the gap, and he even extended calculations to outside the gap in order to scrutinize a possible displacement from the 12/5 exact commensurability of motions, as given in the last

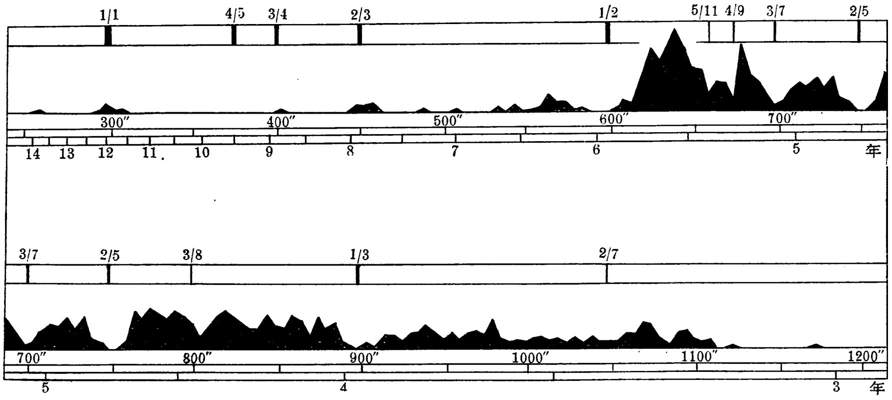

Fig. 4 Condensations of asteroids indicated on the mean motion diagram (adapted from Hirayama 1935a).

Table 2 Asteroids commensurable with Jupiter where n_0 is the mean motion per day of an asteroid and n' is that of Jupiter. Following Hirayama, we call n_0/n' the class. T is the Themis family ($620'' < n_0 < 660''$); E the Eos family ($670'' < n_0 < 685''$) and K the Koronis family ($720'' < n_0 < 740''$) (after Hirayama 1917a: 47)

n_0/n'	Order	n_0 ($''$)	Q_{-1} ($''$)	Q_1 ($''$)	Width ($''$)		Displacement of center
2/1	1	598.26	18.76	9.58	28.34		−4.59
13/6	7	648.12	0.67	0.06	0.73		−0.30
11/5	6	658.09	3.43	0.81	4.24	T	−1.31
9/4	5	673.04	1.56	0.96	2.52	E	−0.30
7/3	4	697.97	2.66	5.73	8.39		+1.54
12/5	7	717.91	0.52	1.93	2.45	K	+0.70
5/2	3	747.82	6.17	4.33	10.59		−0.92
8/3	5	797.68	2.76	1.26	4.02		−0.75
11/4	7	822.61	0.17	−0.99	−0.82		−0.58
3/1	2	897.39	12.12	10.92	23.04		−0.60
10/3	7	997.10	0.80	−3.22	−2.42		−2.01
7/2	5	1,046.96	1.69	5.24	6.93		+1.78

column in Table 2. Also, he did similar computations for the class $n_0/n' = 5/2$, and eventually his calculations covered all known asteroids with mean motions between 700″ and 750″. As a result, he could be sure about a conspicuous concentration of asteroids which we indicate by the symbol ‘K’ in Table 2; later Hirayama named this the Koronis family. Similarly, the discovery of other families, shown by the ‘T’ and ‘E’ in Table 2 was also brought about through painstaking computations of secular perturbation theory.

From our description above of Hirayama’s line of thought in attempting to solve the mystery of the Kirkwood gaps, we can see that the concept of asteroid families emerged as an unexpected byproduct of his initial research. However, we also have to emphasize that the discovery of these families could never have been achieved without the combined use of advanced perturbation theory, skillful statistical analysis of the asteroid data and Hirayama’s wide knowledge and deep insight. For a more detailed discussion, refer to Hirayama (1935a) and Yoshida and Sugiyama (1997).

Here it may be worth noting that Hirayama’s main interest was not to solve the dynamics of individual objects but to consider the behavior of asteroids as a *group* (see Nakamura 2008). His attitude towards conducting astronomical research seems to be found in other subjects he studied as well, such as the formation hypothesis of a binary star system in which he treated stars orbiting in nebular matter as a whole; this theme will be mentioned later, in Sect. 5.

3.4 Japanese Perspectives on Hirayama’s Discovery

Because of the importance of asteroid families in planetary science astronomers currently tend to regard Hirayama as a theoretical astronomer who achieved his historic discovery using secular perturbation theories. But according to Hagihara

(1943), at the time he made his discovery the Japanese scientific community held a different view: that the discovery of the Hirayama families was merely the outcome of statistical work.

Considering that Japanese astronomy was evolving from classical positional astronomy to a more advanced level involving theoretical celestial mechanics when Hirayama discovered the asteroid families, it might be understandable that Hirayama's monumental achievements were seen by the majority as being simply statistical. It is also possible that such a view was influenced by his statistical analysis of the Z-term discussed in the next Section. In addition, it is evident that the first half of his series of papers on asteroids implanted strong impressions in readers' minds that his work was purely statistical. Because of this perception the theoretician Y. Hagihara (1943, 1947) could not help but emphasize the excellence of Hirayama's technique in celestial mechanics, and this approach also was adopted by Y. Kozai (1994).

3.5 Recent Developments in the Study of Asteroid Families

In the last decade or so, the number of binary and multiple asteroid systems has rapidly increased (e.g. see Merline 2002). The existence of such systems is further evidence of collisions between asteroids. Regarding it, we call attention to the fact that Hirayama predicted the possibility of these types of asteroids and discussed their cosmological significance in the preface of his famous book *Showakuse*i (*Asteroids*) in 1935, more than three-quarters century ago, thereby indicating his far-reaching foresight.

4 Statistical Analysis of Latitude Observations

In this section we introduce Hirayama's research on latitude observations based on a statistical approach during the years 1898–1905. In this respect, it is noted that he opposed the then widely-accepted view on the cause of Kimura's Z term.

4.1 The E–W Problem in Latitude Observations

As mentioned in Sect. 3, Hirayama was involved in latitude observations at the TAO. In 1907 he noticed that an unusual phenomenon was present in the data collected during 1902–1905 (Hirayama 1907a). This was first pointed out by H. Battermann and A. Marcuse (see Marcuse 1902) and was called the 'East–West problem' of latitude observations meaning that in zenith telescope observations there exists a systematic difference between the latitudes obtained from stars on the eastern side of the zenith and the western side. Later this was discussed by S. Abe

Table 3 O–W–W–O differences at TAO, 1902–1905 (after Hirayama 1907a: 97–98)

Tokyo. 1902–05

Group and pair	Z_1 (°)	O–W–W–O (″)	Group and pair	Z_1 (°)	O–W–W–O (″)	Group and pair	Z_1 (°)	O–W–W–O (″)	Group and pair	Z_1 (°)	O–W–W–O (″)
B 7	−21.5	−0.08	F 7	−11.1	−0.02	G 6	−0.8	−0.06	A 8	+11.1	+0.01
D 6	−20.7	+0.01	E 4	−10.8	−0.13	C 5	0.0	−0.02	G 4	+11.6	−0.08
G 7	−20.0	−0.07	D 2	−10.8	−0.11	D 5	+0.4	−0.04	H 6	+12.1	0.00
C 2	−19.8	−0.17	F 1	−10.3	−0.15	D 4	+1.1	−0.07	C 4	+12.3	+0.07
C 6	−19.2	+0.03	D 7	−10.0	−0.05	H 1	+1.2	+0.06	A 2	+14.8	+0.01
E 2	−17.9	−0.001	G 5	−8.8	−0.06	D 8	+1.8	−0.02	F 5	+16.6	−0.04
B 8	−17.7	+0.01	F 8	−8.6	−0.11	B 6	+1.8	−0.01	E 5	+16.9	−0.05
H 8	−16.9	+0.03	B 2	−7.2	+0.01	C 8	+2.4	−0.04	B 3	+17.1	−0.01
H 2	−16.8	−0.11	H 3	−7.1	−0.07	E 8	+2.5	−0.01	E 1	+18.3	+0.04
H 4	−16.7	−0.06	C 1	−6.1	−0.16	D 3	+2.8	+0.03	A 7	+18.4	−0.04
A 3	−16.3	−0.08	G 2	−3.9	−0.04	H 7	+3.9	+0.01	D 1	+18.7	−0.10
H 5	−16.2	−0.11	B 4	−3.5	−0.01	F 4	+3.9	0.00	E 3	+19.0	−0.05
B 1	−15.0	−0.11	C 3	−3.4	−0.08	G 1	+5.3	−0.01	A 6	+19.2	−0.01
E 7	−14.1	−0.04	C 7	−2.7	−0.03	E 6	+5.9	+0.04	F 2	+19.3	−0.05
F 6	−13.5	+0.01	B 5	−1.5	−0.12	G 8	+6.4	−0.02	F 3	+19.4	−0.05
G 3	−13.0	+0.02	A 5	−1.0	−0.04	A 4	+7.5	+0.09	A 1	+21.4	−0.06

(1996) and S. Uematsu (1967). This phenomenon is quite different from the Z-term in the latitude variation. In the following discussion we adopt Hirayama's notation and refer to it as the O–W problem.

Hirayama did not agree with the conclusions reached by Battermann and Marcuse that this systematic difference should be attributed to physiological effects of the micrometer reading, which was dependent upon the stellar magnitudes. With his own observations and analysis (see Table 3), Hirayama (1907a) claimed that no correlation was detected between the O-W differences and the magnitudes of stars. Namely, he computed the systematic differences (O–W)−(W–O) for the pairs of stars selected by Battermann in Berlin, and we present his results in Table 3, where Z_I stands for the zenith distance. After computing an arithmetical mean of eight successive values (Table 4), Hirayama drew a graph with the (O–W)−(W–O) on the ordinate and Z_1 on the abscissa (Figure 5).

Hirayama obtained similar results during his first observations in 1898–1900 and 1901, and then noticed similar trends in the data of Mizusawa, Potsdam and Berlin. He thought that there existed a common peculiarity in all of the variations of (O–W)−(W–O) with respect to Z_I, and analyzed the difference by fitting an odd function of Z_1.[4]

Hirayama (1907a:104–105) also suggested the cause of the systematic difference:

> Such an effect might be physiologically produced by the speed of the star in the field of view varying proportionally as the cosine of declination. It is natural that the personal error of bisection should be governed by the speed of the stars as well as their magnitudes.

However, he did not say whether the trend shown in Figure 5 was due to personal errors or instrumental ones; he merely stressed the existence of these systematic errors.

4.2 *Hirayama's View on Kimura's Z-term in Latitude Variation*

Based on the results of the International Latitude Service during the years 1900–1904, Hirayama (1908) inferred that Kimura's Z-term was not absolutely invariable, but depended on the mean zenith distance. He also thought that he found a new

Table 4 List of the E−W differences analyzed by Hirayama (after Hirayama 1907a: 97–98)

Tokyo. 1902–05

Z_1 (°)	O−W−W−O (″)	Deviation of O−W−W−O from the mean (″)	Z_1 (°)	O−W−W−O (″)	Deviation of O−W−W−O from the mean (″)
−19.2	−0.031	+0.006	+1.0	−0.025	+0.012
−15.2	−0.060	−0.023	+4.8	+0.016	+0.053
−9.7	−0.078	−0.041	+14.1	−0.011	+0.026
−3.7	−0.069	−0.032	+19.2	−0.040	−0.003
			Mean −0.037		

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[4] When Uematsu argued the E–W problem in latitude observations in 1967, he referred to Hirayama's work.

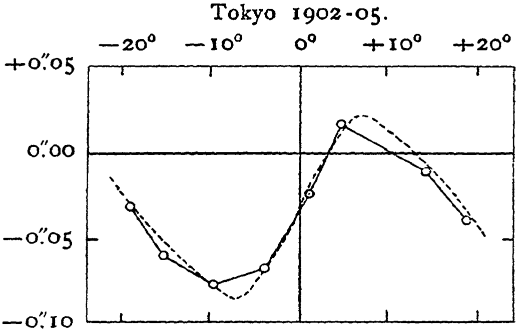

Fig. 5 The (O–W)–(W–O) difference as a function of zenith distance, Z_l (after Hirayama 1907a: 99).

difference which seemingly included Kimura's Z-term, and mentioned that the cause was due to the difference in the thermal expansion coefficients between the steel of the micrometer-screw and the telescopic tube which was made of brass (ibid.).

Later, when this interpretation was criticized by an overseas astrometrist, Hirayama reconsidered a large error in the results of the observations made with zenith telescopes in 1909. He thought that these might have been caused by a gradual change in flexure of the telescope, and he speculated that the variability of the flexure could be attributable to the heat from an observer's body, or a hand-lantern in the case of meridian circle observations (Hirayama 1909).

We comment that Hirayama did not intend to solve the Z-term problem completely. However, he was regarded as an opponent to the common Japanese view that the Z-term was not caused by the telescopes used for the observations (Hagihara 1947).[5] Japanese scientists, including Tanakadate, a senior physicist and Kimura's collaborator, were convinced that the cause of the Z-term problem was not instrumental.

5 Hirayama's Other Scientific Work

5.1 Determination of the Japan–Russia Border on Sakhalin Island

After the Russo-Japanese War of 1904–1905 as a result of the Portsmouth Peace Treaty Conference it was decided that Russia should cede half of Sakhalin Island to Japan. On 29 May 1906, just 3 weeks after he had been promoted to Associate Professor at the TIU, the Japanese Government appointed Hirayama as a member of the Committee that would determine the Russo-Japanese border.

Although the Portsmouth Peace Treaty ruled that the border should be located at 50° north latitude, nobody knew what type of latitude should be used. There were three options, namely geocentric, astronomical and geographical latitude, and each

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[5] Astronomers and physicists discussed the Z-term and Hirayama's opinion openly at a colloquium held at the TAO on 7 May 1908 (see Shinzi Honda 1908).

of these would influence the location of the border between the two countries. It was a very delicate problem, from both a political and a scientific viewpoint.

The Committee, which consisted of Russian and Japanese members, decided to adopt astronomical latitude after one of the Russian astronomers and Hirayama pointed out that astronomical latitude was the most suitable option in this case; moreover, they recognized that luckily the latitude variation affecting the border was very small from 1906 to 1907. Hirayama then went to Sakhalin Island by sea, and actually conducted latitude observations. Expeditions involving military and astronomical personnel were dispatched twice: first in June–November 1906 and later in May–October 1907. The Japanese Committee adopted the Talcot-Horrebow method, using meridian transit instruments to measure 20 star pairs taken from Newcomb's catalogue. Then as a final outcome, they erected four cornerstones along the new border (see Figures 6 and 7).

At the end the first expedition's visit, a Committee meeting was held on 13 November in the special guest room at the Otaru branch office[6] of the Nippon Yusen Kabushiki Kaisya (the Japan Mail-steamer Company) (see Figure 8). Determining the 50° latitude on Sakhalin Island was a career highlight for Hirayama as a practical

Fig. 6 An historic oil painting by Yasuda Minoru. showing members of the Japanese-Russian geodetic expedition on Sakhalin Island (courtesy the Meiji Kinenkan Kaigakan).

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[6] At that time, Otaru (Hokkado) was a key port of the Sakhalin Line, linking Japan and Russia.

Fig. 7 The *circular inset* image shows one of the boundary stones, on both sides of which the national emblems of the two countries were inscribed. The main photograph shows how trees around each stone and along the border between the four stones were all removed in order to allow a clear view of the location of the border (photograph courtesy of the Otaru Museum).

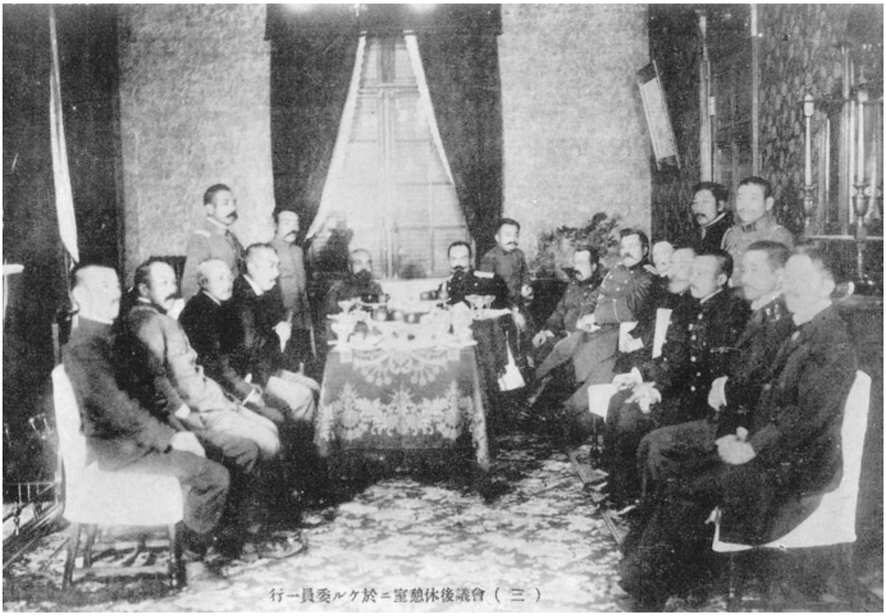

Fig. 8 Group photograph of the Japan–Russia Committee meeting at Otaru on 13 November 1906. Hirayama is possibly the man on the extreme *right* (photograph courtesy: the Otaru Museum).

astronomer, and he was awarded St. Anna's Decoration by the Russian Government, and by the Japanese Government as well (Anonymous 1910; Hirayama 1907c, 1935b; Hayakawa 1976).

5.2 Research on the Stability of Motions of Solar System Small Bodies

We can say that research on the stability of the motions of small bodies in the Solar System (i.e. asteroids and satellites) which originated from Hirayama subsequently became one of Japanese astronomy's research traditions. As we mentioned in Sect. 3, Hirayama's studies began with the Kirkwood gaps while he was in the USA (Hirayama 1917a), but he maintained an interest throughout his life in the motions of those asteroids whose mean motions were nearly commensurable with that of Jupiter.

Ten years after his seminal 1917 paper, Hirayama applied his theory of the libration to the motion of the asteroid Hecuba. After a long computation, Hirayama "… pointed out the incorrect view of Wilkens (1927) that Wilkens's computation showed the asymptotic behavior in the secular recession of Hecuba's mean motion from the exact commensurability with Jupiter's mean motion." (Hagihara 1947).

Hirayama concluded that Hecuba would never stay long near the calculated position but would come back very close to its initial position. His finding was that after a long interval of about 34 revolutions of Jupiter, the variations in the mean motion and eccentricity of Hecuba would be repeated. Hirayama (1928) added the following: if Wilkens had continued his computations for 17 more revolutions of Jupiter he would surely have altered his conclusion.[7] Hirayama revealed in his 1917a paper (which dealt with the types of motion of asteroids) that Hecuba exhibited revolutional motion, as outlined in Sect. 3.2.3

In his final paper, which was published just 6 years before his death, Hirayama, with help from K. Akiyama, discussed the orbit of Hilda (Hirayama and Akiyama 1937).

5.3 The Resisting Medium and the Hirayama Families

The resisting medium – comprising particles and gas-like material – was a key element in Hirayama's research on asteroids, and he confessed (Hirayama 1917b) that Brown had suggested the idea to him. It is also no exaggeration to say that Hirayama felt an enthusiasm for the planetesimal hypothesis of T.C. Chamberlin (1901) and

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[7] In 1927, Hagihara Yusuke reached a conclusion similar to Hirayama about the stability of Hecuba, but he used a different approach (see Hagihara 1927, 1947).

F.R. Moulton (1905). According to S.G. Brush (1996), many astronomers were interested in the resisting medium in those days.

Hirayama's supposition was that (1) resisting materials the sizes of ordinary meteoroids move around the central body in circular orbits; (2) they consist of loose aggregates of small bodies with rare gaseous envelopes; and (3) most of the resisting particles pass freely through this meteoric swarm. The fact that this resisting medium was purely hypothetical did not seem to pose a problem for Hirayama. This was probably because he needed the resisting medium to explain the Kirkwood gaps. If the resisting materials existed at all, then the effect of the resistance should be larger for smaller asteroids, and would work naturally to decrease the eccentricity and at the same time to increase the mean motion of asteroids. However, such results obviously conflicted with his research on asteroid families so he had no choice but to abandon the assumption of a resisting medium. He then conjectured that the formation of the asteroid families may have occurred after the resisting medium had dissipated (Hirayama 1933d).

5.4 The Resisting Medium and the Capture of Stars

The resisting medium was a convenient tool for Hirayama, and between 1931 and 1935 he considered the motion of stars in nebulous matter where the latter served as the resisting medium. Starting with his capture theory of stars, he tried, in succession, to apply this idea to the Solar System, a binary system, the origin of the energy in stars and the interpretation of periodic variable stars. Thus, for Hirayama (1931a, 1931b, 1931c, 1932) the resisting medium provided a way for him to investigate problems associated with stellar evolution.

Based on the two-body problem and using an approximately qualitative means, he considered first the case in which a star passes through a spherical cloud. He says that the transit of the star is repeated, decreasing the value of its semi-major axis every time, until the star is completely captured. So the cloud can capture a star by this repeated action, and the remaining matter, being absorbed gradually, will become small in mass compared with that of the captured star. A star system, like our Solar System, may have been formed in this way.

According to Hirayama (1931c), if the cloud is large and dense enough, it can capture two or more stars. He also speculated, using the same mechanism, on the formation of a binary star system,[8] and even on the formation of a globular cluster. Here we would like to stress that Brown (1921) had much earlier discussed the motion of the stars entering a nebulous cloud.

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[8] Hirayama (1931c: 183) was very interested in seeing how the relative motion of the two stars was influenced by the absorption of the cloud. He said that the case of a planet was treated by Tisserand (1886: chapter XIII) and by Poincaré (1911: chapter VI).

Another aspect of Hirayama's capture theory is that the stellar energy can be provided not by sub-atomic energy or the annihilation of matter but by the energy originating from meteoric materials (Hirayama 1931d). Karl Hufbauer (1981) has shown that since 1920 Eddington's ideas on sub-atomic energy have been effective in explaining the stellar energy problem. In 1983, David DeVorkin and R. Kenat reviewed the literature on the stellar energy problem that existed in the 1930s, and discussed the situation connecting the formation of elements with stellar energy. While these developments were occurring, Japanese astronomers were shifting their interests from classical astronomy to astrophysics (Blaauw 1994). This subject is discussed further by Nakamura (2008).

But Hirayama did not (or could not) use a physical approach to the heavenly bodies and their observed phenomena: rather, he tried by all means at his disposal to solve the problems using only celestial mechanics. It is commonly recognized that in those days most older astronomers lacked the knowledge of atomic physics required to solve the above-mentioned problems. In this sense it could be said that although Hirayama addressed astrophysical issues he remained a disciple of classical astronomy.

5.5 Speculation on Periodic Variable Stars

Hirayama (1931b) refused to accept that pulsation theory was a suitable model for explaining the behavior of periodic variable stars. Instead, he felt he could interpret the behavior of some types of periodic variable stars, such as Cepheids, by using a combination of his binary theory and his capture theory of stars under the influence of nebulous matter. Developing this line of thought, he imagined that a Cepheid variable was a contact system consisting of a giant star and an almost dark dwarf star. Their relative orbits were supposed to be nearly circular, in accordance with a general tendency of the binary stars, so the small companion was destined to be abraded by the surface of the primary star (see Figure 9).

Hirayama's speculation originated from an explanation presented by J. Hellerich in 1925, but in fact Hellerich considered neither abrasion of the small companion by the primary's surface nor a resultant dropping into the primary star. On the other hand, Hirayama (1931b) neglected several of the preconditions that Hellerich set in order for his concepts to be valid.

5.6 A Survey of the Archival Astronomical Records of China, Korea and Japan

In 1908, Hirayama started computing ephemerides of the Moon and the planets at the TAO. As part of his new duties he subsequently directed his attention towards ancient eclipses and comets that appeared in Chinese, Korean and Japanese historical

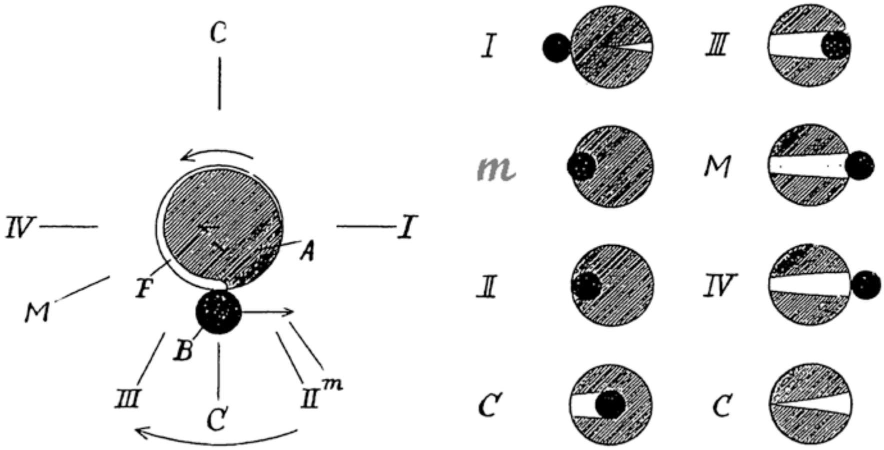

Fig. 9 Schematic illustrations of Hirayama's abrasion process for a contact binary (after Hirayama 1931a).

records, and between 1910 and 1929 published a number of papers on them (see Hirayama 1910, 1911, 1929; Hirayama and Ogura 1915). His 1933 book, *Rekihou to Jihou* (*Calendrical and Time Systems*) (Hirayama 1933c) has long been cited, mainly for its material on historical calendars in China and Japan. Indeed, Hirayama lectured on the Chinese *Shoushi* calendar (*Juji reki* in Japanese) at the second annual meeting of the History of Science Society of Japan held in 1942, and then reported on the history of the solar calendar in Japan at a regular meeting of this Society later that same year.[9]

According to Hagihara (1947), after Hirayama retired his professorship "… he was eagerly engaged in the study of the history of astronomy in Japan. He never published his results … but only talked about them at the colloquia at the Azabu Observatory." These comments need correcting, because a survey of the old publications by Kanda (1962) revealed that Hirayama assembled the first extensive catalogue of Japanese books on astronomy before the Meiji Restoration (of 1868).[10] Second, we have to add that Hirayama acted as a scholastic advisor when Yabuuchi Kiyoshi (1906–2000) launched his study on the history of astronomy. Yabuuchi later became a leading specialist in Chinese history of science and technology, rivaling Sir Joseph Needham in that field.

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[9] See the following web site: http://wwwsoc.nii.ac.jp/jshs/his_jshs/hist.html.

[10] By about 1940 Hirayama had assembled an extensive card catalogue of Japanese books on astronomy that pre-dated the Meiji Restoration. Unfortunately this invaluable research tools was destroyed by fire during WWII (Kanda 1962).

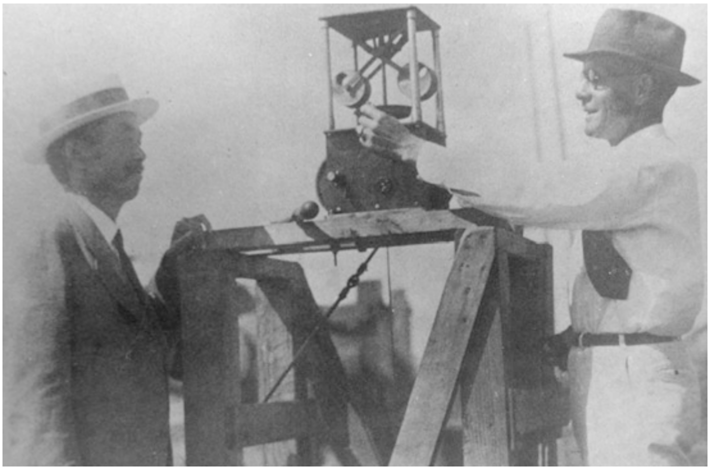

Fig. 10 Photograph of the 1932 solar eclipse expedition to the state of Maine (USA). Hirayama is on the left and the name of the gentleman on the *right* is unknown (Hirose Hideo 1979: 15; courtesy: Abe Akira).

Finally we mention that Hirayama participated in several overseas solar eclipse expeditions (e.g. see Hirayama et al. 1903), sometimes in collaboration with Terao and Hirayana Shin (e.g. see Figure 10).

6 Conclusion

Hirayama Kiyotsugu was Japan's first theoretical astronomer, although during his career his astronomical interests and research gradually shifted from observational astronomy to theoretical astronomy. His success culminated in the discovery of the asteroid families but recognition of these by the international astronomical community was slow until his cause was taken up by Dirk Brouwer. Although Hirayama also contributed in the field of the orbital stability of asteroids and satellites, he continued to adhere to the autonomous explosion hypothesis for the origin of asteroids, and his attempts to address astrophysical problems, such as the capture of stars and an explanation of periodic variable stars, were unsuccessful.

If Kimura's Z-term was the first 'big crop' cultivated within the framework of so-called classical astronomy that the Japanese learned from the West, then Hirayama's discovery of the asteroid families could be called a 'victorious harvest' for Japanese astronomy, allowing us to move to the next phase of more modern astronomical research.

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7 Appendix 1. The Biographical Table of Hirayama Kiyotsugu (1874–1943)

The following table was developed from a hand-written manuscript by Kanda Shigeru (1894–1974), which is a biographical note of several eminent astronomers in Japan (courtesy of National Astronomical Observatory of Japan).

1874	As a son of a civil engineer, he was born on 3 October in Sendai
1894	He entered the Tokyo Imperial University after his graduation from high school
1897	He graduated from the Imperial University (Astronomy) and started to study the textbook of celestial mechanics by Tisserand
	He obtained a position as a teacher in the engineering school attached to the General Staff Office of the Japanese Army, where he taught practical astronomy from 1897 to 1901
1898	On 25 September he began latitude observations at Tokyo Astronomical Observatory (1898~1903)
1901	In February he was a member of a Solar Eclipse Expedition to Sumatra, with Hirayama Shin
1906	On 9 May he was appointed Assistant Professor of Astronomy at Tokyo Imperia University (specializing in practical astronomy)
	On 29 May the Japanese Government appointed him a member of Committee to determine the latitude 50° border at Sakhalin after the Russo-Japanese War. He went to Sakhalin (1906–1907), and was awarded St. Anna's decoration by Russia
1908	He was one of the promoters of the Japanese Astronomical Society. Assisted by Terao, he started to compute the ephemeris of the Moon and the planets at the TAO
1909	He discussed the E–W problem of latitude observation and the cause of Kimura's Z term from 1907 to 1909
1910	He tried to survey historical records (ancient eclipses and comets) in China, Korea and Japan
1911	He received a doctoral degree with several papers about the latitude variation
1915	He went to the U.S. Naval Observatory in Washington and Yale University (1915~1917). At Yale he helped to compute a part of Brown's lunar table. Brown inspired him with an explanation of gaps in the distribution of the mean motion of the asteroids
1917	He published the paper "Researches on the distribution of the mean motions of the asteroids." in the *Journal of the College of the Science, Tokyo Imperial University*
1918	He published the paper "Groups of asteroids probably of common origin." In *The Astronomical Journal*
1919	He became a Professor of Astronomy at Tokyo Imperial University after Terao's retirement (celestial mechanics)
1922	He published the paper "Families of asteroids." in the *Japanese Journal of Astronomy and Geophysics*
1928	He published the paper "Note on an explanation of the gaps of the asteroidal orbits." in *The Astronomical Journal*, vol.38 no.903 (1928), 147–48
1931	He tried to consider the motion of stars in a nebulous matter as the resisting medium from 1931 to 1935
1932	When he attended the 4th IAU at Cambridge in US, he saw young Brouwer at the meeting
1935	He published his main work, *Asteroids*, and retired from the Tokyo Imperial University
1943	He died on 8 April 1943 in Tokyo

8 Appendix 2. Historical Evolution of Subjects Taught at Department of Astronomy, TIU

1877–	Astronomy
1886	Theory and Practical Work for the Measurement of Gravity
1886–	Astronomy, Spherical Astronomy, Method of Least Squares, Differential and Integral Calculus, General Mathematics, General Physics and Advanced Physics, Dynamics
1897	Experiments and Practical Sessions (astronomical observation, physics, mathematics)
1897–	Astronomy and Method of Least Squares, Spherical Astronomy, Analytical Geometry, Celestial Mechanics, Differential and Integral Calculus, Theory of Differential Equations, Theory of Functions, Spherical Function
1901	Astrophysics, Dynamics, Experiments and Practical Sessions (astronomical observation, physics, mathematics)
1901–	Astronomy and Method of Least Squares, Celestial Mechanics, Differential and Integral Calculus, Theory of Differential Equations, Theory of Functions, Spherical Function, Astrophysics, Elementary Class in Theoretical Physics, Applied Physics
1919	Potential theory, Experiments and practices (Astronomical observation, physics, mathematics)
1919–	Compulsory subjects: Spherical Astronomy, Celestial Mechanics, Calendar, Theory of Periodic Orbits, Method of Least Squares, Theory of Orbits, Differential and Integral Calculus, Astrophysics, General Physics, Dynamics, Practical Astronomy, Astronomical Observation
	Irregular subjects: General Astronomy, Special Perturbation, Tidal theory, The Motion of the Moon and Satellite, The Spectrum, Thermodynamics, Relativity and Gravity, Electron Theory, Quantum Theory, Geometrical Optics
	Optional subjects: Electromagnetism and Optics, Material Science and the Theory of Heat, Theory of Differential Equations, Theory of Functions, Hydromechanics, Geometry

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The 1395 Planisphere, *Cheongsang Yeolcha Bunya-Ji-Do*, and Two Earlier Star Maps in Korea

Nha Il-Seong and Sarah L. Nha

Abstract A number of star maps that predate the 1395 planisphere are recorded in Korean histories such as the *Samguk Sagi, Koryo-sa* and *Munheon Bigo*. A number of scholars have been searching for such star maps over the last decade or so, but without success. Fortunately, while one of us (NIS) was preparing the first volume of his series on the *History of Korean Astronomy*, he discovered two old star maps in the Yonsei University Library, and concluded that both maps may possibly predate the oldest-known Korean planisphere, *Cheonsang Yeolcha Bunya-ji-Do*. Of these two star charts, the older looking one has neither a title nor the name of its maker. However, the other star map has the title *Geonsang Yeolcha Bunya-ji-Do*. Its maker's name is Kwon Keun and it dates to 1395, the same year as the *Cheonsang Yeolch Bunya-ji-Do*.

In this paper we first discuss the 1395 planisphere in some detail, and then introduce the two early star maps.

1 Introduction

Korea has a long history of star map-making as one of her earlier astronomical achievements in the east Asian region (see Nha 2012). The earliest recorded star map is on a stone slab planisphere that was located at Pyongyang, the later capital of the Koguryo Kingdom, but was sunk and lost in the Daedong River in 668 when Pyongyang was attacked by the Tang army. The Koguryo Kingdom dated from 37 BC to AD 668, and was one of the Three Kingdoms of ancient Korea. Its location is shown in Figure 1 on page 200 in these Proceedings.

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Fig. 1 Both surfaces of the black stone slab CYBD Planisphere. The (**a**) surface (*left*) shows the title on the lower part of the slab, while the (**b**) surface (*right*) has it on the top but the whole planisphere is reversed up side down (and the *right side* of Figure 2 shows this more clearly).

In 692, a star map was presented to the king of the Silla Kingdom (57 BC to AD 935) by a famous Buddhist monk, Do Jeung (道證), after returning from Tang earlier that same year. This map has been lost for a long time ago, so there have been questions about what kind of map it was. One of us (NIS) has proposed that it must be a copy of the Dunhuan Xingtu (敦煌星圖) of Tang (Nha 2012).

Baikje, the third kingdom (18 BC to AD 663) in the Three Kingdom period, has no record of any early star maps. However, in 602 a monk named Kwan Reuk (觀勒, or Kan Roku in Japanese) went to Japan taking with him books on the calendar, astronomy and geomancy, and he taught astronomy to some Japanese scholars, including the Prince (Han 1912; *Nihon Shoki* 1965). This would imply that Baekje also would have had early star maps, in keeping with the high standard of astronomical knowledge at that time.

2 The Cheonsang Yeolcha Bunya-Ji-Do Planisphere

The Cheonsang Yeolcha Bunya-ji-Do Planisphere (天象列次分野之圖; hereafter CYBD Planisphere) was first introduced in English in 1907 and subsequently by W.C. Rufus (1913, 1915). Since then it has become the most representative of all ancient Korean star maps. The planisphere was inscribed on a black stone slab 211 cm high, 122.5 cm wide and 12 cm thick which weighs approximately 1 ton. This planisphere was made by 12 scholars led by Kwon Keun (1352–1409) during the fourth year (AD 1395) in the reign of King Taejo, the first king of the Joseon Dynasty (which ran from 1391 to 1910).

Photographs of both surfaces of this stone slab are shown in Figure 1. Having become worn little by little over the years and cracked during transportation on several occasions, identification of some of the stars and other characters is now extremely difficult. Therefore, in studying the features of this planisphere some recent investigators have used old rubbings of the (b) surface.[1]

The contents of both sides of the slab are exactly the same but the arrangements are slightly different, as shown in Figure 2. The contents in the CYBD Planisphere are as followings:

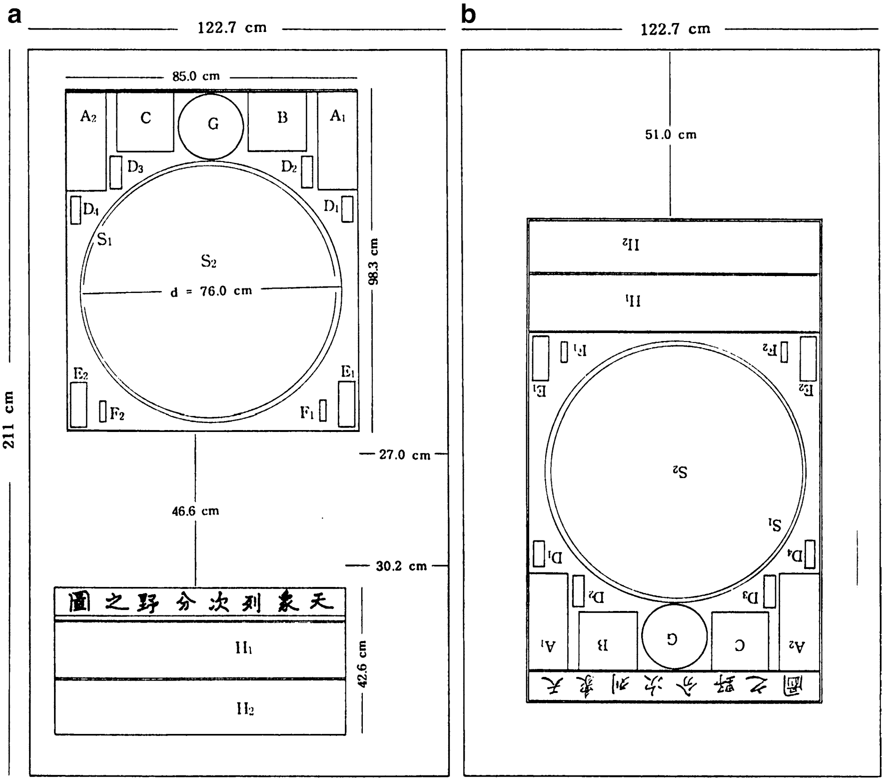

Fig. 2 Outlines of the contents of both surfaces of the 1395 planisphere (CYBD).

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[1] Although it is generally believed that these old rubbings were made from the (b) surface of the CYBD Planisphere, as yet no one has examined the possibility that they in fact came from another Korean planisphere that was manufactured in AD 1687.

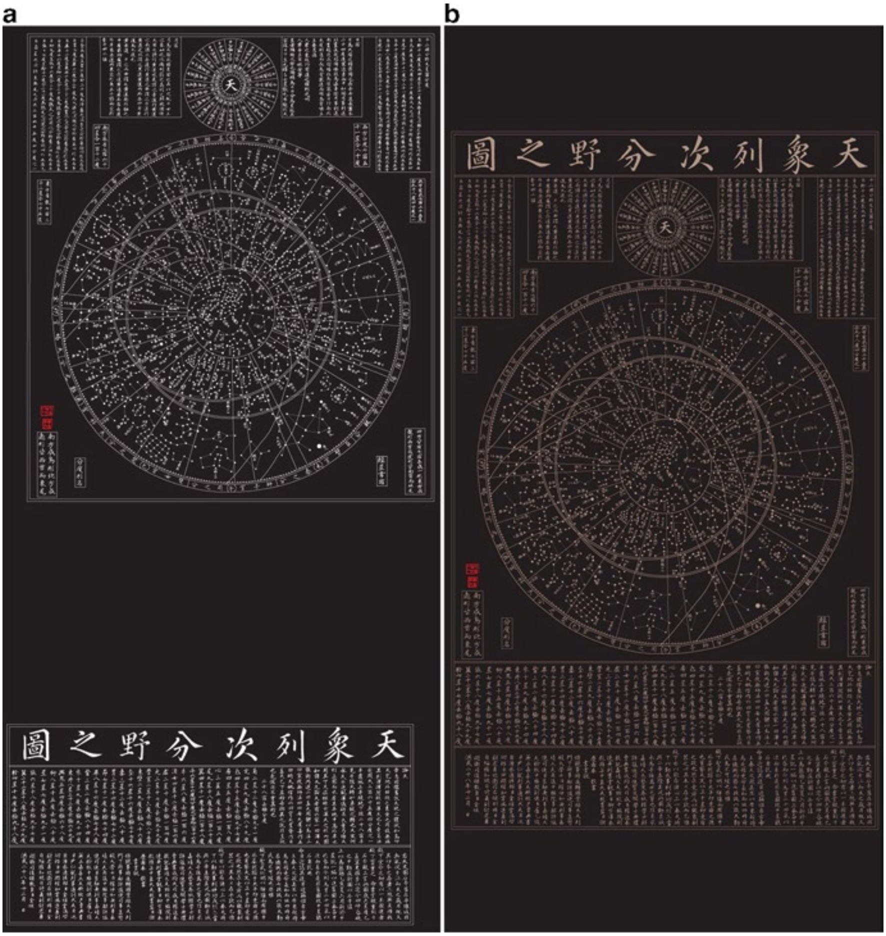

Fig. 3 Restored rubbings of the CYBD Planisphere*, prepared by the authors.*

[A1,2]: Descriptions of the territories of the 12 old Chinese Countries.
[B]+[C]: Descriptions of the Sun and the Moon.
[D1,2,3,4]+[E1,2]+[F1,2]: Four divisions of the heavens, four mystic animals and a number of stars.
[G]: A list of meridian stars at dusk and dawn for the 24 solar periods.
[H1]: A description of the heavens and a table of the 28 xius (lunar mansions).
[H2]: A history of the planisphere and the official titles and names of the scholars involved in its manufacture in 1395.
[S1,2]: The central astral chart and the 12 zodiacal divisions.

The central astral chart has a diameter of 76 cm, within which 290 constellations with 1,467 stars are represented by engraved circles of several different sizes according to brightness. A total of 2,932 Chinese characters naming and describing the constellations were also engraved on each side of the slab. This planisphere is now honoured as Korea's National Treasure No. 228, and is preserved in the National Palace Museum in Seoul. But both surfaces are heavily damaged making the reading of their contents extremely difficult.

No old rubbings of the (a) surface of the CYBD Planisphere have been found to date, which is puzzling, but there are quite a number of old rubbings of the (b) surface located in Korea and abroad. Unfortunately none of these old rubbings has been preserved in perfect condition, and even the best ones have defects which make the identification and reading on some parts impossible. The present authors made an attempt to restore all of the stars and characters on both surfaces using several of the best rubbings available, and frequent reference to the original. The restored rubbings are shown in Figure 3.

The CYBD Planisphere had a profound influence on later Korean star map makers, and the original rubbings of the (b) surface were hand copied and recopied by those who had no access to the original stone or other rubbings. As a result, a trend developed to follow the overall form of the (b) surface of the CYBD Planisphere, and this is continuing even today as domestic museums and private collectors cannot access the original rubbings and poor hand copies of them.

3 Records of Korean Star Maps that Predate the CYBD Planisphere

One of the best sources of information about star maps that predated the CYBD Planisphere can be found in the right hand side of [H2] in Figure 2. Here we reproduce Rufus' (1913) English translation (and note that some of the words are spelt slightly different today):

> The lost stone model of the above astronomical chart was kept in Pyeongyang, but on account of the disturbance of war it was sunk in the river; many years having passed since it was lost, existing rubbings of the original were also out of stock.
>
> However, when His Majesty (the first king of Joseon dynasty) began to reign, a man having one of the originals tendered it to him. His Majesty prized it very highly and ordered the court astronomers to engrave it anew on a stone model. The astronomers replied that the chart was very old and the degrees of the stars were already antiquated; so it was necessary to revise it by determining the present midpoints of the four seasons and the culminations at dark and dawn and to engrave an entire new chart designed for the future.
>
> His Majesty responded, "Let it be so!"
>
> They spent the time until the sixth moon of 1395 preparing the new Choongseong-gi (中星記) when part I was written out. On the old chart at the beginning of Spring (列春) Pleiades (昴) culminated at dark (昏) but now Aries (胃) does. Consequently the 24 solar divisions were changed in succession to correspond with the meridian stars of the old chart. The stone was carved and just now completed.

Pleiades and Aries differ by ~10° in longitude, which equates to around 700 years of precession. We can assume that Kwon Keun and his 11 associates adopted Koguryo's chart as a main reference.

There are two other records of star maps in the histories of the Koryo Dynasty (918–1392). The first refers to the astronomical chart of Oh Yoonbu (伍允孚, ?-1305). According to the *Koryo-sa* (which relates the history of the Dynasty) he was a dedicated observer: whether it was exceedingly hot or unbearably cold he continued to observe without fail all night long. Oh is said to have produced an astronomical chart which harmonized all the doctrines and was much in favour by other observers at this time. He also acquired a wide reputation as an astrologer. Since Oh died in 1305, we can assume that his star chart was not known (or well known) to Kwon Keun, and there is now little hope of finding extant copies of it.

The second early star map was in the possession of the Bongseon Temple (奉先寺), which was located on the outskirts of Songdo, which was the capital of the Koryo Dynasty. *Koryo-sa* records indicate that King Gongmin (恭愍王, who reigned between 1351 and 1374) visited the temple and saw the map in the 7th month of the 4th year of his reign (i.e. in AD 1355). This star chart therefore preceded the CYBD Planisphere by 40 years, and would surely have been known to Kwon Keun. There is no information as to whether this chart was produced by Oh or some other astronomer.

4 The Discovery of Two Early Star Maps

For several decades various scholars (including the authors of this paper) searched unsuccessfully for the Oh and Bongseon Temple early star maps, then in early 2008 a rare looking star map captured the attention of one of us (NIS). It was a hanging scroll star map 73.4 cm wide and 141 cm long with the name Keonsang Yeolcha Bunya-ji-Do (乾象列次分野之圖, hereafter KYBD Star Chart), and for decades had resided in the Yonsei University Library (see Figure 4a). Back in 1984 NIS had carelessly reported only the existence of this star chart without mentioning its date of manufacture (Nha 1984). This star chart was made by Kwon Keun in the June of the same year of the CYBD Planisphere was manufactured, but precede it by 6 months. It is quite confusing that these two charts have almost identical names, with the difference only being the first Chinese characters, ‘Cheon’ (天) and ‘Keon’ (乾). But both characters have the same meaning, indicating the ‘sky’ or ‘heaven’. When Kwon Keun attempted to design a new model for His Majesty, he made a preliminary model and used Keon for the name of his chart. This chart has the same content as the CYBD Planisphere except that [J1] and [H2] are completely different (see Figure 4b). [J1] has a list of 14 xius out of 28 with degrees. At this moment, we have no idea what these degrees mean. On the other hand, the arrangement of all of the contents is also exactly the same as found on the CYBD Planisphere, except for [J1].

It is now clear that Kwon Keun completed his model of the star chart 6 months before completing the final version for His Majesty. But before he finalized it, he had discussions with his collaborators about the model. By this time the first character of the name of the planisphere had changed and the lowest part [J1] was replaced by [H2]. We assume that Kwon Keun had access to some reference chart(s) and consulted them when creating his model.

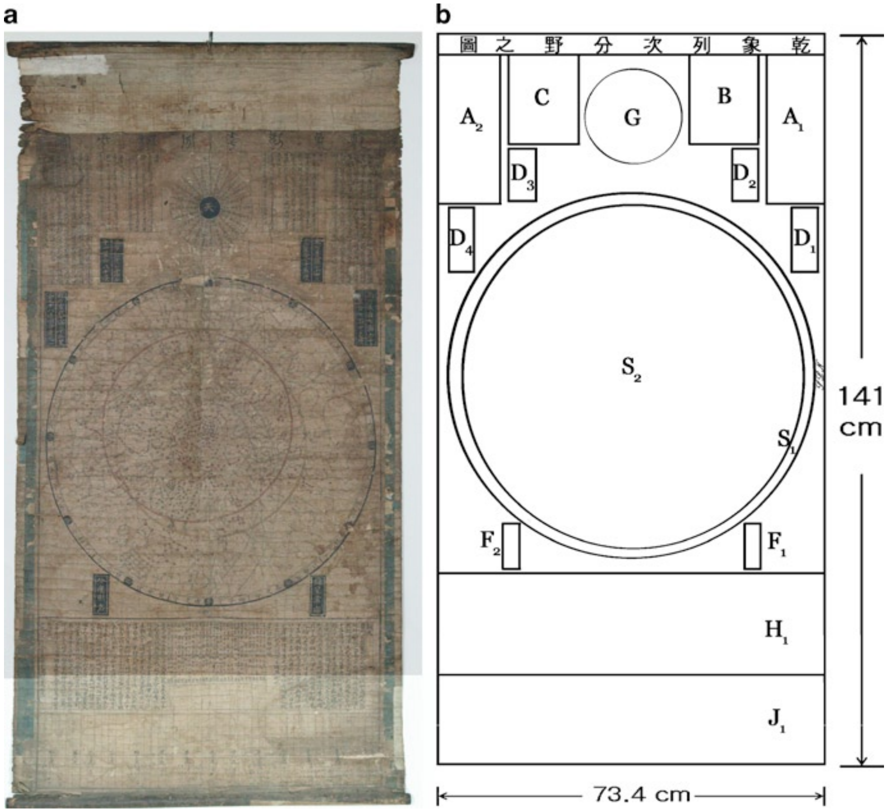

Fig. 4 The *Keonsang Yeolcha Bunya-Jido*, a hanging scroll star map, by Kwon Keun.

When the Yonsei University Library held an exhibition to mark its 123rd Anniversary in May 2008, the peculiar-looking star chart shown in Figure 5a was on display beside the KYBD Star Chart. However, this second early star map has no name and the maker is not mentioned. Overall, the shape is similar to the previous one, but this star chart is more crudely made. The hanging scroll is 74.3 cm wide and 120 cm long, and the chart showing the stars is 72 cm in diameter and occupies the center of the scroll. Other contents are separated into two parts. The contents of both the CYBD Planisphere and the KYBD Star Chart such as [A1,2] are located in the upper right corner, while [D1,2,3,4], [E1,2] and [H1] are below the circular star map. Meanwhile, the contents [B], [C], [F1,2], [H2] or [J] found in the CYBD Planisphere and the KYBD Star Chart are missing altogether. This looks like a simplified chart when compared to the two previous star charts and the star map is oriented nearly 90° degrees in a clockwise direction relative to these other two maps. Although a more detailed investigation has yet to be made, it is certain that the shapes of the constellations are also quite different from these in the two 1395 star maps, and from later Korean star maps. It has been suggested by Mr Kim Yeongweon of the Yonsei University Library (pers. comm., 2008) that this star map was kept in

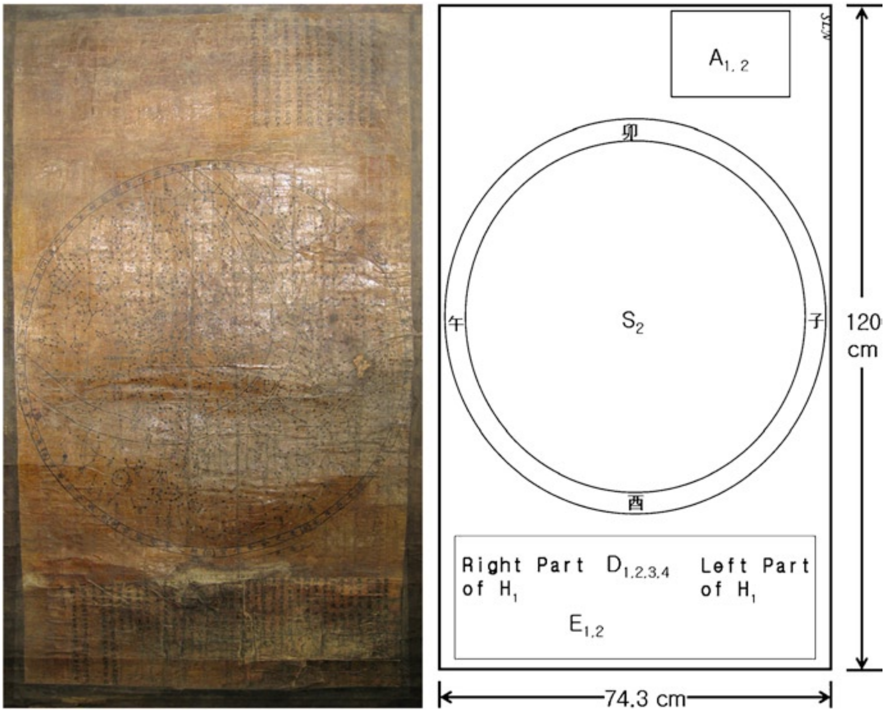

Fig. 5 The Koryo star map.

the home of one of Kwon's descendents before it was transferred to Yonsei University some decades ago, but this has yet to be confirmed and there is no record of this donation in the Museum archives.

We assume that this star chart preceded Kwon Keun's KYBD Star Chart and served as a reference for his work. This leads us to assign the temporary name of Koryo Star Chart to this star map, and it could be Oh Yunboo's star map or the historic star map associated with the Bongseon Temple. Alternatively, it may have been produced by somebody else during the Koryo Dynasty.

5 Conclusions

We have reported on the Cheonsang Yeolcha Bunya-ji-Do (CYBD) Planisphere and included information which was not reported in previous papers. We wish to emphasize the prime importance of this planisphere from the time it was manufactured up until the present time in Korea. Its profound popularity among scholars and intellectuals during this period tended to stifle the activities and creativity of other star map makers. Thus, only limited numbers of independent star maps were produced, whereas numerous rubbings and copies of the CYBD Planisphere were made.

Two star charts that predate the stone slab CYBD Planisphere have been discovered. The first one of these was made in AD 1395, but 6 months prior to completion of the CYBD Planisphere. It is known as the Keonsang Yeolcha Bunya-ji-Do (KYBD) Star Chart and was made by Kwon Keun, who also supervised the construction of the CYBD Planisphere. The KYBD Star Chart was produced as a model for His Majesty. The second early new Korean star map appears to be older than the KYBD Star Chart, and since it lacks a formal name we have called it the Koryo Star Chart. This is a very crude star map compared to two later ones mentioned above, but its value and importance lie in the fact that it may have provided the main source of information during the production of the KYBD Star Chart and the CYBD Planisphere.

Acknowledgements We express our gratitude to Mr Kim Yeongweon, Head of the Center for Korean Classics Collection at the Yonsei University Library, for permission to reproduce images of the two early star maps, and to Mrs Kim Myungju, Librarian of the Center for Korean Classics Collection, for her generous help in finding references.

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The *Seungjeongwon Ilgi* as a Major Source of Korean Astronomical Records

F. Richard Stephenson

Abstract The importance of early Korean records of supernovae, comets, meteors and aurorae in modern astronomy is well-known. However, the most extensive Korean source of such data, the *Seungjeongwon Ilgi* (*Daily records of the Office of Royal Secretariat*), has received relatively little attention among historians of astronomy. Written in Chinese (*Hanmun*), the *Seungjeongwon Ilgi* is a day-to-day chronicle of important events. The main emphasis is on matters of court and state, but observations of a wide variety of astronomical phenomena are regularly included. Although maintenance of the chronicle began early in the Joseon Dynasty (AD 1392–1910), due to wars and rebellions only the records from AD 1623 to 1894 now survive. Nevertheless, the remaining text is substantial, containing more than 3,000 chapters. In this paper, the general format of the astronomical records in the *Seungjeongwon Ilgi* is discussed, together with examples of the various types of celestial observations which this huge compilation contains.

1 Introduction

Several major historical sources of Korean astronomical records – between them covering the period from ancient times to the late nineteenth century – are well known to modern scholars. Copies of these works are available in major libraries worldwide. In each case the text is written in *Hanmun* (Classical Chinese): only in the twentieth century did the use of *Hangul* – the Korean alphabet, invented around

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AD 1450 – become widespread in Korea. As was the case in China, celestial events witnessed in Korea were regarded as omens affecting the ruler and State. This attitude led to numerous observations being made by official Korean astronomers at the royal capital. Many of their reports – mainly in the form of summaries – are still preserved today.

Several of the historical (i.e. non-astronomical) details in the following outline of Korean historical sources are taken from the impressive monograph by Kim Tai-jin (1976).

The earliest Korean historical source which contains reports of celestial phenomena is the *Samguk Sagi* (*History of the Three Kingdoms*). The *Samguk Sagi*, a work in 50 chapters, was compiled by Kim Busik in AD 1145. Much of this history is in the form of a brief chronicles for each of the three ancient kingdoms into which the Korean peninsula was divided from earliest times (nominally ca. 50 BC) to AD 668. These kingdoms were Silla, Goguryeo, and Baekje. After the unification of Korea under the Silla Dynasty in AD 668, the chronicle of Silla continues until the fall of the Dynasty in AD 935.

By comparison with later Korean histories, the *Samguk Sagi* contains few astronomical records, and individual reports are usually very brief. Celestial phenomena which are noted in the *Samguk Sagi* consist mainly of solar eclipses, conjunctions of the Moon with planets, comets and meteors. Most of these events (apart from meteors) would be visible over a wide area of the terrestrial surface. Yet, during the period of the three separate kingdoms (prior to the Silla unification in AD 668), very few celestial events are reported in the chronicles of more than a single state – whether Silla, Goguryeo or Baekje. Furthermore, as comparison with the astronomical records in Chinese history reveals, there is clear evidence that many of these entries are copied *verbatim* from Chinese sources. Having myself made a careful (as yet unpublished) study of the astronomical records in the *Samguk Sagi*, I find it difficult to avoid the impression that Kim Busik inserted most of these earlier observations more or less at random in his history.

Observations recorded in the *Samguk Sagi* which were made after the Silla unification are usually original but they are fairly rare and most reports are very brief.

A much more substantial compilation than the *Samguk Sagi* is the *Goryeosa* (*History of Goryeo*), which covers the subsequent Goryeo Dynasty (AD 936–1392). The *Goryeosa* is modelled on a typical dynastic history of China. A work in 137 chapters, it was based on data in the *sillok* ('veritable records') of the reigns of the various Goryeo kings; regrettably, none of these Goryeo *sillok* are now extant. The *Goryeosa* was compiled between AD 1449 and 1451 by a team of scholars under the direction of Kim Cheongso. However, in AD 1453, Kim Cheongso was executed as the result of a political incident, and in the *Goryeosa*, Cheong Inji – one of his fellow compilers – is cited as project director instead. It should be emphasised that – unlike much of the data in the *Samguk Sagi* – the numerous astronomical records which the *Goryeosa* contains are virtually all independent of China.

Most of the reports of celestial events in the *Goryeosa* are to be found in a special Astronomical Treatise forming Chaps. 47–49 of this history. Further astronomical records are contained in the Annals of the Goryeo Kings (Chaps. 1–46 of the

Goryeosa), while aurorae are frequently noted in the Treatise on the Five Elements (Chaps. 53 and 54). As in a typical Chinese dynastic history, all sorts of celestial phenomena are cited: solar and lunar eclipses; sunspots; sightings of Venus in daylight; conjunctions of the Moon with planets and stars; conjunctions of planets with one another and stars; comets and meteors; stellar phenomena (e.g. the occurrence of novae); and aurorae – as well as solar and lunar haloes. Regrettably, scarcely any astronomical records prior to around AD 1010 (essentially the reigns of the first seven Goryeo kings) are preserved in the *Goryeosa*. However, from this date onwards this history is replete with celestial observations.

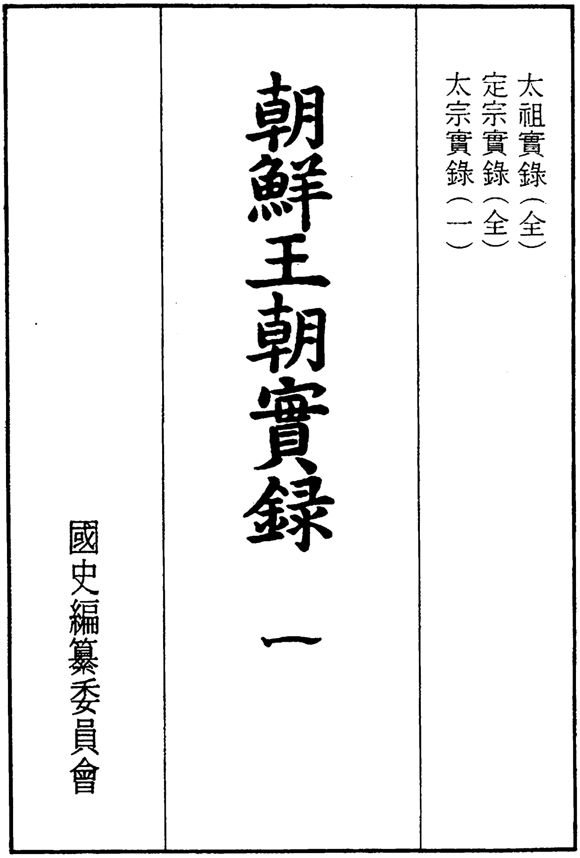
A useful supplement to the *Goryeosa* is the *Goryeosa Cheolyo* (*Summary of the History of Goryeo*), a history of the Goryeo Dynasty which cites events in purely chronological order. This work, in 35 chapters, was compiled in AD 1452 by the above-mentioned Kim Cheongso, together with other scholars, and was first published in AD 1453. It is based on early versions of the *Goryeosa* which are no longer extant. Although relatively brief, the *Goryeosa Cheolyo* contains some material which is not found in the *Goryeosa* itself.

No formal dynastic history exists for the subsequent Joseon (or Yi) Dynasty (AD 1392–1910). However, an extensive reign-by-reign chronicle, entitled the *Joseon Wangjo Sillok*, (*Veritable Records of the Joseon Dynasty*) spans the entire interval from AD 1392 to 1863 (see Figure 1). Only the reigns of the last two kings (Gojong and Sunjong) are omitted from the *Veritable Records*. Retrospective compilation of the *Sillok* – back to the start of the Joseon Dynasty (AD 1392) – began in AD 1413 during the reign of King Taejong, the third monarch of the Joseon Dynasty.

The *Sillok* is a compendious work, in 1893 chapters. At its most detailed, the *Veritable Records* is a day-to-day chronicle, but throughout the text there are numerous lacunae, often lasting for several days. Most of the entries in the *Sillok* are concerned with matters of court and State. Reports of celestial events are usually inserted near the beginning or end of the entry for the appropriate day. One of the most important series of astronomical records in the *Sillok* relates to the supernova of AD 1604/5. This brilliant 'guest star' was monitored for several months by the Korean astronomers (Figure 2). These almost daily observations provide valuable information on the changing brightness of the supernova (Stephenson and Green 2002).

For safe keeping, copies of the *Sillok* were stored at several separate repositories, some of which were in remote locations. Even so, preservation of the *Veritable Records* proved to be a most difficult task. Much damage occurred to individual sets of the *Sillok* as the result of severe fires, notably during the Japanese and Manchu invasions which took place in AD 1592 and 1633. Fortunately, restoration from the surviving copies of the *Sillok* proved possible. Today, only two early copies of the *Veritable Records* exist: both printed versions, these are in the Central Library of Seoul National University. Modern photographic reprints of the *Sillok* are typically bound in some 50 large volumes, each containing around 1,000 double pages. However, in 1998, the entire *Sillok* was made available on CD-ROM; it is also accessible on-line.

A useful summary of the astronomical (and other) data in Korean history down to AD 1770 is contained in an historical encyclopedia: the *Jeungbo Munheon Bigo*



太祖實錄（全）
定宗實錄（全）
太宗實錄（一）

朝鮮王朝實錄 一

國史編纂委員會

Fig. 1 Title page of the first volume of the *Joseon Wangjo Sillok*.

(*Enlarged Official Encyclopedia*). This work, published in 1908, is a revised version of the *Tongkuk Munheon Bigo* (*Official Encyclopedia of the Eastern Kingdom*), which was compiled in AD 1770 by a team of scholars led by Hong Pong-han. The *Tongkuk Munheon Bigo* was modelled on the great *Wenxian Tongkao* (*Official Encyclopedia*), compiled by the thirteenth century Chinese scholar Ma Duanlin. In fact, the last four characters in the Korean title (*Munheon Bigo)* are identical to the title of the compilation by Ma Duanlin (*Wenxian Tongkao*).

The contents of the *Jeungbo Munheon Bigo* – a work in 250 chapters – are arranged in 16 categories. The first section (Chaps. 1–8) is on astronomy, highlighting the importance with which this subject was regarded by the editors. Unfortunately, the information in this section is far from complete and there are several serious errors. For instance, all reference to the many eclipses of the Moon recorded in Korean history is lacking. Furthermore, the *Bigo* cites false records of 'guest stars' in both AD 1600 and 1664. In reality these are misplaced reports of the supernova which appeared in AD 1604 (Stephenson and Green 2002).

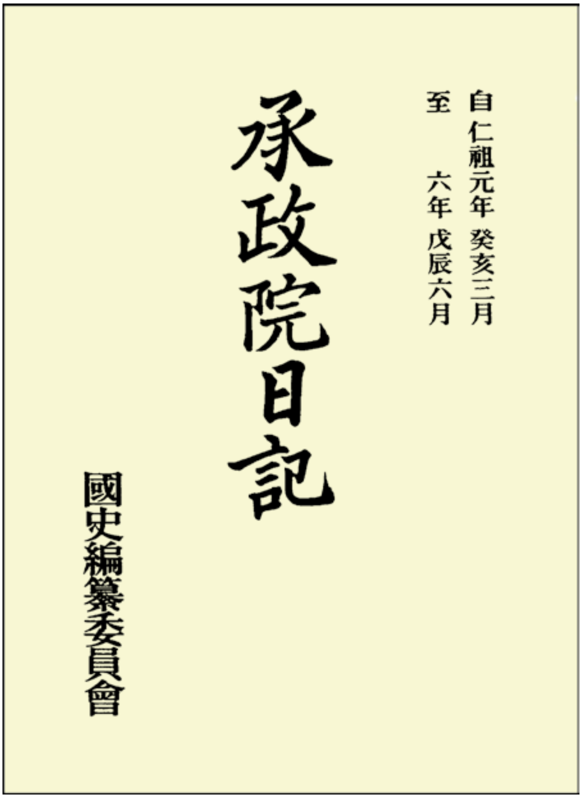
〇未時 上御別殿受針〇壬申〇卯時辰時沉霧 夜一更客星見於
大江星上在尾宿十一度去極一百九度大如歲星色黃赤動搖〇朝
王世子問安〇憲府啓曰兩司例兼春秋並令仕進于實錄廳
臺諫體面與庶官自別以郎廳供仕之際必有齟齬拘碍之弊臺諫兼
帶之員請勿進叅高陽郡守權愰濫率成婚子弟多有騷弊之事請 命
罷職麟山僉使朴命壽至率京妾二人侵虐軍卒日以貿易皮物爲事
貪虐泛濫之狀不一而足請 命罷職多大浦僉使李雲以本道鄕吏
性且悖妄不合巨鎭邊將請 命遞差 答曰依啓〇癸酉〇巳時午
時日暈 夜一更客星見於天江星上在尾宿十一度去極一百九度大
如歲星色黃赤動搖 五更月暈〇朝 王世子問安〇午時 上御
別殿受針〇甲戌〇辰時太白見於巳地 夜一更客星見於天江星上
在尾宿十一度去極一百九度大於歲星色黃赤動搖〇上不豫〇朝
王世子問安〇午時 上御別殿受針〇乙亥〇朝 王世子問安
〇天朝遊擊董正誼入來 上命宰臣申欽迎慰于門外又遣注書李
惕問安于所館處遊擊接見後引出第二門外送之云〇命原任大
臣李德馨設宴于遊擊德馨罷宴後書啓曰臣承 命往董遊擊下

宣宗大王實錄 卷之一百七十八

二十六

Fig. 2 Records (*highlighted in blue*) of the supernova of AD 1604/5 from the *Sonjo Sillok* (*Veritable records of the reign of King Sonjo*).

We come now to the main subject of the present paper: the *Seungjeongwon Ilgi* (*Daily Records of the Royal Secretariat*). By comparison with the works cited above, this is a relatively neglected source of astronomical (as well as other) records. Very few modern historians of astronomy – Korean or otherwise – have consulted the *Ilgi* in any depth. Yet it is a key source of astronomical observations made since AD 1623.



自仁祖元年癸亥三月
至　六年戊辰六月

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Fig. 3 Title page of the first volume of the *Seungjeongwon Ilgi*.

2 The *Seungjeongwon Ilgi*

The great chronicle entitled *Seungjeongwon Ilgi* (Figure 3) began its life early in the Joseon Dynasty. During the reign of the third king, Taejong (AD 1400–1418), the *Seungjeongwon* (Office of Royal Secretaries) was set up at the capital (Hansong: later known as Seoul). This office consisted of six *Seungji* (Royal Secretaries) and two *Cheuso* (Recorders). Assistant Recorders were also appointed. The six Royal Secretaries kept records of all official business. The duties of the Recorders were to register significant events on a daily basis – often at considerable length. A *Cheuso* was required to possess a sound knowledge of the Confucian Classics, as well as having a talent for writing. Secretaries and Recorders had to be available to serve the King at all times – both day and night. As even cursory inspection reveals, changes in calligraphy between the texts written by successive Recorders are often readily apparent (see Figure 4).

Regrettably, the *Seungjeongwon Ilgi* now only survives in its *original* form between AD 1722 and 1832, from 1835 to 1848, and from 1889 to 1894. However, *restored* versions of the *Ilgi* – following destruction of the original – cover the intervals from AD 1623, 1625 to 1721, 1833 to 1834, and 1849 to 1888. The *Ilgi* text,

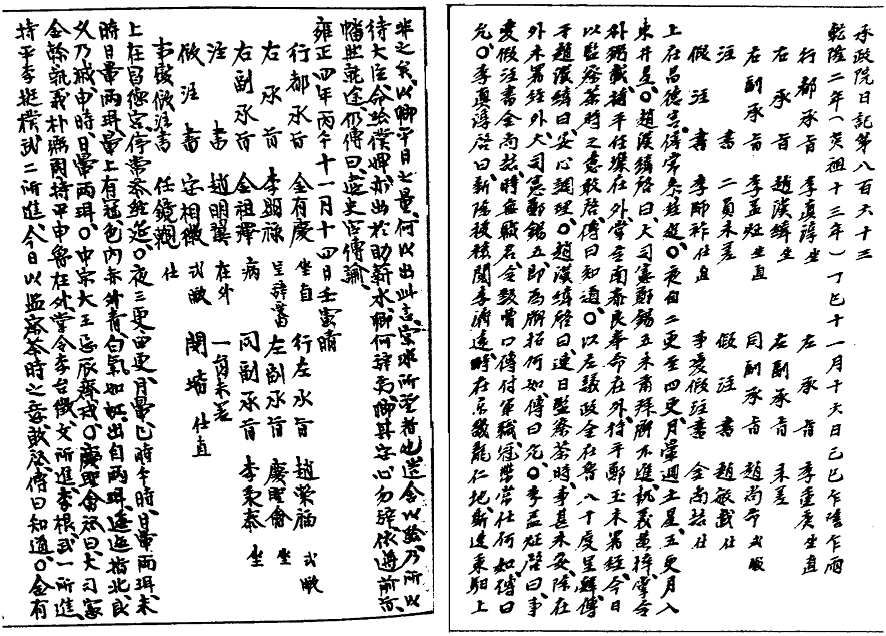


Fig. 4 Examples of different styles of calligraphy in the *Seungjeongwon Ilgi*.

which evidently never existed in more than one copy until modern times, has had a chequered history. In AD 1592, the first two centuries or so of the *Ilgi* were burnt when the palace was destroyed during the Japanese invasion of Korea led by Hideyoshi Toyotomi. Sadly, the destroyed text was never restored. Although maintenance of the *Ilgi* continued from AD 1592, in AD 1623 the entire chronicle over the previous 30 years was burnt during a rebellion.

Restoration of the *Seungjeongwon Ilgi* since AD 1592 from surviving archives took place in AD 1623. However, in AD 1744 another severe loss occurred; almost the whole of the *Ilgi* from AD 1592 to 1721 was burnt. Restoration again began in AD 1747, but only for the *Ilgi* beginning in AD 1623; due to the lack of source materials, the task was never again extended prior to AD 1623. Fortunately, from AD 1747 to 1888 there were no further mishaps. However, in the latter year most of the *Ilgi* since 1849 was burnt, but the text was soon restored. Finally, in 1894, during the reign of King Gojong, the office of *Seungjeongwon* was abolished; by then it had served the Yi Dynasty for more than 500 years. Today, only the *Ilgi* for AD 1623 and from 1625 to 1894 is preserved. Judging from the high quality of the surviving material, the loss of the data in the *Ilgi* over the more than two centuries prior to AD 1623 is a major literary disaster. Fortunately, as noted above, the *Joseon Wangjo Sillok* fared better (due largely to the keeping of several separate copies of this chronicle). Although the *Sillok* survives since AD 1392, it is apparent from comparison between it and the extant *Ilgi* that in general the *Sillok* contains far less detail than the *Ilgi*.

If the entire *Ilgi* had still been preserved since its inception, the complete 'Daily Records' would have contained some 6,400 chapters – roughly one for each month. Today only 3,050 chapters are extant. Nevertheless, these in total contain some three times as much text as the *Joseon Wangjo Sillok*, which covers twice the span of years. In total, the surviving Ilgi from AD 1623 to 1894 contains around 150 million characters. Photographic copies, bound in about 100 substantial volumes, each with approximately 1,000 double pages, are to be found in major libraries. In addition to photographic copies, this huge compilation is now available on-line, making the content of the *Ilgi* much more accessible to scholars worldwide.

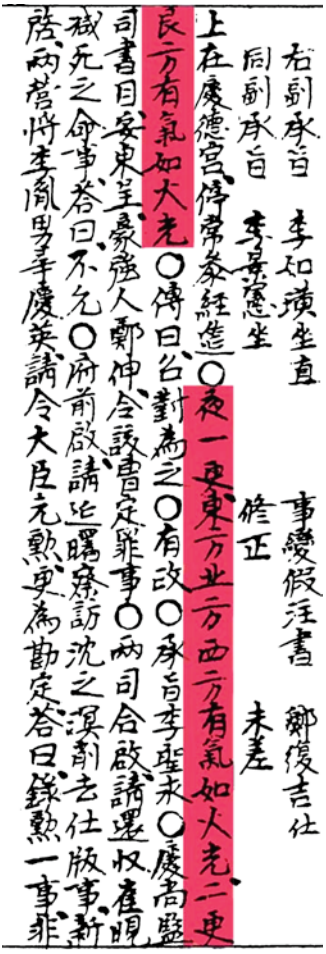
Park (1977) has made the following helpful remarks on the celestial observations in both the *Ilgi* and *Sillok*:

> Reports of the (court) astronomers were copied in the diaries of the Royal Secretariat … (These diaries) were far better than any other personal memoirs in portentology … From what we have from 1623 on(wards), we discover that a considerable amount of trimming was done to the records of the *Seungjongwon Ilgi* when they were transcribed into the *Sillok*.

In brief, the astronomical records in the *Sillok* are often little more than a summary of the corresponding material in the *Ilgi*, often with the loss of considerable detail.

As noted above, only the text of the *Ilgi* between AD 1722 and 1832, from 1835 to 1848, and from 1889 to 1894 is preserved in its pristine form. At all other times, especially the long interval from AD 1623 to 1721 only later restorations of the text are available. Reports of celestial phenomena are usually – but by no means always – included near the beginning or end of the entry for the relevant day. Although the original *Ilgi* was essentially a day to day chronicle, there are several major gaps in the extant text, especially in the earlier years when some lacunae last for several months. Clearly, a restored chronicle lacks to some extent the consistency of the original version. However, there can be little doubt that the *Ilgi* is a prime source of astronomical records from the early seventeenth century to the late nineteenth century.

Recently David Willis and I made an extensive study of the astronomical records in the *Ilgi* over a selected short period (Stephenson and Willis 2008). This period extended from the beginning of the third year of King Injo (AD 1625) to the middle of his sixth year (AD 1628). The very first bound volume of the *Ilgi* covered most of the period from the start of the first year of King Injo (AD 1623) to the middle of his sixth year. However, although the data for the first year of King Injo are fairly well preserved in the *Ilgi*, the corresponding material for the whole of his second year is lost. Fortunately, the material for the subsequent 3.5 years is relatively continuous, although there are still several significant lacunae – one of about 1.5 lunar months in AD 1626 and a longer gap, covering the first 4 months of AD 1628. During these two intervals, no astronomical records of any are preserved in the *Ilgi*. Evidently the data from these periods had been lost by the time restoration from archives was attempted in AD 1747. It might be mentioned here that my scanning twice by eye of the text of the selected section of the *Ilgi* over the 3.5-year period (some 1.5 million characters) proved to be a huge undertaking; it was a task not to be undertaken lightly! Yet this represented only ~1% of the surviving *Ilgi*.



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同副承旨 李景憲坐 修正 未差
上在慶德宮、侍常參經筵○夜一更東方北方西方有氣如火光、二更
艮方有氣如火光○傳曰、台諫爲之○有政○承旨李聖求○慶尚監
司書目、安東呈、豪强人鄭伸、令該曹定罪事○兩司合啓、請還收崔晛
減死之命事、答曰、不允○府前啓、請迎曙察訪沈之溟削去仕版事、新
啓、兩營將李胤男李慶英、請令大臣元勳、更爲勘定、答曰、錄勳一事、非

Fig. 5 Sample auroral records ("… vapours like fire light", *marked in red*) in the *Seungjeongwon Ilgi*: during the first and second watches of the night on 27 January 1628.

Our main purpose in undertaking this investigation was to better understand the many reports of "… vapours like fire light." (e.g. see Figure 5) seen during the night in various directions, as recorded in Korean history over several centuries (Lee et al. 2004; Yau et al. 1995). Usually, both the *Ilgi* and the *Sillok* quote estimates of the directions in which the 'vapours' occurred to the nearest octant. However, the *Ilgi* almost invariably gives greater detail. In particular, unlike the *Sillok*, the *Ilgi* systematically cites the night watch(es) during which the phenomenon was seen.[1]

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[1] For this purpose, the night from dusk to dawn was divided into five equal watches.

To give an example, on a date corresponding to AD 1626 April 22 it is recorded in the *Ilgi* that

> At night in the first watch and the second watch in the NE direction. In the E and SE directions and in the S directions there were vapours like fire light. In the fifth watch in the SE direction there was a vapour like fire light.

The *Sillok* reports the first part of the above entry verbatim but without noting the time of night. However, the observation made in the fifth watch is only noted in the *Ilgi*. The first display would last from about 19.3 to 23.1 h local time as seen from the capital of Seoul; the later event would take place between 2.8 and 4.7 h.

These presumed references to the aurora borealis are without parallels in either Chinese or Japanese history. However, the Korean sources at this period are unrivalled for their detail – especially in astronomical reports. In my searches of the *Ilgi* and *Sillok*, I uncovered as many as 96 reports of these "… vapours like fire light." between the start of AD 1625 to the middle of 1628. Of these observations, 69 were cited in the *Ilgi*[2] and 54 in the *Sillok*, but only 27 are common to both sources. A full list is published by Stephenson and Willis (2008). Clearly, both sources as they exist today are far from complete – at least for the period investigated. Nevertheless, taking into account the additional detail in the *Ilgi* reports, the superiority of this source over the *Sillok* is apparent. Based on both the recorded times and directions in the *Ilgi*, it is clear that the "… vapours like fire light." were not simply extended sunrise or sunset glows prolonged by volcanic dust in the upper atmosphere. Further, our investigation of the many lunar and planetary observations in both the *Ilgi* and the *Sillok* over this same period – using retrospective computation – testifies to the reliability of the astronomical reports.

Based on available statistics, the above frequencies (averaging more than two events per month) are much greater than might be expected for aurorae at such a low geomagnetic latitude (ca. 30°). In our joint paper (Stephenson and Willis 2008), we suggested that a possible generation mechanism might involve coronal mass ejections or co-rotating interacting regions.

My preliminary survey of later volumes of the *Ilgi* suggests that "… vapours like fire light." were recorded frequently at various periods, such as in 1747 just 3 years before European records indicate that solar activity reached a peak. For instance, during the third lunar month of AD 1747 (= 24th year of King Yongjo), these events were reported on six occasions between April 10 and May 6. During this interval the *Sillok* only mentions a single occurrence (on the first of these dates). Whether the frequency of these vapours shows a correlation with the solar cycle is a matter for future research in the huge corpus of the *Ilgi*. It is hoped that Korean scholars might be encouraged to embark on (or at least join me in) this task.

One of the many lunar conjunctions with planets or stars is recorded in the *Ilgi* on a date equivalent to AD 1625 November 10: "At night in the first watch the Moon trespassed against Mars." This same observation is reported in the *Sillok*, but without

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[2] During this 2.5-year period, in some months the *Seungjeong-won Ilgi* records as many as 10 of these occurrences. Each separate record cites the night watch during which the event was observed and also the relevant octant or quadrant of the sky.

mention of the time of night. The term translated ‘trespassed against’ normally implied a close approach but not an occultation. On this evening, the first watch would last from about 17.8 to 20.3 h LT. Computation shows that around the middle of this interval, the Moon, then about 130° E of the Sun, would be about 0.8° to the SE of Mars. This would be a fairly close approach. Here, as on many other occasions, retrospective computation confirms the accuracy of observation in the *Ilgi* records.

One of the most interesting series of observations in the first few years of the *Ilgi* relates to the disappearance of a star. On a date corresponding to AD 1625 October 3, it is recorded that “At night, in the first watch, the star *Ziwei Yuan Tianyi* became dim and was not seen.” On as many as 15 other dates between October 4 and 25 it is reported that “The star *Ziwei Yuan Tianyi* was not seen.” After the last date, there is no further mention of the star, and there is no record of its recovery. By comparison, the *Sillok* only cites a single report on the star: a summary of the observation on October 3.

Identification of the constituents of the East Asian constellations by Pan Nai (1989) and Yi Shitong (1984) suggests that *Ziwei Yuan Tianyi* was probably 10 Dra, an M3 giant (see Figure 6). The observation of a close approach of the Moon to the stars in Bi (α Tau, etc.) on October 18 is closely confirmed by computation: around midnight, the Moon and α Tau were less than 1° apart. This suggests that records of the star’s disappearance are also reliable. However, such marked variations in the brightness of 10 Dra do not appear to have been noted on other occasions.

Numerous comets are recorded in the *Ilgi* – notably the apparitions of Halley’s Comet in AD 1682, 1759, and 1835. In each case an almost nightly account of the appearance of this ‘broom star’ and its changes in position are reported in the *Ilgi*. For instance, at the apparition in AD 1682, Halley’s Comet was closely monitored from August 25 to October 19. The record of the first sighting (Figure 7) may be translated as follows:

> At night, in the fifth watch, third point, after the clouds had dispersed, a star like a broom was seen in the NE direction among the stars of *Beihe*. On account of the moonlight, it could be seen clearly.

The report on the day that Halley’s comet finally disappeared (AD 1682 October 19) yields an intriguing insight into the organisation of the Astronomical Bureau at the capital:

> Officials of the Observatory requested release of duty. The comet from early this month was gradually extinguished. However, after the moonlight had flourished, it was difficult to know its location. Last night (the 18th day of the lunar month) the moonlight was not very bright. All the stars were visible, but where the comet was situated could not be seen. No doubt it had been extinguished. The Special Observing Team should now be disbanded. Request received and noted. (Translation courtesy K.K.C. Yau).

3 Conclusion

In this paper, the importance of the *Seungjeongwon Ilgi* as a major source of celestial records since AD 1623 has been emphasised. In addition to the historical significance of the various observations, there seems to be considerable potential for using the

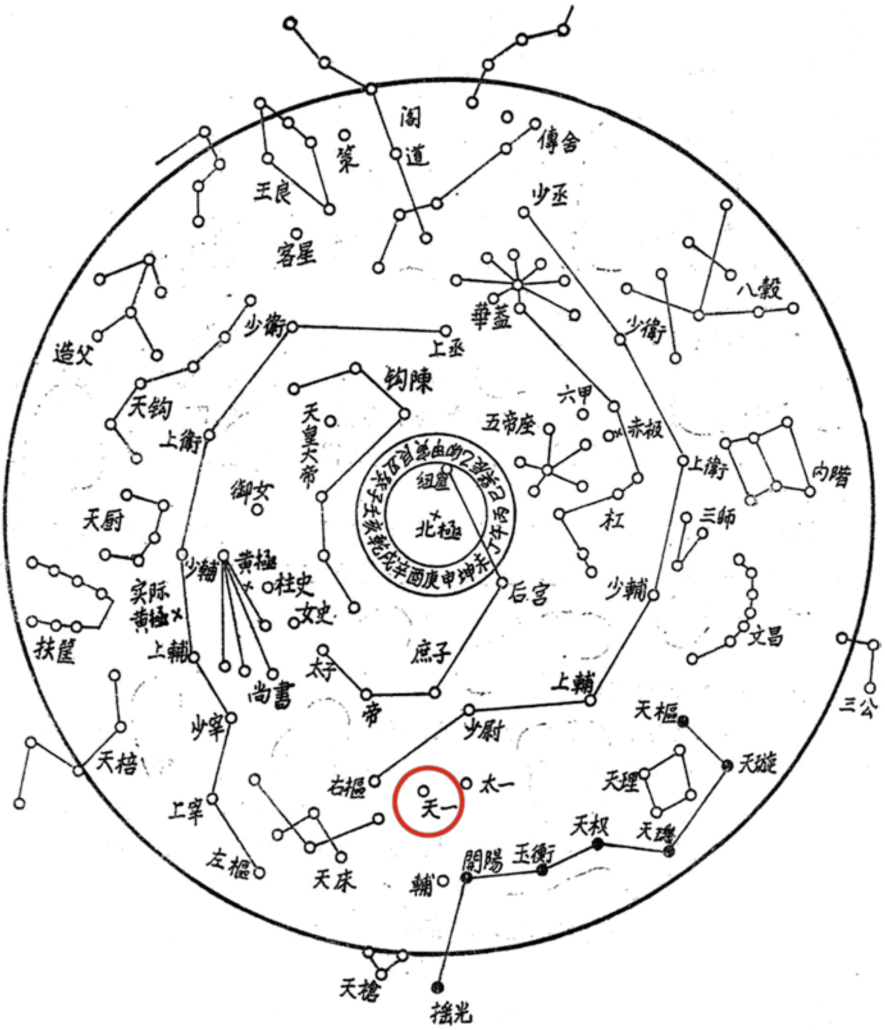

Fig. 6 Sketch of a Chinese star chart of the north circumpolar region from the Tianhougong Temple, Putian showing the location of the star *Ziwei Yuan Tianyi* which disappeared on AD 1625 October 3 (after Pan Nai 1989).

numerous auroral records for studying long-term solar variability. As the disappearance of the star on a date corresponding to AD 1625 October 3 – as well the detailed cometary observations (including Comet Halley) – suggest, there may well be a wide variety of data in the *Ilgi* which are important in Applied Historical Astronomy. It is my hope that 'mining' of these data may commence in earnest in the near future.

Until the numerous accounts of celestial events in the whole of the *Ilgi* have been examined, we shall only possess a disappointingly incomplete record of the astronomical observations reported in East Asian history since the early seventeenth century.

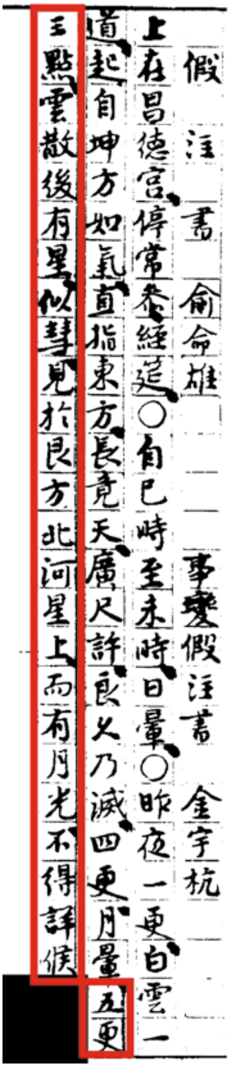
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Fig. 7 Record of the first sighting of Halley's Comet in AD 1682 (August 25), as recorded in the *Seungjeongwon Ilgi*.

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Part IV
Nineteenth Century Transits of Venus and Solar Eclipses

The 1874 Transit of Venus and the Popularisation of Astronomy in the USA as Reflected in the *New York Times*

Stella Cottam, Wayne Orchiston, and Richard Stephenson

Abstract Given uncertainty surrounding the true value of the astronomical unit following the 1761 and 1769 transits of Venus the next transit, in 1874, offered hope for a substantial refinement in the value of this fundamental yardstick of Solar System astronomy. Part of the reason for this successful anticipated outcome was that both photography and spectroscopy would be applied to a transit of Venus for the first time. Consequently expectations were high, and this unusual event enjoyed a high public profile, thanks to frequent articles published in newspapers and in magazines. Because of the importance of this transit, many nations dispersed expeditions to Asia, the Pacific and the Australia–New Zealand region where the entire event could be seen. The USA sent out eight transit parties to this part of the world, and their activities and results, along with those of other nations' transit parties, were widely reported back home. In this paper we focus on the US expeditions, and the ways in which their activities were reported on back in the USA through the pages of the *New York Times*.

1 Introduction

Transits of Venus are rare events that occur in pairs just eight years apart, with more than a century elapsing between succeeding pairs (for an excellent overview see Sheehan and Westfall 2004). On present evidence, only six different transits have been observed by astronomers: in 1639, 1761, 1769, 1874, 1882 and 2004.[1]

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[1] While observations of all of these transits are on record, Trejo and Allen (2004) have also outlined a possible Mayan observation of an earlier transit of Venus. Meanwhile, Stephenson (1990) carried out an unsuccessful search for evidence of pre-1639 transits of Venus in Chinese astronomical records.

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Edmond Halley (1656–1742), promoted the use of transits of Venus as a means of accurately determining the astronomical unit, that "basis yardstick" of Solar System astronomy and in 1716 he submitted a proposal to the Royal Society:

> Scarce any problem will appear more hard or difficult than that of determining the distance of the sun from the earth, very near the truth; but even this, when we are made acquainted with some exact observations, taken at places fixed upon and chosen beforehand, will, without much labor be effected. And this is what I am now desirous to lay before this illustrious Society (which I foretell will continue for ages), that I may explain beforehand to young astronomers, who may perhaps live to observe these things, a method by which the immense distance of the sun may be truly obtained within a five-hundred part of what it really is (cited in Proctor 1874: 31–32).

This led to enormous scientific interest in the 1761 and 1769 transits (see Woolf 1959), which Halley would not live to see, but these two transits produced conflicting results. Values for the solar parallax obtained during the 1761 transit ranged from 8.28″ to 10.60″, and even though the 1769 transit produced a much smaller range of "reliable" results, namely between 8.43″ and 8.80″, even these represented a variation in the measure of the astronomical unit of ~6.57×10^6 km. According to Hughes (2001: 21–22),

> Two factors were to blame for the magnitude of this parallax range. One was the inaccuracy of the timing of the Cytherean ingress and egress, due to the black-drop effect. Errors in estimating when Venus had left the solar limb, or reached it, could easily be between 10 and 15 s of time. The other was due to poor knowledge of the latitudes and longitudes of some of the observing sites …

This created tremendous interest in the next pair of transits, in 1874 and 1882, which addressed what Britain's Astronomer Royal, George Biddell Airy (1857: 208), described as "… the noblest problem in astronomy." In this paper we examine the 1874 event, especially as viewed from a US perspective, and ways in which it was documented in the pages of the *New York Times*.

2 The 1874 Transit of Venus

2.1 Introduction

After reviewing Halley's approach to the transits, French astronomer, Joseph-Nicolas Delisle (1688–1768) proposed an alternate method that required observation of either the contacts of ingress or egress from locations widely separated in longitude. The difference in the time of contact would lead to an indirect measurement of Venus' rate of travel in miles per minute. This difference in absolute time, with the knowledge of the longitude at each site, would lead to an indirect measurement of Venus' distance, and this was the approach that was adopted for the pair of nineteenth century transits.

With this strategy in mind, one of the greatest episodes in international astronomy was launched with an all-out assault on the 1874 transit (Meadows 1974; Sheehan 2004). For example, France (Débarbat and Launay 2006; Lauga 2004) and Germany (Duerbeck 2004, 2007) each sent out six international expeditions, and Britain

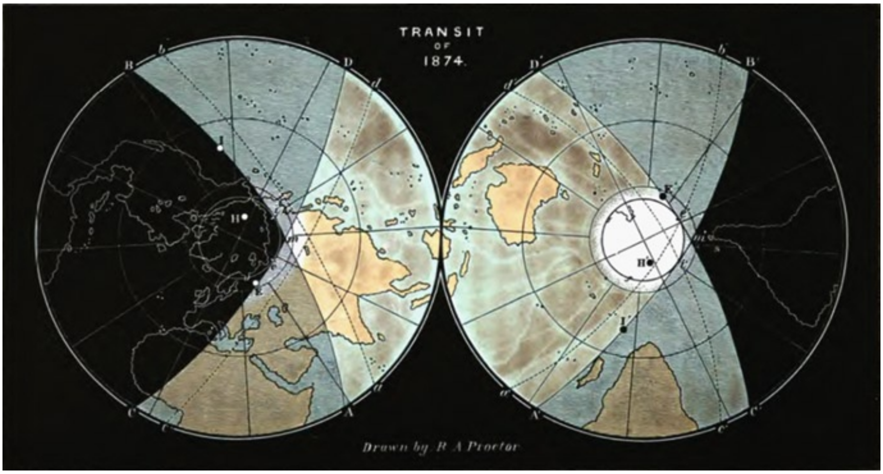

Fig. 1 Map showing those areas of the globe (in *blue*) where part or all of the 1874 transit of Venus would be visible (after Proctor 1874: Plate VI).

twelve (see Brück 2003, 2004; Chauvin 1993, 2003; Ratcliff 2008). Other European nations were also involved, including Italy (Chinnici 2003; Pigato and Zanini 2001), Holland and Austria (Kopper 2004), and the Russians – not to be outdone – dispatched twenty-six expeditions, but all of these were based on their own soil (Werrett 2006). Further afield, Brazil and Mexico both sent expeditions to Japan (see Freitas Mourão 2004 and Allen 2004, respectively).

In the century or so since the 1769 transit the international situation had changed markedly. With Britain and France no longer at war, one might expect better cooperation among the many nations participating in the 1874 transit expeditions. The astronomers also were far better prepared and equipped than previously. Both photography and spectroscopy would play a key role (e.g. see Lankford 1987; Pigato and Zanini 2001), in the hope that these new tools would eliminate once and for all problems associated with visual observations, especially the notorious "black drop effect" (see Schaefer 2001). France's Jules Janssen even invented a special kind of rotating-plate camera in a bid to obtain successful multiple images of the grand event (see Launay and Hingley 2005).

The transit was expected to last more than 4 h (Dick et al. 1998: 231), and it was established that Australia, New Zealand, southeastern Asia and most of the Indian Ocean would provide the best sites for observing the whole transit (see Figure 1). Consequently, Australia attracted two US expeditions (see Orchiston and Buchanan 1993, 2004) but also had stations of its own established by the professional observatories in Adelaide (Edwards 2004), Melbourne (Clark and Orchiston 2004; Orchiston 2004b) and Sydney (Lomb 2004; Orchiston 2004a, b). New Zealand had a network of "local" observing stations across the nation maintained by Government officials and leading amateur astronomers (Orchiston 2004b), but it also hosted British, French, German and US transit parties either at sites on the mainland or on its adjacent islands (Dawson and Duerbeck 2008; Orchiston 2004b; Orchiston et al. 2000).

2.2 The US Transit Program

2.2.1 The Expeditions

In the USA, the 1874 transit of Venus program was seen as a major scientific undertaking (Dick 2003; Janiczek 1983), and in order to carefully plan for and implement this a special Commission was created by Congress in 1871. Dominating the Commission were astronomers from the US Naval Observatory, one of the most influential of whom was that doyen of American astronomy, Simon Newcomb. The Commission decided to send eight expeditions to view the transit, three in the northern hemisphere and five in the southern hemisphere. As it transpired, landing an eclipse party on Crozet Island in the Indian Ocean proved impossible and this group continued on to the island of Tasmania and ended up based at Campbell Town, close to the Hobart transit party. The geographical distribution of the sites where the different American transit parties finally were based is shown in Figure 2.

Each transit party normally comprised a Chief Astronomer, an Assistant Astronomer, a Chief Photographer and two or three photographic assistants, along with a small number of local volunteers (Herman 1984). The two astronomers were responsible for the visual observations and for maintaining a time-service, while the photographers conducted the photographic aspects of the program. The Chief Photographer was always a professional photographer, but his assistants were typically "… young

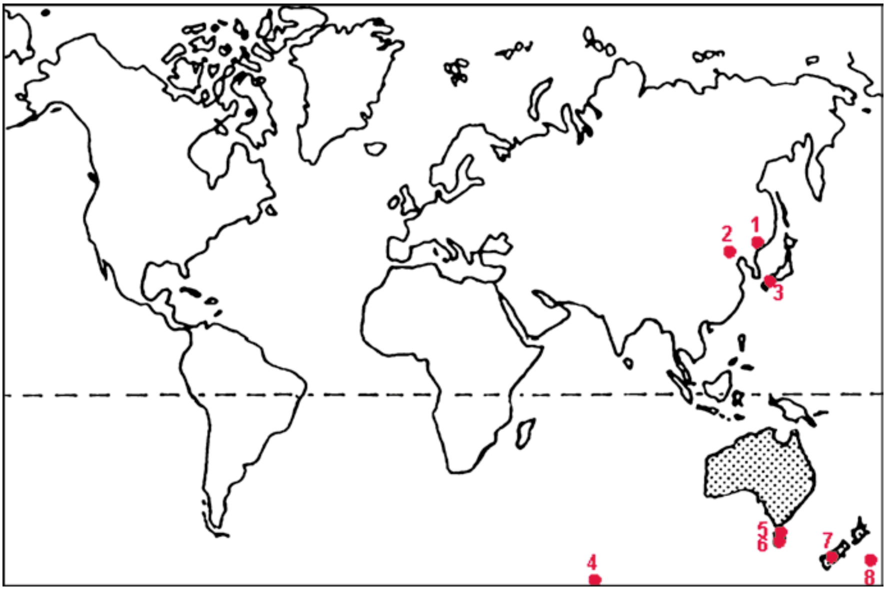

Fig. 2 The distribution of US 1874 transit of Venus stations. 1 = Vladivostok, 2 = Peking, 3 = Nagasaki, 4 = Kerguelen Island, 5 = Campbell Town, 6 = Hobart, 7 = Queenstown, and 8 = Chatham Islands.

gentlemen of education, recent graduates of different colleges, who had been practiced in chemical and photographic manipulation." (Newcomb 1880: 16).

2.2.2 The Instrumentation

One of the most contentious decisions facing the US Transit of Venus Commission was the types of instruments to be employed during the transit. This revolved around whether the transit parties should rely upon visual observations or a photographic approach, and while it was agreed that both options would be employed, photography was to play the leading role. In deciding upon the most appropriate type of photographic equipment, the Commission selected the fixed horizontal solar telescope first conceived by Joseph Winlock and used by Harvard College Observatory rather than the equatorially-mounted heliograph developed by Walter de la Rue and favoured by the British 1874 transit parties.

At the "heart" of the American photoheliograph was a 203-mm square brass plate-holder (see Figure 3) which was mounted on a solid metal pier that was sunk

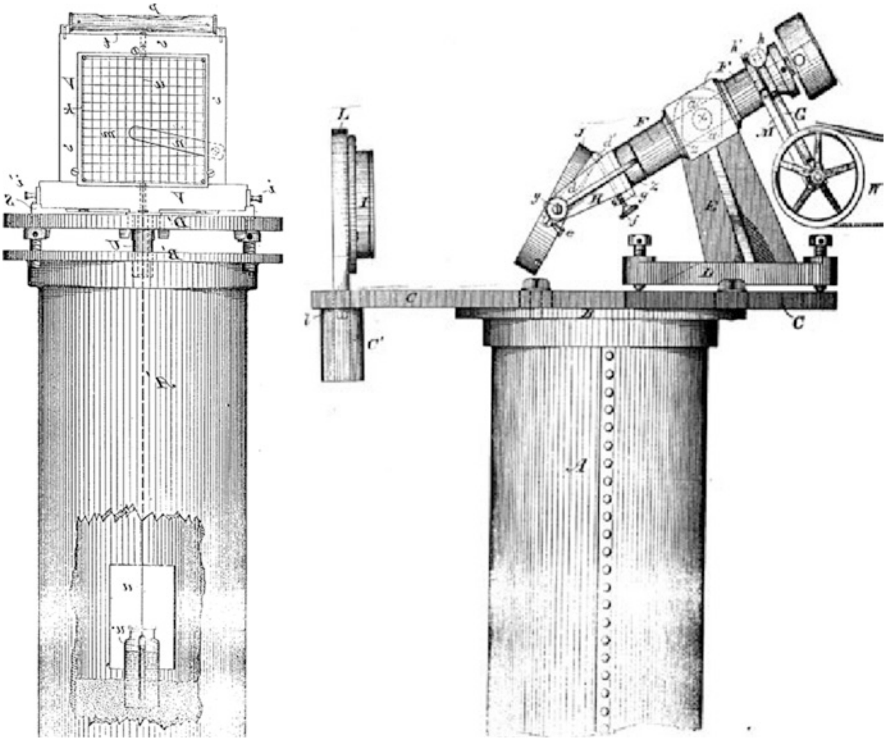

Fig. 3 Details of the critical components of the photographic telescope. *Left*: the plate-holder; *right*: the heliostat.

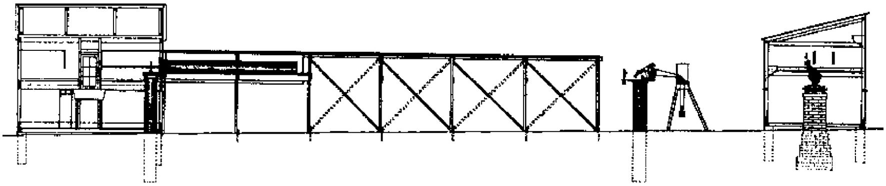

Fig. 4 Side elevation showing the overall arrangement of the photoheliograph and transit telescope.

into the ground. A sheet of transparent plate glass about 7.6 mm thick was cemented onto the plate-holder. This plate glass was

> … divided into small squares by very fine [etched] lines … [and] the sensitive [photographic] plate goes into the other side of the frame, and … there is a space of about one-eighth of an inch between the ruled lines and the plate. The former are, therefore, photographed on each picture of the sun which is taken … (Newcomb 1880: 189).

A plumb-line was also attached to the plate-holder, and this was used to indicate vertical on each photograph. A wooden "Photographic House" protected the plate-holder from the elements and also offering facilities for preparing and developing the photographic plates. This simple, flat-roofed prefabricated building was part of the cargo manifest.

Out in the open air some 12 m from the Photographic House was a second metal pier which supported a 17.8-cm unsilvered glass heliostat mirror and a 12.7-cm objective. The heliostat (Figure 3) received the incoming sunlight, and the lens focused it on the photographic plate. Figure 4 shows the weight drive that allowed the heliostat to track the Sun during the transit. Extending between the heliostat and the plate-holder was a measuring rod which was used to accurately determine the focal length of the telescope, a parameter that was critical in establishing the plate scale. The measuring rod was supported by a wooden framework which itself was protected by a narrow roof. The ultimate aim of the exercise was to produce an image of the Sun about 10.8-cm in diameter on the photographic plate. The overall arrangement of the photoheliograph is depicted in Figure 4, which also shows the tube extending about 4 m from the Photographic House through which the light from the heliostat passes.

Also conspicuous in Figure 4 is the simple prefabricated Transit House, which lies beyond the heliostat pier and housed a 6.35-cm aperture transit telescope made by Stackpole Brothers (Figure 5), an astronomical clock built by the Howard Clock Company of Boston, and three box chronometers. The transit telescope was of the broken-tube variety,

> … a prism being placed in the center of the tube, by interior reflection from which the pencil rays is [sic] thrown along the axis; and the image is thus formed at the end of the latter … This form of instrument has the great advantages of convenience in observing and rapid and easy manipulation, but is still subject to the disadvantages of collimation varying with zenith-distance of the object observed (Newcomb 1880: 14).

Fig. 5 The Stackpole Brothers broken-tube transit telescope.

Those responsible for the Transit House were charged with maintaining an accurate local time-service, and with using the instruments therein to determine the precise latitude and longitude of the transit station and the critical N-S alignment of the photographic telescope.

Apart from relying solely on the photoheliograph, the Commission decided that each transit party should also be supplied with a 5-in (12.7-cm) equatorially-mounted f/14 refracting telescope by Alvan Clark, so that independent visual observations of the transit could also be made. This instrument was supported by a solid metal pier rather than a tripod, and came with the all-important double-image micrometer so that positional measurements of Venus' position on the solar disk could be taken during the transit. The telescope and accessories were protected from the elements by a prefabricated "Equatorial House." This 3 m diameter octagonal wooden observatory contained a rotating conical dome with a single hinged shutter.

In order to accommodate all of these instruments and their associated buildings a level site extending ~25 m N-S was required, that offered a firm foundation, protection from the wind, and a clear view of the Sun for the duration of the transit (Commission …, 1874). While the N-S orientation of Transit House and photographic telescope was unchanged at each US transit station, the actual positioning of the Equatorial House varied somewhat according to circumstances. By way of example, the layout of two different transit stations is shown in Figure 6.

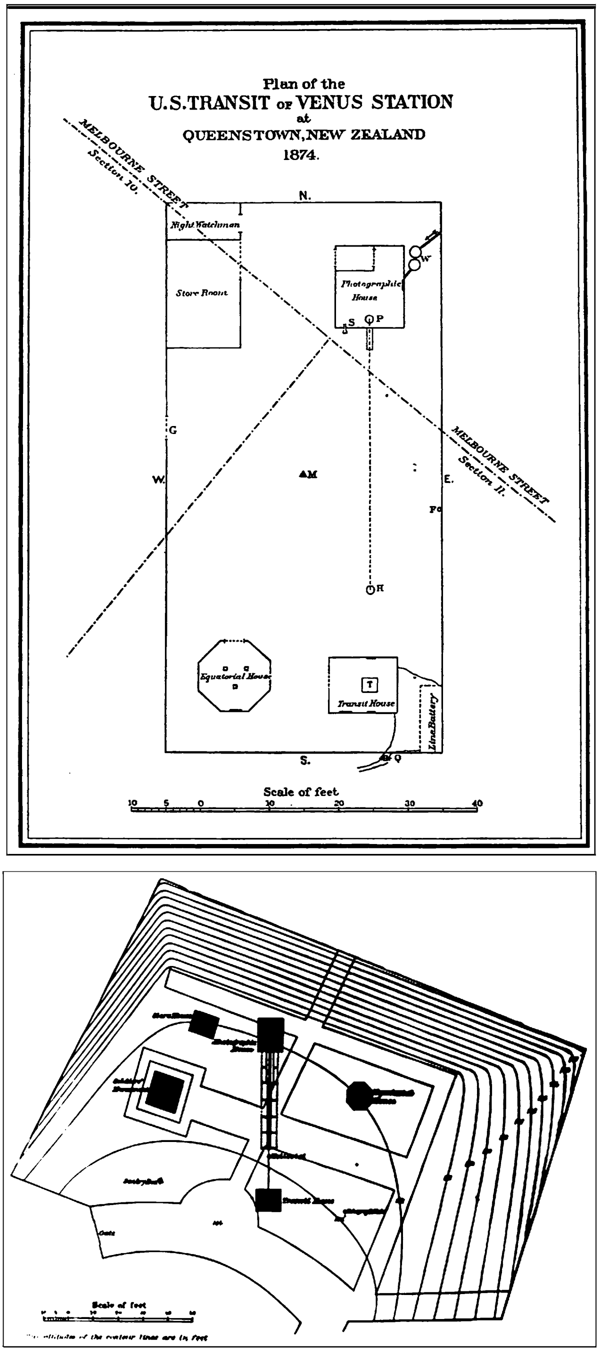

Fig. 6 Plans of the Queenstown (*top*) and Hobart (*bottom*) transit stations showing in each case the locations of the photographic telescope, "transit house" and "equatorial house".

2.2.3 The Observations and Results

As we have seen, the Americans relied for their 1874 parallax result on the photographic observations, and they ended up with 350 different images provided by the eight different transit stations (see Table 1). William Harkness from the US Naval Observatory was assigned the task of measuring the plates, and although these yielded excellent results for the interval when Venus was on the Sun's disk, there were serious concerns about the quality of the photographic images during the ingress and egress phases (Harkness 1883). Nonetheless, the measurements of all of the American photographs were completed by the end of 1877, and then Harkness faced the laborious task of establishing the longitudes of the various transit stations. When this was accomplished the official report of the 1874 American transit program was to have been published in a succession of volumes, but funding issues only allowed the appearance of the first of these (Newcomb 1880). Unfortunately, this contained none of the results, as these were planned for subsequent volumes. After further delays it was D.P. Todd from the Nautical Almanac Office who eventually published a provisional American value of 8.883 ± 0.034 for the solar parallax (Todd 1881). This value and results obtained by other nations during this transit represent a significant improvement on the uncertainty that surrounded the 1761 and 1769 transits, and with the benefit of hind-sight we can see that the 1874 transit of Venus produced an overall result that was close to the currently-accepted value adopted by the International Astronomical Union in 1976 (see Table 2).

Table 1 Photographs from 1874 American transit stations used in deriving a value for the solar parallax (adapted from Dick et al. 1998)

Station	Number	% of Total
Vladivostok (Russia)	13	3.71
Nagasaki (Japan)	60	17.14
Peking (China)	90	25.71
Kerguelen Island (Indian Ocean)	26	7.43
Campbell Town (Australia)	55	15.71
Hobart (Australia)	39	11.14
Queenstown (New Zealand)	59	16.86
Chatham Islands (New Zealand)	8	2.29
Total	350	99.99

Table 2 Solar parallax determinations (adapted from Dick et al. 1998)

Publication date	Author	Transit(s) or method	Parallax (″)
1881	Todd	1874 (American)	8.883 ± 0.034
1878	Tupman	1874 (British)	8.82 – 8.88
1888	Auwers	1874 (German)	8.810 ± 0.120
1888	Auwers	1874 (German)	8.8796 ± 0.0320
1895	Newcomb	1874 + 1882	8.857 ± 0.023
1895	Newcomb	1761 + 1769 + 1874 + 1882	8.794 ± 0.018
1895	Newcomb	System of constants	8.800 ± 0.0038
1976	[IAU]	Radar	8.794148 ± 0.000007

3 The 1874 Transit of Venus and the *New York Times*

The 1874 transit of Venus generated immense public interest, resulting in the publication of a number of books (e.g. Forbes 1874; Grant 1874; Proctor 1874; Stock 1874). However, newspapers would offer the most effective means of bringing the on-going saga of the various international transit parties before a wide cross-section of the general public. In her paper "Parlors, Primers and Public Schooling …," Sally Kohlstedt (1990: 434–436) recognizes that the early nineteenth century was a period of increased literacy in the United States, and printed matter on science published in journals, newspapers and books was becoming increasingly desirable and readily available to the public. Reading also became physically easier with the production of eyeglasses and improved lighting.

In the USA most printed matter of scientific value had been reprints of English works, until the appearance of the first American books on astronomy, such as John Gummere's *Elementary Treatise on Astronomy* (1822) and Elijah Burritt's *Geography of the Heavens* (1833). American-published journals specific to particular topics of interest were increasingly available and many localities in the United States had sufficient readership to support local newspapers. Many of these journals and local newspapers printed articles on the transits of Venus.

The *New York Times* began publication in 1851 and has been in print continuously ever since. At the time of the 1874 transit of Venus it was a daily publication, usually only 8 pages in length. The only illustrations were occasional diagrams (Mott 1962: 428–429).

During the years surrounding the two nineteenth century transits of Venus the *New York Times* would educate the public on the science of these events, intrigue them with tales of adventurous expeditions to alien lands, update them on the successes and failures of the various parties and provide them with further material relating to astronomy in order to cater for continuing public interest in this field.

Probably the most significant of the many articles on the transit of 1874 published by the *New York Times* was that which appeared on 8 December 1874, the very day of the transit. On this date the reader would find a detailed 6-column article defining the transit and describing the two primary methods for its use in the determination of the value of the astronomical unit, complete with diagrams (see Figure 7). The instrumentation used to observe the transit and maintain a local time service was briefly discussed and practical difficulties that might be encountered were described. Preparations made by the various nations were summarized (*New York Times*, 8 December 1874, 3).

Preliminary to this article were a number that served to inform the public and provide them with relevant resources. References were made to useful writings in other periodicals and books (*New York Times*, 14 March 1874, 8; 23 September 1874, 2; 22 October 1874, 2). There was also a summary of an informational lecture given by Professor Richard Proctor at Cooper Union "… before a large and attentive audience." (*New York Times*, 4 April 1874, 5). There was an opinion column published on 19 April 1874 expressing concern about America's slow start to involve itself in the transit expeditions.

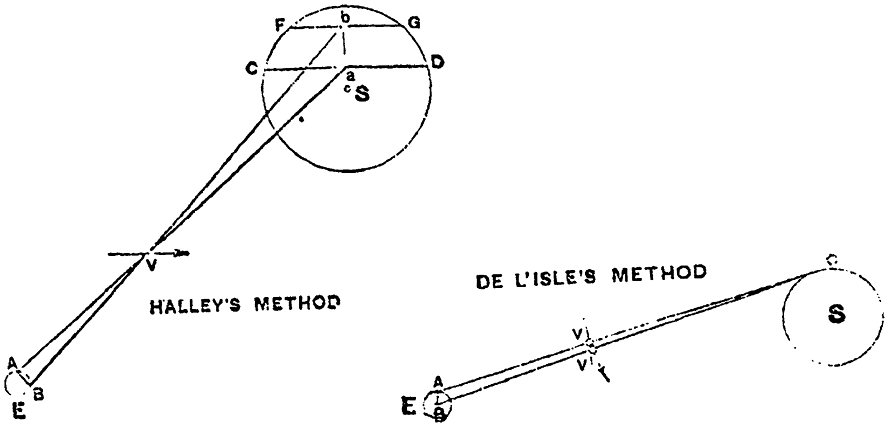

Fig. 7 Diagrams and descriptions of Halley's and de L'Isle's methods were included in the long article about the transit that appeared in the *New York Times* on 8 December 1874.

There were human interest stories of the adventures of past transits that would intrigue the reader and might increase his or her interest in the current ones. On 25 July and 30 August 1874 articles were published about the trials and tribulations of Le Gentil de la Galasiere, commissioned by the French to observe the transit of 1761 from Pondicherry in India. As war had broken out between the French and the English, he was forced to wait several months before a frigate could deliver him to his destination. Finally arrived, he found the town had been taken into British possession. He was forced to watch the transit from the boat and was unable to collect any usable data. He opted to wait in that part of the world until the next transit of 1769, using his time admirably in other miscellaneous scientific pursuits. At the appointed time in 1769 at Pondicherry he was frustrated yet again, this time by an overcast sky. He headed home and upon his arrival learned that, thinking him dead, the Academy of Sciences had filled his place and his relatives had divided his possessions. Everyone likes a good story (*New York Times*, 25 July 1874, 2; 30 August 1874, 4)!

Americans with interest in the expeditions of their adopted country might have followed closely a series of articles in the *New York Times* "From Our Own Correspondent," who accompanied the USA's southern expeditions to Australia and New Zealand. This unnamed individual started his series with an explanation of the transit's significance and the funding for its observation. He continued the series with reminiscences through the months of travels to exotic places. Finally he would describe the results obtained by the many parties.

In the first article, which was published on 21 May 1874, the correspondent gave some background on the anticipated expeditions. He stated the reasons for the interest in the transits of Venus and described the initial activity of the Government of the United States in providing funding and creating the Commission which would oversee the activities of the various parties. The equipment and methodology to be used also was described. The reader learned that the S.S. *Swatara* (Figure 8) was designated to transport all of the equipment and personnel

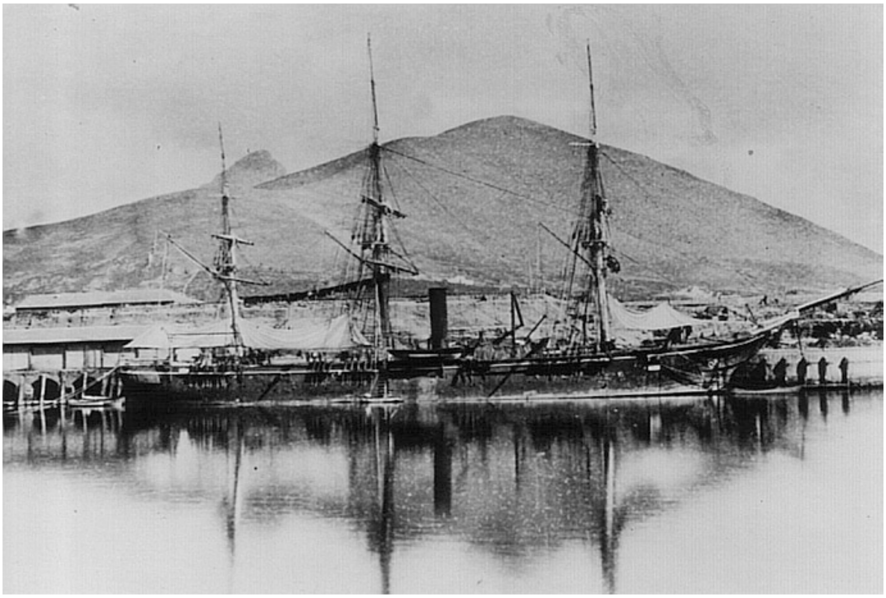

Fig. 8 The S.S. *Swatara* anchored in Bluff Harbour, New Zealand, during the American 1874 transit of Venus campaign (courtesy: Hocken Library, Dunedin, New Zealand).

of the southern expeditions, and would leave from New York on 1 June. Speaking of one of the southern sites, on one of the Chatham Islands to the east of New Zealand, he remarks: "This island is either uninhabited or inhabited by cannibals; it is not definitely known which is the fact." Mention also was made of the northern parties, which would leave for Yokohama on a later date (*New York Times*, 21 May 1874, 3).

On 19 September 1874, the correspondent reported on the progress of the *Swatara.* The parties had by then reached Bahia in Brazil. This article did not deal with the transit. It was rather a description of local flora and fauna, and the native culture, in itself of great interest to the general public (*New York Times*, 19 September 1874, 3).

The front page of the 6 December 1874 issue of the newspaper featured the correspondent's latest report, dated 17 August 1874. By this time the *Swatara* had reached the Cape of Good Hope. Museums and gardens were described, and curious details were noted: "… an American cannot fail to notice that carriages passing each other always turn to the left instead of the right." There were reminiscences of astronomical accomplishments that had taken place here earlier by Abbé Lacaille and John Herschel, but "The most important scientific establishment now existing at the Cape is, without doubt, the Royal Observatory." Ostrich farming was described as an interesting local industry. The reader learned that the US astronomers met with the British party that was also heading for Kerguelen Island in the Indian Ocean. For good measure, there was also information about local social events and entertainment (*New York Times*, 6 December 1874, 1).

The correspondent's report of 10 October 1874 appeared in the 7 December issue of the *New York Times*, by which time the *Swatara* had reached its first target destination, the bleak and desolate Crozet Islands. The correspondent shared some local color as he related his conversation with a man who used to be a member of a sealing party there in years past. Ultimately bad weather conditions led to the decision to abandon the Crozet Islands as an observation site and move on to Kerguelen Island (*New York Times*, 7 December 1874, 5).

On 30 December 1874, the report of 9 November was printed in the newspaper. The first US southern transit party was installed at Malloy Point on Kerguelen Island, a rocky place with little flora and only birds, ducks and penguins for fauna (*New York Times*, 30 December 1874, 1).

Finally, on 9 February 1875 readers were treated to the correspondent's report of 17 December 1874, a full nine days after the transit. Here the author went into great detail about the activities of Professor Harkness' group at Hobart in Tasmania. After the usual description of the local geography, the correspondent described the set-up of buildings and instruments for the astronomers at the site. He described the transit itself as "… a sad disappointment." since observations were periodically interrupted by clouds and heavy rain. Nonetheless, some photos were obtained. It was noted that Captain Raymond's party at Campbell Town to the north of Hobart, which originally was to have been located on the Crozet Islands, had similar bad luck with weather, although they did obtain about 125 photographs (*New York Times*, 9 February 1875, 8). One of these is reproduced here in Figure 9.[2]

On 23 February 1875 the report of 13 January 1875 was printed, which brought the reader up-to-date on the final two southern transit parties, which were based at Queenstown in the South Island of New Zealand and at the Chatham Islands to the east of New Zealand. Queenstown was an inland village of about 780 inhabitants on the shores of Lake Whakatipu, and although difficult to reach (it involved 40 miles of travel by railroad, then 60 miles by stage coach and finally 20 miles by steamboat) it proved to be an ideal sight with excellent visibility. The party saw most of the transit and obtained more than 200 photographs. Finally, the Chatham Island party had been delivered to their site on 19 October 1874. They had cloudy weather during most of the transit and obtained only 13 photographs. There was no mention of cannibals! In this installment the correspondent related how Captain Chandler of the *Swatara* responded to a request by the German Council at Melbourne and went in search of and successfully found the German transit party located on the

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[2] None of the original photograph glass plates exposed at Campbell Town has survived, and in the course of an extensive search for photographic records relating to the Campbell Town program the photograph shown in Figure 9 was the only one that could be traced (see Orchiston and Buchanan, 2004). But even its survival was fortuitous, as it forms part of the astronomical records of Alfred Barrett Biggs, a Campbell Town school teacher with an interest in astronomy who assisted the American party during the transit program. Following the transit, Biggs went on to become Tasmania's foremost astronomer, publishing a number of research papers – mainly about his micrometric observations of comets and double stars – in the *Papers and Proceedings of the Royal Society of Tasmania* and in *Monthly Notices of the Royal Astronomical Society* (see Orchiston, 1985).

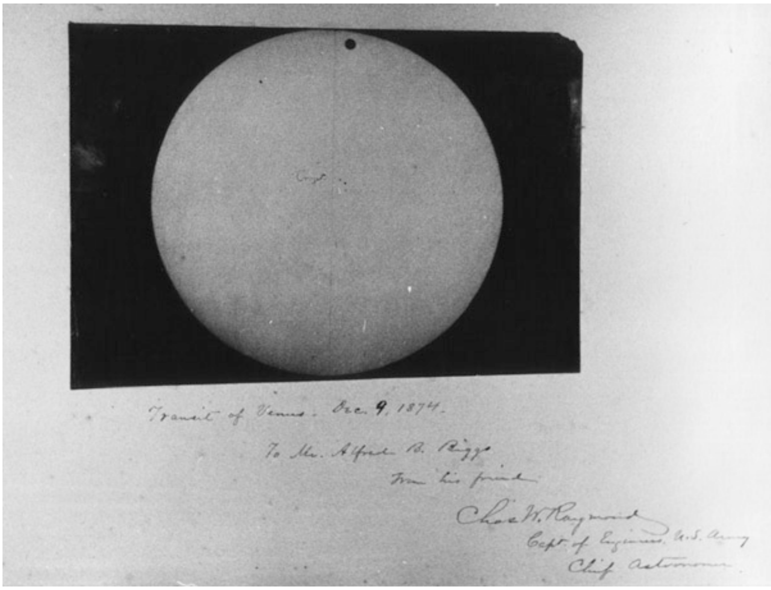

Fig. 9 Photograph of the transit of Venus taken at Campbell Town. The inscription on the card upon which the photograph was mounted reads: "Transit of Venus. Dec. 9, 1874. To Mr. Alfred B. Biggs From his friend Chas. W. Raymond Capt. of Engineers, US Army Chief Astronomer." Raymond was in charge of the Campbell Town expedition (courtesy: Queen Victoria Museum and Art Gallery, Launceston, Tasmania).

subantarctic Auckland Islands (far to the south of New Zealand), which had not been heard from in some time (*New York Times*, 23 February 1875, 2).

On 29 March 1875 the *New York Times* printed the final installment in the saga of "Our Own Correspondent" which was dated 9 February 1875. It described the final days of the expedition members at the Chatham Islands and their move to Hobart in preparation for the return to the United States (*New York Times*, 29 March 1875, 3).

Finally, it was only on 5 August 1875 that the *New York Times* published an article titled "The Astronomer's Work," which summarized the accomplishments of all of the 1874 American transit of Venus expeditions (*New York Times*, 5 August 1875, 3).

In addition to the foregoing articles the *New York Times* responded to public curiosity by also publishing frequent reports about the successes of the various American and foreign expeditions. Besides substantial articles about particular expeditions there would often be one or two-line fillers updating the reader on a particular success.

4 Discussion

As evidence of the sustained interest in astronomical topics following the success of the 1874 transit of Venus over the next few months and years the *New York Times* would feature articles discussing future astronomical events. In addition, one might read "Letters to the Editor" debating the value of the expense of such astronomical expeditions, while in the classified advertisements one might find announcements of new books on astronomy. Announcements of public lectures, frequently given by participants in these expeditions, were particularly intriguing to the interested public.

It was apparent from the number and nature of articles in the *New York Times* during the second half of the 1870s that there was a growing anticipation of the next transit of Venus which would occur in 1882. This time the event would be visible over much of the United States, so necessarily the US participation in this upcoming transit would be of a very different nature. Besides planning for their own expeditions on home soil, Americans could expect to host foreign expeditions. Public lectures delivered prior to the transit, such as ones given by the well-known British astronomer, Richard Proctor, in New York in November 1879, would be announced and summarized in the *New York Times* (14 November, 1879, 2).

5 Concluding Remarks

The 1874 transit of Venus played a key role in helping unravel one of the primary mysteries of Solar System astronomy, the true value of the astronomical unit. The USA mounted an ambitious transit program, establishing eight different transit stations in Asia, the Indian Ocean and the Australia–New Zealand region, and news of the transit was relayed to an American public already well-versed in the significance of this transit and the crucial part that their nation was playing in this important astronomical venture. One of the principal outlets used to bring this ever-changing scientific saga to the American people was the *New York Times* newspaper, which even sent its own astronomical correspondent on the S.S. *Swatara* in order to accompany the Southern Hemisphere expedition parties to Australia and New Zealand. Through the various reports by this correspondent and accounts of non-US transit expeditions published in the *New York Times*, the "astronomical literacy" of readers of this newspaper was raised, standing them in good stead for the much-anticipated 1882 transit of Venus. Weather-permitting, this magnificent spectacle would be visible across the North American continent.

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Some Highlights of the Lick Observatory Solar Eclipse Expeditions

John C. Pearson, Wayne Orchiston, and J. McKim Malville

Abstract Over the four decades from January 1889 to August 1932 15 different expeditions were sent out by the Lick Observatory with the primary mission of observing the Sun during the brief moments of a total solar eclipse. During this same interval, considerable advances were made in our understanding of the Sun, but particularly the photosphere and the corona, and a significant portion of this new knowledge came from the investigations that could only be made at the time of a total solar eclipse.

The solar corona, the chromosphere and reversing layer were the focus of the Lick Observatory's visual, photographic, and spectrographic solar investigations. Additional studies included a photographic search for intra-Mercurial planets in the vicinity of the eclipsed Sun, and verification of Einstein's General Theory of Relativity by the examination of photographic plates for evidence of the deflection of starlight caused by the gravitational field of the Sun.

A substantial investment in staff time, financial resources and effort went into the planning and execution of these expeditions, both at the local and international levels. These research ventures were truly expeditions in every sense of the word as obstacles and challenges presented themselves during the planning, staffing and implementation phases. Despite this, the Lick Observatory astronomers had a total of just 39 min of totality spread over all of the eclipses in which to ply their trade.

This paper discusses the instrumentation and the scientific highlights of the various Lick Observatory solar eclipse expeditions, and summarizes the overall scientific accomplishments that derived from the expeditions.

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1 Introduction

During the first half of the nineteenth century, knowledge of the solar corona developed at a very slow pace due to the rarity of viewable total solar eclipses. Then astronomers began using photography to generate permanent records that could be subjected to latter analysis. The first successful coronal images were obtained by Fr Angelo Secchi and Warren De la Rue in 1860 from two different locations (Clerke 1908; Proctor 1871; Ranyard 1879). While coronal imaging slowly improved as photography switched from a wet process to a more sensitive dry process, it was the Lick Observatory's first eclipse expedition, in January 1889, which set a truly new standard for producing high-resolution coronal images.

1.1 The Lick Observatory

In 1873 the American philanthropist, James Lick, decided to fund an observatory that would "… rank first in the world." (Wright 2003: 11–15). Lick made his fortune manufacturing and selling pianos in Brazil, and then brought his resources to San Francisco where he was equally successful in real estate and soon became an elite member of the San Franciscan business community. Lick Observatory was his personal monument, and was erected on Mt. Hamilton in the vicinity of San Francisco. To guarantee the Observatory's international reputation, Lick commissioned the largest equatorially-mounted refracting telescope in the world, with a 36-in. objective, but regrettably he did not live to see its completion and was entombed in its base. When the great refractor became operational in 1888 the fledging Lick Observatory was turned over to the University of California, which was governed by the UC Board of Regents (Osterbrock et al. 1988).

1.2 The Directors and the Expeditions

Edward S. Holden (Figure 1) from the United States Naval Observatory (USNO) was appointed the first Director of the Lick Observatory in 1888, and his authoritarian style of leadership would influence the outcome of the early eclipse expeditions. Holden's primary talent was his ability to socialize with and obtain funding from San Franciscan 'high society', and he was also known for his success in seeking out wealthy women. He made a point of mentioning the large numbers of staff present at the Harvard, Paris and Pulkovo Observatories and comparing them with the meager staffing levels at the Lick Observatory in order to make potential donors feel guilty (see Osterbrock et al. 1988: 90).

Holden organized the Lick Observatory's first solar eclipse expedition on 1 January 1889, just months after commissioning the 36-in. refractor. He had previous eclipse experience, having led a USNO expedition to the Rocky Mountains in July 1878 and

Fig. 1 Edward S. Holden, 1846–1914 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

organized a USNO expedition to the distant Caroline Islands in the South Pacific for the 6 May 1883 eclipse. By contrast, the Lick Observatory's first solar eclipse expedition involved a short jaunt from Mt. Hamilton, and requiring little effort. As an added incentive, many U.S. and international astronomers were expected to attend and Holden would rise to the occasion and introduce the Observatory to the astronomical community. Despite this auspicious start, Holden was urged to resign in 1897 (effective 1 January 1898), after years of contention with his staff, the UC Board of Regents and the San Francisco press.

John M. Schaeberle took over as Acting Director of the Lick Observatory in 1899. He is credited with the design and construction of the 40-foot eclipse camera, and his 'Mechanical Theory of the Corona', first proposed in 1889, attracted world-wide attention. Schaeberle served as Acting Director for just 1 year and was justifiably upset when he was passed over and James E. Keeler was appointed as the new Director. This prompted Schaeberle to abandon the field of astronomy (see Whitesell 2003: 90–92).

Keeler (Figure 2) had joined the Lick Observatory staff early in Holden's tenure, but he served as Director for just 1 year prior to his untimely death in 1900. He was the Observatory's 'house expert' on spectrographic issues and made numerous refinements to the Observatory's spectrographic instruments. He also designed the Bruce spectrograph for the 36-in. refractor. Yet through his work on the shape and nature of galaxies using the 36-in. Crossley Reflector he is credited with making the reflecting telescope (rather than the refractor) the principle research tool of astrophysicists. Osterbrock (1984) thought him an "… astute astrophysicist." Keeler's use of the spectroscope during the January 1889 eclipse showed the power of this instrument in the hands of a capable observer and scientist, but Holden used his directorial power

Fig. 2 James E. Keeler, 1857–1900 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 3 William W. Campbell, 1862–1938 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

to insist on an all-photographic program during the eclipses of December 1889, 1893, 1896 and 1898, and the potential of the spectrograph was ignored. Consequently, Keeler was not directly involved in any of these eclipse expeditions.

William W. Campbell (Figure 3) then served nearly three decades as Director, from 1901 until 1930. Under his directorship the Lick Observatory became a 'factory' for radial velocity measurements (Osterbrock et al. 1988). He designed the Mills Telescope and spectrograph, which was shipped to Chile in 1902 and used to survey stars in the southern sky. Campbell made pioneering studies of the spectra of young hot stars, and he delineated the Sun's motion in relation to other stars in the Galaxy and established that many apparently single stars were in fact spectroscopic binaries. In 1923 he was appointed President of the University of California. During his time at the Lick Observatory Campbell was an active participant in the nation's astronomical organizations, serving as President of both the Astronomical Society of the Pacific and the American Astronomical Association. He was also a President of the International Astronomical Union for one 3-year term. Campbell was aggressive in his leadership of and participation in eclipse expeditions, and when he was awarded the Bruce Gold Medal of the American Astronomical Association, the President of this body was moved to state:

> It is, in fact, impossible to overrate the importance of the influence which our Medalist has exercised on the eclipse expeditions … and probably only those who have taken part in such expeditions can fully appreciate his powers of organization, and his skill and resourcefulness in devising special lines of research and instrumental means for rendering such researches practicable. (Crawford 1915: 156).

Campbell was the first Lick Observatory Director to launch a tradition of mixing world touring with eclipse expedition duties, and while this demanded that he spend considerable time away from the Observatory he was able to network with astronomers worldwide and effectively promote the Observatory and its research programs.

Robert G. Aitken became Associate Director of the Lick Observatory in 1923 under Campbell and then served as Director from 1930 to 1935. Aitken was considered to be an old-style observational astronomer rather than an astrophysicist: he conducted visual measurements of double stars down to the ninth magnitude, and in 1932 published the *New General Catalogue of Double Stars within 120 degrees of the North Pole*. Aitken actively supported the eclipse expeditions up to 1933, but his last published report of the work of the Observatory for the year 1934 to 1935 contains no mention of solar eclipse expeditions.

2 The Lick Observatory Eclipse Instruments

While staff from the Observatory used off-the-shelf instruments for some observations, most of the research was accomplished with purpose-built equipment. These instruments had to be as precise and almost as sturdy as their fixed observatory counterparts. This required design innovations specific to the observational sites (although modifications were often necessary *in situ* to accommodate local circumstances). The instruments had to survive long sea and land voyages, and rough handling by shipping and railway crews, not to mention indigenous people enlisted to help at some eclipse destinations. Then at eclipse time, the instruments had to function perfectly for intervals ranging from seconds to nearly 7 min. But often 'Mother Nature' intervened by adding clouds and wind, which at times made observing difficult, if not impossible.

2.1 The 40-ft Schaeberle Camera

One Lick Observatory custom-built instrument, the 40-ft Schaeberle Camera, stands out for producing very high quality large-scale photographic images of the solar

Fig. 4 John M. Schaeberle, 1853–1924 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

corona at totality (see Eddy 1971; Pearson and Orchiston 2008). This Camera became the ‘work horse’ of the Observatory’s eclipse expeditions, and its basic design was copied by other institutions around the world. Schaeberle (Figure 4) decided on a direct-imaging design over the horizontal type heliograph then in favor with other solar researchers. Schaeberle (1895) reasoned that the additional optical surfaces of a traditional horizontal heliograph were certain to degrade the quality of the image due to heat expansion issues induced by the additional optical surfaces. Furthermore, his design would eliminate the image-rotation issues and driving clock errors that were more pronounced with the horizontal heliograph.

Moreover, the 40-ft Schaeberle Camera components could be rigidly fixed in place and supported independently of one another. This arrangement would ensure that any vibrations from the tube section would not transmit to the lens or the plate holder. Schaeberle (ibid.) realized that “Any advantage due to the large scale given by a telescope 40 feet long will, in a great measure, be lost unless great stability of the image on the photographic plate is secured.” His reasoning would stand the test of time. Campbell (1908b, e) subsequently published his thoughts on the advantages of Schaeberle’s design: a lens, with its tube assembly mounted well above the ground, was easily ventilated and was subjected to far less image-degrading ground heat-radiation. By 1930, Ross W. Marriott had concluded that the direct camera was highly superior to the horizontal camera (Young 1969).

The initial form of the 40-ft Schaeberle Camera was tested on Mt. Hamilton in the autumn of 1892 (see Figure 5). The Camera’s length was kept near the sloping ground with its lens supported on an inclined plank-tripod arrangement. The photographic moving plate carriage system was mounted on its own pier. The Camera’s tube was made of canvas, which was painted black. The tube canvas was secured to the supporting wood framework with cord via iron rings. The tube frame support consisted of wooden posts that were placed vertically in pairs at intervals up the sloping hillside. The rigid wooden tube frame was secured to the posts. A canvas tent covered the plate area. The Camera survived several stormy days and produced

Fig. 5 The 40-ft Schaeberle Camera undergoing testing on Mt. Hamilton in 1892 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

good test exposures of star fields and of the Moon. The ability to change plates quickly was tested and found satisfactory (Schaeberle 1895). The Camera was provided with a unique moving plate holder that would follow the diurnal motion of the Sun for time exposures of nearly 1 min. Maximum plate size was 18 × 22 in.

By the time of the 1896 and 1898 eclipses Schaeberle and Campbell had revised and refined the components, alignment, and focusing procedures of the Camera. The wooden tube frame was replaced by a 5-in. iron pipe frame. A new tube was made of an exterior white duck cloth cover and lined on the inside with two thicknesses of black muskin. Campbell (1899) commented that "Black outside absorbs the heat which is extremely objectionable." This cover was fitted with iron rings along its length in order to secure it to the pipe frame. The hill support system was changed to a twin tower arrangement in 1898. As late as 1902 at least one prominent overseas astronomer, Frank Hagar Bigelow, was sure that this instrument would not produce quality images, and Campbell (1902) felt obliged to write to him and point out "… a few errors that I think you will be glad to have corrected."

2.2 The ‘Portrait Camera’ Lenses and Other Cameras

Numerous wide-field and medium-field cameras were applied to coronal photography. Some were standard cameras used for everyday photography while others required more rigid wooden box bodies for their stock lenses. Because timed exposures were needed to reveal the fainter parts of the corona during eclipses these cameras were usually attached to clock-driven mountings. Two lenses stand out, however, and are worth mentioning. Both of these featured large 5 to 6-in. aperture relatively short focal-length ‘portrait’ lenses that were used in the days of wet-process photography from the late 1840s through almost to 1870.

The ‘Dallmeyer lens’, patented in 1866, is a 6-in. f/5.5 Portrait Group D lens of 30 to 33-in. focus with a plate scale of 8 × 10-in. and field coverage of 25 × 21-in. According to its manufacturer, “Dallmeyer Patent Portrait Lenses were constructed on a different principle from the old Petzval type … and excel them in definition, freedom from distortion, and flare and in equality of illumination …” (Dallmeyer 1914). They had a unique feature which made them stand out for eclipse photography: the rear lens element could be turned, allowing fine control of the sharpness of focus throughout the field of view. While intended to control ‘softness’ in portraits, this feature was found to control the spherical aberration and central focus of the lens. The lens performed equally as well at full aperture but was often stopped down to 4-in. aperture. In 1893 the Lick Observatory borrowed a Dallmeyer lens from a San Francisco amateur astronomer, and they used it continuously from the eclipse of that year through to and including the 1908 eclipse expedition. The Observatory also borrowed an identical lens from the USNO and used this during the December 1889 eclipse (Holden 1890h).

The other portrait lens of special interest was the ‘Willard lens’, which was supplied by Willard & Co. although the actual maker was Charles F. Usner in New York City. According to Barnard (1913: 12) “The so-called ‘Willard’ lens is of more than passing interest and a brief account of what is known of it may be of historical value.” The lens was of 6-in. (5.85) aperture with a 31-in. focus. It was of the Petzval configuration consisting of two sets of doublet lenses. Holden purchased a Willard lens second-hand from portrait photographer William Shew after seeing the fine eclipse photos obtained by a Mr Ireland during the 1 January 1889 eclipse. Holden had the lens refigured by John A. Brashear for even better full field focus. According to Holden (1889a),

> We have been trying the photographic lens bought from the eclipse fund and it turns out to be a veritable bonanza … The Willard lens excels over the big refractor of 36-in. as photographic efficiency depends on the ratio of aperture to focus … this gives an advantage to the Willard lens over the refractor of 8 to 1.

It would see some use during solar eclipse expeditions (Figure 6), but Barnard (1913) also used it to make the most important photographs of the Milky Way obtained up to that point (see Holden 1890a, h). Brashear made a clock-driven equatorial mounting for the lens with monies gift by C.F. Crocker and from this time on the camera was known as the ‘Crocker Telescope’ (Holden 1890f). The mounting was fitted with camera supports for the Willard and Dallmeyer lenses, which were mounted side by side (Holden 1890h).

Fig. 6 The Willard Camera (*left*) and a Ross Camera (*right*), at the 1930 eclipse station (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Another example of an off-the-shelf coronal imager was the medium-field 'Floyd Telescope' which had an Alvan Clark and Sons objective of 5-in. aperture and 68-in. focal length. It was named after an influential gentlemen who was a friend of James Lick and whose talents were important in the building of the Lick Observatory. The Floyd Telescope was considered splendid for recording the general features of the inner and outer corona. This instrument was first used at the 1898 eclipse in India (Campbell 1898b: 130). At the 1908 Flint Island eclipse it was mounted horizontally, receiving its image via a clock-driven 12-in. coelostat mirror. It was used continuously through to the 1930 eclipse (Figure 7).

2.3 Campbell's Moving-Plate Spectrographs and Other Spectrographs

Another set of unique instruments was Campbell's moving plate spectrographs (e.g. see Figure 8). These instruments were designed by Campbell, and boasted two new features:

1. A slit placed so that only the central portion of the uneclipsed Sun's edge at second or third contact could reach the photographic plate.
2. The plate was moved at a uniform rate, with a gas-driven piston in the direction of the spectral lines for an exposure of about 24 s. This permitted the continuous recording of the flash spectrum on one spectrogram.

Fig. 7 The Floyd Camera on an equatorial mounting at the 1923 eclipse station (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 8 Campbell's moving-plate spectrographs at the 1930 eclipse station (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Although this method had its doubters, such as Anton Pannekoek and Marcel Minnaert, Campbell stood by his results as advantageous over the fragmentary and discontinuous record of the spectrum produced by fixed plate spectrographs that required several separate exposures (Menzel 1931). Accumulated spectrograms from several eclipse expeditions of the changing flash spectrum, chromospheric spectrum and coronal spectrum were to play an important role in Donald H. Menzel's

Fig. 9 One of Menzel's jumping-film spectrographs at the 1932 eclipse station (courtesy: Mary Lea Shane Archives of the Lick Observatory).

atomic analysis of the surface and atmosphere of the Sun in the second quarter of the nineteenth century.

There were numerous other spectrographs in use during the Lick Observatory eclipse expeditions, and they are briefly mentioned within each expedition's discussion. Prism trains and slits were often borrowed from other observatories or were the personal property of researchers. These instruments offered a broad range of dispersion and spectral sensitivity, and consisted of either prisms or gratings and slit or slitless configurations. Menzel introduced two jumping-film spectrographs during the 1932 eclipse, when motion picture film was advanced one frame at a time over a timed interval by the turn of a crank (Figure 9). Exposures of about 1 s were controlled by a pendulum-style electromagnetic shutter. With this method heights in the chromosphere could be determined by either measuring the extent of the crescents or determining on which images the lines fade out.

2.4 The Intra-Mercurial/Einstein Cameras

The intra-Mercurial cameras evolved over the four decades of the Lick Observatory expeditions. The Observatory began its Vulcan search program during the 1901 eclipse using four cameras with Clark 3-in. aperture 11.25-foot focal length objectives borrowed from the Harvard College Observatory. Two sets of four lenses with the same specifications were first used at the 1908 eclipse and again were set up in

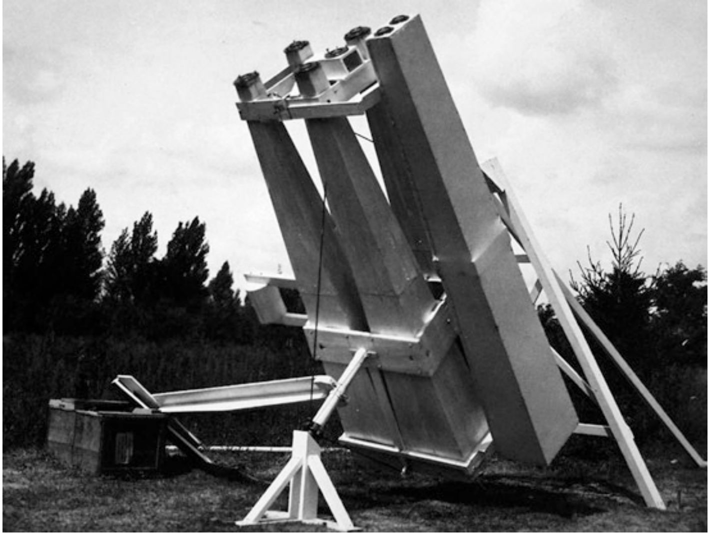


Fig. 10 The intra-Mercurial and Einstein four camera array. On the outside to the right is the pair of photometer cameras (courtesy: Mary Lea Shane Archives of the Lick Observatory).

1914 (Figure 10). For the 1918 eclipse, two Brashear 4-in. aperture 15-foot focal length lenses were borrowed from the Chabot Observatory for the Einstein project and a Vulcan search. By 1922 the Observatory had acquired four fine lenses for the Einstein and Vulcan projects. Two of these were Hastings-Brashear lenses of 5-in. aperture, 15 foot focal length, and the other two were Ross-Brashear lenses of 4-in. aperture, 5-foot focal length (Figures 11 and 12). The limiting magnitude of these lenses was better than 10th magnitude. By 1932 the Ross-Brashear lenses had replacing the 40-ft Schaeberle Camera.

2.5 The Polarigraphs and Photometers

Polarigraphs were not new instruments, having been present at solar eclipse expeditions since at least the 1870s. These instruments were meant to map the solid particle density of the corona and operated on the principle that scattered sunlight from solid particles would appear polarized. Campbell initiated the Lick Observatory's coronal polarization studies during the 1901 eclipse, using a polarigraphic camera of 1⅛-in. aperture, 20¾-in. focal length with a front-mounted rotatable double prism. By the 1905 eclipse, to solve the aberration problems of the double prism Campbell had assembled four polarigraphs (see Figure 13). One would be the regular double-prism spectrograph; 2 had glass mirror reflectors mounted at right angles to each other in front of the objectives, and the fourth was a single unpolarized camera for standardization purposes. The four polarigraphic camera package would see use through the 1914 eclipse expeditions.

Fig. 11 The 15-ft twin Einstein cameras in 1922 that would serve as the coronal cameras replacing the 40-ft Schaeberle Camera by 1932 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 12 Inspecting one of the Brashear Einstein camera objectives at the 1922 eclipse station (courtesy: Mary Lea Shane Archives of the Lick Observatory of the Lick Observatory).

For the 1905 eclipse, an extra-focal photometer consisting of a lensless camera using plates with standardized light squares was pressed into service. By 1914 there were two of these instruments, and there is mention of their continued use through the eclipse of 1923.

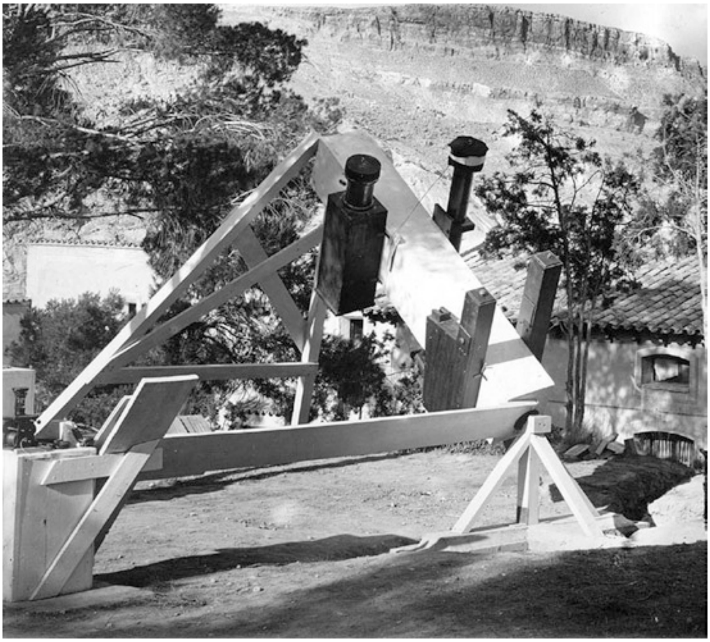


Fig. 13 The four polarigraphic cameras used at Alhama, Spain, in 1905 Spain. The *top two* are plane-mirror cameras and *bottom two* are double Nicol prism cameras (courtesy: Mary Lea Shane Archives of the Lick Observatory).

3 The Nature of Coronal Research During the Second Half of the Nineteenth Century

A robust scientific program relating to total solar eclipses resulted from these Lick Observatory expeditions, with the corona the primary focus of the photographic and spectrographic investigations. During the late nineteenth century the true nature of the corona and its relationship to the Sun was still in doubt, as some astronomers believed that the corona was a feature of the Moon rather than the Sun. The Lick Observatory initially promoted the idea that the corona was composed of solid particles and was the result of material ejected forcibly from the chromosphere into the upper solar atmosphere. Then astronomers began to assign a gaseous content to the inner corona and to the outer corona. They also examined the possible relationships that might exist between photospheric flares, sunspots and faculae, chromospheric disturbances such as prominences and the form of the corona. Following is an overview of the science associated with the various Lick Observatory expeditions, along with two notable non-solar research programs that were pursued by the Observatory's astronomers during total solar eclipses. Further details are presented in Sect. 4, within the accounts of the individual eclipse expeditions.

3.1 Coronal Motion

During observations of the 29 March 1652 total solar eclipse Dr Wyberg reported an apparent Moon-to-corona rotary shift after second contact, but a far more vivid description of rotary coronal motion was given by Don Antonio d'Ulloa after second contact during the eclipse of 1778. He mentioned that the corona had a rapid rotor motion like a revolving firework (Proctor 1876: 328–334). During the 1842 total solar eclipse, Francis Baily described the corona as being like a flickering gas flame, while Otto Struve mentioned that the corona was the subject of violent agitation. A Mr Royal's view of unchanging light within the corona during the 1851 eclipse conflicted with others who reported rapid flickering and rotary motion. During the 1860 eclipse Carl Christian Bruhns described the corona as intense twinkling light, while Robert Grant saw the corona as perfectly motionless (Proctor 1876; Ranyard 1879). Richard Proctor (ibid.) claimed the observations of rapid motion were due to optical illusions but conceded that with so many differing observations it would be far easier to accept internal coronal motion as being real. Meanwhile, Professor Charles A. Young (1910) wrote off rapid movement observations as mere imagination.

It was really only with the advent of photography that proof of the unchanging nature of the corona was forthcoming, thanks to photographs taken by Angelo Secchi and Warren De la Rue at different stations during the 1860 total solar eclipse. Young (ibid.) also used a number of eclipse plates obtained from different eclipses and from different eclipse stations as proof of lack of rapid motion within the corona, but he did suggest that longer-term changes over intervals of days or months and very small-scale changes might occur (Proctor 1876). Simon Newcomb specifically looked for evidence of coronal rotation during the 1868 eclipse, but results were negative (Proctor 1871). Coronal motion studies would extend well into the Lick Observatory's eclipse expedition series.

3.2 Coronal Brightness

The first scientific attempt to measure coronal brightness was made during the 1842 eclipse by a short-sighted Mr Belli who compared the light of the fuzzy coronal image to that of a candle placed at a distance of 1.8 m (Young 1895). Crude estimates of coronal brightness were made by Struve who found the innermost part of the corona to be exceptionally bright, and George Biddell Airy who equated coronal brightness with that of a full Moon (Proctor 1871). During the 1860 eclipse, Secchi estimated the coronal light to be equal to that of an electric lamp, and Bruhns gave a more general description of coronal light as highly-intense twinkling light. During the total eclipse of 1867, Louis Grosch compared the brilliance of the corona to that of the bluish light produced by electro-magnetism (ibid.), while A. Brothers estimated, from his photograph, that the coronal brightness was of the order of the full Moon (Ranyard 1879). William Harkness reported an 1870–1871:1878 ratio of 7:1, while Norman Lockyer gave a higher ratio, of 10:1 (Mitchell 1969). Coronal brilliance during the 1882 eclipse was reported as well exceeding that of the 1878 corona but with no comparison ratios to previous eclipses being made (Clerke 1908). The intrinsic photographic brightness of the 1886 corona was found by Harvard's William H. Pickering to be 1/54 that of the full Moon when he used a standard lamp to expose squares of known brightness and then compared them with the recorded coronal light (ibid.).

The Lick Observatory established brightness investigations following Pickering's method of exposing standard squares on the plates with a standard lamp. This practice would continue through the entire four decades of the Observatory's expeditions, with more stable standard lamps and standardization procedures being utilized as time progressed.

3.3 Coronal Particle Content and the Polarization of Coronal Light

The non-photographic instrument, the polariscope, was used at the 1858 eclipse by French astronomer Emmanuel Liais who found coronal light to be polarized. By the 1883 eclipse, Jules Janssen and Professor C.S. Hastings had observed what they believed were large quantities of solid particles in the corona. Various nineteenth century astronomers, including Giovanni Schiaparelli, Proctor, Young, Lockyer and Holden, worked with the idea that these solid coronal particles were meteoric in nature (Lockyer 1887; Proctor 1876; Young 1895). Campbell incorporated the study of coronal polarization within the Lick Observatory's program beginning with the 1901 total eclipse.

3.4 A Study of the Reversing Layer

The reversing layer exists between the photosphere and chromosphere. It is best observed spectroscopically at the moment of second and third contacts when a brilliant bright-line spectrum, the so-called 'flash spectrum', appears for only a brief moment. This appearance of the flash spectrum is present for too short a time for meaningful visual observations to be made. Astronomers would find a large temperature differential to occur within this layer.

3.5 The Chromosphere, and the Elemental Composition of the Corona

The potential to explain the chemical composition of the Sun through spectroscopic observations emerged at about the time of the 1860 total solar eclipse thanks to the pioneering efforts of Gustav R. Kirchhoff. Working with Robert W. Bunsen, Kirchhoff discovered that known spectral lines from heated elements in the laboratory matched those found in the solar spectrum, and the spectroscope became a standard tool of eclipse and coronal research beginning with the eclipse of 1868 when moments before second contact and after third contact Janssen observed a strong yellow line. Leon Golub and Jay Pasachoff (1997) believe this to be the most significant discovery ever to come from a total eclipse. Janssen erroneously believed the line was the Fraunhofer sodium D line pair but noticed the wavelength was not correct so he labelled it the D_3 line and called it helium, meaning *helious*, the Greek name for the Sun. Helium was not identified in a laboratory until 1895. Major-General James F. Tennant observed a faint continuous spectrum from the corona devoid of any bright or dark lines, and later predicted that if he had narrowed the slit of the spectroscope he might have seen any existing lines (Proctor 1871). In addition to the continuous spectrum, John Herschel found three emission lines in the red, orange and blue that emanated from a long solar prominence (Abbot 1929; Clerke 1908; Guillemin 1870).

During the 1871 total eclipse, Lockyer, at Young's suggestion, applied a slitless spectrograph and made the first attempt to determine the height of gases in the solar corona. He found that hydrogen extended uniformly out from the Sun to the height of 200,000 miles. Professor Lorenzo Respighi, observing from Poodacottah also with a slitless spectroscope, noted three spectra from coronal material to a height of 200,000 miles. Two of the spectra corresponded to hydrogen in a hot gaseous state. Janssen (1872) used his spectroscopic observations during the 1871 eclipse to prove the existence of matter in the vicinity of the Sun which displayed the physical and chemical properties of emission, absorption and polarization. This material was in addition to any cosmic matter of which meteors and comets may have been a part. He predicted a corona that was a rarified atmosphere of mostly hydrogen which extended well beyond the chromosphere and prominences. He suggested that this rarified coronal atmosphere was similar to that of comets, and assumed that coronal material derived from prominences.

During the 1876 eclipse Young discovered that the bright D_3 line was double, and Kirchhoff and Anders Jonas Angstrom assigned the brighter line to iron. It was considered very unlikely that the vapor of iron could exist in the corona and problematic that it exceeded hydrogen in abundance (Young 1895). For the 1882 eclipse, Lockyer used a prismatic spectral camera to record at least two emission lines relating to the corona. Arthur Schuster used his slit spectrograph to record some 33 lines, and found that the H and K lines appeared evenly spaced across the surface of the Moon during totality. Pietro Tacchini observed new lines in the red and Louis Thollon found new lines in the violet. As many of the emission lines were observed only during totality and not shortly after second contact and not before the end of third contact, they were considered as originating from the corona. Some astronomers suspected that these lines were emitted by the chromosphere (e.g. see Clerke 1908; Meadows 1970; Mitchell 1969). The Fraunhofer spectral lines were photographed in the corona by Janssen during the 1883 eclipse and were used in the study of Lockyer's (1887) 'Dissociation Theory'. The Lick Observatory astronomers began their investigation of the elemental composition of the solar corona during the 1898 eclipse.

3.6 The Mysterious Green Line

It was during the total solar eclipse of 1869 that Harkness and Young found the single most promising clue to the constitution of the corona to that date. Both men independently observed a green emission line at 1474 K during totality. This line came to be identified as an unknown element and was labeled ‘coronium’. Young confused the line with a known chromospheric line and assumed that coronium was lighter than hydrogen. Young and Professor Eastman found the green 1474 K line to be present entirely around the Sun’s limb to a distance of 340,000 miles (Clerke 1908; Mitchell 1969). The green line was faintly observed at the 1871 eclipse. Importantly, Tennant and Herschel observed that this line was as conspicuous in a coronal rift as in the adjacent streamers. It was surmised that the visible structure within the corona was independent of the gaseous content of the corona (Clerke 1908; Mitchell 1923; Proctor 1876). According to Golub and Pasachoff (1997: 37–38), the existence and identification of the coronal 1474 K line would dominate solar astrophysics for the next 50 years (see Proctor 1871; Young 1895).

3.7 The Temperature of the Corona

Evidence that the corona is extremely hot was overlooked when Lockyer made his spectroscopic sightings of coronal emission lines out to nearly one solar diameter during the 1869 eclipse. The discovery of incandescent gas within the corona was an indication of highly-heated coronal material in a gaseous state. Thomas Edison used his tasimeter to measure for the first time the presence of a heated corona (Clerke 1908). According to Golub and Pasachoff (1997), there would not be a further understanding of coronal temperatures until nearly 60 years later with the invention of the coronagraph by Bernard Lyot in 1930. The only direct coronal temperature recordings made by a bolometer during a Lick Observatory solar eclipse expedition was when C.A. Abbot attended the 1908 eclipse as a guest of the Observatory.

3.8 The Search for Vulcan

In 1859 Urbain Leverrier predicted the existence of a possible planet between the Sun and the orbit of Mercury on the basis of perturbations he detected in the orbits of Mercury and Venus. This missing object was assigned the name Vulcan and during the second half of the nineteenth century it was the focus of numerous international search programs (see Baum and Sheehan 1997). Holden first searched for Vulcan during the 1883 solar eclipse and later, in 1889, he would conclude that the Lick Observatory eclipse cameras were incapable of recording such a dim object, which was probably fainter than magnitude 5.5. The Vulcan search ended in 1922, by which time eclipse plates had failed to reveal any unknown bodies. It was by then assumed that any object large enough to be responsible for the perturbations would have been revealed.

3.9 *Verification of Einstein's General Theory of Relativity*

If Albert Einstein's theory was correct, a distant star's light would be deflected by the Sun's gravitational field, and a simple empirical test involved measuring the positions of stellar images recorded near the Sun during totality and seeing if these were displaced from their true positions. This test required a rich field of stars in the vicinity of the Sun on eclipse day, so only a few total solar eclipses would qualify. In 1911 Leo Courvoisier and Erwin Finlay Freundlich from Berlin University proposed such a test and they approached C.D. Perrine wanting to examine plates obtained during previous Lick Observatory eclipse expeditions. Perrine had to advise them that these plates were unsuitable for the task at hand. The following year, Lick staff joined another eclipse expedition and took Freundlich's cameras with them, but they were clouded out. When it came to the 1914 eclipse, the Lick Observatory loaned Freundlich some cameras but the wooden mountings proved unstable. Meanwhile, the Lick's own expedition to Brovary, Russia, was clouded out. The Lick Observatory astronomers had planned a 1919 expedition but they were not allowed access to the desired eclipse site by the Brazilian government (Perrine 1923). Instead, it was Arthur Eddington's British party which would receive the credit for the first definitive Einstein test, in 1919.

4 The Lick Observatory Solar Eclipse Expeditions

Between 1889 and 1932 15 different field expeditions were sent out by the Lick Observatory to make scientific observations of the Sun during a total solar eclipse (see Table 1, and Osterbrock 1980). A small number of these expeditions involved multiple field stations. In Table 1 the site coordinates and altitude are listed for each eclipse station, along with the time difference between the two internal contacts, while the paths of totality and the geographical locations of the observing stations are plotted in Figure 14.

Over this four-decade period the Lick astronomers had just 39 all-too-brief minutes of totality to apply their trade. Thanks to clouds, no observations were possible at the 1896 station, one of three 1905 stations, the 1914 station and the 1923 station. A portion of the precious 39 min was also wasted because of instrument failure, operator error, mis-timing of second and third contacts and variable seeing conditions during totality.

The impact of weather and other unpredictable events on these expeditions becomes apparent upon reading the summaries of the expeditions presented in this paper. Yet, at times bad conditions changed to good at the moment of totality, rewarding the persistence of the Lick staff and their colleagues. A substantial investment in staff time, financial resources and effort went into all stages of planning and mounting these expeditions.

Beginning with the second total solar eclipse in 1889, Charles F. Crocker, a UC Regent and "… liberal friend of the Observatory …" began what would become a tradition by fully funding this small-scale expedition (Holden 1889e). Members of

Table 1 Lick observatory solar eclipse expeditions, 1889–1932

Date Year/ Month/Day	Eclipse site location	Site coordinates (longitude/ latitude)	Eclipse site elevation (ft)	Time difference contact II – contact III
1889/01/01	Bartlett Springs, California, USA	08h 00m 11s 39° 00m 17s	2,040	02m
1889/12/22	Cayenne, French Guiana	52h 20m 07s W. +04° 56m 38s	100+	01m 58s
1893/04/17	Mina Bronces, Chile	+4h 41m 22.5s −28° 26m 03s	6,600	02m 51s
1896/08/09	Akashi, Japan			Clouds
1898/01/22	Jeur, India	75h 09.5m E. +18° 12.1m	1,700	01m 59.5s
1900/05/28	Thomaston, Georgia, USA	05h 37m 18.8s W +32° 53.7m		01m 12.7s
1901/05/17	Padang, Sumatra, Dutch East Indies	06h 41m 20s E. 00° 56m S.		06m 09s
1905/08/30	Cartwright, Labrador, Canada	03h 47m 59s W. 53° 42m 30s N.		02m 30s
1905/08/30	Alhama, Spain	07h 35.5m W. +41° 17m 40s	2,200	03m 39s
1905/08/30	Elephantine Isle, Aswan, Egypt			Clouds
1908/01/03	Flint Island, Pacific Ocean	10h 07m 13s W. 11° 25m 27s S.	16	03m 52s
1914/08/21	Brovary, Russia	02h 03m 5.5s E. +50° 30m 24s		Clouds
1918/06/08	Goldendale, Washington, USA	08h 03m 21.5s +45° 48.9m		01m 57.4s
1922/09/21	Wallal, Western Australia, Australia	08h 02m 43.7s E. 19° 46m 00s S.	~50	05m 15.5s
1923/09/10	Ensenada, Baja California, Mexico	116° 31m +31° 46m		Clouds
1930/04/28	Camptonville, California, USA	39° 29.9m 121° 02.0m	3,100	00m 1.5s
1932/08/31	Fryeberg, Maine, USA			01m 41.6s

the Crocker and Hearst families would then fund all future Lick Observatory solar eclipse expeditions.

As the Observatory was continuously trying to survive on a meager budget it was not uncommon for just one member of staff to be sent into the field on paid leave, and this person was then expected to assemble a ‘volunteer army’ to help establish the eclipse station, set up the instruments and man them on eclipse day. The most desirable volunteers were academics and military officers (who were used to obeying orders without question). A full list of the participants in the various Lick Observatory solar eclipse expeditions is given in Table 2.

Fig. 14 Map showing the centre paths of total solar eclipses, 1889–1923, and the locations of the Lick Observatory observing stations (the eclipse paths are courtesy of Tony Misch).

Table 2 Members of the different Lick Observatory solar eclipse expeditions

Date: year/ month/day	Eclipse site location	Personnel (Lick Staff, Donors, Guest Researchers, Volunteers, Dignitaries)
1889/01/01	Bartlett Springs, California, USA	Lick Staff: E.E. Barnard, J.E. Keeler, C.B. Hill and A.O. Leuschner (graduate student). Volunteers: Messrs F.B. Staples (Oregon), Geo. W. Yount, Fred. Klays and P. McGee, H.A. McCraney (Editor of the *Lakeport Avalanche*) and Mrs Hill.
1889/12/22	Cayenne, French Guiana	Lick Staff: S.W. Burnham, J.M. Schaeberle and A.O. Leuschner. Volunteers and Dignitaries: L. Wacogne (American Consul), Admiral Mouchez, and Messrs Burke, L'hote, Reache and C.H. Rockwell (New York).
1893/04/17	Mina Bronces, Chile	Lick Staff: J.M. Schaeberle. Volunteers and Dignitaries: John King (British Consul in Carrizal Bajo), Hon. J.J. Aubertin (London), Messrs Walter F. Gale (amateur astronomer, Sydney, Australia), A. Hole (London), R.A. Walker (Valparaiso), Mr Woolfe (*New York Herald* correspondent in Valparaiso), Captain Bray and Messrs Curmey and Tirepegui from the mine at Mina Flores.
1896/08/09	Akashi, Japan	Lick Staff: J.M. Schaeberle. Volunteers, Guest Researchers: Mr Burckhalter (Director, Chabot Observatory), Professor H. Terao (Director, Imperial Observatory of Tokyo), Dr G.E. Shuey and Mr Louis C. Masten.
1898/01/22	Jeur, India	Lick Staff: W.W. Campbell. Volunteers and Dignitaries: Major S. Comfort (United States Consul in Bombay) and Mrs Comfort, Captain Henry L. Fleet, R.N. (in charge of the marine forces in Bombay Harbour), Royal Navy Lieutenants Kinehan, Mansergh and Corbett; Major Boileau (Royal Engineers), Rev. J.E. Abbott (USA), Mr Garwood, Miss Rowena Beans and Mrs Campbell.

(continued)

Table 2 (continued)

Date: year/ month/day	Eclipse site location	Personnel (Lick Staff, Donors, Guest Researchers, Volunteers, Dignitaries)
1900/05/28	Thomaston, Georgia, USA	Lick Staff: Dr W.W. Campbell and Dr C.D. Perrine. Volunteers and Guest Researchers: Dr Eugene T. Booth, Professor A.H. Buchanan (Cumberland University, Lebanon), Professor H.D. Curtis (University of the Pacific, San Jose),Professor John A. Miller (University of Indiana), Dr A.A. Nyland (Director, Utrecht Observatory, Holland), Professor W.P. Russell (Lincoln University, Illinois), Professors Rembert G. Smith and George K. Orr (R.E. Lee Institute), Dr J.H. Wilterdink (Royal Observatory, Leiden, Holland), Mr G.E. Lumsden (President, Toronto Astronomical and Physical Society), Major J.R. Atwater, Colonel John H. Lewis, and Messrs Joseph E. Hannah and Albert A Matthews.
1901/05/17	Padang, Sumartra, Dutch East Indies	Lick Staff: Dr Herber D. Curtis and Dr C.D. Perrine. Volunteers: Mr F.A. Delprat (Chief Executive, Government Railways), Lieutenants P.L. de Fortman, E. Sieburgh and W.H. Warnsinck, Messrs F. Bouman, Cleton, D'hanens, Guldenaar, Junius, J. Kempens Lagerwey, Nieuwenhuvs, van Leeuwen Boonkamp and von der Straeten, and. Mrs Fortman.
1905/08/30	Cartwright, Labrador, Canada	Lick Staff: Dr Heber D. Curtis, Volunteers and Guest Researchers: Dr W.T. Grenfell (Labrador Deep Sea Mission), Professor E.R. Marle (Methodist College, St. Johns), Professor W. Taylor Reed (formerly Princeton University), Professor Joel Stebbins (University of Illinois), W.E. Swaffield (Hudson's Bay Company), Sir William MacGregor, Commodore Sir Alfred Paget and Sub-Lieutenant Viney (Royal Navy), Captain C.H. Elgee, Lieutenant Reinold, Messrs A.C. Cleminson, E.F. Harvey, A.R. House, Henry Reeve, Mrs Curtis and Mrs Stebbins.
1905/08/30	Alhama, Spain	Lick Staff: W.W. Campbell and Dr C.D. Perrine. Volunteers and Guest Researchers: Professors S. Arrhenius and G. Kobb (Stockholm University), Professor Jose Casares (Central University, Madrid), Dr R.S. Dugan (Princeton University), Hilarion Gimeno and Antonio Rocasolano (University of Zaragoza), D.E. Ernesto Greve (National Observatory, Santiago), Professor J. Hartmann (Potsdam Astrophysical Observatory), Lieutenant Manuel Hernandez (Geodetic Survey, Madrid), Felipe Lavilla (University of Hernandez), Dr T.E. McKinney (Marietta College, Ohio), C.M. Olmsted (Bonn University student), Frederick Palmer Jr. (Haverford College), Dr V. Ströyberg (formerly Copenhagen Observatory), D. Esteban Terradas (University of Madrid), D. Arturo Cuyás (Madrid), D.E. Ibañez (Secretary of the Municipality of Alhama), D.F. Herreros (Alhama Telegraph), Sergeants E. Barabajossa and J. Blanco (Spanish Civil Guard), Mrs Campbell and Mrs Perrine.

(continued)

Table 2 (continued)

Date: year/ month/day	Eclipse site location	Personnel (Lick Staff, Donors, Guest Researchers, Volunteers, Dignitaries)
1905/08/30	Elephantine Isle, Aswan, Egypt	Lick Staff: W.J. Hussey. Volunteers and Guest Researchers: Mr Joy (Oberlin University), Professors West and Nelson (University of Chicago), Messrs Dray, Trimen and Curry (Survey Department, Cairo), Messrs Swift and Wild (Ministry of Public Instruction), Messrs Bruce and B.J. Giffen (American Mission at Luxor), Messrs George C. Brackett (New York), Godfrey (Zagazig) and Arthur Knowles (Cairo), and Mrs Hussey.
1908/01/03	Flint Island, Pacific Ocean	Lick Staff: W.W. Campbell, Dr C.D. Perrine, Dr S. Albrecht, and R.G. Aitken. Volunteers, Guest Researchers and Dignitaries: Professor Benjamin Boss (U.S. Naval Observatory, Pago Pago), Professor E.P. Lewis (University of California, Berkeley), C.J. Merfield (Sydney Observatory), Mr Mortimer, Consul Dreher and Mrs Dreher, and Mrs Campbell.
1914/08/21	Brovary, Russia	Lick Staff: W.W. Campbell and Dr. H.D. Curtis. Volunteers and Dignitaries: Messrs Iliinsky and Zenchencko (Kiev Circle of Amateur Astronomers), Messrs W. Campbell, D. Campbell, K. Campbell, C.F. Brush, Linnik, Mereli and Morgilevsky, General Nicolskov and his son, G.M. Day (American in Charge, International Y.M.C.A, Russia), Mrs Campbell and Mrs E. Thompson (her mother).
1918/06/08	Goldendale, Washington, USA	Lick Staff and Donors: W.W. Campbell, Dr H.D Curtis, Dr J.H. Moore, J.E. Hoover, Mr and Mrs William H. Crocker, and F.W. Bradley. Volunteers and Guest Researchers: Miss L. B. Allen (Wellesley College), A.H. Babcock (Southern Pacific Company), Professor S.L. Boothroyd (University of Washington), D. Campbell (Stanford University), E.A. Fath (Redfield College), Miss E. Glancy (Argentine National Observatory), Dr E.P. Lewis (University of California, Berkeley), Dr J.S. Plaskett and R. Young (Dominion Astrophysical Observatory, Canada), John A. Brashear, Dr Ambrose Swasey, Mrs Campbell, Mrs Moore and Mrs Plaskett.
1922/09/21	Wallal, Western Australia, Australia	Lick Staff: W.W. Campbell, J.H. Moore and Dr Robert Trumpler. Volunteers and Guest Researchers: Dr Adams (Government Astronomer of New Zealand), Dr Baldwin and Mr Hosking (Melbourne Observatory), Professor A.D. Ross (University of Western Australia), Lieutenant-Commander Quick, Mr Keane, Mrs Adams and Mrs Campbell.
1923/09/10	Ensenada, Baja California, Mexico	Lick Staff: W.W. Campbell, J.H. Moore, Robert Trumpler, W.H. Wright and Messrs C.A. Bergmann, F. Cox, R. Shields and D. Tachet. Volunteers: Dr E.P. Lewis and J.A. Pearce (University of California., Berkeley), H.M. Jeffers (University of Iowa), W.J. Luyten (Harvard Observatory), Z.A. Merfield (University of Melbourne), Messrs A.H. Babcock, Wallace Campbell, Hyde, R. Leib, W.F. Meyer and A. Swasey, Mrs Campbell, Mrs Grace Leib and Mrs Wright.

(continued)

Table 2 (continued)

Date: year/ month/day	Eclipse site location	Personnel (Lick Staff, Donors, Guest Researchers, Volunteers, Dignitaries)
1930/04/28	Camptonville, CA. Oak Valley, USA	Lick and University Staff: President Campbell, Vice-President Hart, Father Ramm (Regent), Dr R.G. Aitken, D.H. Menzel, J.H. Moore, F.J. Neubauer, J. Cosh, J.W. Marley and B. Olsen. Volunteers and Guest Researchers: Professor G.B. Blair (University of Nevada), Professors William F. Meyer and C.D. Shane (University of California, Berkeley), and Mrs Aitken, Mrs Campbell, Mrs Hart and Mrs Ramm.
1932/08/31	Fryeberg, Maine, USA	Lick Staff: D.H. Menzel, J.H. Moore, W.H. Wright, D.H. Menzel, J.F. Chappel, Ben Olsen and Miss L.G. Potwin. Volunteers and Guest Researchers: Professor E.A. Fath (Carleton College), Miss R. Jones (Wheaton College), Professor C.D. Shane (University of California, Berkeley), Professor E. Stephens (Washington University), Messrs Douglas Campbell, Kenneth Campbell, W. Edwards, E. Fletcher, C.E. Mulford and C. Swanston, and Mrs Kenneth Campbell.

4.1 The 1 January 1889 Expedition to Bartlett Springs, California, USA

The first total solar eclipse to be visible from mainland USA following the founding of the Lick Observatory occurred at the start of 1889, and as fortunate would have it the path of totality run through northern California (Holden 1889d). Compared to later eclipse expeditions mounted by the Observatory, this made for a relatively simple and comparatively cheap 'local' excursion, though being the first of its kind it was not without its challenges.

The planning for this first eclipse expedition was well under way when Holden (1888a) published a pamphlet titled "Suggestions for Observing the Total Eclipse of the Sun on January 1, 1889." This was distributed to interested parties and in northern California along the predicted eclipse path. Holden also published a meteorological report in *Monthly Notices of the Royal Astronomical Society* for the benefit of international visitors. He also held meetings with the Photographic Association of the Pacific Coast, chaired by Charles Burkhalter, Director of the Chabot Observatory, who had organized a group to make scientifically-useful observations. The Astronomical Society of the Pacific was founded as a direct result of these meetings (Holden 1889e).

The Lick Observatory made plans to observe the eclipse from two stations. The first station was the Observatory itself where the partial phase of the eclipse would be visible. The second station, to study totality, was established after careful consultation of meteorological reports, some of which were sent by Harvard College Observatory (Holden 1888b). Holden arranged for time signals issued from the Lick Observatory to be supplied by a telegraph network to all locations where eclipse expeditions were expected to be based.

Fig. 15 The Lick Observatory eclipse party setting up camp on the croquet court at Bartlett Springs in December 1888 in anticipation of the 1 January 1889 eclipse (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Four staff members, Keeler, Barnard, C.B. Hill, and A.O. Leuschner, were sent to the second station, with funds for the expedition approved by the Regents. Keeler saw to the preparation of the instruments and their packing for transport. Preparations included fitting the clock drive from the Observatory's 12-in. Clark refractor to a wooden polar axis especially made for the camera array, and attaching the Chabot Observatory's spectroscope to the 6.5-in. Clark refractor (Holden 1889e).

The party departed on 16 December, stopping in San Francisco for 2 days. A day's travel on the Southern Pacific railroad took them to the town of Sites in Colusa County where they transferred to a narrow gauge rail service which took them to Colusa Junction. Arriving here on 24 December, a stage coach would take them over 35 miles of muddy roads westward into the mountains.

The eclipse site was established on the croquet court of a hotel (Figure 15) at Bartlett Springs, a mineral springs resort, and the Observatory's cameras, telescopes, spectroscope, timekeeping and auxiliary equipment were set up within 2 days during fair weather. The Chabot Observatory's spectroscope was patterned after an instrument used by C.S. Hastings during the 1883 eclipse.

Although the Bartlett Springs site had the best weather projections of all the possible eclipse site locations, it rained continuously right up to the day of the eclipse, putting a damper on everyone's mood. Nonetheless, the volunteers arrived and were assigned their duties and given the necessary training, and a local resort member, W. Yount, was assigned the task of seeing to the housing and comfort of the eclipse staff (Barnard 1889; Keeler 1889).

To the immense relief of all, the morning of the eclipse was clear and last minute practice sessions were conducted to familiarize everyone with their expected duties. Time signals were received by telegraph directly from the Lick Observatory.

During totality the scientific observations were eagerly carried out by the astronomers and the volunteers. Keeler (1889) used the spectroscope to repeat the observations that Hastings had made at the Caroline Islands during the 1883 eclipse, which led to his theory of coronal diffraction. Keeler noted a continuous spectrum on both sides of the Sun at totality. He also observed the green line at 1474 K (whose identify at the time was unknown), but did not notice the changes to it reported by Hastings in 1883. He also looked for other coronal changes, but those that he did see at second and third contacts differed from those observed by Hastings. Then suddenly, near third contact, on the right limb Keeler (1889: 45) saw bright lines appear, describing them as "… brilliant and vivid in hue as the colored fires of pyrotechny." He attributed these lines to the chromosphere. When totality occurred

> The Corona was beautifully bright and distinct … with broad "fish-tail" mass of light extending some two diameters of the Moon on each side; nearly in the direction of the ecliptic … *Mercury* shone brilliantly a short distance to the southeast. (Keeler 1889: 37; his italics).

Barnard conducted all of the photographic work with the array of three cameras, making two exposures with each. His assignment was to obtain the highest possible resolution images of the corona, and to record inner coronal detail and the extent and form of the outer corona. His images would be compared with those from other eclipse stations for a study of uniformity of the corona. Two of these cameras were wide-field coronal cameras equipped with 'portrait' style studio lenses of which the 5-in. aperture Dallmeyer lens produced very fine images. The third camera was the 3-in. aperture Clark 'water reservoir' telescope fitted with a plate holder that magnified the image significantly over the other cameras. Barnard used this latter camera to obtain the fine coronal image shown in Figure 16, which he and the Lick Observatory became well-known for, yet he found totality to be an "… excessive disappointment …" (Barnard, 1889: 59).

Hill timed the first, second, third and fourth contacts, guided the 6.5-in. refractor while Keeler adjusted the spectroscope slits, and inspected the corona for changes in color or shape.

Leuschner's task was to make comparisons of the brightness of the entire corona during totality. He observed the diffused light of the corona and compared it with the light of an ordinary candle using a Brashear wheel-photometer as a calibrated comparison source. He recorded a series of readings at the beginning of totality, even though he could not accurately adjust the candle and photometer. He then made seven more readings at three different positions of the candle.

In addition to the above tasks, Mr Yount, Mrs Hill, F. Klays and P. McGee all sketched their impressions of the corona at totality. At this point in time, drawing and photography were seen as equally important when it came to obtaining permanent records of a total solar eclipse.

Prior to and following totality, none of the observers saw any of the diffraction bands that were occasionally prominent during total solar eclipses.

In the final analysis, the number of successful photographs and photometer readings were less than anticipated, perhaps because of the overwhelming impact of the eclipse and the excitement experienced by this novice group of eclipse viewers

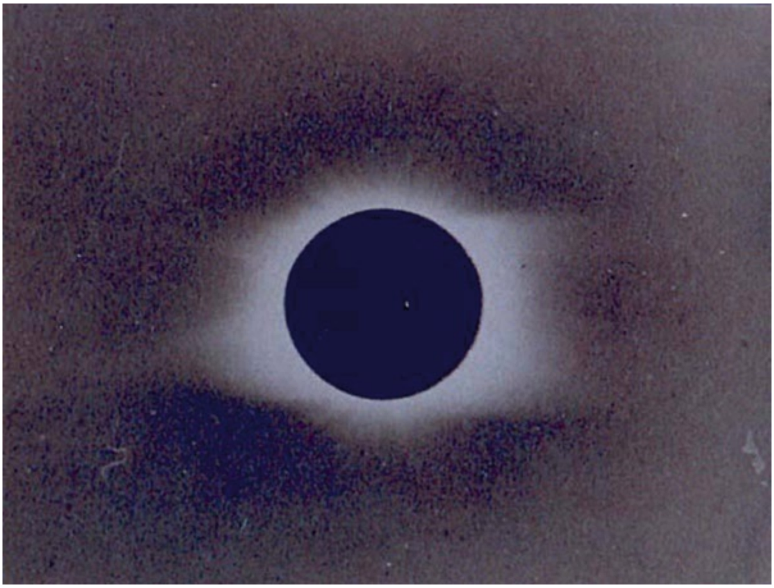


Fig. 16 A Barnard 'water reservoir' telescope image of the solar corona in January 1889 (Lick Observatory Contributions No. 1, 1889).

(Keeler 1889). On a more positive note, Holden (1889b, e) was proud to report that Barnard's best image gave more coronal detail than the best of the images brought home by the well-equipped Harvard College party under W.H. Pickering.

The expedition members departed for home on a muddy road in heavy rain. Barnard suffered the further indignity of having to ride on top of a trunk as the stage compartment was already full, and he had to get off the wagon on hills and slog through the mud on foot, unhappily complaining that "It was uphill all the way to Sites."

Upon returning to the Observatory, the plates were processed with a developer that had been adjusted to prevent overexposure and loss of coronal detail within the very bright light near the limb of the Moon. All of the negatives were of fine quality and five of the best were selected for standardization with the Carcel standard lamp for brightness analysis of the corona (Barnard 1889). A diagram of the corona was made for the purposes of mapping and indexing individual structural features and for brightness variability within the corona (Figure 17). It was produced as a composite drawing from Barnard's photographs along with those supplied by Messrs Ireland and Lowden of the Amateur Photographic Association eclipse expedition (Holden 1889c). The ordinary candle was standardized to the Carcel standard lamp in order to compare results with the Harvard Observatory's images (Holden 1889e), but there is no evidence that the comparison actually was carried out.

An interesting experiment introduced with this eclipse was an attempt by the Lick astronomers to convert the intensity of coronal light shown on the photographs into contours, as illustrated in Figure 18.

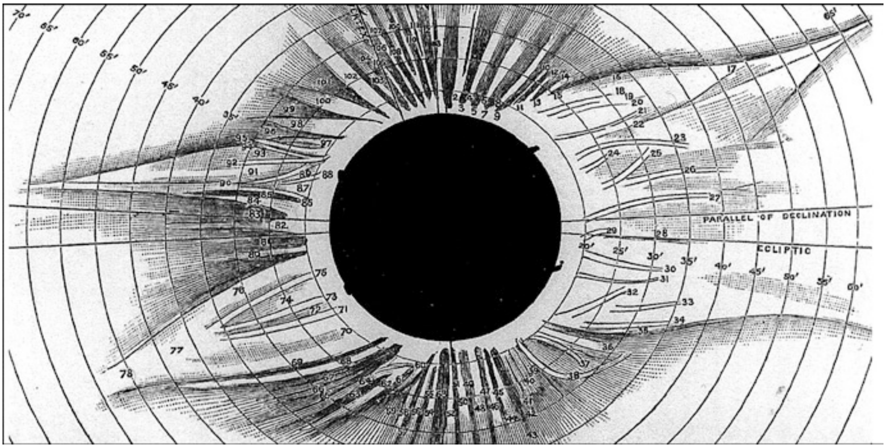


Fig. 17 Holden's composite drawing of the solar corona in January 1889 made from photographs and drawings. The drawing is indexed for reference to coronal structure and form (after Holden 1889b: 345).

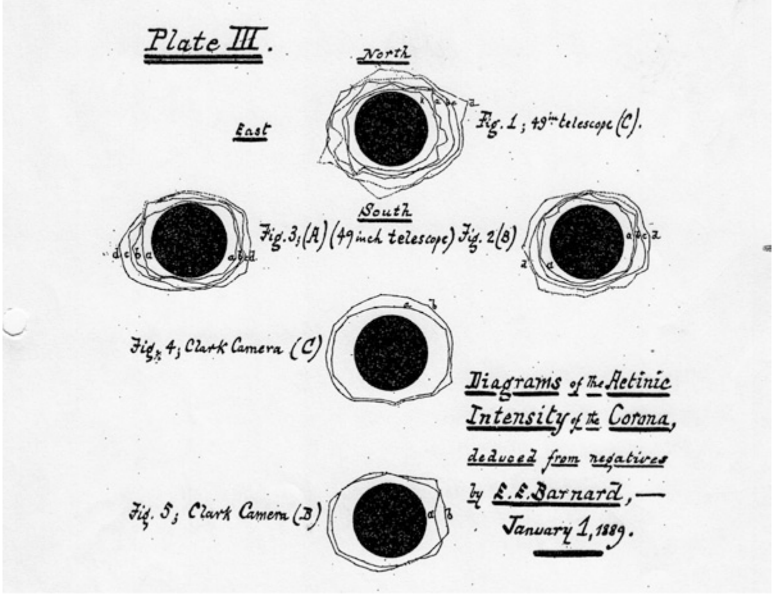


Fig. 18 Examples of Barnard's brightness contour drawings made from the larger images of Schaeberle's 'water reservoir' telescope and the smaller images of the Clark Camera (after Barnard 1889).

Finally, Keeler (1889: 54–55) summarized the findings of this expedition as follows:

1. The corona appears to exist mainly due to reflected light by solid particles surrounding the Sun.

2. The corona nearest the Sun is self-luminous and might be the result of the ejection of material from eruptive disturbances within the photosphere and chromosphere.
3. The ejected material forms the rifts, streamers and other coronal forms in an irregular distribution around the Sun.
4. Within the inner corona there appeared a bright ring of nearly uniform light that is caused by diffraction of light from the chromosphere and is not a diffraction effect by the lunar limb.
5. The gaseous nature of the solar atmosphere does not reach a great depth.

4.2 The 21–22 December 1889 Expedition to Cayenne, French Guiana, South America

Initially the Lick Observatory was unable to obtain funding from the University of California for an expedition to South America for the December 1889 eclipse, but UC Regent and "… liberal friend of the Observatory …," Charles F. Crocker, came forth and offering to fully fund a small-scale expedition (Holden 1889c). It was resolved that Burnham would lead the expedition, assisted by Schaeberle.

The Observatory would conduct a wholly photographic program designed by Holden and the other staff astronomers. Additional primary support came from the USNO through the loaning of equipment, while planning information was offered by the Royal Astronomical Society's Eclipse Committee which was chaired by Professor H.H. Turner.

The expedition departed from New York on 31 October aboard the *Bermuda* and during a sea voyage of nearly 2 weeks eight tropical Caribbean islands were visited whilst *en route* to Port of Spain, Trinidad. After a 10 day delay, Burnham and Schaeberle boarded the *Venezuela* for an unpleasant 6 day voyage to Cayenne, arriving on 1 December.

The Governor of the colony, M.G. Réache, graciously assisted the party in locating the eclipse site at a battery overlooking the shoreline near town (Figure 19).

Fig. 19 The battery site at Cayenne in December 1889. The 18-in. reflector is mounted on the cannon carriage third from the left and part of the wooden tube can be seen in silhouette. The Clark refractor is located far right-center, and the Dallmeyer camera is immediately to the right of the reflecting telescope (courtesy: Mary Lea Shane Archives of the Lick Observatory).

It rained often, sometimes torrentially, in the period preceding the eclipse, but the equipment was kept dry inside a boiler house (Burnham and Schaeberle 1889).

The Lick staff assembled a timber base for the 6.5-in. Clark refractor, spending a significant amount of time getting the telescope to work in the wet tropical climate. The Dallmeyer camera, with its fine Clark equatorial mount, was positioned and adjusted, receiving the addition of a 3-foot focal length finder loaned by Barnard.

More time-consuming was the preparation of an 18-in. reflecting telescope whose primary mirror Schaeberle had figured in 1880. The tube was fashioned from wood scantlings and barrel hoops and then covered with black cloth. The mirror was backed with cloth padding and placed in a tub which served as a mirror cell. The hour-axis of the mount consisted of a wooden beam fitted with bolts whose heads served as the inner bearings. The outer bearings consisted of nothing more than large steel washers mounted on the carriage framework of one of the large cannons. To provide the required diurnal tracking, a screw abutting an upper piece of the tube could be turned by hand with a wrench, each turn of the screw giving 10 s of tracking time. Aligning and adjusting this awkward telescope and mounting continued right up to the very moment of the eclipse (ibid.).

According to Holden (1889b), the objectives of the expedition in the order of importance were:

1. To obtain negatives of the inner corona, which will replace the inaccurate sketches made during previous total eclipses and will show clearly the form of the corona and details in gradations of light.
2. To obtain negatives of the outer corona.
3. To use negatives that have been standardized at the Lick Observatory for photometric measurements of the brightness of various parts of the corona. From these plates attempts will be made to determine a law that can be used to account for the distribution of coronal light and compare the total coronal light from eclipse to eclipse. The standardization procedure will permit numerical data to be obtained.
4. To obtain a standardized negative immediately after third contact for measurements of the distribution of light in the sky.
5. To make other astronomical observations as time permits. These could include a search by Burnham for new southern stars doubles and photographic determination of the law of atmospheric absorption by Schaeberle.
6. To accurately determine the latitude and longitude of the eclipse station.

Holden's program was 'set in stone' long before the eclipse and made no provision for changes that might be necessary under variable seeing conditions. For example, the precise exposure times were laid out in advance with no provision for sky conditions, moisture, temperature or eclipse brightness. One exception permitted Burnham to add a couple of exposures, using his own judgment, at the end of the exposure sequence but in practice he never took the extra photographs as totality had ended (Burnham and Schaeberle 1891). Holden believed discipline and order would eliminate errors of human judgment in the moments of excitement and confusion that were expected at the time of totality.

On eclipse day it rained and drizzled until twenty minutes before the start of the grand event, but during totality Burnham was able to obtain five exposures with the Clark refractor (with the objective stopped down to 3 in.). The shutter comprised a black velvet flap over the objective that was attached to a string that could be pulled from the eyepiece of the telescope. Meanwhile, Schaeberle took five exposures with the Dallmeyer camera at full aperture, the shutter again consisting of Burnham's clever velvet flap over the objective. Mr L'Hote took four exposures with the Newtonian reflector while R. Rockwell adjusted the screw of its makeshift drive. The shutter consisted of a large black cloth cap placed over the front end of the tube which was removed at the appropriate time (ibid.).

Schaeberle (ibid.) provides a visual description of totality:

> … the coronal light, was so surprisingly bright that the belief in the possibility of bringing the phenomenon within the reach of observation in full sunshine … certainly appeared to have nothing absurd about it … [and] the illumination appeared *much more effective* than that due to the light of the full Moon … terrestrial objects were plainly visible and sharply defined, but entirely devoid of all color, only the difference in the degree of colorless darkness appeared to be the boundary line of things seen.

When the eclipse party returned to Cayenne all of the exposed plates were leisurely processed. Those taken with the reflector showed the effects of bad focusing, vibration and tracking errors, while images taken with the Dallmeyer lens were grossly overexposed. Because of the brighter Sun and more luminous sky conditions encountered in the tropics Holden's predetermined exposures that had worked so well during the January 1889 eclipse were ineffective and all the plates were overexposed (ibid.). This was a direct result of Holden's (1889b; 1900) inflexible expedition directives, and a contemptuous argument was to ensue over the Carcel standard lamp used to standardize the plates for photometry (Holden 1890c).

The Lick Observatory party boarded the *Venezuela* in Cayenne on 3 January and after transferring to an American steamer reached New York on 9 January.

Despite the overexposed negatives (e.g. see Figure 20), the Lick astronomers were able to utilize the images for photometric and coronal studies. Schaeberle worked on the first draft of his Mechanical Coronal Theory on the trip home and used the images to support his new hypothesis.

When Holden (1890a) reviewed the badly-overexposed plates and heard of the lack of success experienced by other expeditions he sent the following missive to the Board of Regents:

> The Lick Observatory expedition succeeded while NO other expedition (as I know) has succeeded at all. These twelve photographs will be the data on which *all the world* will have to depend. It is a great *credit* to America, to the state, and to the Lick Observatory. Burnham and Schaeberle have no superiors … *The English astronomers, I see, are doubting the reality of the extensions of the corona first photographed.* There is no doubt, *really*, for I found it on photographs taken from different places and on eye drawings.

After the eclipse Holden held Burnham and Schaeberle to account for failing to keep accurate details of expenses during the trip but Crocker was satisfied with their records and dismissed Holden's concerns. Holden (1890e) then proceeded to dress down Schaeberle for a miscommunication regarding use of the Dallmeyer camera.

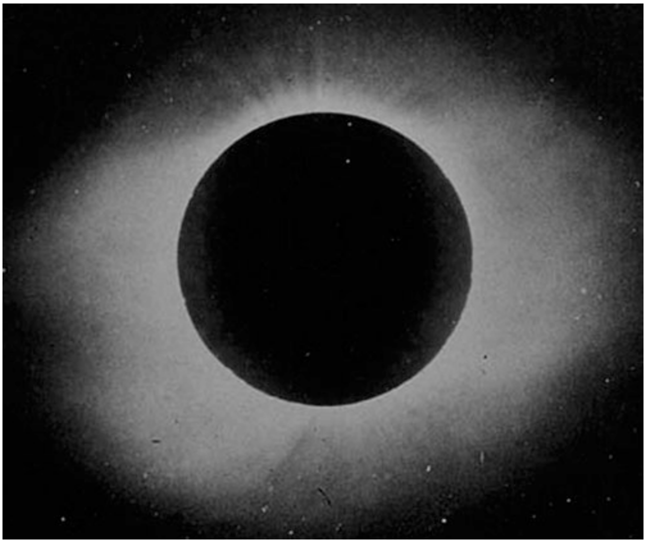


Fig. 20 An example of the overexposed and slightly out of focus coronal image obtained using Schaeberle's 18-in. Newtonian reflecting telescope in December 1889 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

With the passage of time, Holden's relations with these two astronomers would continue to deteriorate.

4.3 The 17 April 1893 Expedition to Mina Bronces, Chile

Mrs Phebe Hearst, a friend of the University of California and of the Lick Observatory donated $1,000 to fund an expedition to Chile for the April 1893 eclipse. Planning for the trip began in the fall of 1892, and Schaeberle alone was sent on paid leave by the Observatory. He selected a high altitude site that promised clear dry atmospheric conditions.

The Lick Observatory contingent departed San Francisco on *The City of Sydney* on 25 January with 13 crates of equipment and supplies. They experienced a pleasant voyage to Panama arriving on 10 February, but missed their connection with a English steamer that was to take them to Carrizal Bajo in Chile and had to wait a week for another ship. Eventually they reached their destination without incident (Schaeberle 1895).

The eclipse station was at the mining camp of Mina Bronces (see Figure 21) which was reached by rail, then a 5-h trip along a rough dusty road that wound its way through a dry barren mountainous landscape. According to Schaeberle (1895), reckless determination was required to transport the equipment and provisions over such a difficult road. But the eclipse site proved ideal. Schaeberle was impressed by the extreme

Fig. 21 Panoramic view of the Mina Bronces mining camp (courtesy: Mary Lea Shane Archives of the Lick Observatory).

steadiness of the daytime atmosphere, and the presence of a large mountain in the direction of the Sun was to prove beneficial as it blocked out a significant portion of unwanted background ambient sky light. All of the Chilean officials encountered *en route* to Minas Bronces went out of their way to help the eclipse party in any way they could, and at the eclipse site itself the mine manager, Bray, was continuously available to the Lick staff. Schaeberle found many highly-qualified volunteers, especially among military officers, to man the equipment during the eclipse.

Three different instruments were used to photograph this eclipse. The newly-developed 40-foot Schaeberle Camera (see Eddy 1971; Pearson and Orchiston 2008) and the 6.5-in. Clark equatorial were used for narrow-field coverage in order to reveal fine coronal detail, while a 6-in. Dallmeyer ‘Portrait’) lens loaned by William N. Pierson was selected for its excellent sharpness and wide-field coverage of the entire corona. Two other small cameras were also used to record the overall appearance of the corona.

This was to be the first field use of the 40-ft Schaeberle Camera (Figure 22). The coordinates of the eclipse site were obtained by repeated sextant readings as precise positioning of the Camera was critical. During these preparations, Schaeberle (1895: 41) was forced to admit: “I confess to having asked myself several times, Will the sun’s image fall centrally upon the photographic plate at the critical moment?”

Assembly and stabilizing of the Camera were accomplished with the upmost care and attention to detail by Schaeberle and his assistants. The upper end of the slope where the Camera was located was excavated 2 feet deep into broken rock for the lens pier. A three foot pit was then excavated in the broken rock for the plate system. The track and plate carriage framework were securely fastened to the ground with a liberal supply of mortar. Guy wires were rigged to the top of all supporting frame

Fig. 22 The 40-ft Schaeberle Camera's as it appeared on its first field expedition, in 1893 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

posts and anchored firmly to the ground with iron pins. A curtain was attached to the front end of the Camera for wind protection. The ground within the plate area tent was covered in a plaster 'barro' to prevent dust. The lens was arranged very close to the tube material, without actual contact, to minimize any stray light leakage into the interior of the tube. Another light trap was arranged, by sewing a piece of black fabric on the front of the tube in front of the lens mount, but leaving a hole for the lens. A cardboard partition, with a hole, was placed 1 foot in front of the objective to prevent off-axis light from the sky reaching the lens (Schaeberle 1895: 33–36).

The next stage in preparing the Camera was collimation of the objective lens and the plate holder. Using a plane mirror at the slide holder, the slide plane was first collimated by reflecting the light of a lantern from an observer at the top end back to an observer looking down the optical axis and adjusting the plate holder as necessary. The objective lens was then collimated in the same manner by reversing the positions of the plane mirror and the observer respectively. The final alignment of the plate holder was accomplished by using an eyepiece at the focal plane to view stellar images and after that exposing a plate at night to record star images (ibid.).

The Clark refractor was installed on its equatorial mounting and the field cameras were attached to the non-tracking mountings. Aiming of the telescopes and cameras was accomplished by repeated sightings using a chronometer and a sextant. A fence was assembled around the entire area to keep stray sheep, horses and the curious locals at bay. The nearby mining office served as a makeshift darkroom. Setting up and adjusting these instruments continued for up to 1 week before the eclipse, during which time the various volunteers began arriving and enthusiastically practicing their assigned duties.

The photographic mission, essentially the same as for the December 1889 expedition, was to obtain high-resolution images of the inner and outer corona and of corona form, and to conduct accurate photometric measurements (Schaeberle 1895).

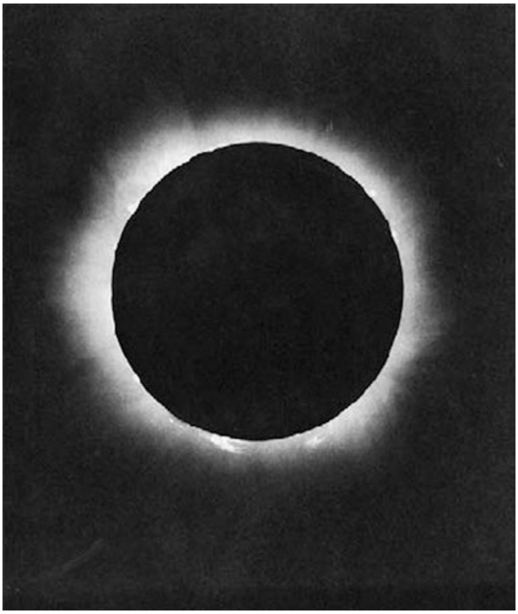


Fig. 23 One of the positive coronal images taken with the 40-ft Schaeberle Camera in 1893 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

To accomplish these goals, the following instructions were given for the operation of the instruments, but this time Holden (1892) made some provisions for adjusting exposures, whilst still maintaining rigid control over the observations:

1. To make at least two exposures with the 40-foot ‘photoheliograph’.
2. To make at least four exposures at the listed times with the Clark refractor stopped down to 3-in. aperture. At least two plates will be standardized as stated.
3. To use the Dallmeyer camera stopped down to 4 in. aperture.
4. To obtain two exposures, one short and one long, but adjusted if the Dallmeyer camera is clock-driven.
5. To adjust the exposures accordingly if the day is not clear or if different type plates are used.
6. To copy all plates and send them back to the Lick Observatory in two different ships.

Meanwhile, a set of plates was exposed at night to provide an independent value of the light absorption of the Earth’s atmosphere (Schaeberle 1895).

Eclipse day was cloudless and clear, and Schaeberle’s “… little army of scientific assistants …” took up their positions (ibid.). At eclipse time, Schaeberle alone operated the 40-ft Camera and commanded the start of all the eclipse instruments while viewing the large image present at the plate holder. His start command at second contact was “Expose” and at third contact “Cover your slides!” Schaeberle made eight exposures with the 40-ft Camera on 18×22-in. plates. Figure 23 shows an example of one of the images. Assistants W.F. Gale and R.A. Walker obtained ten exposures with the Clark equatorial refractor. Mr Tirepegur and A. Hole made

6 exposures and 18 exposures respectively with the 4×5-in. and 5×7-in. plate cameras, while J. King and Captain Bray made four exposures at 3-in. aperture and seven images at full aperture with the Dallmeyer camera. Mr Curmey beat time signals on a wooden box, and volunteers Aubertin, Bodger, Brown, Parr and Wilson all made naked eye sketches of the corona (ibid.).

The most memorable visual observations made at totality were noted by Schaeberle (1895: 42–50), when "… the coronal white light filled the whole view." To the prominent Australian amateur astronomer, Walter Gale,

> … the landscape presented a slaty, sickly aspect … [and the] heavens exhibited a peculiar darkness … [The] corona presented a most delicate and complex structure of faint penciling and curvatures while a narrow rift of curious clearness separated the corona in a vertical direction.

Fellow-volunteer, Aubertin, exclaimed: "God's picture … one grand, overwhelming figure is the symmetrical corona, of a deep, circular margin extending all around into valance or festoons of lovely texture." (quoted by Eddy. 1971: 7). Walker noted, "The rays, so splashy … most beautiful spectacle it has ever been my fortune to witness."

All together, 52 negatives were developed over a period of several nights. The plates from all of the cameras were considered outstanding and would be standardized and subjected to critical analysis back at the Lick Observatory. Only the exposures obtained with the Clark refractor were spoiled, due to the driving clock being disengaged.

Schaeberle (1895) reported that the corona presented a great number of highly complex, intertwined, features and groups of features, and he devised a skeletal diagram of the inner and outer corona to show the location of the most prominent of these (see Figure 24). Eight of the original 18 x 22-in. plates, covering a broad range of exposures, were individually traced in order to produce a master glass plate which in turn was used to produce this diagram.

After the eclipse Schaeberle visited Santiago Observatory and the state university. On 17 May, he travelled by rail for 8 h to Arequipa where the Harvard College Observatory had established its eclipse site. Once there, he visited the observatory directed by Professor Baily and joined an expedition – lead by Baily – to reach the summit Chachani's west peak. Seriously ill from altitude-sickness, Baily stopped at 17,000 feet, but Schaeberle and one guide, both suffering the effects of altitude, continued on to the 18,100 foot summit. They descended to the sound of "mucho frio" mumbled many times by Schaeberle's barefooted companion (ibid.). Schaeberle left Arequipa with fond memories, and the rest of the voyage home was uneventful.

4.4 The 8 August 1896 Expedition to Akashi, Japan

Schaeberle would again represent the Observatory in an assault on the August 1896 solar eclipse in Japan, but this time with funding provided by C.F. Crocker. Schaeberle was supplied with regular meteorological reports right up to the time

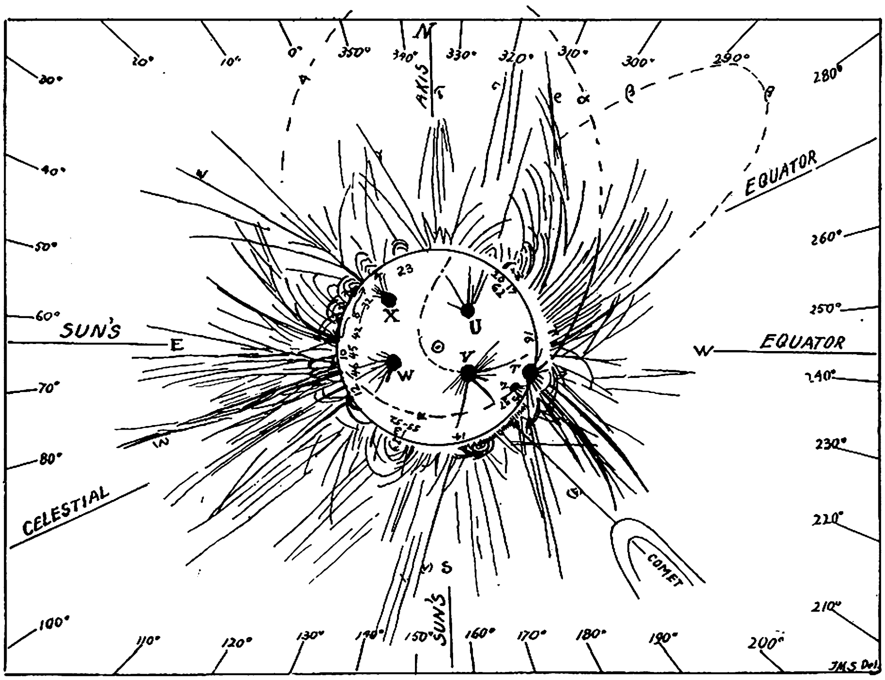


PLATE IX. SKELETON DIAGRAM OF CORONA.

Fig. 24 Diagram showing the locations of prominent coronal features noted during the 1893 eclipse (after Schaeberle 1895).

of the eclipse by Professor Hiroi of Sapporo (Japan) and from five other stations on the island of Yezo (Campbell 1894).

The 40-ft Schaeberle Camera was again taken on the expedition and supported by a suitable hill, as in 1893 (see Figure 25), but this time the Observatory's Floyd camera – fitted with a 5-in. Willard portrait lens refigured by Brashear – was taken in place of the Clark refractor. Meanwhile, Burckhalter from the Chabot Observatory obtained a special photographic telescope of 4-in. aperture and 20-feet focal length sent at the expense of William M. Pierson, a prominent San Franciscan amateur astronomer, and additional funds were provided by Mrs Phoebe Hearst (Holden 1896).

The program was to be entirely photographic, as in 1893, and with the same goals as in 1893, but no observations were made as the eclipse was obscured by clouds (Schaeberle 1896).

4.5 The 22 January 1898 Expedition to Jeur, India

By 21 June 1897, Campbell still did not have a field expedition approved for the January 1898 solar eclipse in India (Holden 1897b), but 4 days later the expedition was approved by the Regents and Holden asked Sir Robert Ball, President of the

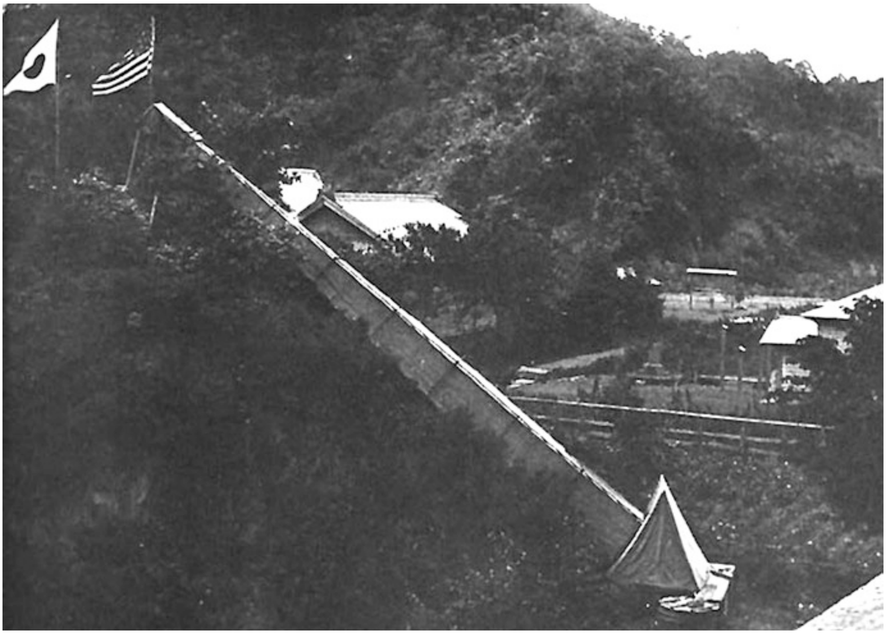


Fig. 25 The Schaeberle Camera as it appeared at the 1896 Japan eclipse site (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Royal Astronomical Society, to help obtain the necessary permissions and site arrangements in India (Holden 1897a). At this time, India was under British rule. The British Government in India sent Holden detailed meteorological reports, and C.F. Crocker agreed to fund the expedition to the tune of $1,250.00 (Schaeberle 1897).

William W. Campbell led the expedition with Mrs Campbell and R. Beans as female volunteers. Up to this point female volunteers on eclipse expeditions were infrequent. This would be the first of several eclipse expedition where Mrs E. Campbell would accompany her husband. She maintained a lengthy diary of the trip which was titled "In the Shadow of the Moon," which remains unpublished to this day (Mrs Campbell 1898a). The diary documents the expedition members' travels and gives insight into the actual conditions of travel and living in an environment often devoid of the comforts of home. Some of Mrs Campbell's writings tell quite a different tale of expedition life compared to the 'official' accounts published in the astronomical journals.

On 21 October 1897 the expedition departed San Francisco aboard the *China* for the Pacific crossing to Hong Kong. The Campbells ended up spending hours, sometime entire days, in their stateroom suffering from seasickness, with their luggage sliding back and forth across the floor. They then boarded the *Ancona* for the 17-day trip to Bombay, reaching this port on 10 December. By this time, Campbell (1898b) was feeling very ill from the terrible food.

In Bombay Campbell rounded up a small army of military and scientific volunteers and all were soon mired in logistical red tape. They learned that their intended destination, Karad, was closed due to an outbreak of bubonic plague. Campbell selected another site 4 miles from the railroad station at Jeur. The promised time signals, used to establish the exact location of the site, did not exist, and when Campbell asked the station official for a time reading accurate to 1 s, he was told: "Why should he be so impatient over 1 s? There are plenty of seconds." (Campbell 1898b). Mrs Campbell (1898a) was placed in charge of the entire camp, involving 24 volunteers and numerous scientists and dignitaries.

Campbell roped off an area for the eclipse instruments, and began erecting the 40-ft Schaeberle Camera. Faced with the absence of a hill to support the Camera, he had to improvise and ended up constructing two towers to raise the lens and the tube of the Camera to an altitude of nearly 51°. One tower would support the objective independent of the tube which rested on the outer tower (see Figure 26). The tube end was held in place by iron pins driven into the ground. The tube was further anchored with a system of duplicate wire cables. A nine foot rock wall surrounded and anchored the bottom of the tower, and a nine foot pit was dug into the hard ground to protect the plate holder from wind and rain. This also served to lower the towers, thereby exposing less of the Camera to the elements. The work would have progressed much more easily had Campbell not fired the local lead worker and most of the workers, so he ended up doing most of the construction and excavation himself. The locals were amazed by his ability to work hard, and Mrs Campbell (1898a)

Fig. 26 The 40-ft Schaeberle Camera as Campbell redesigned it for the flat ground at Jeur. The plate-holder pit area is to the left and note the rock wall bracing the towers that support the Camera's tube and objective lens (courtesy of the Mary Lea Shane Archives of the Lick Observatory).

noted in her diary: “He is working from before dawn till after the sun has left the sky. Stones that four men cannot move he lifts with ease. And he is never tired!” Because of this over-exertion, Mrs Campbell soon became vey concerned about the long-term health of her husband.

In all, nine items of photographic and spectrographic equipment were assembled. Campbell’s four spectrographs were of his own design. Two driving-clocks were loaned by astronomers Hussey and L. C. Masten (Campbell 1898b). One of the spectrographs featured a Rowland grating and was fitted with a moving plate-holder. Young, of Princeton University, loaned a train of four compound prisms for the spectrographs. A clock-driven polar axis mount made from shipping crates carried five of the instruments (ibid.).

From 17 to 21 January additional highly-qualified volunteers arrived and began practicing their assigned duties for the eclipse. Eclipse day arrived with perfectly calm and clear, and all non-participants were kept away from the eclipse station by the Government (ibid.). See Figure 27 for a group photograph of the official eclipse party.

Fig. 27 Group portrait at the 1898 eclipse site (courtesy: Mary Lea Shane Archives of the Lick Observatory).

The scientific program would focus on direct coronal photography as in the past, and on obtaining spectrograms of the chromosphere, reversing layer and overall coronal spectra. The Lick astronomers had not attempted eclipse spectroscopy since the 1889 January eclipse, but Campbell (1897) wanted to test whether the K or H lines were truly coronal or due to diffusion by the chromosphere and prominences as suggested by Deslandres' theory of the corona. Photometric studies of coronal brightness were also made using selected standardized plates.

Eclipse time arrived and Captain Fleet who was positioned at the 40-ft Schaeberle Camera called out the traditional "Go" signal at second contact. The rest of the eclipse party carried out their observations in a calm professional manner. According to Campbell (1898b: 139), "It is plain that no astronomer was ever more ably assisted by volunteer observers."

When totality arrived, Campbell remarked:"… it is impossible to describe the beauty of the Sun's surroundings. The corona was exquisite, more beautiful by far than anything else we saw in a journey around the world." (ibid).

The plates were processed at night in moments of cool weather, and the results (e.g. see Figure 28) obtained with the 40-ft Schaeberle Camera were considered excellent by Campbell. Prominently displayed on the plates were coronal streamers, beautifully shown with streamer hoods enclosing the prominences (ibid.).

After the eclipse the plates were shipped home via Hong Kong, while the Campbells separated from the main party and set off on a world tour of observatories in Cairo, Rome, Florence, Milan, Nice, Paris, Greenwich, Tulse Hill, Kensington, Cambridge, Oxford and finally Williams Bay (ibid.).

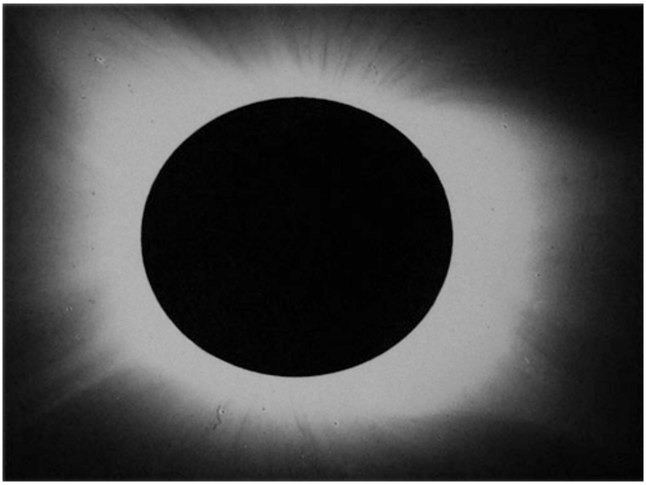


Fig. 28 The corona during the 1898 eclipse, as it appeared from an enhanced print (courtesy: Mary Lea Shane Archives of the Lick Observatory).

4.6 The 28 May 1900 Expedition to Thomaston, Georgia, USA

On short notice the Lick Observatory decided to assemble an expedition for the May 1900 eclipse which was visible in the USA from eastern Alabama and western Georgia. Since eclipse parties from other observatories chose sites in Alabama, Keeler decided on isolated Thomaston in Georgia for the Lick site and he assigned Campbell and Perrine to the expedition. They would be supported by a contingent of volunteer professional astronomers.

The party arrived on 30 April, and started preparing the site and setting up the instruments the next day (see Figure 29 for a sketch used to lay out the camp and Figure 30 for the actual site). One polar-axis mounting was set up to carry four spectrographs and a medium-sized camera. A second polar-axis mounting was fitted

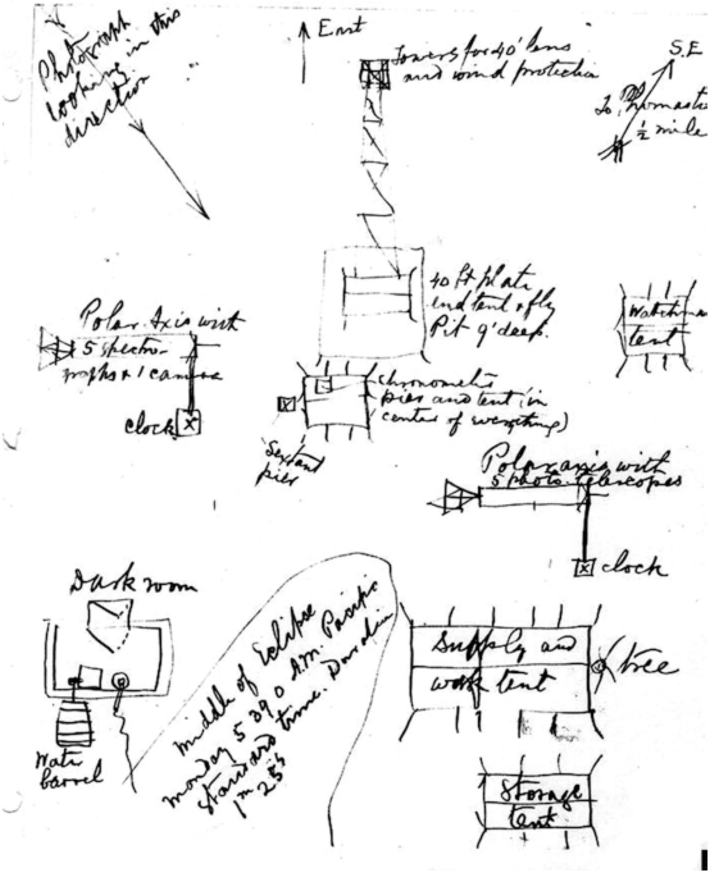


Fig. 29 The sketch used to organize the layout of the Thomaston eclipse station (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 30 View of the Thomaston eclipse camp. Note that the lower end of the Schaeberle Camera extends into a pit that was dug in the ground (after Campbell and Perrine 1900: 175).

with two medium-sized photographic telescopes and four small cameras. The 40-ft Schaeberle Camera was set up in the normal fashion, and a darkroom was erected.

Time signals were received directly from the USNO via the Western Union telegraph lines and then by wired connection to the chronograph. This enabled the astronomers to obtain a precise set of location coordinates for the station (Campbell and Perrine 1900).

By 26 April Perrine had fallen very ill and was bedridden with hemorrhaging of the bowels, and other members of the expedition also were ill. The suspicion was that they were not conditioned to digest the food prepared by the locals. Despite his condition, Campbell (1900a, b, c, e) managed to perform his duties on eclipse day.

The scientific program was again photographic and spectrographic in nature. The coronal program included spectroscopic investigations of the reversing layer, the chromosphere and the corona. The objective-grating spectroscope was the same one used during the 1898 eclipse in India. Large-scale photography would permit the recording of small-scale fine structure of the corona and allow separation of the corona from the background sky and photometric coronal observations. An attempt to correlate the coronal streamers and the prominences would also be made.

Eclipse morning arrived cloudy but Campbell was surprised when a hole opened in the clouds just in time for them to observe totality and closed up again afterwards, allowing successful observations to be made with all 11 instruments (Campbell and Perrine 1900). Perrine gave the program "Go" command at second contact and then made eight exposures with the 40-ft Schaeberle Camera. Visual observations of the corona were carried out by Buchanan, Curtis, Hannan, Lumsden and Miller, who agreed with each other on the lengths of the visual streamers. Messrs Buchanan and Lumsden observed the shadow bands at the beginning and end of totality (ibid.).

The plates were processed during the cooler night hours and according to Campbell and Perrine (ibid.) “They are of great excellence. The structure of the prominences, the thick chromospheric stratum, and the coronal streamers are beautifully shown.” The plates also revealed one streamer hooding a medium-sized prominence, and humps over the prominences appeared to exist. Negatives from the smaller cameras showed details and features of the corona, and although the Floyd camera had been jarred its plates were still of use.

By way of contrast, the spectrogram obtained with the moving objective prism plate spectrograph was considered by Campbell to be of little value. While it revealed the bright-line and dark-line spectra of the Sun’s limb at third contact, second contact was missed as the plate drive was not started until midway through totality. The resulting shift of the green coronal line to the far end of the spectrum caused by the defective drive was a great disappointment to Campbell, especially since the driving clock had tracked perfectly during the pre-eclipse rehearsals. Fortunately, at least 600 bright lines and the dark line continuous spectrum were visible on the plates obtained with the other spectrographs, and upon examining these plates the bright lines were seen to fade away as totality ended.

The objective-grating spectroscope recorded the green coronal 5,303 Å ring on the west side of the Sun, agreeing well with the results obtained in India. Coronal streamers radiating with the green light appear strongest near sunspot regions. And again, just like during the Indian eclipse, the spectrum of the inner corona produced with the slit spectroscope was free from dark lines (Campbell and Perrine 1900).

The party departed for home on 4 June, and had their first regular meal in days in Atlanta and Charlottesville (Campbell 1900a, b, c, e). Subsequently, Campbell learned of the failure of the other eclipse parties, commenting that despite the success of the Lick party there seemed to have been a ‘hoodoo’ on this eclipse (Campbell and Perrine 1900: 183; Campbell 1900d).

4.7 The 17–18 May 1901 Expedition to Padang, Sumatra, Dutch East Indies

The long duration of totality and the high altitude of the Sun during the May 1901 eclipse meant that the Lick Observatory could not pass up this promising event in Sumatra (Dutch East Indies), and William H. Crocker agreed to fund the expedition given that his brother, C.F. Crocker, had died. Planning for this eclipse was delayed by Keeler’s death on 12 August 1900, but when they could proceed the preparations were finalized by the entire staff within just 1 month, and new instruments were even designed and fabricated during this short interval. It was decided that Perrine would lead the expedition, with the help of 15 volunteers. Campbell (1901c) asked H. Curtis to assist Perrine, noting that “There will be many occasions on which heroic efforts on your part will be necessary.” Additionally, Campbell reminded both gentlemen that they were going to Dutch territory and that they were representing the Lick Observatory. Padang on the island of Sumatra was selected for the eclipse station (Perrine 1901a, b).

The Lick party left San Francisco 19 February on the *Nippon Maru* stopping in Honolulu where they met the USNO party travelling on the *Sheridan*. They arrived in Singapore on 27 March, reached Batavia (present-day Jakarta, in Indonesia) on 31 March and Emmahaven on 5 April (where they again met up with the USNO party). The Lick Observatory party finally arrived in Padang after a 7 week voyage (Perrine 1901a).

Upon arrival, the Dutch government helped them locate a suitable site for their eclipse station at an abandoned race course (see Figure 31). During 10 days of frequent heavy showers Perrine and his volunteers assembled the clock-driven polar axis mountings and installed the cameras and spectrographs. The inner and outer towers of the 40-ft Schaeberle Camera were 36 feet high and were constructed of bamboo and covered with thatch. All of the instruments were covered by bamboo and thatch structures to provide shelter from the hot tropical Sun (Figure 32). The rain was too heavy for canvas so 'atap', a native material, was substituted. All of the instruments were operational by 12 May, but the promised telegraph network failed to materialize (ibid.).

Perrine faced his first substantial problem at this site when local religious leaders prophesied that the expedition had causing an epidemic in the nearby superstitious town of Kampong. It was feared that the local population might attack the eclipse camp, but luckily this did not happen. Nonetheless, Perrine (1901b) decided to play it safe and hired security guards.

According to Perrine (1900, 1901b) and Campbell (1901a) the entire program was to be photographic:

1. To record the prominences, hoods around the prominences, streamers and inner coronal structural detail with the 40-ft Schaeberle Camera.
2. To conduct medium-field coronal imaging with the Floyd telescope.
3. To make wider-field negatives of the outer corona with the Pierson Dallmeyer camera.

Fig. 31 Panoramic view of the eclipse station in the abandoned race course at Pandang, Sumatra (courtesy: Mary Lea Shane Archives of the Lick Observatory).

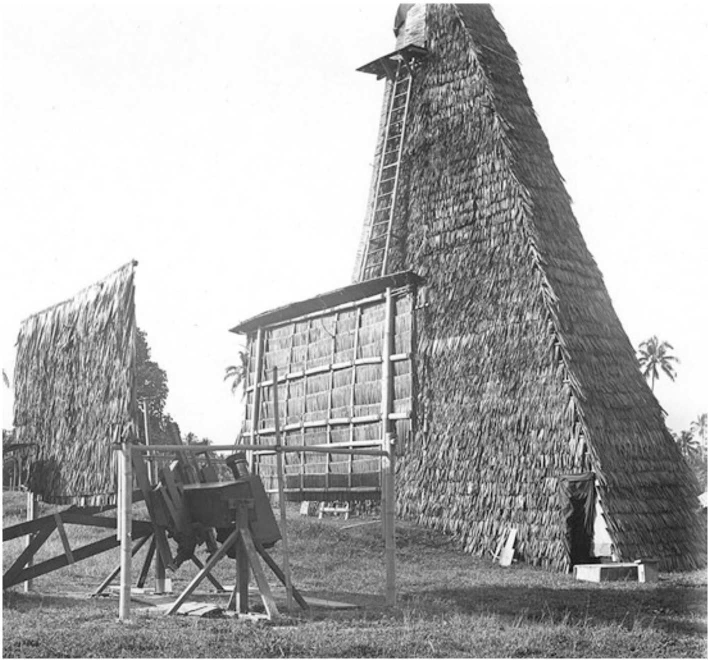


Fig. 32 Close-up showing the instruments assembled and protected from the Sun and rain by bamboo and palm thatch. In the foreground are the medium focal length cameras and the 40-ft Schaeberle Camera is in the background (courtesy: Mary Lea Shane Archives of the Lick Observatory).

4. To produce one spectrogram of the coronal spectra looking for Fraunhofer lines, with a radial slit single prism spectrograph with the slit placed east-west across the Sun's center, and one spectrogram with a similar spectrograph to record coronal Fraunhofer lines, with a tangential north and south slit.
5. To obtain negatives of the corona with a double-image prism polarigraphic camera, designed by Campbell and Wright to give further evidence of polarization within the corona. Rotation of the prism during totality would show any existing polarization within the corona. According to Campbell (1901b),

> The polarization effects of the corona are bringing up questions of great importance in eclipse work. In my opinion they have so far settled nothing, and given very slight indication of the truth. Their result is simply to emphasize the necessity of more and better observations on every point brought up. For my part, I do not see how we can expect strongly marked planes of polarization in the corona to reveal themselves. Any point on the corona must be receiving light from the whole visual photosphere, and hence from widely different directions. Further, we do not observe a single point, but a very long line of points lying in the visual ray. The difficulty of observing such phenomena seems to me much greater than one would suspect from reading the many papers on methods of observing polarization effects …

6. To secure a series of plates for a Vulcan search with four duplicate paired telescope-cameras made for this purpose.

Eclipse day arrived with the sky covered with light cirrus clouds and haze. At totality the corona appeared to be of the minimum type, with the clouds increasing somewhat before third contact. Twelve plates were exposed with the 40-ft Schaeberle Camera, 8 with the Floyd Camera, 10 with the Pierson-Dallmeyer Camera, 3 with each of the 4 Vulcan cameras and 1 each with the spectrographs. Ten exposures were made with the double image prism polarigraph with two exposures taken at each of the five positions of the rotating prism at 22.5° intervals.

Upon developing the plates in the cooler hours of the night, it was a pleasant surprise to find that successful images had been secured with all ten instruments. The negatives were filled with valuable and interesting details. Campbell (1901d) declared:

> The results … are exactly those which many of the astronomical expeditions have been hoping to bring home from the last two eclipses. They relate to the points which have been most prominently under discussion by eclipse observers in recent years. The photographs from these instruments could scarcely have been better.

The plates most affected by haze and clouds were those obtained with the Vulcan cameras where a lower limit was set on the recorded stellar magnitudes. Again the presence of hoods over prominences was observed. One of the most interesting features ever observed within the corona was a tremendous funnel-shaped disturbance appearing to emanate above the area where a sunspot had recently existed. Perrine (1902a: 151) described this feature: "… clouds of coronal matter were piled up as if by an explosion on the Sun's Surface …" (cf. Perrine 1902b).

Results from the polarigraph indicated that strong coronal polarization occurred in the outer corona >10′ from the limb. Measurements within the inner corona showed a small amount of polarization. The cloudy conditions at the time of the eclipse were actually a benefit as some detail was retained that would have been lost to plate overexposure. Campbell (1904a) later mentioned that the difficulty was in interpreting and evaluating the results.

Comparison of the spectrum of the sky with that of the corona made with the radial and tangential slit spectrographs were essentially the same in the blue and violet regions of the spectrum. The general coronal spectra were recorded to one lunar diameter and the H and K bright lines were seen within the streamers out to 40′ from the lunar disk. Like the 1898 eclipse, no Fraunhofer lines were found in the inner corona. The presence of coronal bright lines indicated the existence of a thin gaseous envelope surrounding the Sun (Perrine 1901a, b).

The results from the spectrographs and polarigraph indicated that matter in the inner corona was primarily incandescent and that the light of the outer corona could be attributed to scattered light from particles in a more solid state. It was also concluded that matter was ejected from the Sun's surface at great velocity. It was believed that the streamers and other coronal features were directly connected to eruptive events on the solar surface. Further study was needed to verify if matter was ejected in an incandescent or a solid state form (Campbell 1901c; Perrine 1901b).

Only faint shadow banding was observed before second contact and none after third contact as clouds, for the most part, obscured this part of the event (Perrine 1901a).

As a special treat for the eclipse expedition party, a great comet was observed and photographed with the Pierson camera on 5 May. The nucleus was brilliant, and the tail was 6–7° long. Observed within the tail were two slightly curved and nearly parallel streamers, and a faint streamer to the south making an angle of 35° with the principal trail (ibid.).

Perrine (ibid.) summarized the expedition with these comments: "The greatest enthusiasm was manifested by all in the preliminary rehearsals as well as in the observations on eclipse day." After the eclipse, the instruments and plates were shipped home from Padang, arriving at the Lick Observatory on 11 October (ibid.).

4.8 The 30 August 1905 Expeditions to Canada, Spain, and Egypt

In August 1905 three different Lick Observatory eclipse stations would be set up in Labrador (Canada), Spain and Egypt in order to take advantage of a unique opportunity: to obtain coronal photographs from locations 2.5 h apart along the path of totality. The Observatory began its preparations well in advance and secured full funding from William H. Crocker. The budget for the Labrador expedition alone was $1,598.00 dollars (Campbell 1904c).

4.8.1 Cartwright, Canada

After reviewing the scant meteorology reports furnished by the Hudson Bay Company, Campbell chose Indian Tickle, Labrador, in Canada, as the site most free of fog. He then contacted W. Macgregory, the Governor-General of Newfoundland, request assistance from "… four or five men of steady nerves, who have training in astronomy or in the navy for similar duties." In his reply, Macgregory (1905) recommended Cartwright over the Indian Tickle site and promised to provide support and volunteers.

The Lick Observatory party was under the leadership of Curtis, and left New York on 8 July bound for St. Johns, Newfoundland, on the *Rosalind*. Transferring to the *Virginia Lake*, they finally reached Cartwright on 18 July after experiencing cold, rainy and foggy weather *en route* and encountering icebergs and pack ice. Cartwright was a Hudson Bay Company township with a population of 16 set within a bleak, but impressively grand landscape (Campbell 1905; Curtis 1905).

W.E. Swaffield from the Hudson Bay Co. provided a house for the eclipse party but the local labor force was busy working the local salmon run and was unavailable to assist with eclipse preparations. The eclipse party members therefore had to prepare the site themselves, and in the process found the biting flies and hoards of mosquitoes very disagreeable. The instruments were set up, and all functioned well, and in place of a chronometer Campbell (1905) brought along a fine watch of great accuracy.

Observations scheduled for Labrador included:

1. To make a photographic Vulcan search within a star field 8.5° along the celestial equator and from 4° below to 15° above the Sun.
2. To photograph fine coronal structure and prominences with a replica of the 40-ft Schaeberle Camera. These plates would be compared with plates from the other two eclipse sites to see if there was any evidence of changes in coronal form or motion among structural components (ibid.).

No spectrographic or polarization studies were planned for this station.

After a couple days of fine weather, a fierce gale arrived putting the towers of the 40-ft Schaeberle Camera at risk. On eclipse day the site was clouded in and no observations were possible.

4.8.2 Alhama, Spain

As leader of the Spanish expedition, Campbell selected the city of Alhama for the eclipse station on the basis of maps prepared by the Madrid Observatory. Alhama was located in the Almazan-Ateca-Daroca region of Spain, and its high altitude offered the chance of good seeing conditions (Campbell and Perrine 1906; 1907; Curtis 1905).

The Lick Observatory party left New York on 6 July on the *Romantic*, and after experiencing fair weather and calm seas they disembarked at Gibraltar and travelled by land to Alhama, arriving on 21 July. They found a pleasant town of ~1,500 people. They settled in at the Hotel Los Termas and spent the next 9 days on site preparations whilst awaiting the arrival of the instruments. When they did eventually arrive there were 18 instruments in all, and these quickly were set up in 6 groups (Figure 33) thanks to help offered by the various assistants. But even with this assistance, Campbell described the process as "… exceedingly strenuous." (Campbell and Perrine 1906).

Coronal photography, generation of spectrograms, and an intra-Mercurial planet search were the basis of this eclipse party's program, and the primary goals were:

1. To record coronal detail with the 40-ft Schaeberle Camera.
2. To photograph the corona to reveal motion by comparing the plates taken at all three stations.
3. To make a polarigraphic study of the corona to measure the variability of polarization within the corona.
4. To conduct spectroscopic studies using a variety of spectrographs in order to:
    - (a) Obtain continuous records of changes in the spectrum of the Sun's limb at second and third contacts;
    - (b) Determine the precise wavelength of the green coronal line;
    - (c) Determine the accurate wavelengths at the moment when the dark lines gives way to bright lines, and vice versa; and
    - (d) Make a spectrogram of the general spectrum of the corona.

Fig. 33 The Alhama eclipse station instrument field established by Campbell (courtesy: Mary Lea Shane Archives of the Lick Observatory).

5. To make a photographic Vulcan search covering 9.25° along the celestial equator, and from 14° above to and 14° below the Sun.

Eclipse day arrived with some thin cloud cover, and to Campbell's profound disappointment the Sun was obscured by light clouds at eclipse time and only ten photographs were made with the 40-ft Schaeberle Camera (e.g. see Figure 34) and seven each with the Dallmeyer Camera and the Floyd Camera. As a result of totality arriving 17 s earlier than expected the startup of the spectrographs was late, resulting in the loss of initial information. The objective-prism spectrograph recorded a series of the changing spectrum of the Sun's edge at and near second and third contacts. Of special interest was the flash spectrum of the reversing layer. The first exposure revealed the photosphere isolated from the reversing layer. The continuous spectra appeared with the dark line spectrum of the photosphere. The bright line spectrum appeared for the reversing layer. The Hβ line appeared double (Campbell and Perrine 1906).

The moving-plate objective-prism spectrograph recorded a continuous image of the changing spectrum (see Figure 35). The coronal rings at λ 4231 and λ 3987 were strongly recorded along with the changing spectrum of some 600–800 lines recorded in the region of λλ 3800–5200 with the Hγ line appearing central on the plate (Campbell and Perrine 1906). Another moving-plate spectrograph was fitted with a lens of ultra-violet glass and two prisms of Jena ultra-violet glass and recorded the coronal spectra in the UV region. The recorded spectrum was weak as clouds blocked some of the UV transmission. Two strong coronal rings were recorded at λ 3388 and λ 3456, as had been observed at all total solar eclipses since the 1898 eclipse.

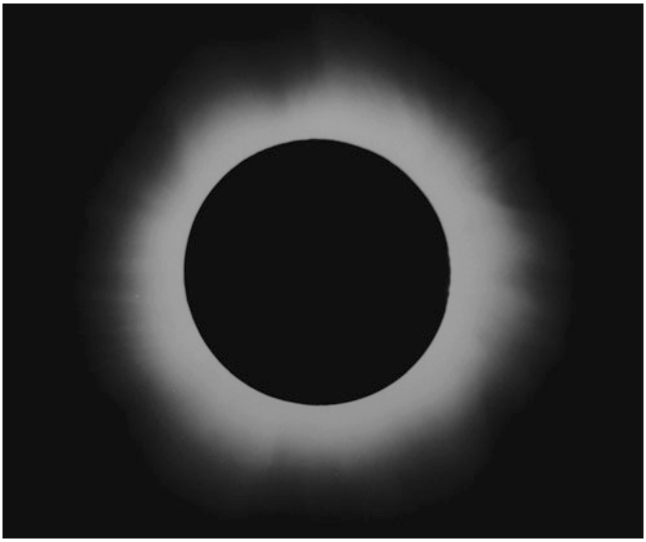
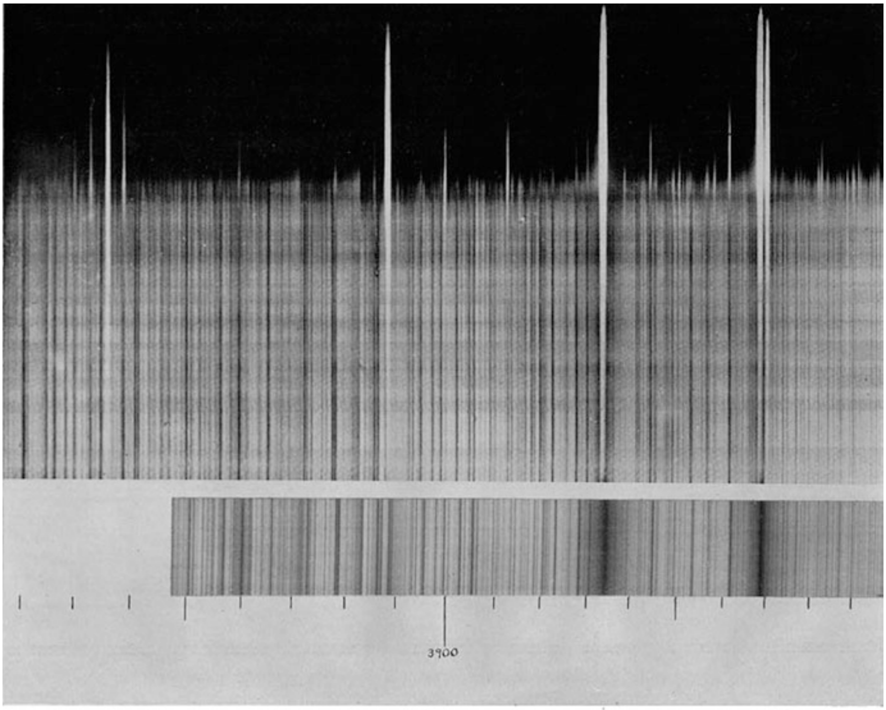


Fig. 34 The 1905 solar corona photographed with the 40-ft Schaeberle Camera (courtesy: Mary Lea Shane Archives of the Lick Observatory).



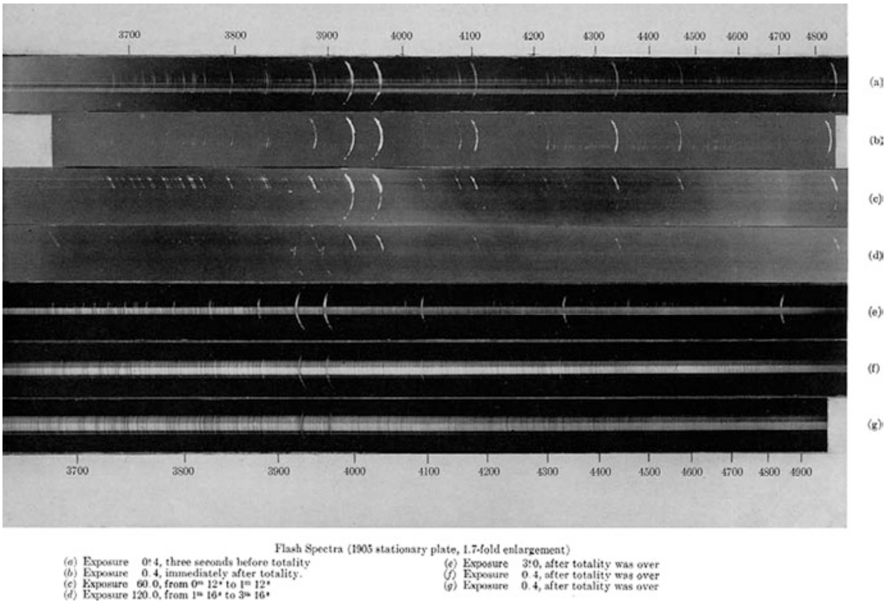
Flash Spectrum (1905 moving plate, four-fold enlargement) with normal solar spectrum below. Region λλ3820–4000

Fig. 35 A portion of the spectrogram recorded by the moving-plate spectrograph (courtesy: Mary Lea Shane Archives of the Lick Observatory).

The objective-grating spectrograph recorded the green coronal ring, and showed that the solar layer that gave rise to its light was of irregular intensity rather than being uniformly distributed around the Sun. A three-prism slit spectrograph recorded only a faint image of the coronal green line. The goal had been to determine the green line's wavelength more accurately and this attempt was considered unsuccessful. The single-prism spectrograph recorded the general spectrum of the corona. The spectrum of the inner corona showed no Fraunhofer lines, but these lines were strong in the spectrum of the outer corona. They were also weakly recorded on the area occupied by the Moon and were thought due to the scattering of light in the Earth's cloudy atmosphere (ibid.). See Figure 36 for the spectra from the fixed plate spectrographs.

The polarigraphs and photometer produced sharp images. Upon initial inspection, the negatives from the polarigraphs appeared be fine for the planned polarization measurements, while the photometer results were of a quality that would permit an accurate determination of coronal brightness to be made (ibid.).

Upon being developed, all plates from the cameras were considered to be of excellent quality. Solar streamers out to two solar diameters from the limb of the Sun were recorded along with large prominences on the eastern limb (see Figure 37). Smaller prominences were hooded by coronal arches. Campbell (ibid.) was pleasantly surprised that the plates were of such good quality as he had expected that the thin clouds would have caused problems. This was only the case with the plates taken with the Vulcan search cameras, which were lightly fogged and of little value.



Flash Spectra (1905 stationary plate, 1.7-fold enlargement)

(*a*) Exposure 0$^{\mathrm{s}}$4, three seconds before totality
(*b*) Exposure 0.4, immediately after totality.
(*c*) Exposure 60.0, from 0$^{\mathrm{m}}$ 12$^{\mathrm{s}}$ to 1$^{\mathrm{m}}$ 12$^{\mathrm{s}}$
(*d*) Exposure 120.0, from 1$^{\mathrm{m}}$ 16$^{\mathrm{s}}$ to 3$^{\mathrm{m}}$ 16$^{\mathrm{s}}$
(*e*) Exposure 3$^{\mathrm{s}}$0, after totality was over
(*f*) Exposure 0.4, after totality was over
(*g*) Exposure 0.4, after totality was over

Fig. 36 Spectrograms generated by fixed-plate spectrographs covering a broad bandwidth of the solar spectrum (courtesy: Mary Lea Shane Archives of the Lick Observatory).

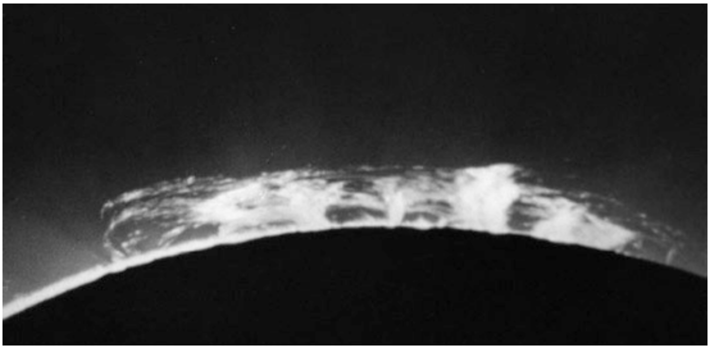


Fig. 37 Large prominences and a highly disturbed chromospheric region on the eastern limb photographed with the 40-ft Schaeberle Camera during the 1905 eclipse (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Post-eclipse, once the instruments were safely packed and on their way home the Campbells concluded their stay in Spain with a return visit to Madrid where a banquet was held in honor of all the visiting astronomers. A number of guests also attended a bull fight. The Campbells then continued on their world trip, visiting observatories and astronomers throughout Europe (ibid.).

4.8.3 Aswan, Egypt

Hussey and Perrine were assigned to this expedition, and the equipment was shipped together with that bound for Spain. Mr and Mrs Hussey started their sojourn with a holiday in Switzerland and Italy and met up with Perrine and the equipment in Alexandria. Here they were introduced to Captain H.G. Lyons, Director-General of the Survey Department and Inspector B.F.E. Keeling who was the Acting Director of the Helwan Observatory. These two gentlemen would see to the expedition's logistical needs and would secure qualified volunteers on behalf of the Egyptian Government (Hussey 1906).

The next stop was Cairo where they met with Professor Turner from Oxford University and Professor Robert H. West from the Syrian Protestant College at Beirut, both of whom would assist the Lick party. While awaiting the arrival of the Russian and British expeditions they toured the wonders of the Nile. The Russian party was delayed, so the Lick Observatory group and the British contingent went on to Luxor by rail. After reaching Aswan, they used sail boats to reach the island of Elephantine, where they were put up at the Savoy Hotel (ibid.).

Hussey found a location on the bank of the Nile that he considered ideal, as it had a suitable work area, a small building for storage and trees that provided some degree of protection from the hot Sun (where temperatures rose as high as 113°F). The skies were clear but Hussey rated the seeing poor due to heat radiated by the hot landscape. Here they set up the instruments in a routine fashion (Figure 38).

Fig. 38 The 40-foot camera is set up beside the Nile River at Aswan for the 1905 eclipse. The Vulcan cameras are in the foreground on the right (courtesy: Mary Lea Shane Archives of the Lick Observatory).

As the journey was considered too harsh for transport of the Observatory's chronometers, three highly-accurate Elgin watches were selected to serve as chronometers, one for each of the three Lick expeditions (Campbell and Perrine 1906).

According to Campbell (1904c), the observational goals of the Egyptian contingent included:

1. To photograph coronal detail and prominences with a replica of the 40-ft Schaeberle Camera equipped with a 5-in. lens loaned by the USNO.
2. To conduct a photographic Vulcan search 8.5° along the celestial equator and from 4° below to 15° above the Sun. Campbell hoped that on this occasion this search would prove the existence or non-existence of this object. His hopes did not materialize, partly due to the hazy skies which limited the number of faint stars that could be recorded on the plates.
3. To generate a spectrogram showing the general spectrum of the corona.

Eclipse day was perfectly clear and all of the experiments ran smoothly (Hussey 1906). The corona was of the sunspot maximum type with the most prominent coronal feature being a long slender recurving streamer. In all, 19 negatives were developed. The eclipse participants celebrated their accomplishments over tea and shandygaff. Later that night a banquet was held at the hotel in honor of all of the eclipse parties, hosted by the Secretary of State for Finance, Mitchell-Innes. The Lick Observatory then returned to the USA.

4.9 The 3 January 1908 Expedition to Flint Island, Line Islands, South Pacific

The Clash of the Clans;
or
The Flint Island War.

When Greek meets Greek there is a fearful fight,
When Scot meets Scot 'tis worse by a darn sight,
The earth doth hide in blackest night,
The moon grows dark with sudden fright,
The sun doth cease to shed its light,
When McClean and Campbell meet to match their might.
Moko (Mary Lea Shane Archives)

Initially, no other major observatory was planning an expedition for this particular eclipse so Campbell arranged for the Lick Observatory to set up a station on Flint Island, 450 miles from Tahiti in French Polynesia. Flint Island is a member of an isolated chain of islands known as the Line Islands in the South Pacific.

By June of 1907 Campbell had finalized plans, with W.H. Crocker funding the expedition. The party of 8 people and 35 tons of instruments and supplies departed San Francisco for Tahiti on 22 November aboard the *Mariposa* (Campbell 1907a; Campbell, et al. 1908). Also sailing was a hastily put together party sponsored by the Smithsonian Institution and Professor Lewis from the University of California Berkeley's Physics Department, which would share expenses with the Lick Observatory party. They arrived in Tahiti on 5 December where they were joined by Professor Benjamin Boss from the USNO station at Pago Pago.

From Tahiti, the United States Navy provided transport to Flint Island on the U.S. gunboat *Annapolis* (Figure 39), which arrived on 9 December. The eclipse

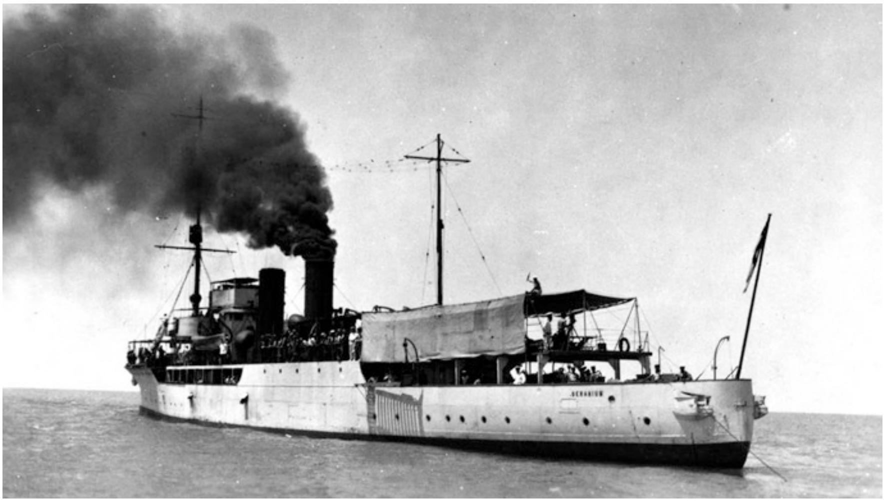


Fig. 39 The United States Naval vessel *Annapolis* (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 40 Mrs Campbell sitting for her portrait on a turtle that was later served up for dinner (courtesy: Mary Lea Shane Archives of the Lick Observatory).

parties landed under very hazardous surf conditions, which apparently was the norm for the island. Coconut-thatched huts were assembled for living quarters and two work buildings. Droves of mosquitoes and biting flies were present, yet Mrs Campbell managed to sit for a formal portrait on the back of one of the island's turtles (see Figure 40).

The Smithsonian Expedition set up their observing station 1,200 feet away, and on 23 December, a private British expedition of Francis and K. McClean, FRAS, arrived with its contingent of scientists from Australia and New Zealand.

At the Lick eclipse station the Repsold alt-azimuth was set up immediately so that positional sightings could be taken, and the remaining instruments were made ready over the following 12 days (Figure 41). The lumber for the 40-ft Schaeberle Camera was part of the cargo manifest. Two towers were constructed in the usual fashion, but it was not possible to dig a pit for the plate holder given the hard coral ground. The Floyd camera was mounted horizontally, receiving reflected sunlight from a coelostat mirror. The moving plate spectrograph also received its light by a coelostat mirror. The array of four polarigraphic cameras included a double-image prism camera, two larger cameras equipped with plane-glass mirror analyzers and one general camera used for unpolarized calibration purposes.

Fig. 41 The two 4-camera intra-Mercurial camera arrays in the foreground and the 40-ft Schaeberle Camera in the background among the palms at Flint Island in 1908 (courtesy of the Mary Lea Shane Archives of the Lick Observatory).

The Lick Observatory's mission for this expedition would be the most ambitious yet in terms of research objectives (Campbell 1908f; Campbell and Albrecht 1908a, b; Perrine 1908; Perrine 1909), and included:

1. To determine the precise latitude and longitude of the station and the eclipse contact times.
2. To carry out high-resolution coronal photography with the 40-ft Schaeberle Camera and the Floyd Camera (Campbell 1908a).
3. To continue the search for intra-Mercurial planets.
4. To conduct photometric measurements of the light from the corona and surrounding sky and a study of the total effective photographic action of the coronal radiation utilizing plates standardized with a Hefner lamp. Images were also to be taken of the sky when no clouds were present in order to determine the sky brightness in the immediate vicinity of the corona.
5. Using a moving-plate spectrograph to observe the spectrum of the Sun's edge as it is covered and uncovered by the Moon. This spectrograph could be rotated about its axis-of-incident light beam.

6. To make coronal and second contact flash observations with the quartz spectrograph in the ultra-violet region of the spectrum.
7. To observe the coronal spectrum, prominences and area over the Moon with the two single-prism slit spectrographs.
8. To make a spectrogram of the coronal green line with great accuracy using a three-prism high dispersion spectrograph.
9. To conduct polarization studies of the corona.

This would be the first time on a Lick Observatory eclipse expedition that a study of the heat radiation of the corona would be made using a bolometer. The world-renowned spectroscopic researcher, C.G. Abbot (1909), had begun this line of research during the 1900 eclipse.

On eclipse day it was raining heavily 5 min before totality but then the rain subsided and the protective tarps were hastily pulled off the instruments. A few thin clouds were present but the instruments – although wet – performed as planned. Eleven observers and 2 helpers operated the 20 instruments.

Albrecht made six exposures with the 40-ft Schaeberle Camera. Two of the plates had standard squares exposed with the Hefner amyl-acetate standard lamp the night before the eclipse. Mortimer made eight exposures from 0.5 to 8 s with the Floyd Camera. Coronal streamers were recorded out to two solar diameters and were uniformly distributed around the Sun.

This eclipse was lighter than the eclipses of 1898, 1900 and 1905, and the corona was rather remarkable for the number of very straight, long and slender streamers (see Figure 42). Observers were struck by the faintness of the middle and outer coronal structure (Campbell 1908c). According to Campbell (1908d), "There was a conspicuous conical pencil of radiating streamers … whose vortex, if on the sun's

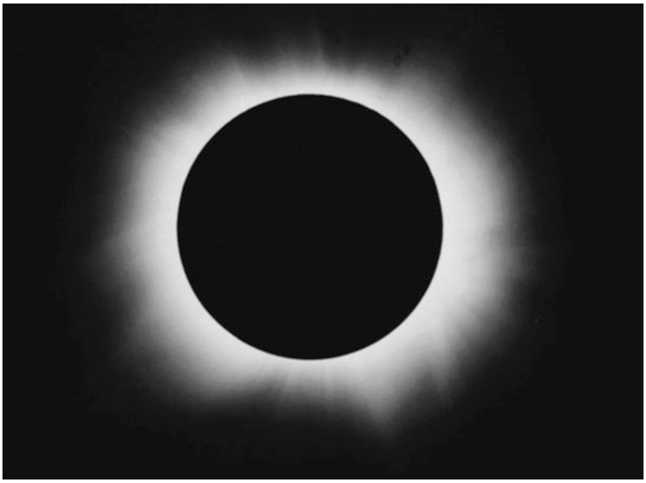


Fig. 42 The solar corona recorded with the 40-ft Schaeberle Camera (courtesy: Mary Lea Shane Archives of the Lick Observatory).

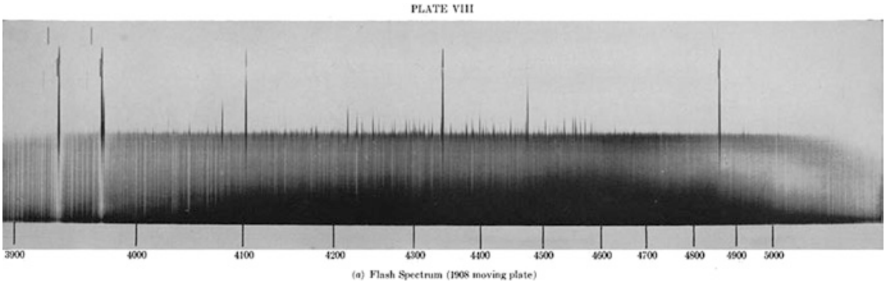


Fig. 43 A portion of the flash spectrum recorded with the moving-plate spectrograph (courtesy: Mary Lea Shane Archives of the Lick Observatory).

surface, would be within the largest sunspot group visible on June 3." Campbell and Albrecht (1908a, b) also observed a highly-unusual large disturbed region within the corona.

The moving-plate spectrograph recorded a continuous spectrogram of the solar spectrum before, during and after totality (Figure 43), as during the 1898, 1900, and 1905 eclipses. The resulting image showed hundreds of bright lines within the 3,800–5,100 Å region. As the photospheric surface of the Sun was uncovered by the Moon, the lengths, locations and thickness of the corresponding vapor strata with their changes into dark lines were recorded. This spectrum was found to contain a mine of information on the structure and composition of the Sun's higher atmosphere (Campbell, et al. 1908: 1–4).

No trace of the coronal green line was found on the negative from the three-prism high dispersion spectrograph. This failure might have been due to the strong absorption of the prisms and lack of sensitivity of the plate emulsion at 5,300 Å.

One of the party members, C.J. Merfield from Sydney Observatory, made images with the two single-prism spectrographs designed by Campbell. All had slits that extend east and west across the Sun's image. The first spectrograph recorded a spectrum of the coronal light diffused in the Earth's atmosphere and only the green 5,303 Å line and a bright line in the ultra-violet were present. The spectrum of the inner corona appeared to be free of dark lines that showed faintly in the spectrum of the outer corona and in the Moon's area. The plates from the other spectrograph revealed the coronal spectrum strongly, with good focus to 6,000 Å. There was a faint trace of a Fraunhofer spectrum in the violet region. Lewis' quartz spectrograph recorded bright coronal lines suitable for the determination of accurate positions from 3,200 to 5,100 Å. Several of the bright lines appeared to be new.

Perrine, Campbell and Dreher made observations of the effects of polarization on the coronal light using four cameras mounted on a clock-driven axis. Polarigraphic negatives showed the existence of strong polarization in the coronal light even up to the very edge of the Sun (ibid.).

After the eclipse, the Lick party joined the other eclipse groups and dignitaries for a joyful banquet which featured fresh turtle meat. They then processed their plates and boarded the *Annapolis* on 5 January. During the final stages of the loading there was high surf, making the exit process dangerous. Upon arrival in Tahiti they were hosted by Chief Tati Salmon, and Campbell made a point of visiting the location where James Cook had observed the 1769 transit of Venus to check Cook's sextant observations. The sea voyage to San Francisco was stormy but otherwise unremarkable (ibid.).

Campbell (1908d) later announced that he was ending the search for intra-Mercurial planets as a result of inspecting the plates obtained on this expedition and of the negative results from previous eclipses, but warned that

> It is not contended that no planets exist in the intramercurial region, but it is believed that undiscovered planets do not exist in sufficient numbers to provide the mass necessary to explain the anomalies in the motion of Mercury and the other minor planets.

Yet in the future, refinements in photography, instruments and the verification of Einstein's General Theory of Relativity would lead to a continued Vulcan search by the Lick Observatory.

4.10 The 21 August 1914 Expedition to Brovary, Russia

W.F. Crocker, his brother, and Phoebe A. Hearst funded what was considered a "… powerfully equipped eclipse expedition." to observe the August 1914 total solar eclipse from Russia, and Campbell decided on a site at Brovary very close to the center-line of totality (since the moving-plate spectrograph required this precise positioning).

The instruments, under the supervision of Curtis, were shipped separately on the *Czar* which reached Libau, Russia, on 8 July. Curtis and the equipment reached Kiev by rail on 11 July, while Campbell and the rest of the party traveled through Europe *en route* to Russia (Campbell and Curtis 1914).

After considerable effort, Curtis located a suitable site on an estate known as Datcha Lavrovskavo which belonged to Judge Lavrovskoy. Several buildings were made available to the expedition so that temporary accommodation and workrooms did not have to be erected. The instruments and supplies arrived on 18 July and Campbell and the rest of the eclipse party on the 21st. The full array of Lick Observatory equipment was set up in an orderly unhurried fashion (Figure 44) while Mrs Campbell saw to the management of the camp and supervised the hired indigenous workers. Camp life was described as pleasant and delightful (ibid.).

The observation plans covered a wide range of coronal and chromospheric science. In addition, the Einstein General Theory of Relativity verification project was to be the primary focus of this expedition. An overview of the work to be completed included:

1. To obtain large-scale direct images of the corona with the 40-ft Schaeberle Camera in order to reveal fine detail for structural and motion analysis.
2. To record the variability and intensity of polarized light within the corona.
3. To generate a spectrogram with a one-prism spectrograph of the general coronal spectrum for a study of its light distribution.

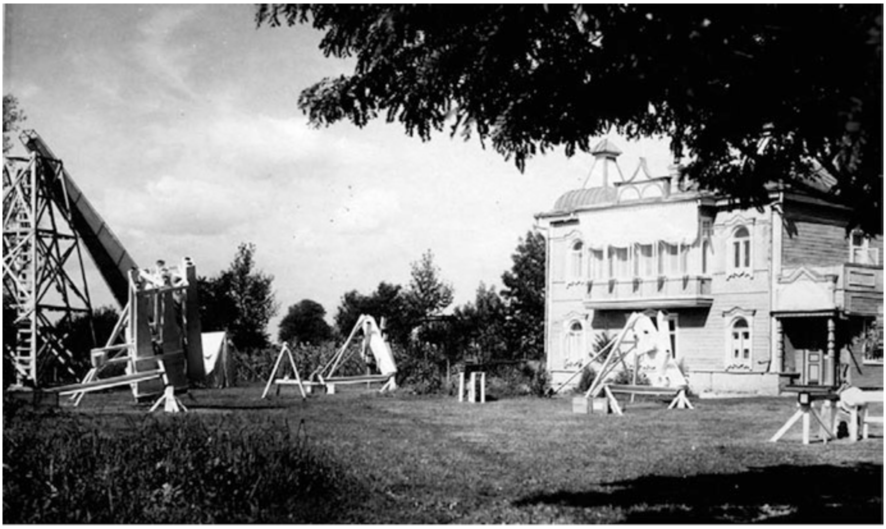


Fig. 44 General view of the eclipse camp instrument field at the Datcha Lavrovskavo estate, Brovary, in 1914 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

4. To make a spectrogram with a three-prism high-dispersion spectrograph in order to obtain a more precise determination of the wavelength of the coronal green line.
5. To study the gas distribution within the inner corona from spectrograms made with an objective-grating spectrograph.
6. To conduct photometry and to record the violet and ultra-violet regions of the coronal spectrum with an ultra-violet objective spectrograph.
7. To record the flash spectrum of the reversing layer with a moving-plate spectrograph.
8. To use direct photography of the outer corona and coronal form using the Floyd telescope.
9. To obtain star-field photographs with a four-camera array in order to test for starlight deflection as predicted by Einstein's General Theory of Relativity.
10. To search for intra-Mercurial planets using the same plates from the four-camera array.
11. To study the density of coronal matter with two long focal length cameras using standardized plates. The cameras were the former Vulcan cameras.
12. To obtain precise recordings of the second and third contacts and exact exposures with the moving plate spectrograph and with a chronograph connected to the 40-ft Schaeberle Camera and the shutter of the moving-plate spectrograph.

As if to thwart this ambitious program, cloudy weather totally obscured the eclipse.

By this time Russia was involved in World War I, and the expedition hastily packed its equipment and prepared to escape from the immediate war zone. There was a fear among the Lick group that local inhabitants might somehow connect the

Fig. 45 Some of the Russian dignitaries who visited the eclipse camp and helped the Lick Observatory party successfully leave the war zone (courtesy: Mary Lea Shane Archives of the Lick Observatory).

American eclipse party with the war in an unfavorable way. Russians under General Nicolskoy aided the party (see Figure 45), arranging special rail transport of the instruments to the National Observatory at Pulkowa where they would be kept in storage for the next 4 years. Meanwhile, members of the eclipse party successfully made it to Petrograd with the aid of the Russian Imperial Academy of Sciences and Professor Backlund from the Pulkowa Observatory, where they boarded a steamer which took them to the safety of Newcastle in England (ibid.).

The failure of this expedition to produce results due to weather conditions was accepted as one of "… the fortunes of war." (Campbell and Curtis 1914). Campbell was anxious to have the instruments returned to the USA, but did not want to expose them to unnecessary harm by transporting them through a war zone, so they remained in Russia for the duration of WWI (Merrritt 1915; Ziel 1915).

4.11 The 8 June 1918 Expedition to Goldendale, Washington, USA

Despite Campbell's requests the instruments left in Russia would not be returned in time for the June 1918 total solar eclipse, which was visible from mainland USA, so the Lick Observatory astronomers assembled what they could from existing and borrowed equipment during the relatively short period of time between 1 April and the first 2 weeks in May (Campbell 1918a, c). Professor Lewis made available his chronometer, chronograph, driving-clock and spectrograph slits; Burckhalter loaned the Chabot Observatory's Brashear lenses; and Leuschner made available a break-circuit chronometer, chronograph, sextant, theodolite, telescope driving clock and various spectrograph parts from the Student's Observatory at the University of California, Berkeley (Campbell 1918a).

Campbell consulted the "Average Weather Conditions in June" published by the USNO, and also considered the possibility of wild fires, common at this time of year in Northern California, and the possible last-minute return of instruments from Russia before deciding to locate the observing station at the farming village of Goldendale in the State of Washington. This site was situated to the east of the Cascades relatively near the Columbia River, and there was good rail access to and within one-third of a day's travel from Portland, Oregon. The Morgan family graciously agreed to host the expedition and provide their large home and outbuildings with all of the amenities required (Campbell 1918a, b).

From 20 May to 4 June, the volunteers, guest researchers and numerous other curious astronomers arrived. Long-time eclipse expedition philanthropists, Mr and Mrs W. H. Crocker, came in on 7 June and no doubt enjoyed the luxuries of the Morgan estate. The installation and positioning of the instruments on the lawn (see Figure 46) immediately west of the main house and about 140 feet north of the center

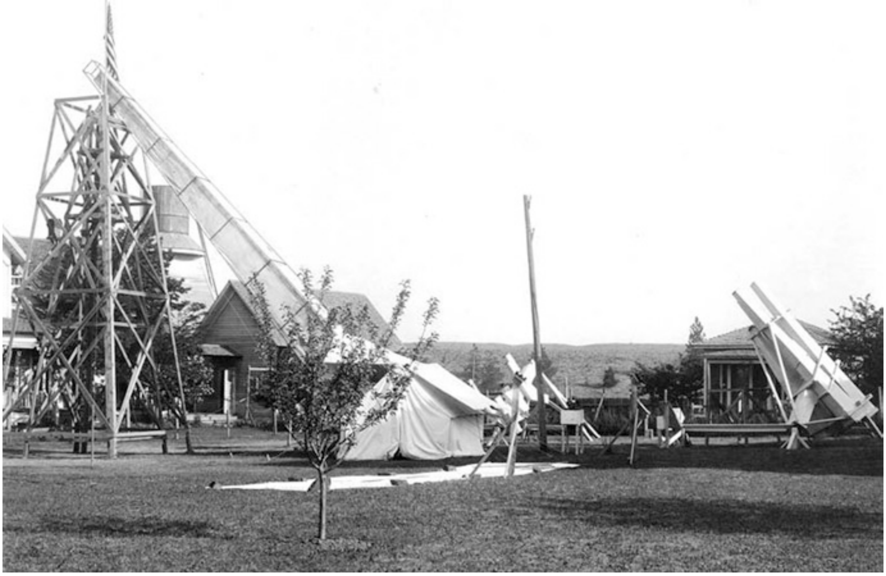


Fig. 46 The eclipse station at the Morgan Estate, Goldendale, in 1918 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

line of the main roadway went exceptionally well given the large number of helping hands. The towers for the 40-ft Schaeberle Camera were fashioned from local timber. Long forgotten, a 6-in. aperture 40-foot focal length Brashear lens that was obtained by the Observatory under Holden's tenure was installed on the camera. From the rail station, a chronometer was used to transfer time signals to the eclipse site (ibid.).

An ambitious program was planned with the modest instruments. Emphasis was placed on the intra-Mercurial planet search and photography dedicated to the Einstein effect verification (Curtis 1919). Photography to investigate coronal structure, form and motion would be accomplished with a complement of cameras of varied field coverage. Spectrographic studies would look at the coronal green line (Figure 47), particle strength and distribution within the corona, coronal elemental makeup and the flash of the reversing layer. Polarization studies of the corona would continue, in the same manner as during previous eclipses.

Eclipse day saw throngs of people gather in Goldendale to witness the eclipse, but it was cloudy. Remarkably, the clouds parted less than 1 min before totality, and closed in to cover the Sun a few moments after totality! According to Campbell (1918a), seeing conditions during totality were magnificent and the atmosphere was tranquil. The corona was unusually dark and intermediate between maximum and minimum type.

The direct photographic program ran as planned and a set of good quality plates was secured. From the 40-ft Schaeberle Camera's results it was rediscovered that the Brashear lens suffered ghost effects, yet useful information was obtained in that the exposures revealed beautiful groups of streamers that surrounded all of the

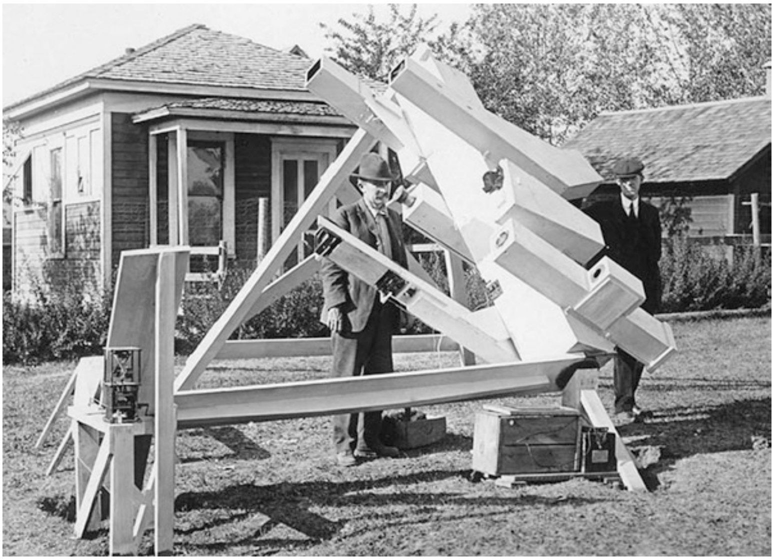


Fig. 47 Professors Moore and Lewis with the fixed-plate spectrographs mounted on a polar axis (courtesy: Mary Lea Shane Archives of the Lick Observatory).

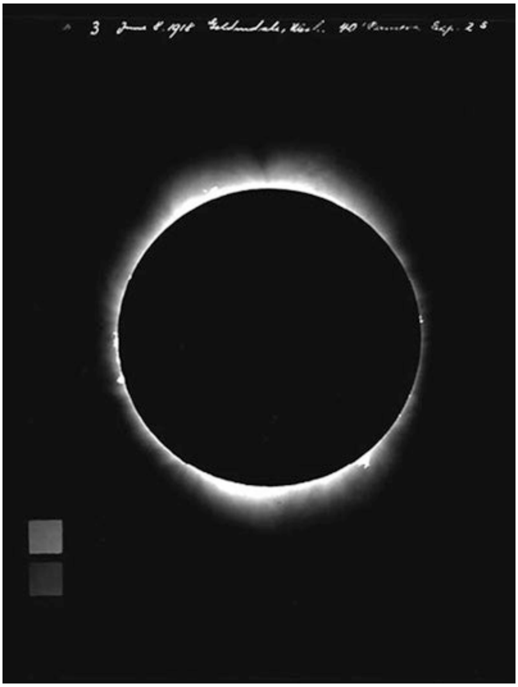


Fig. 48 The corona recorded by the 40-ft Schaeberle Camera with a short exposure revealed prominences and disturbed chromospheric areas. At the *bottom-left* are 'standardization squares' which were used to estimate coronal intensity (courtesy: Mary Lea Shane Archives of the Lick Observatory).

principal prominences (ibid.) (see Figure 48). Mrs Campbell made eight exposures with the 3-in. f/16 camera, and the resulting images of the general outline of the corona were the best obtained of all the instruments. L.B. Allen made eight exposures with the 11-in. camera and recorded coronal streamers east of the Sun out to three solar diameters.

The Einstein verification investigation, delayed from the clouded-out 1914 expedition in Russia, now received a second chance, and at the same time the associated plates would be examined for evidence of an intra-Mercurial planet (Curtis 1919). A good data set of field stars was recorded on the master plates of the four camera array and comparison plates, and although stellar displacements were noted, Campbell (1922b, c; 1923b) decided that the optical quality of the images was not fine enough to achieve the accuracy required.

The spectrographic program secured a variety of useful spectrograms. J.H. Moore, who was in charge of the simple one-prism spectrograph, recorded the general spectrum of the corona and the wavelength of the as yet unindentified green coronium line. There was some mystery as to the absence of the expected coronal lines in the streamer extensions (Campbell and Moore 1918a, b). A single three-prism spectrogram, provided by Moore, revealed the coronal spectrum to the east and west of the Sun, a comparison spectrum of iron between the two coronal spectra, and two outer comparison spectra of iron. The goal was to determine a more precise position for the coronal green line and to study the bright line spectra (Campbell 1918a, b; Campbell and Moore 1918a, b). The spectrogram from the

Rowland grating-objective spectrograph contained the elliptical third order green coronal line and a much shorter spectra depth than had been expected. An irregular distribution of coronal material was found to exist on the Sun's perimeter, with none present on the Sun's northern edge (Campbell 1918a).

Professor Lewis used his large two-prism quartz spectrograph to obtain a spectrogram which showed only two or three true coronal lines instead of the larger number recorded in 1908. A number of prominence lines was present, possibly showing the presence of scattered light within the corona. The flash spectrum from second contact consisted of only a few lines due to a late starting of the exposure. The flash spectrogram at third contact displayed nearly 250 lines. Lewis' small quartz-fluorite prism objective spectrograph provided an overexposed plate showing a double spectrum with the green line as the only coronal line. The plate would be further studied for any polarization of the line (ibid.; Lewis 1918).

Lewis' polarigraph, consisting of a double-image calcite prism camera, recorded the polarization of the corona. According to Lewis (1918), strong polarization was found out to the very limits of the corona. This strengthened the view that condensed metallic vapors were projected to great distances from the Sun (Campbell 1918a).

A general-purpose camera was operated by Miss Glancy who made five plates of the corona and surrounding sky through a set of colored filters. Dr Perrine of Cordoba would measure the spectral response found at predetermined regions of the spectrum (ibid.).

J.A. Brashear and A. Swasey made visual observations of the inner corona with a 2-in. aperture telescope but saw little to no detail. They and the other visual observers estimated the greatest visible extent of the east and west coronal streamers being from 1.5 solar diameters to 2.7 solar diameters (ibid.).

Six observers made precise detailed records of the shadow banding that preceding and followed totality. These bands moved from northwest to southeast and were monitored as they passed rods placed at strategic positions on white sheets. The velocity, period and time the bands were visible were all recorded. General readings with a standard thermometer were made before, during and after the eclipse; the temperature dipped 4°F during totality (ibid.).

It was anticipated that the reduced staff of the Observatory due to the war effort would delay any report of the expedition (ibid.), and as it turned out little in the way of results was indeed published.

4.12 The 21 September 1922 Expedition to Wallal, Western Australia

Given strong support from the Australian Government, Campbell convinced W.H. Crocker to finance a fair-sized expedition to observe the September 1922 total solar eclipse. The Lick Observatory station would be located at Wallal Downs, a sheep-telegraph-post station situated along Ninety-Mile Beach (now Eighty-Mile Beach), on the northwest shores of Australia (Burman and Jeffery 1990; Jeffery et al. 1989). This site promised clear skies and an eclipse with a totality of long duration. Campbell would lead the main party, assisted by two other staff astronomers (Campbell 1923b).

The first stage of the expedition began with just R. Trumpler, who travelled to Tahiti for the months of April, May and June in order to secure a set of plates of the star fields at night in the position where the Sun would be in September in order to test for the Einstein effect. He arrived in Tahiti on 10 April and set up the Einstein cameras on the estate of a Mr Fred Hawe. With assistance from an American, a Mr Lieber, the observations and production of the plates went well (Campbell 1922a, c; 1923b). Trumpler then arranged for the Einstein cameras to be shipped to Wallal, via New Zealand and Sydney.

The Campbells and the main eclipse contingent set forth for Australia on 7 July aboard the *Tahiti* and during a short stay in Wellington, New Zealand, were joined by Dr C.E. Adams, Government Astronomer of New Zealand. The expedition reached Sydney on 5 August where they met up with Trumpler and the Einstein cameras. Lieutenant-Commander Quick, R.A.N. and a small naval party was assigned to transport the group to Wallal, via Melbourne, Adelaide and Perth. In Melbourne they were joined by J.B.O. Hosking from the Melbourne Observatory, and in Adelaide an eclipse expedition from Toronto (Canada) boarded the vessel. They all reached Perth on 16 August.

Campbell had planned to leave the Tahiti plates and a measuring microscope at the Perth Observatory, but instead decided to ship them on to the town of Broome, nearer the eclipse camp. It was expected that Trumpler would made the first set of definitive star position measurements from these plates, but he had been caught up in long delays getting the eclipse cargo shipped to Fremantle (Perth's port). Campbell was quite disappointed by this turn in events. Professor A.D. Ross from the University of Western Australia and a Perth Observatory party then joined the growing group headed to their respective eclipse sites (ibid.).

From Fremantle, the Lick Observatory party embarked on the coastal steamer *Charon* for the 8-day trip along the Western Australian coast to Broome, then for the final leg of the voyage to Wallal they took the sailing schooner *Gwendolen*, which was towed by the steamer *Governor Musgrave* to speed up the passage. The women in the expedition transferred to the relative comfort of the steamer and enjoyed the considerable hospitality of the ship's officers while the men and instruments followed behind on the crowded sailing vessel (ibid.).

The anchorage near Wallal was reached on 30 August, and despite 26-ft tides along Ninety-Mile Beach the expedition found it relatively easy to off-load the equipment (Figure 49) and transport it to the eclipse site. Mr Davidson, head of the Wallal Downs sheep station, coordinated a small army of Aborigines along with donkeys and carts to assist with the moving of the freight (Campbell 1921; 1922a, c; 1923b).

The naval contingent, under Lieutenant-Commander Quick, took over the installation of the camp, assisted in erecting the instruments and performed many of the daily camp operations. Trumpler oversaw the erection of the 40-ft Schaeberle Camera and large ventilated buildings designed to protect the sensitive Einstein instruments (Figure 50). The towers of the Schaeberle Camera provided additional

Fig. 49 With the *Gwendolen* at anchor, the freight for the eclipse station is off-loaded at Ninety-Mile Beach, Western Australia, in 1922 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 50 White cloth was used to cover the 40-ft Schaeberle Camera, the Einstein instrument building and the tent at Wallal in 1922 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

shade for the Einstein cameras. The eclipse site and instruments were subjected to a continuous spray of fine dust which was of special concern in the darkroom, so in order to reduce this problem and limit heat radiation from the ground the Aborigines covered the ground with coarse sand and placed green branches around the instruments. On eclipse day, they sprinkled copious amounts of water on the ground surrounding the instruments (ibid.).

The Perth Observatory party under Curlewis determined the exact longitude and latitude of the 40-ft Schaeberle Camera and then estimated its height above sea-level. Time signals arrived from Bordeaux (France) by telegraph line and then were relayed to Campbell who received them from atop the Camera tower. Additional time signals were sent by telegraph line from Perth Observatory to Wallal and were used by Dr Adams to regulate the chronometer (ibid.). Adams assumed responsibility for providing the eclipse site with an accurate time service.

Although emphasis centered on the Einstein experiment, the coronal studies were continued in the Lick tradition. Coronal plates would be exposed with long, medium (Figure 51) and short focal length cameras for photometric brightness studies. A search would be made for evidence of motion within coronal structures by comparing the large-scale images from Wallal with images from the Adelaide Observatory expedition at Cordillo Downs (which was loaned the second Lick Observatory 40-ft camera). The two sites were 35 min apart on the path of totality. Plates of the partial phase taken with the Schaeberle Camera would be used to determine the relative positions of the Sun and Moon (Campbell 1922c; 1923b).

Campbell took charge of the guiding of the smaller Einstein cameras, while Trumpler guided the large Einstein cameras which was supported by a newly-designed

Fig. 51 The spectrographs and Floyd coronal camera. Mrs. Campbell has drawn the slide on the plate-holder of the Floyd camera (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 52 The 15 foot focal length Einstein cameras with their guide telescope on a redesigned polar mounting of great stability (courtesy: Mary Lea Shane Archives of the Lick Observatory).

equatorial mounting (see Figure 52). According to Campbell (ibid.), finding the correct predetermined guiding stars was a great challenge at second contact. Nonetheless, the developed plates contained numerous stars suitable for the proposed tests.

Moore was in charge of three spectrographs that were used to investigate the distribution of several of the corona's gaseous constituents. This was to be accomplished by analysis of the coronal bright lines and distribution of the Fraunhofer lines in the corona. It was hoped to assign more precise positions to the coronal bright lines, but these turned out to be surprisingly faint. It was determined that the light within the inner corona consisted mostly of continuous emission with a few bright lines and a lesser degree of reflected sunlight. It was further confirmed that the coronal lines were fainter at sunspot minimum. Moore's inspection of the spectrograms for any coronal radial motion yielded no results (Campbell 1922c; Moore 1923a, b).

A preliminary inspection of the photographic plates showed that the Sun was in a quiet state (Figure 53), with prominences and coronal structure appearing simple, small and regular. The lack of fine coronal structure would for the most part prevent the search of the Lick and Adelaide plates for evidence of motion (Campbell 1923b).

After the eclipse, the local Aborigines preformed a folkloric show and hosted a banquet for the astronomers. This was merely one in an almost endless round of 'receptions' from Governments, universities, the states' Royal Societies, various astronomical societies and other groups that Campbell and his party were treated to

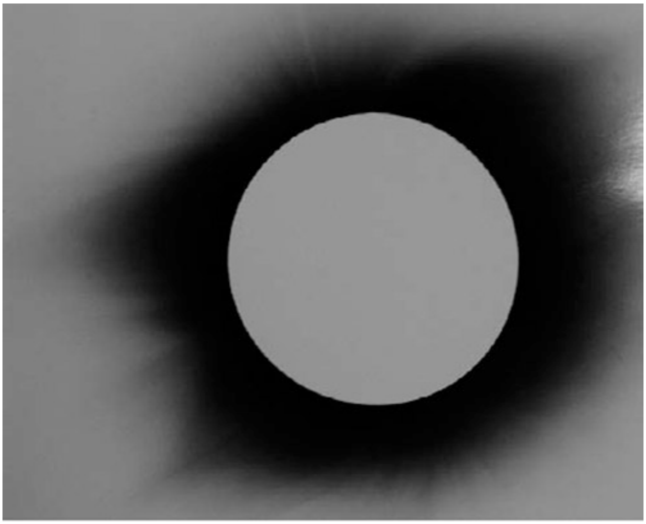


Fig. 53 A negative image of the corona made with the 40-ft Schaeberle Camera (courtesy: Mary Lea Shane Archives of the Lick Observatory).

while in Australia, and in return they gave numerous lectures and addresses (see Campbell 1922a, c; 1923b).

Upon embarking from Wallal the Lick party experienced mixed sea conditions: some of the instruments were loaded under fairly calm seas, but on one day huge seas from a recent storm swamped one of the boats carrying the steel parts of the Einstein cameras and they had to be retrieved on the outgoing tide. After loading, the schooner was taken in tow by the naval steamer *Geranium*, which reached Broome on 28 September. Here the rest of the eclipse plates were processed and a start was made on measuring the Einstein test stars. A week later the Lick Observatory party left for Fremantle on the *Bambra*, arriving on 12 October. Meanwhile, 600 pounds of photographic plates were sent separately to Sydney with the instruments. From Fremantle the eclipse party had to endure numerous steamer delays and seven train changes before reaching Sydney. The return voyage to San Francisco, via Auckland, Fiji and Honolulu, was made on the *Niagara* and the *Matsonia*, with the expedition finally arriving home on 21 November (ibid.).

One of the primary research objectives of the Lick Observatory team during the 1922 eclipse was to explore the ‘Einstein Effect’, and nearly all of the measurements of deflections of the test stars would occur back at the Lick Observatory (see Figure 54). Consequently, Campbell (1922d) wanted the Lick party back in the USA as soon as possible in order to begin the analysis, as reflected in the following rather impatient telegram which he sent while they were still in Australia: “Intense public pressure for Einstein results. Please make Swiss visit minimum possible.”

Back at the Observatory, the smaller Einstein plates were compared with the plates that Trumpler had exposed in Tahiti in a search for intra-Mercurial planets but none was found (Campbell and Trumpler 1923).

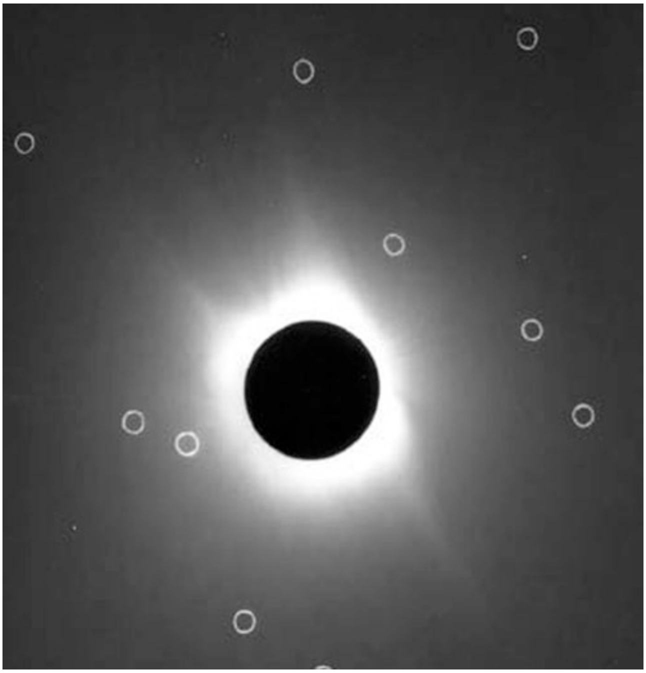


Fig. 54 A Wallal photograph of the 1922 total solar eclipse, with *circles* around the Einstein test *stars* (courtesy: Mary Lea Shane Archives of the Lick Observatory).

4.13 The 10 September 1923 Expedition to Ensenada, Baja California, Mexico

Campbell had the 'local' September 1923 Baja California eclipse in the back of his mind even before he planned the 1922 Wallal expedition. The Eclipse Committee of the American Astronomical Society, comprising W.W. Campbell, H.D. Curtis, J. Gallo, W.J. Humphrey, F.B. Littell and S.A. Mitchell, contributed to the development of the observing program.

Campbell received regular meteorological reports from the Mexican Weather Service and predicted that the chances of clear weather were promising in Ensenada. After a scouting trip with W.H. Wright, he decided to locate the instruments in a valley near the Santa Clara River (Figure 55) some 30 miles by road from Ensenada and 25 miles from the coast. The site was in a mountainous region of widely-scattered valleys accessed from Ensenada by rough roads that were subject to erosion following rain (Campbell 1921; Wright 1923). For some unstated reason, Campbell chose to pass over a much closer possible site, San Clemente Island, off the California shore. Just 90 miles from Los Angeles, the island also offered fair weather prospects.

Wright was assigned to direct this expedition, and it is worth noting that a large contingent of Lick Observatory staff would be present on this occasion, along with

Fig. 55 The 1923 Lick Observatory eclipse camp near the Santa Clara River in Baja California, Mexico (courtesy: Mary Lea Shane Archives of the Lick Observatory).

instrument-maker A. Swasey and one of C.J. Merfield's sons, Z.A. Merfield from Melbourne, Australia (Wright 1923). Transportation of the instruments to Ensenada was by truck with personnel using a prearrange stage service from the border to Ensenada.

Time and voice signals would be sent from the U.S. Navy's radio station on Mare Island to the Ensenada site by radio (Wright n.d.; 1923).

This was the first time the new standardization technique using the Hefner standard lamp and the Parkhurst 'sensitometer' box would be put into practice, and it took less than an hour; previously these calibrations had required an entire night's work (ibid.).

The addition of a declination axis to the traditional polar-axis permitted the placing of the instruments on the mounting on the day before the eclipse, and a simple adjustment of the declination-axis was all that was needed to correct for the daily change in declination of the Sun (ibid.).

Wright (1923) assembled a large program that focused primarily on coronal observations:

1. To photograph the corona with a wide range of image scales for the continuation of various Lick Observatory solar research programs.
2. To photograph stars in the vicinity of the Sun with the Einstein Cameras to measure the stellar displacement due to the Sun's gravitational field. From these measurements an attempt would be made to determine a law that accurately describes a star's displacement in relation to its angular distance from the center of the Sun.
3. To make photometric observations with the lensless cameras.

4. To confirm an earlier observation by Moore of the displacement of the coronal Fraunhofer spectrum towards the red.
5. To secure spectrographs in order for Moore to make a new determination of the wavelengths of the coronal 5,303 Å and 6,374 Å lines and to study the intensity of the emission exhibited by these two radiations in different parts of the corona. In addition, he would seek spectral data for the determination of radial velocities in the outer corona.
6. To record the continuously-changing spectrum of the Sun's limb at second and third contacts and at totality with Campbell's moving-plate spectrograph.
7. To accurately determine the geographical position of the eclipse site.

Additional observations were planned by Merfield who brought with him spectroscopic and polarigraphic instruments belonging to the University of Melbourne. Meanwhile, Wright planned to observe with a slitless quartz-fluorspar spectrograph.

Three days before the eclipse violent thunderstorms spread over the region, and although it cleared partially on eclipse day it clouded 1 h before the eclipse preventing any observations (Wright 1923).

4.14 The 28 April 1930 Expedition to Camptonville, California, USA

In a demonstration of how important the rare moments of a total eclipse can be to astronomers, Moore was selected to head a Lick Observatory expedition for the April 1930 eclipse which boasted a totality lasting just 1.5 s. Director R.G. Aitken labeled this type of eclipse as annular-total, and W.H. Crocker again agreed to provide the necessary funding. Extreme accuracy was required to locate the party on the very narrow 1 mile wide path of totality. The eclipse path was first derived from the *Nautical Almanac* with further corrections made by the Yale University Observatory. The Department of Commerce's U.S. Coast and Geodetic Survey computed the isostatic deflections of the vertical for the eclipse site and further corrected those figures by visual observations of abnormal densities in the Earth's crust so as to derive a very accurate longitude and latitude. From this information, a site was selected at Oak Valley, ~3 miles northeast of Camptonville, which offered the best chance of clear skies and being at a higher altitude would provide stable atmospheric conditions. Upon viewing the results of the observations at totality it appears that the calculation of the center line was the most accurate one ever made (Aitken 1929; 1930; Moore 1929; 1930).

Aitken and Moore planned to place one eclipse camera on the computed center line and two others about one-third of a mile to the north and to the south. The shortness of totality required fast exposure times, which precluded the use of the long focal length, narrow field cameras. Initially Aitken and Moore intended to send an airplane up to at least 10,000 feet, where an observer could capture a small-scale image of the corona, but this innovative plan was eventually dropped. The logistics of planning a flight in coordination with the military was a challenge, and it is also worth mentioning that J.M. Jeffers, a staff astronomer at the Lick Observatory, leaked these plans to the press and then tried to cover this up (see Campbell 1930; Galligan 1930; Moore 1930; Parker 1930; Van Horn 1930).

The ground-based instruments for the expedition were packed onto trucks 2 weeks before the eclipse for the trip to Oak Valley. Upon arrival at the eclipse site the weather changed from clear to cloudy, followed at times by heavy rain, but the instruments were set up during periods of fair weather. Time signals were sent by the United States Navy's radio station at Mare Island. It rained heavily on the day before the eclipse but by good fortune the clouds parted on eclipse day just 2 min before totality. The program of observations proceeded as planned except for the timing of first contact (Moore 1930).

Due to the shortness of totality, a very limited range of observations was planned. Emphasis would be placed on making a series of short exposures of the corona and producing spectrograms of the flash spectrum of the reversing layer. The spectral observations would be aimed at the chromosphere (Aitken 1929; 1930).

C.D. Shane was set to record with precision the times of the four contacts, but first contact was missed because of clouds. Nonetheless, he found that the central station was very close to the actual center line of totality (Moore 1930).

Cameras to record the corona were set up at three stations located some distance apart on the path of totality (see Figure 6 in this paper for a photograph of one of the stations). At the centerline location, the Willard camera and the 4-in. Ross camera recorded the prominences and innermost part of the corona with 0.25 s exposures. At a station some 1,500 feet SE of the central line, Meyer made a 0.5 s exposure with each of two cameras. One was a Ross camera similar to the one at the centerline station, and the other was a camera with a Goetz lens of 2-in. aperture. Blair set up the Floyd telescope 1,450 feet NW of the central line, and made a 0.5 s exposure. Near the time of second contact, a beautiful eruptive prominence extending 100,000 miles from the Sun's limb and accompanied by a disturbed area in the inner corona appeared on the plates at all three stations (ibid.).

Two regions of the chromospheric spectrum, from the K band to 4,713 Å and from the Hß line to the Hα line (i.e. 4,860–6,563 Å), were recorded using two 3-prism moving-plate spectrographs designed by Campbell. Both spectrographs (see Figure 8 earlier in this paper) received sunlight from the same coelostat mirror. The flash spectrum was recorded only at second contact due to the shortness of totality. On one spectrograph a slit was placed tangent to the Sun's limb with the width of one chromospheric layer. This was done to isolate this feature for recording the flash. The highest level chromospheric lines were recorded but the lower level lines were lost due to an error in synchronizing the exposure with the exact time of the flash. Standardization of the absolute photometric standards on the plates would provide an estimate of the absolute intensity of coronal emission and would permit comparisons of these plates to be made with those of other total eclipses. The green coronal line was successfully recorded and a value of 5,303.0 Å was assigned, which agreed with the results obtained by other observers (see Moore 1930; Moore and Menzel 1930).

4.15 The 31 August 1932 Expedition to Fryeburg, Maine, USA

The stated purpose of the August 1932 expedition, according to expedition leader Moore (1932: 344), was to continue the systematic accumulation of observations of total solar eclipses, especially those relating to the constitution of the solar corona and the chromosphere. These data would not only supplement those obtained previously by the Observatory, but in certain cases would extend back to earlier investigations through the use of improved methods and instruments (Aitken 1932a, b).

Aitken consulted meteorological reports and by May 1931 had decided to locate the eclipse station near Fryeburg, Maine, on the grounds of the Fryeburg Academy (see Figure 56) where the Principal, Professor Elroy O. La Casce and his Board of Trustees, were willing to host the visiting Lick Observatory group. There was good rail access to Fryeburg, and electric power and accommodation were readily available on campus, greatly simplifying logistics. Moore (1932) notes that throughout the expedition's stay in Fryeburg the local residents went out of their way to help in any way possible.

Prior to the eclipse, the instruments were assembled in the Observatory's workshop by foreman B. Olsen and instrument-maker J. Cosh. The four former Einstein 5-in. aperture Brashear-Ross photographic cameras replaced the 40-ft Schaeberle

Fig. 56 The Fryeburg eclipse camp of 1932. Instruments (*left to right*) are the jumping film, moving-plate and fixed-plate spectrographs and the coronal cameras (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Camera. Two of the cameras were of 5-foot focal length and the other two were of 15-foot focal length. The objective lenses were highly corrected for best possible stellar focus and producing an exceptional flat field. With these optical attributes, the Lick Observatory could continue obtaining the highest-quality coronal images. The technique of using shorter focal length cameras and then enlarging the images in the darkroom, proved highly successful. This eliminated the need to transport the large, difficult to set up, tower-type cameras for direct coronal photography. The smaller plate magazines permitted the rapid changing of plates compared to the handling of the large plates of the former instrument.

Pre-eclipse days were mild, with some clouds and occasional brief rain, and there was growing concern that the chance of clear skies on eclipse day was falling below the 50% margin. Eclipse day duly arrived, and there were decreasing clouds as the day progressed but then suddenly the Sun was obscured by clouds just 30 min before totality. Although clouds were present during totality, the eclipsed Sun and the corona were visible (Figure 57). The occurrence of an especially large Bailey's bead delayed the start of totality by a few moments which caused the determination of the mid-totality observation to be nearly 3.7 s off.

Three areas of investigations were implemented: general photography of the corona, the spectra of different levels of the chromosphere and the spectrum of the corona. Upon processing the plates, it was found to everyone's relief that the results were satisfactory. The coronal form was typical of that seen at sunspot minimum. The corona was especially brilliant and large prominences, fine coronal structure and highly-disturbed chromospheric areas were recorded on 18 plates (e.g. see Figure 58). One of the cameras recorded the corona in the light of the following colors: violet, green, red and in the infrared. There was a faint trace of the inner

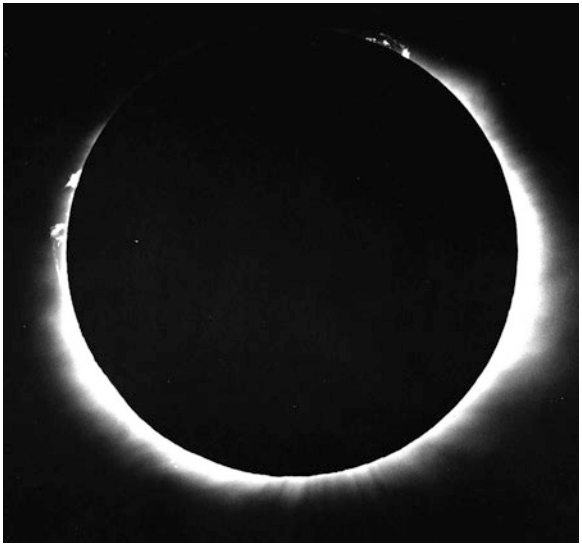


Fig. 57 A coronal image produced with one of the 15-foot cameras in 1932 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

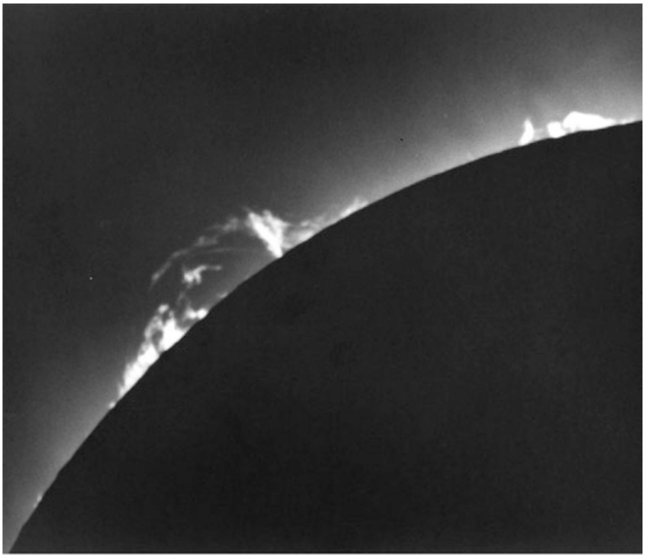


Fig. 58 An example of large prominences that were photographed during the 1932 solar eclipse (courtesy: Mary Lea Shane Archives of the Lick Observatory).

corona on the infrared plate, with the image increasing in strength inversely with the spectral sequence. This was believed to be a sign of exceptional strength at the shorter wavelengths (Moore 1932; Wright 1932).

According to Aitken (1932a, b), Menzel (1932), Moore (1932; 1933a, b) and Shane (1932), the aims of the spectral investigation were:

1. To more accurately determine the wavelength of the 5,303 Å green line in the coronal spectra using Shane's Fabry and Perot etalon interferometer spectrograph. Due to the precision of the instrument there was a possibility of recording motion within the inner corona. The spectrogram clearly showed the coronal green line to be wider than had been previously thought. Previous attempts using an interferometer to measure the exact wavelength of the 5,303 Å line had failed, as did this attempt.
2. To record the coronal red lines with a plane-grating spectrograph. The resulting spectrogram would be used to accurately determine the wavelengths of the coronal red lines at 6,374 Å and 6,775 Å. An exposure of 97 s gave no trace of the 6,775 Å line and only a very faint trace of 6,374 Å line.
3. To record the inner coronal emission lines using a one-prism spectrograph with an east-west slit and an iron spark comparison spectra. Only the stronger coronal emission lines were recorded and the coronal Fraunhofer spectrum was present. An analysis preformed later on the Fraunhofer spectrum indicated some signs of radial motion, however this was not at all certain.

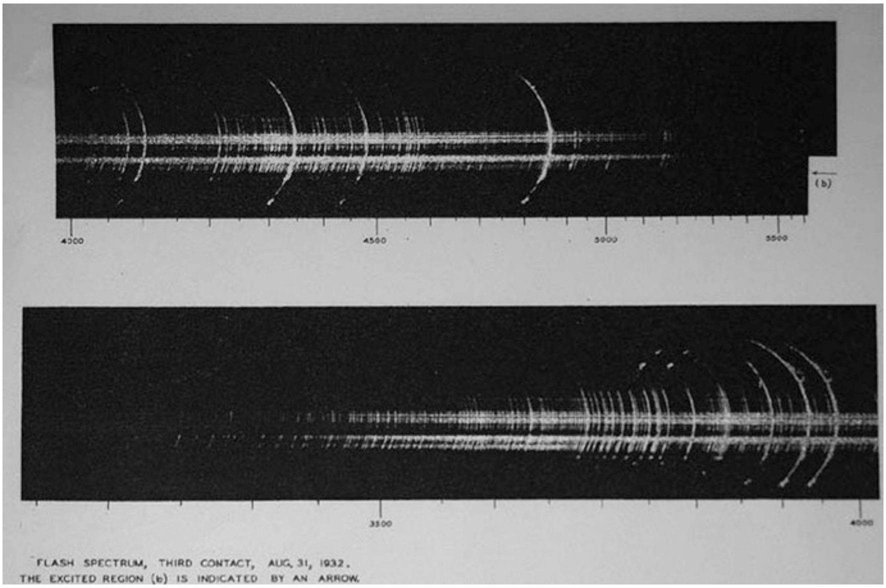


Fig. 59 Images of the flash spectrum, as recorded during the 1932 eclipse (courtesy: Mary Lea Shane Archives of the Lick Observatory).

4. To record the middle emission line coronal spectrum with a two-prism spectrograph with an east-west slit and an iron spark comparison spectra. Only the stronger coronal emission lines were recorded, along with the coronal Fraunhofer spectrum.
5. To record the outer coronal spectrum using a three-prism spectrograph with its slit set east-west and an iron spark spectra. Once again, only the stronger coronal lines were recorded and the coronal Fraunhofer spectrum.
6. To record the coronal spectrum within the infra-red using a concave-grating spectrograph. No results were achieved with this instrument.
7. To record the flash spectrum (see Figure 59) and the chromospheric spectrum from the lowest to highest levels, and make a continuous record of the regions covered from Hß to Hα and from the K band to 4,713 Å. To accomplish this task, two coelostat-fed moving-plate spectrographs were used (these are shown in Figure 8 earlier in this paper). A study would follow of the chromospheric spectra with a possible relationship to the corona.
8. To record the chromospheric spectrum with two jumping-film slitless spectrographs (these are shown in Figure 9 earlier in this paper), one focussed on the *UV* coronal spectrum and other, utilizing a plane Michelson grating, recording the visual coronal spectrum. Seventy-five spectrograms were obtained by advancing motion picture film frame by frame with short exposures, and fine detail in the chromosphere and prominences were recorded. Individual chromospheric spikes were revealed, as well as several *UV* rings. The red coronal ring was discovered to be more uniform about the Sun than the green line, with both appearing intensified in the region of particular eruptive prominences.

5 Discussion

5.1 Logistics and the Eclipse Expeditions

The Lick Observatory eclipse expeditions to distant continents or oceanic islands involved complex logistics at many levels. Delicate scientific instruments needed time-consuming preparations, including assembly and testing, and the Lick astronomers needed to know beforehand that their equipment would function efficiently and produce the desired scientific results. The instruments had to be carefully packed to survive rough handling and environmental conditions during their transport by ship, rail, pack animals and wagons over difficult terrain. Then there were the foreign customs agents *en route* and at the destinations who enforced rigid rules governing the entry of the parties and their equipment. Advance approval of the host governments and their involvement with customs procedures was often necessary. Obtaining supplies within a host country could never be taken for granted, and it was often necessary to bring from the USA all relevant tools and construction materials.

Sufficient time before totality was needed to select volunteers and train them to accurately make the required observations during the brief moments of totality. The professional astronomers on the expeditions also needed time to set up the instruments, establish a reliable local time-service, determine the latitude and longitude of the eclipse station and practice their observing routines. The astronomer charged with the duty of bringing all these things to pass was often an anxious optimist, but at all those times when he needed assistance there are men ready to help him (see Campbell and Perrine 1906). One important aspect was learned on these expeditions: although the success of the science program was critical, equally important were the careful planning and execution of the expedition's logistical and its human needs.

5.2 Improvements in Determining the Eclipse Station Coordinates

The *Nautical Almanac*, sextants and chronometers were used to determine the exact latitude and longitude of the first Lick Observatory eclipse stations, and repeated sightings were made to statistically derive the positional coordinates. Average time estimates were often obtained using multiple chronometers. Latter expeditions relied upon improvements in calculations, chronometers and time services. Time signals could be received by telegraph wire or radio transmission, and their accuracy improved over the decades. Even the source of the time services changed as the role of local observatories was usurped by the United States Naval Observatory, which issued time standards directly or from its official stations. By 1930, the coordinates of an eclipse station could be computed with considerable accuracy, as the account of the 1930 eclipse expedition to Camptonville in Sect. 4.14 above revealed.

5.3 *Lick Observatory Solar Eclipses and the General Public*

During the first Lick Observatory solar eclipse expedition members of the Amateur Photographic Association of the Pacific Coast drew and photographed the eclipse, commencing a pattern of close cooperation between the local amateur astronomical community and the professional astronomers on Mount Hamilton. According to Aitken (1917), amateur astronomers made a significant contribution to the analysis of the coronal structure of the Sun. Holden's organization of the local groups that later became the Astronomical Society of the Pacific was a fortunate occurrence for the future of the Observatory in terms of active public support and the publication of results. Meanwhile, the Observatory's commitment to popularizing astronomy continued down through the decades, with the staff always willing to come down from the mountain and lecture at various public venues. The Observatory also made a point of sending out astronomical information through press releases to the newspapers and other media outlets.

5.4 *The Three Main Eclipse Astronomers at the Beginning, and Value of the Plates*

It was the merging of the highly-regarded talents of three men – E.E. Barnard, S.W. Burnham and J.M. Schaeberle – that successfully launched the acclaimed direct photography program of the Lick Observatory eclipse expeditions.

Barnard was a professional photographer before joining the Lick staff. His experience no doubt was responsible for the fine coronal image he obtained in January 1889, made with an instrument intended to monitor water levels in the reservoir that supplied water to raise and lower the floor in the dome of the 36-in. refractor. Barnard only resigned this for eclipse after he had completed a comprehensive photographic survey of the Milky Way (although this was only published in 1913). He was disgruntled with Holden and was also fighting with Burnham on a regular basis.

Burnham was a skilled photographic processing technician and an expert on emulsions. He had a knowledge of chemistry and control of developer solutions, and was capable of manipulating the darkroom processes to reveal maximum detail in the photographic images.

Schaeberle was a skilled telescope-maker with a background in optical theory and was schooled in astronomy and mathematics. He designed and built the 40-foot Schaeberle Camera that produced the large-image plates that the Observatory became famous for. He also produced the Mechanical Theory of the Solar Corona, the only coronal theory to originate at the Lick Observatory during the nineteenth century.

With the passage of time, the Lick Observatory eclipse plates, but especially the large-scale plates, would prove invaluable for research. Short exposures captured features found in the bright inner corona which could be compared with prominences that were present on the same day. Longer exposures recorded the coronal rays and streamers which can be inspected for any changes. Plates made by cameras

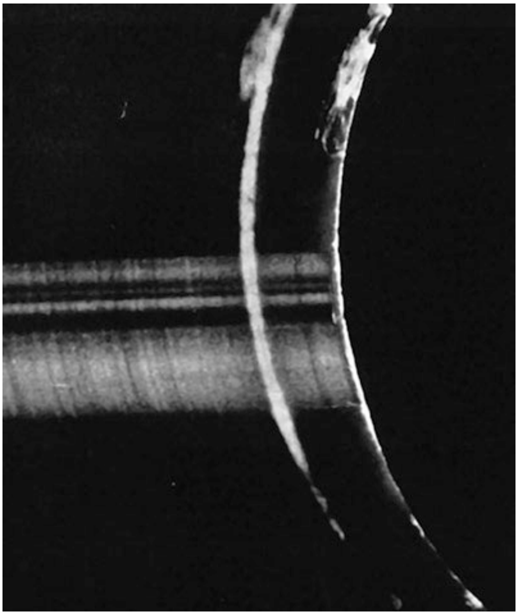


Fig. 60 Comparison of K-line spectra and photographs of the chromosphere taken with the 40-ft Schaeberle Camera during a Lick Observatory solar eclipse (after Menzel 1931).

miles apart could be inspected for motion-related changes. Features on the plates could be compared with spectrograms obtained during the same eclipses (e.g. see Figure 60). Over the years, plates obtained with the 40-ft Schaeberle Camera were used extensively by J.A. Miller (1911), and Menzel (1931a) (e.g. see Figure 61). Much later, Eddy and Goff (1971) produced an atlas of the white light corona using plates obtained during the Wallal 1922 eclipse and Eddy (1973) published a paper titled "Observations of a possible neutral sheet in the corona" which was based upon data contained in the eclipse plates.

5.5 *Women and the Lick Observatory Eclipse Expeditions*

Unlike the colonial culture that the scientific British adhered to which was male dominated and in which women were not in general, official members of an expedition (e.g. see Pang 2002), there are numerous instances of women – either spouses of the staff astronomers or independent volunteers – who were on the official rosters of the Lick Observatory solar eclipse parties. They assisted at many levels, although their names were rarely prominent or their duties listed in the published reports of the expeditions. They did much more than plan meals, wash dishes (see Figure 62), iron clothes and perform typical house-hold duties. They were called on to operate the instruments on eclipse day (e.g. see Figure 51 earlier in this paper), manage and implement camp logistics and give the men support in times of distress and illness. It was the women who helped relieve the astronomers of a significant portion of the stress and anxiety relating to the non-scientific field work. In fact, Mrs Campbell

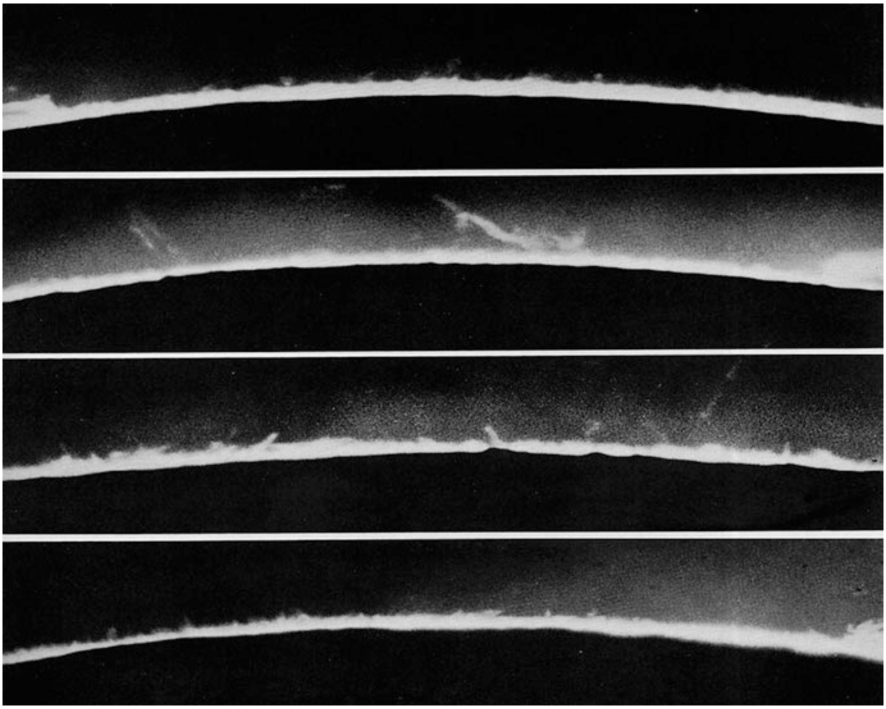


Fig. 61 Photographs of the chromosphere taken with the 40-ft Schaeberle Camera in (*top to bottom*) 1898, 1900, 1905 and 1918 (courtesy: Mary Lea Shane Archives of the Lick Observatory).

Fig. 62 This long-controversial photograph helped reinforce the unfortunate stereotype that women only did menial 'household' type tasks on Lick Observatory solar eclipse expeditions (courtesy: Mary Lea Shane Archives of the Lick Observatory).

(1908g) was encouraged to go on the 1908 Flint Island eclipse expedition as she was the only one with the skills to manage the camp and supply logistics.

In all, Mrs Campbell attended six expeditions, from 1898 to 1922, and her diaries provide a vivid, detailed, non-scientific summary of several of these, although she for some reason rarely mentions other women in the group. Her accounts provide information on the relations between the astronomers and the indigenous populations encountered, and on social interactions with their colleagues, with the volunteers and with their spouses. The life of the expedition was largely seen outside the immediate agenda of the Observatory, and aspects were glimpsed that never graced the pages of the ‘official’ published reports. This was especially true in regard to psychological weaknesses or health-related issues of individual astronomer. Everyday eclipse station life was overviewed outside the thought and minds of the astronomers who were preoccupied with preparation of the instruments and anxiety about the final critical moments before the eclipse when everything had to be ready. As Mrs Campbell (1898a) poignantly noted, “There is never any sleep for the men in charge the night before an eclipse.”

Despite their invaluable support role, there is no evidence that women conducted any of the serious scientific work on any of the Lick Observatory eclipse expeditions. They did not perform astronomical calculations, design any of the scientific instrument or propose any theories or hypotheses regarding the solar corona. Yet, Mrs Campbell believed that she was a vital part of the expeditions. Would the expeditions have failed without her presence? It was clear that a form of anarchy would have prevailed more than once had it not been for her calming presence, her eloquent decision-making and her ability to work well under extreme pressure.

5.6 Publication of Eclipse Expedition Results

Publication of the results of the Lick Observatory’s solar eclipse investigations almost always involved funding difficulties, and it would take years before the manuscripts reaching the state publishing house, which itself was usually overburdened with government printing commitments. A partial solution to this dilemma came with the founding of the Astronomical Society of the Pacific, and the society’s journal, the *Publications of the Astronomical Society of the Pacific,* became an unofficial publishing arm of the Observatory.

But before this happened the Observatory published reports on the first three expeditions in the *Contributions from the Lick Observatory*, a publication that was released at irregular intervals in the early years. This series was later published under the name *Publications of the Lick Observatory.* The Observatory continued to print eclipse reports in the *Lick Observatory Bulletin* which was released on a more regular schedule. Occasionally, eclipse-related articles would appear in the *Lick Observatory Leaflets*.

Sometimes the expedition funding aided the publication of results, but at least in one particular case it did not. Holden once used an expedition’s earmarked funds to publish his own lunar atlas, which in itself was mired in controversy (for details see Osterbrock et al. 1988: 93).

The Lick Observatory directors fared little better when they released larger, more expensive eclipse publications despite their potential value to the astronomical community. An example may be found in the following letter from Campbell (1904b), where he seeks funding to produce an atlas-style publication of the images obtained with the 40-ft Schaeberle Camera and smaller cameras, along with photographs of spectra, eclipse instruments and eclipse camps:

> It is not stating the case too strongly to say that the eclipse work of the Lick Observatory has been on a much larger scale and more successfully conducted than that of any other institution. The first large-scale photographs of the solar corona were made by our expedition to Chile in 1893, and the results were secured far in advance of any astronomer's expectations. The series of photographs at the three succeeding eclipses were equally successful. These results have now led nearly all eclipse observers to plan for the taking of large scale photographs; but we made the start, and no other institution has a service of coronal photographs at all comparable with ours. There should be published for each eclipse, a short exposure showing the inner corona on a large scale; a long exposure showing the details of the corona farther out; and a still longer exposure showing the streamers of great extent. There should also be published photographs of the corona secured with smaller instruments to show the general outline forms of the various coronas, and also photographs of the corona spectra secured at three eclipses, copies of double-image photographs obtained to determine the quality of the coronal light; photographs of the special instruments; and photographs of the four eclipse camps. Thirty images would be required. The large coronal photographs 12 in number will cost in the vicinity of $100. Each plate and the 1,500 sheets, the 18 small photographs will cost from $50 to $60 per plate and 1,500 printed copies. Total cost is $2,250.

5.7 Erroneous Coronal Brightness Measurements

The Lick Observatory's photometric coronal measurements during the 1901 eclipse were subject to possible significant error due to the unpredictability and misuse of the standard Carcel Oil lamp. Holden chose this particular standard lamp in order to replicate the procedures set in place by E.C. Pickering at Harvard College Observatory during the 1886 eclipse. Pickering and Pickering (1895) employed standard light squares on the plates exposed by a Carcel oil lamp. This procedure was also independently suggested by Captain W. de W. Abney in Abney 1886. However, just when Holden began using the Carcel lamp in 1889, Harvard was discontinuing its use in favor of a pentane lamp that provided a more stable light output. The Carcel lamp's output stability was highly dependent on the curves of a specially-made glass chimney, and although the Lick Observatory's Carcel lamp's chimney was missing Holden insisted on its use anyway in 1889 which resulted in a confrontation between Burnham, Schaeberle and Holden. Burnham and Schaeberle could not produce repeatable results because of continued instability of the lamp output and they became frustrated. Holden (1890d) then sent the following memorandum to them:

> To take a case – in speaking of the standard lamp which this Observatory adopted in 1888, in order that our results might be comparable with those of the Harvard College Observatory which was then and is now using such a lamp, you refer to it as "the so-called standard lamp" … The defects of the lamp are known to Professor Pickering and to me … the question cannot be disposed of by a sneer. If treated at all, it must be treated seriously & scientifically … There is no question as to your perfect right to express any scientific opinions you may reach. The point is that if you differ with the principles laid down in your instructions, you are bound to discuss the subject in full, or not at all. A mere expression of your belief as a mere epithet is not enough – so it seems to me …

Barnard (1892) subsequently sent Holden a lengthy memo stating that he refused to standardize the 1893 eclipse plates with the lamp as he felt that the procedure placed the plates at great danger of light fogging. In 1905 the Carcel lamp was eventually replaced by the Heffner standard lamp.

Another source of error was discovered when the light values of the standard squares were seen to change over time. Originally the squares were exposed at the Observatory well before the eclipse, but this procedure was changed and the standard squares were then exposed in the field shortly before totality.

5.8 The Mysterious Coronal Green Line

The true identity of the coronal green line at 5,303 Å (*coronium*) evaded the Lick Observatory astronomers. Great effort was expended in recording this line with a variety of spectrographs, with Campbell pinning down the line's position with a precision that compared with the best of measurements made by other international astronomers. Menzel was certainly on the trail with his projections of highly ionized atoms in the chromosphere and corona. Investigations by B. Edlén from 1936 to 1939 and by Grotrian in 1939 determined that the green line was due to iron in a very highly-ionized state, with electrons in the forbidden transitions.

5.9 Verification of Einstein's General Theory of Relativity

The scientific community currently applauds the findings of Eddington's party during the 1919 eclipse, yet the British recommended that further measurements be made at subsequent eclipses as the image quality on the plates obtained by the two British expeditions was an issue. For example, the Cambridge expedition at the Isle of Principe in West Africa had image problems as a result of its coelostat mirror feeding light to the horizontally mounted telescope, while the plates obtained by the Greenwich party at Sobral in Brazil also suffered from image quality. Measurements taken on the combined plates averaged close to the theoretical calculations (see Young 1969: 423–424).

Lick Observatory Director, W.W. Campbell (1923b), could not see the logic of assigning greater weight to Eddington's plates over the Brazilian plates, and indeed it was Eddington's group that insisted that a truly definitive test should be undertaken during the 1922 eclipse. Campbell decided to conduct this test on behalf of the Lick Observatory at Wallal (Western Australia), using optically-superior instruments that corrected for the optical defects of the British equipment. According to Burman and Jeffery (1990), Campbell selected the Wallal site over the strong objections of the British, but was highly encouraged by Professor Ross from the University of Western Australia. As soon as they had finished their measurements of the test stars observed at Wallal Campbell (1923a) sent a telegram to Berlin stating that

> … three pairs Australia, Tahiti eclipse plates measured by Campbell and Trumpler, sixty two to eighty four stars each five or six measurements completely calculated give Einstein deflection between one point fifty nine and one point eighty six seconds arc mean value one point seventy four seconds.

Later measurements of Lick Observatory plates were even more in agreement yielding a mean of 1.75 ± 0.09 in. of deflection.

After the Lick Observatory expeditions had ended, Wright (1933) mentioned that the total eclipse of 1934 would be the last total solar eclipse prior to the 1950s that would present a good bright star field necessary for this test.

5.10 Solar Physics Comes of Age at the Lick Observatory

The only major coronal theory to emerge from the first Lick Observatory expeditions was Schaeberle's Mechanical Theory of the Corona which was based on gravitational mechanics (see Schaeberle 1890a; 1891a; 1895) and was developed between 1889 and 1995 – see Figure 63 (and also Figure 24 earlier in this paper). Holden (1890g) wasted no time in alerting Agnes Clerke to Schaeberle's work. Holden (1893) was staunchly promoting the theory when he contacted Sir Robert Ball offering material and eclipse photographs for his upcoming book. Yet it was the 40-ft Schaeberle Camera, the very instrument that Schaeberle used during the 1893 eclipse to refine his theory, that ended up revealing coronal detail that did not entirely agree with his findings. Miller used plates from the 1893 through 1905 eclipses to evaluate Schaeberle's theory, and while he agreed with many points he felt that others needed to be modified (see Miller 1911).

Holden heard of Bigelow's theory that the appearance of the solar corona was in part due to magnetic forces. In 1890 he contacted Bigelow (Holden 1890b), stating that he did not fully understand the theory and looked forward to reading more about it. Meanwhile, at about the same time Schaeberle (1890b) was querying Bigelow about some of his findings.

Rather surprisingly, no coronal magnetic studies emerged from the Lick Observatory solar eclipse expeditions despite the great advances made by George Ellery Hale at the Mt Wilson Observatory in 1908. In addition, it is likely that solar physics would have advanced significantly faster during the Lick Observatory's first decade of operation if Keeler had applied his considerable spectrographic and photographic skills to solar eclipses instead of reserving them for galactic and extragalactic targets.

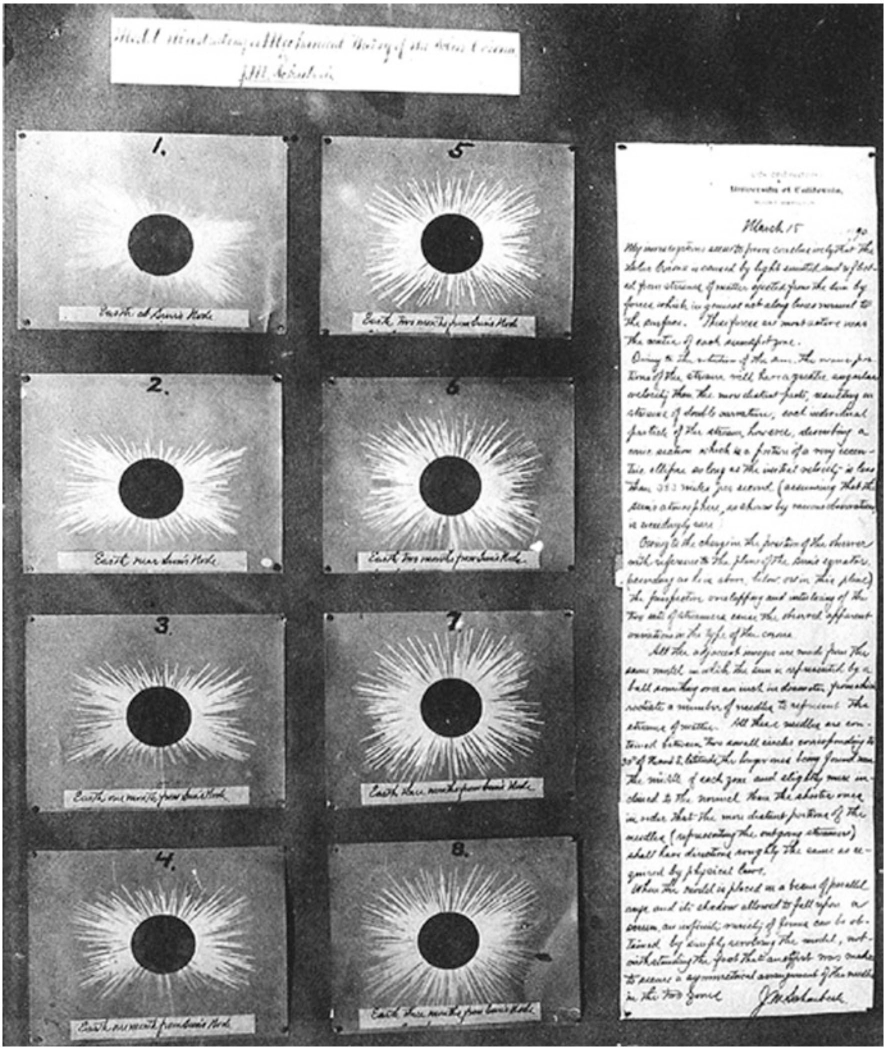


Fig. 63 Eight photographs of a model with *wire pins shaped* to represent solar streamers. The eight images show views of the corona as seen from various terrestrial observing positions during different solar eclipses (after Schaeberle 1891b: Plate VI).

Instead, it was only in 1926 when Menzel was hired that the nature of solar physics changed markedly at the Lick Observatory. Menzel was appointed upon the recommendation of his mentor and professor, H.N. Russell, a highly-accomplished and noted Princeton astrophysicist. Menzel went on to conduct a comprehensive study of the solar chromosphere based upon Lick Observatory photographic plates taken during the 1898 to 1908 eclipses and spectrographic plates made used Campbell's moving plate spectrographs (Golub and Pasachoff 1997: 170–172)

Menzel would apply his keen knowledge of atomic physics to measure the total emission from different layers of the Sun and then find the strength within each layer by the process of subtraction. He discovered that the high temperatures that he found within the outer chromosphere could not be explained by the ordinary classical laws of thermodynamics that the observing class of astronomers believed in. Additionally, he predicted a high abundance of hydrogen in the Sun. Menzel (1931) published his work in the *Lick Observatory Publications*, but his most controversial atomic proposals were edited out by Lick Director, Robert G. Aitken. Menzel (ibid.) then published his previously-edited theoretical findings in *Monthly Notices of the Royal Astronomical Society*.

Menzel resigned in 1932, after the last Lick Observatory solar eclipse expedition, taking up a faculty position at Harvard where he went on to build a distinguished research career. His proposal that the high temperatures which increased outwards in the chromosphere were the direct result of turbulence was considered by Golub and Pasachoff (1997: 172) to be one of the great advances in solar physics.

5.11 Why the Lick Observatory Eclipse Expeditions Ended

The solar eclipse expeditions were discontinued after 1932 even though Aitken had published that these field studies were highly valuable. A good part of the scientific program of the 1932 expedition had to do with Menzel's proposals and upon his departure there was no one with his ability or interest to continue this line of work. There is no mention in the reports of the Observatory of plans to attend any further eclipses.

It is notable that Bernard Lyot had introduced the chronograph in 1930, and by 1932 he was publishing results based upon photography of the corona in daylight. His use of motion picture film permitted him to record the corona for durations of many hours. Aitken (1933) was aware of Lyot's work and recognized it as one of the great advances in observational astronomy. He realized important research could be conducted without expedition travel. Yet the Lick Observatory eclipse expeditions ended on a positive note with Russell (ibid.) writing Menzel that this work "… justified all the observational efforts that had been expended on the Lick eclipse expeditions."

6 Concluding Remarks

For more than four decades solar eclipse expeditions were an important element in the Lick Observatory's overall research portfolio, and considerable time, effort and funding were expended on pressing innovative new instruments into service and dispersing expeditions to the far corners of the globe for what eventually amounted to a paltry total of just 39 min of totality. Although some of America's leading astronomers were involved in these expeditions, no major breakthrough in coronal science occurred, partly because the Lick Observatory was slow to adopt new concepts incorporating solar magnetic fields championed by Mount Wilson Observatory's George Ellery Hale. By the time the Lick Observatory decided to abandon solar eclipse expeditions France's Bernard Lyot's had invented the coronagraph, which offered astronomers ready access to the solar corona outside of eclipse situations. Solar astronomy had changed forever and the Lick Observatory would never again venture into this specialized field.

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The following abbreviation is used:

SA = Mary Lea Shane Archives, University of California at Santa Cruz.

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The Total Solar Eclipses of 7 August 1869 and 29 July 1878 and the Popularisation of Astronomy in the USA as Reflected in the *New York Times*

Stella Cottam, John Pearson, Wayne Orchiston, and Richard Stephenson

Abstract Solar eclipses have long fascinated the general public and served as a means of popularising astronomy. During the nineteenth century a number of different total eclipses were visible from the United States, and in addition to generating enormous scientific interest these created considerable popular appeal. Here we trace the ways in which the total solar eclipses of 1869 and 1878 were portrayed in the *New York Times*, which helped generate a groundswell of interest in amateur astronomy in this country.

1 Introduction

Since time immemorial man has been fascinated by total solar eclipses, those rare totally unforgettable events that, prior to the advent of rapid international air travel and committed ‘eclipse-chasers’, rarely greeted an individual more than once in a human lifetime. During the second half of the nineteenth century total solar eclipses assumed an important role in international astronomy as photography and spectroscopy helped unravel the true nature of the solar corona (see Pearson 2010). This was also an era when education was extending out to the masses and with leisure time on their hands increasing numbers of people turned to astronomy as a hobby. The total solar eclipses of August 1869 and July 1878 were both visible across the USA and – weather permitting – offered very large numbers of individuals a once-in-a-lifetime chance to witness a truly amazing astronomical spectacle. In this paper we will examine the role that these two solar eclipses played in furthering coronal science, and how they also served to educate the public through the pages

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of the *New York Times* newspaper. But before embarking on this quest, we must review the nature of coronal studies in the decades leading up to the 1869 eclipse.

The idea that the corona might belong to the Sun was first put forth by Don Jośe Joaquim de Ferre at the total eclipse of 16 June 1806. He felt that the bright illumination around the Moon, far exceeded the extent that his calculations predicted for a lunar atmosphere and was nearly 50 times higher than the Earth's atmosphere. He concluded that "Such an atmosphere cannot belong to the Moon, but must without any doubt belong to the Sun." Unfortunately his views did not resonate with his colleagues at the time (Clerke 1902).

Through into the 1820s some weight was given to Sir John Herschel's theory of the composition of the Sun and its atmosphere. Herschel hypothesized that the Sun, as a solid body, was encircled by a high layer of dense clouds. The solid body beneath this cloud layer could harbor life. Sunspots and brightness variations, he surmised, were openings in the clouds revealing the dark solid body below and variations in the clouds themselves. Furthermore, based on this hypothesis, Herschel used hydrostatic laws to declare these features would fill up if the Sun's surface were a liquid (Ress 1822; Vose 1827).

During the nineteenth century, four different methods were used to observe and record the nature of the solar corona: (1) visual telescopic observations of coronal color, form, and internal structure; (2) the generation of permanent records by means of drawing and photography; (3) the application of the polariscope to measure scattered light within the corona; and (4) the application of the spectroscope to determine the chemical composition of the corona.

Eclipse photography was a great step forward, but it began as a cumbersome process, utilizing wet emulsions of low sensitivity that required lengthy exposure times. These materials could only record the brightest of coronal light close to the limb of the Sun. The chemicals used to process the plates were difficult to handle and lacked stability. It was only at the beginning of 1870 – in the year following the 1869 eclipse, which is the focus of this paper – that the dry plate photographic process came into use for coronal imaging. Dry plates were more sensitive, allowing shorter exposure times and recorded fainter coronal detail.

The first attempt to photograph a total solar eclipse was made in 1842 when G.A. Majocchi made daguerreotypes and paper images using a 6-in. lens and bromide of silver coated paper. The feeble images which he obtained failed to record the corona during a 2 min exposure and were considered of no scientific value (Ranyard 1879). Contrast this with Francis Baily's visual observations: "… I was astounded by a tremendous burst of applause from the streets below, and at the *same moment* was electrified at the sight of one of the most brilliant and splendid phenomena that can be imagined. For at that instant the dark body of the moon was suddenly surrounded with a *corona*, or kind of bright glory." (Mitchell 1923: 133).

This was the first total solar eclipse where the form and structure of the corona were described in detail by a host of observers (see Proctor 1871: 322–323; Ranyard 1879: 508; Young 1895: 254), and highlights of their observations were:

- Baily compared the corona to the flickering light of illuminated gas.
- Arago and Petit described interlacing lines or jets of light within the glowing corona. Arago observed a luminous spot that appeared to consist of jets interlacing themselves. Picozzi described two gas jets aligned with the ecliptic. Baily saw diverging rays that displaced the circular appearance of the corona.
- Struve observed a violent disturbed coronal ring with uneven extensions to some 4° from the lunar limb. He placed the brightest section of the corona as closest to the lunar edge.
- Airy, Belli and Struve either estimated or measured the brightness of the corona.

Although many observers noticed that the corona appeared on the side of the Moon opposite the vanishing crescent they did not make the connection that this was proof that the corona was a solar (as opposed to lunar or terrestrial) phenomenon (see Chambers 1902: 57). This realization would only come later. Nonetheless, the 1842 eclipse was a hallmark event in solar science.

Photography was also attempted during the 1851 eclipse from Kongsberg (Norway) and a feeble daguerreotype image was produced by Busch using a small heliometer, but the results were considered of no scientific value (Clerke 1902; Mitchell 1923; Ranyard 1879). In contrast, the visual observations were more revealing. A Mr Swan saw brilliant sharply-shaped beams of light radiating well beyond the general coronal form outline. One appeared conidial based at the Sun and the sides outwardly curved (Ranyard 1879: 512). A Mr Royal observed an irregular coronal outline with a light output equal to the planet Venus, and he described the coronal light as "… beamy in structure … a luminous cloud behind the Moon." (Proctor 1871: 325).

During the 1858 total solar eclipse the French astronomer, M. Liais, drew coronal features that had been noticed at previous eclipses. His drawing displayed five conical petal-shaped rays extending as high as 13′ arcminutes from the solar limb (Proctor 1871; Ranyard 1879; Young 1895). These are shown in Figure 1.

Successful photographic images of a total solar eclipse were obtained for the first time in 1860 by Italy's Father Secchi and Britain's Warren De la Rue (Figure 2), who conducted their observations from two different locations. De la Rue's photographs, made with a photoheliograph of 3.4-in. aperture and 50-in. focal length, revealed prominences around the solar disk but only a trace of the brightest innermost region of the corona near the lunar limb, as indicated in Figure 3 (Clerke 1902; Proctor 1871; Ranyard 1879). He observed long streams radiating outward from the corona and his visual observations agreed with a drawing produced independently by Mr Feilitsch.

Secchi's photographic results are shown in Figure 4, where several different negatives have been combined in order to enhance the detail. Secchi reported an overall quadrilateral shape of the corona made up of four broad extensions of projected light located between the solar poles and the equatorial regions (Clerke 1902). He noted that the corona appeared the same at two different observing stations 250 miles apart (verifying a tentative conclusion made on the basis of drawings of the 1851 eclipse). Secchi also made a drawing of the corona (Figure 5) but this differed markedly from a drawing made at the same time by G. Tempel (Figure 6) (Ranyard 1879;

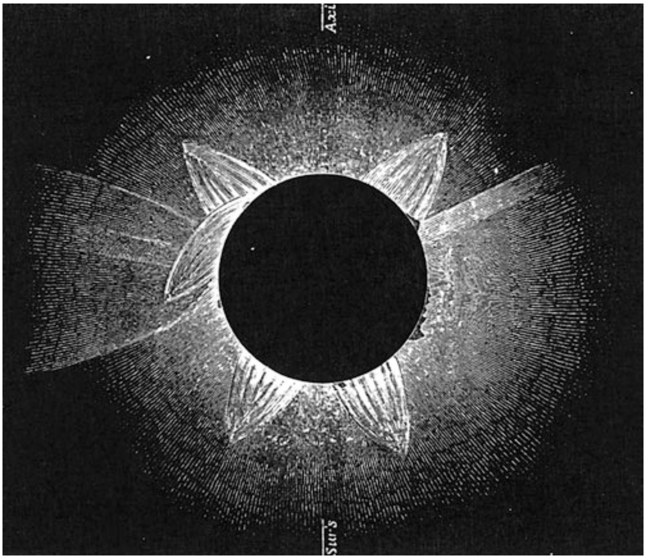

Fig. 1 Liais' 1851 drawing of the corona, with its d-istinctive 'petals' (after Ranyard 1879: 516).

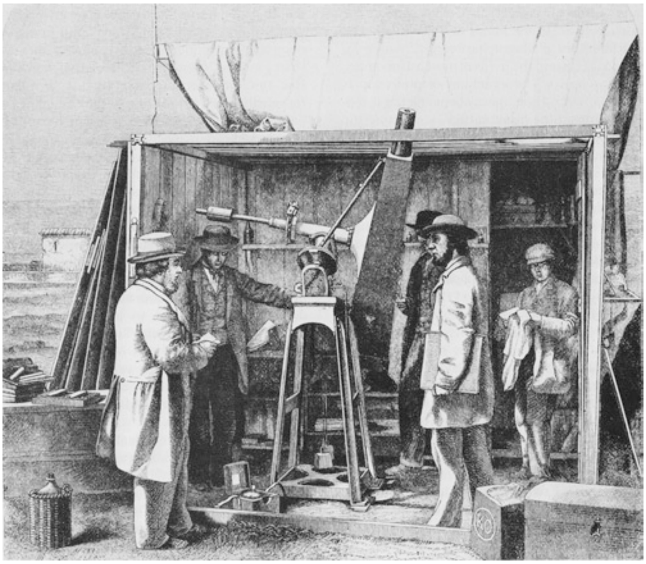

Fig. 2 De la Rue's 1860 observing site (after Lankford 1984: 19).

Young 1895). Meanwhile, Bruhns described a circular-shaped corona that was unevenly distributed about the Sun, and he also noticed what appeared to be long coronal rays on the eastern side of the Sun that extended out to 2 solar diameters. However, M. Auerbach, who assisted Bruhns, observed another curved ray of nearly

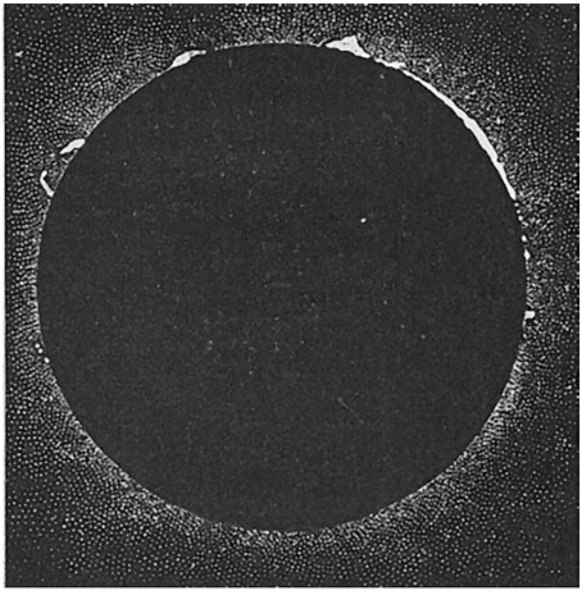

Fig. 3 De la Rue’s 1860 eclipse photograph, as published (after Proctor 1876: 267).

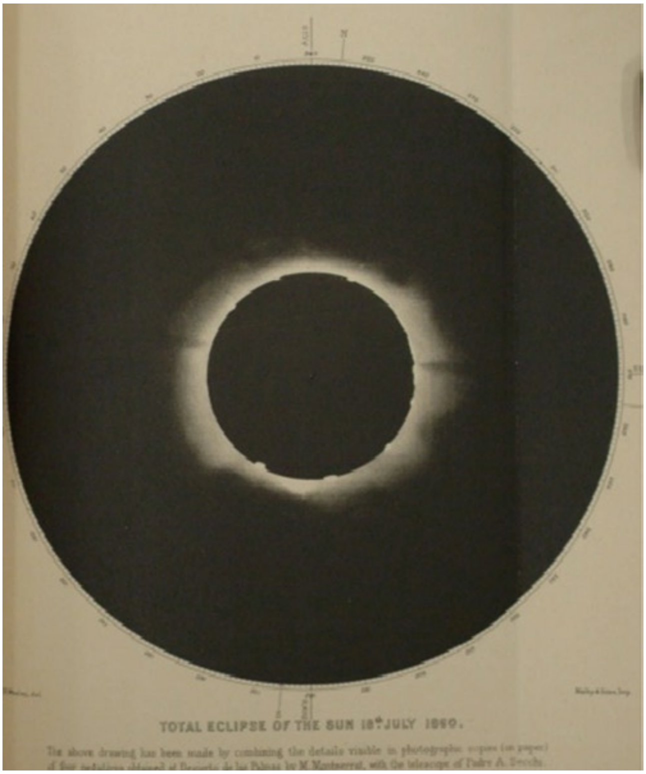

Fig. 4 Secchi’s composite image made with several negatives (after Ranyard 1879: plates).

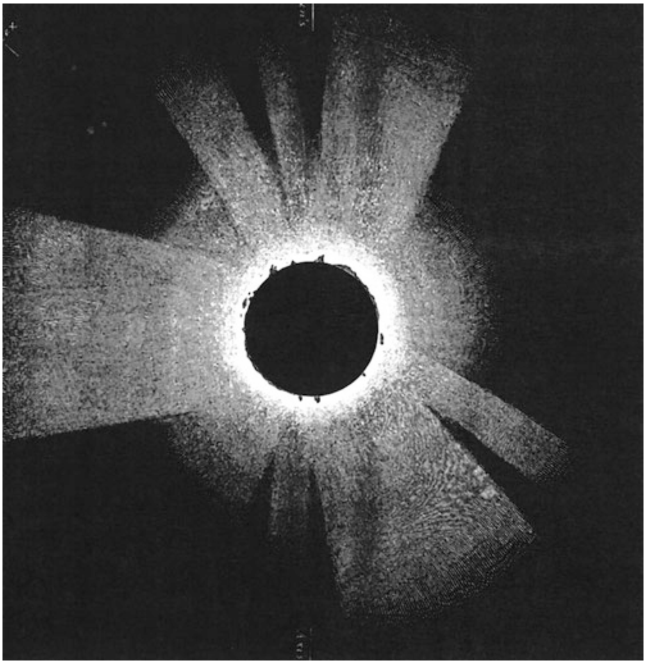

Fig. 5 Secchi's drawing of the 1860 eclipse (after Ranyard 1879: 573).

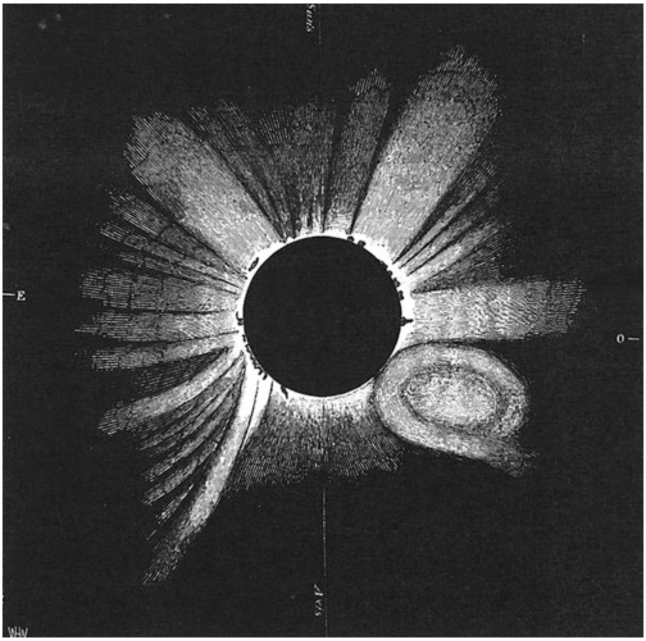

Fig. 6 Tempel's drawing of the 1860 eclipse (after Ranyard 1879: 575).

0.1° in length in the south-western part of the corona (Proctor 1871). All of these discrepant accounts merely highlight the problem of trying to draw conclusions about precise coronal form on the basis of drawings and naked eye observations and reminiscences.

The question then was, would the total solar eclipse of 1867 fare any better and provide more light on the nature of the solar corona? During this eclipse L. Grosch, Vice-Director S. Vergaza and Lieutenant Vidal from the Santiago Observatory made a series of remarkable visual observations. At the moment of second contact they observed a "… reddish glimmering light …" followed immediately by the appearance of the corona. Grosch described the reddish light as surrounding the Moon "… with a border of breadth of at most 5 min, was not sharply bounded in any part, but was highly diffused, and less distinct near the poles." He noted that the corona was longer in the direction of the Sun's equator with no continuous connection to the Sun's surface, so he did not consider the corona to be a solar atmosphere as it did not seem to radiate from the Sun. The coronal observations by Grosch and his collegues are summarised below and are discussed by Proctor (1871: 331–333) and Ranyard (1879: 582):

- The color of the coronal light was white with bluish-colored rays superimposed within.
- Polar coronal extension was 1/3 of a lunar diameter. The equatorial coronal extension was 4/5 of a lunar diameter.
- The rays ran east and west and appeared as pencil beams extending well beyond the white coronal light.
- A number of unmoving arched thin dark curved lines appeared within the corona exactly north, curving east and west. These lines appeared as if they could have originated near the center of the Sun. The lines vanished with the corona after third contact.
- Vidal and Vergaza found the same occurrence of rays near the southern pole of the Sun. They described the appearance of the rays as fan shaped. No dark lines were observed.

Proctor found this series of observations to be compelling enough to substantiate the need to have multiple teams of visual observers to record what they saw, and this, indeed, would be the case at the August 1868 total solar eclipse.

2 Setting the Scene: The Seminal Solar Eclipse of 17–18 August 1868

This eclipse, visible from India and Thailand, has a special place in solar science in that it was the first in which spectroscopy was applied to the study of the solar corona. With totality lasting as much as 6 min 50 s at the Gulf of Siam, this proved to be a particularly timely event.

The British and French would each send two official expeditions (Orchiston et al. 2006). Major J.F. Tennant (1867) requested of the Royal Astronomical Society that two expeditions be sent, one to the Indian shore near Masulipatam or Guntoor,

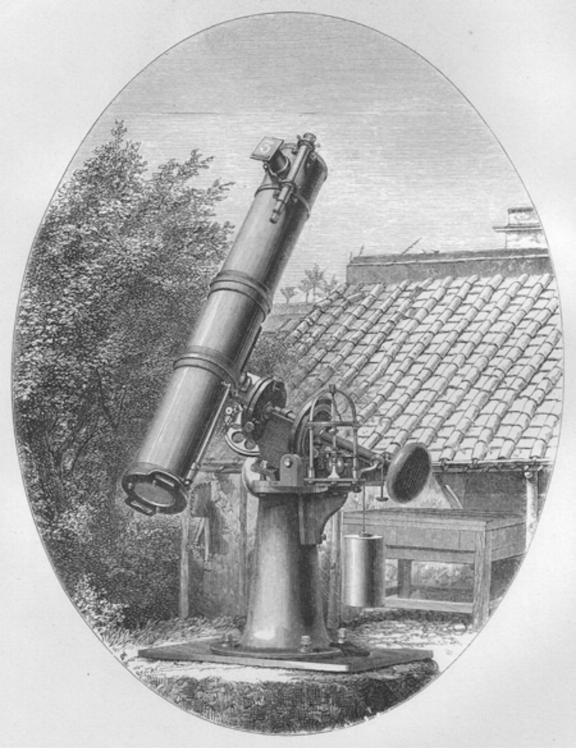

Fig. 7 The equatorially-mounted 22.9-cm (9-in.) Browning-With reflecting telescope used by Tennant to photograph the eclipse (after Tennant 1869: 51).

and one more inland at Hyderabad. Photography (see Figure 7), spectroscopy and polariscopy would be used (Orchiston et al. 2006). *En route* to Calcutta, at which point he would decide on his own expedition site, Tennant stopped at Aden and communicated with some British officers on how they should conduct their studies of the solar corona. Upon arriving in India, he chose Guntoor as the site for his station and his party arrived there on 3 July. He ultimately reported that although the corona was visible (see Figure 8), photographs of the eclipse were underexposed (due to a light cloud cover) so it did not show up (see Figure 9). Nonetheless, Tennant was able to determine that the corona had a continuous spectrum. He also noted that the solar prominences demonstrated bright lines corresponding to Fraunhofer C, D, and B but time ran out before he could confirm the likely F and G. Of these prominences he described in particular a 'Great Horn' which "… burst into sight, a glorious brilliant linear spectrum." (Tennant 1868: 245). Captain Branfill was able to report that the corona was strongly polarized while the prominences, including the 'Great Horn,' were not at all, leading Tennant (1868: 245) to conclude that the corona was not self-luminous but reflecting light. Photography confirmed the solar origin of the prominences which "… were eclipsed and uncovered exactly as the sun itself." (cited in Orchiston et al. 2006: 30).

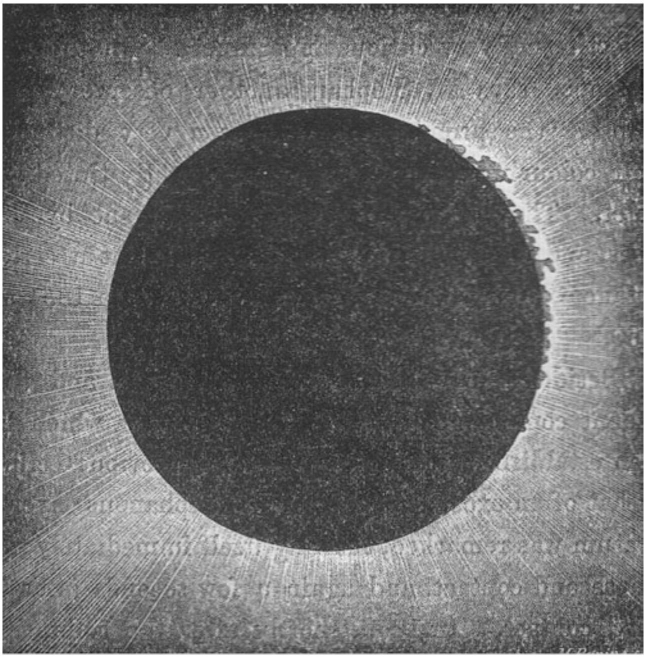

Fig. 8 Tennant's drawing of the eclipsed Sun, showing the corona and some prominences (but not the 'Great Horn') (after Guillemin 1870: 251).

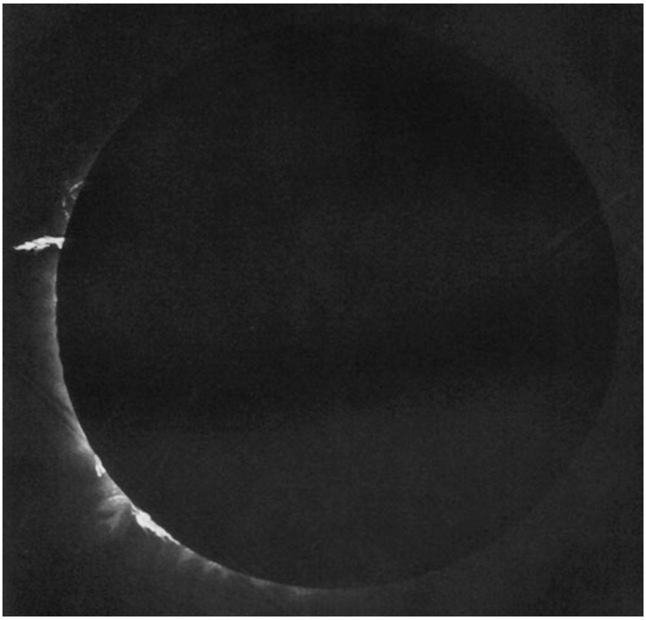

Fig. 9 A photograph of the eclipse showing prominences, including the 'Great Horn', but hardly any indication of the corona (after Tennant 1869: Plate 5B).

The second official British expedition was headed by Lieutenant Herschel and based at Jamkandi, inland and further west than the suggested Hyderabad. Herschel encountered more cloud cover during totality but during a period when the clouds parted he was able to make some spectroscopic observations of the "… long finger-like projection …" (i.e. the 'Great Horn'). He saw the same three lines as Tennant (see Orchiston et al. 2006). Polarization observations also led him to conclude that the corona was reflected sunlight (The Eclipse of the Sun 1868).

A third British party, already present in India, observed at Masulipatam, led by Norman Pogson of the Madras Observatory. They reported success in their efforts (see Orchiston et al. 2006: 32).

Professor Pierre Janssen, a famous figure in international astronomy, led one of the two French expeditions. He, like Tennant, was stationed at Guntoor. He was equipped with several large telescopes and a spectroscope. He was also accompanied by a draughtsman, M. Jules Lefaucher, to draw the eclipse (Janssen 1869a). When rain and clouds cleared sufficiently he was able to make some spectroscopic observations and concluded:

> 1st. The gaseous nature of the protuberances (bright spectral lines). 2nd. The general similarity of their chemical composition (the spectra corresponding line for line). 3rd. Their constitution (the red and blue lines of their spectra being no other than the lines C and F of the solar spectrum, characteristic as we know, of hydrogen gas). (Janssen 1869b: 109).

It was at this eclipse that, having observed the bright prominence lines, Janssen considered the possibility of observing these in the absence of an eclipse. The very next day he placed the slit of the spectroscope over the same location where he had observed the prominence. He succeeded in again finding the C and F lines (Janssen 1869a: 131). British astronomer, J. Norman Lockyer, would speculate independently that it might be possible to make such spectroscopic studies of solar prominences, even during the absence of an eclipse and also succeeded in doing so (Huggins 1868: 4). Another significant outcome of this eclipse was the discovery by both Janssen and Lockyer of a yellow emission line in the spectrum of the solar chromosphere. This line would prove to be that of the element helium, as yet undiscovered on Earth.

Mr Rayet reported on the second French eclipse expedition, which was based at Wah-Tonne, Molucca, in present-day Indonesia. He also noted very bright lines in the spectrum of the prominences and remarked that the light of the corona was faint in comparison (Report of Mr. Rayet 1869).

3 The Total Solar Eclipse of 7 August 1869

During the second half of the nineteenth century there were total solar eclipses in 1869 and 1878 that were visible over large tracts of the United States (see Figure 10), thereby enabling this young nation to apply the new astronomical technologies within their own borders for the very first time. Totality on 7 August 1869 lasted for about 2.75 min at most sites, including Iowa, Illinois, Kentucky and North Carolina, and as long as 4 min at Mt. St. Elias near the Alaska-Canada border (Paine 1869b: 285).

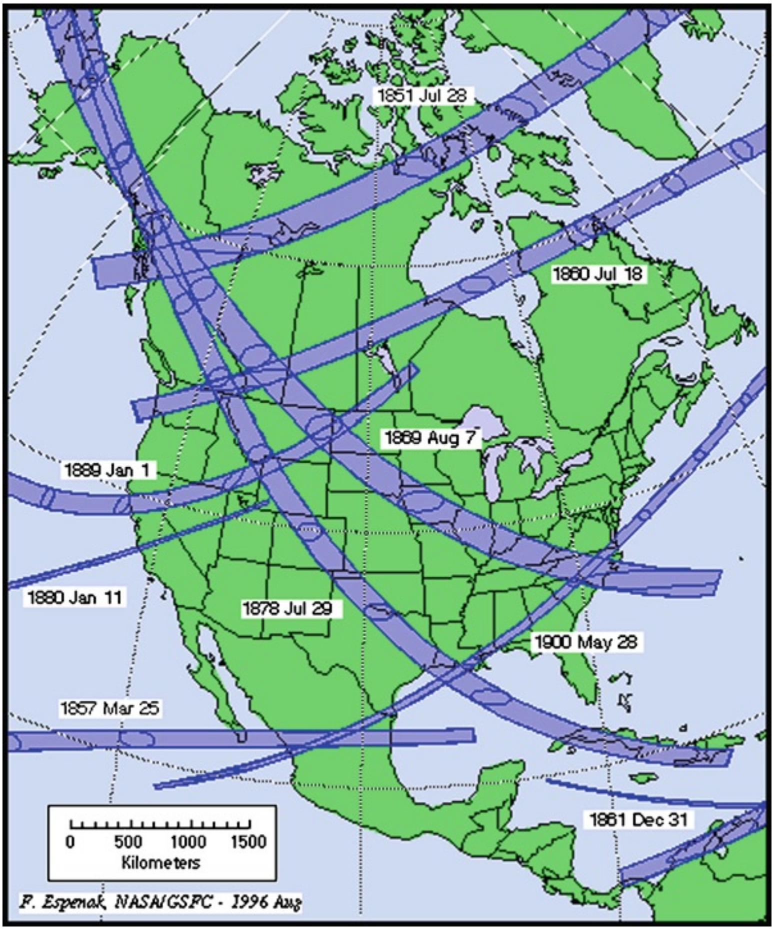

Fig. 10 Map showing the paths of totality of solar eclipses visible from the US during the second half of the nineteenth century (courtesy: eclipse.gsfc.nasa.gov).

The nature of American eclipse expeditions was to be very different from those funded by the European governments, scientific societies or observatories. As Pang (2002: 39) has pointed out, "American eclipse expeditions, in contrast, were local affairs, planned, funded and outfitted by individual observatories and colleges, or by astronomers borrowing instruments and traveling on small grants from various institutions or agencies."

Though astronomers around the world would be interested in the outcomes of the 1869 eclipse observations, it would be Americans who would make the expeditions. In 1869 the event was visible as far west as the Dakota territories and as far east as Newbern, North Carolina, and in the contiguous states and territories (see Figure 10). Observations might also be made further northwest outside of American borders.

For example, the U.S. Naval Observatory led by Asaph Hall sent an expedition to Siberia to make magnetic and positional studies (Sands 1869).

Lockyer (1869: 15) described the degree of participation of Americans in this event:

> The Government, the Railway and other companies and private persons threw themselves into the work with marvellous earnestness and skill; and the result was that the line of totality was almost one continuous observatory from the Pacific to the Atlantic … There seems to have been scarcely a town of any considerable magnitude along the entire line, which was not garrisoned by observers, having some special astronomical problem in view.

Many small towns along the ‘continuous observatory’ would share their experiences with reports to the newspapers. A good number of these were simple descriptions of the event. Noted might be the degree of totality, the weather, effects on animals and/or the human emotions experienced. Newspapers printed such reports from as far east as Boston, Philadelphia and New York, where a partial eclipse was observed by hundreds of thousands, to as far west as San Francisco, where the partial eclipse was experienced on a cloudless day (*Cincinnati Commercial* 1869a). Many smaller towns in between also sent in their reports such as Nicholasville, Big Bone and Prestonville in Kentucky, as well as Vincennes and Martinsville in Indiana (*Cincinnati Commercial* 1869b). Different localities mentioned in this paper in connection with the 1869 eclipse are shown in Figure 11.

Significant scientific expeditions that took place during this eclipse included those of Joseph Winlock from the Harvard Observatory, who would return to his native Kentucky to make his studies, and Cleveland Abbe from the Cincinnati Observatory, who would lead his team of seven to one of the westernmost sites, in the Dakota Territory.

Joseph Winlock (Figure 12) was born in Shelby County, Kentucky in 1826, graduated from Shelby College in 1845 and went on to become Director of the Harvard College Observatory in 1866 (Matthews and Cleveland 2008). He returned to Shelbyville, Kentucky (see Figure 11), in 1869 to lead the observations during the 2 min and 29 s of totality. Alvan Clarke, the well-known American telescope-maker, assisted Winlock. Also present were George Dean and F. Blake, Jr. from the Coast Survey, who had charge of ‘observations of precision’ using the transit instrument, chronograph and astronomical clock; J.A. Whipple of Boston who took photographs; Professor Robert Tevis of Shelbyville who was in charge of meteorological observations; and Professor G.M. Searles of New York who was to observe general phenomena and specifically to search for intra-Mercurial planets. Winlock was in charge of the spectroscopic studies (*Cincinnati Commercial* 1869a). Figure 13 shows the Harvard eclipse expedition site.

Other astronomers from across the country also travelled to Shelbyville to set up observing stations, while a group of amateurs occupied the observatory atop Shelby College (Matthews and Cleveland 2008).

It was at this expedition that the first photograph of the diamond-ring effect was taken (Golub and Pasachoff 1997). During this eclipse Winlock obtained a spectrum of 11 bright lines from the Sun’s prominences, 6 of these seen for the

Fig. 11 Map showing the geographical distribution of U.S. localities mentioned in this paper relating to the 1869 eclipse. Key: 1 = San Francisco; 2 = Sioux Falls (Fort Dakota); 3 = Jefferson; 4 = Des Moines; 5 = Ottumwa; 6 = Mount Pleasant; 7 = Burlington; 8 = Springfield; 9 = Vincennes; 10 = Martinsville; 11 = Jefferson; 12 = Shelbyville; 13 = Nicholasville; 14 = Prestonville; 15 = Big Bone; 16 = Cincinnati; 17 = Chicago; 18 = Wilmington; 19 = Washington, D.C.; 20 = Philadelphia; 21 = New York; 22 = Boston.

Fig. 12 Joseph Winlock (courtesy: www.usno.navy.mil).

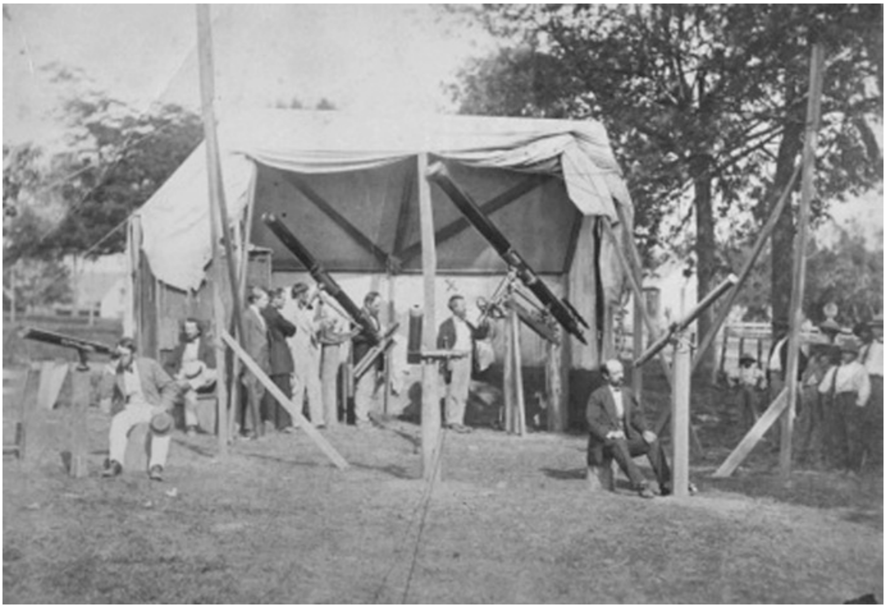

Fig. 13 The Harvard eclipse expedition site (courtesy: Shelbyville Historical Society).

first time, and several good photographs were taken (*Cincinnati Commercial* 1869b), one of which is reproduced in Figure 14. Winlock would not live to participate in the next American eclipse, in 1878, dying in 1875 at the relatively young age of 49.

Cleveland Abbe (Figure 15), Director of the Cincinnati Observatory, was the head of an eclipse party at the position "… furthest northwest of any party this side of the Pacific Coast." (*Cincinnati Daily Gazette* 1869). Their observing site was in remote Sioux Falls City, then called Fort Dakota, in the Dakota Territory (see Figure 11). It was a town of abandoned soldiers' barracks with about half a dozen occupied homes. Armed with a telescope, Abbe would determine the eclipse contact times and note sunspot activity. He was accompanied by several colleagues. These included Mr W.C. Taylor, photographer, with assistant Mr Longstreet; Professor A.G. Compton of New York City Free College who would also note times of contact and make spectroscopic studies of solar prominences; Mr James Haines, the Astronomical Assistant at the Observatory, who was in charge of photometric observations, the recording of all meteors seen and looking for intra-Mercurial planets; Mr R.B. Warder, Assistant Teacher of Illinois Industrial University, who was to record Mr Haines' observations using the photometer, note times of contact, and most specifically was responsible for calibrating the chronometers; and finally Robert Abbe, brother of Cleveland, who was in charge of meteorological observations and was to render assistance to any other party member as needed. More than 3 min of totality would be experienced at this site (ibid.).

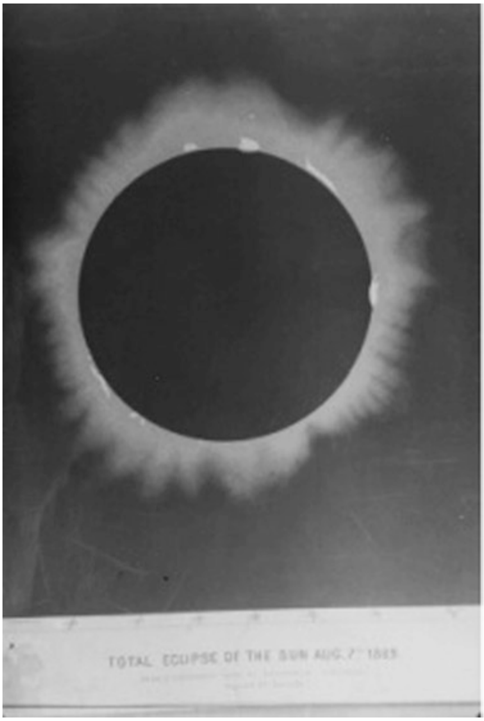

Fig. 14 Totality as seen at Shelbyville (courtesy: Shelbyville Historical Society).

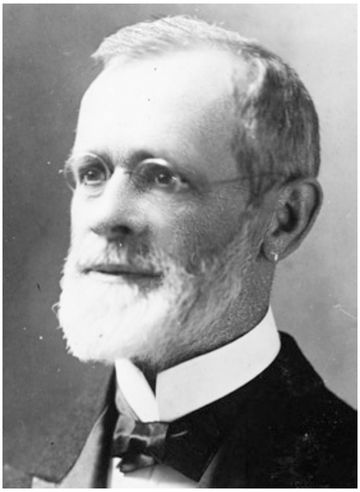

Fig. 15 Cleveland Abbe (courtesy: Wikipedia commons).

Unique to the expedition was the actinometer, an invention of Compton and Taylor. It consisted of

> … a disk of cardboard pierced with several fine holes, revolved by clockwork with great uniformity in front of a disk of sensitive paper, the action of the sun's rays combined with

> the motion of the hole, produced a dark circular line on the sensitive paper, the intensity of whose blackness reveals the varying, photographic power of the sun's rays. (*Cincinnati Daily Gazette* 1869).

The device was used for 3 h, including during the total phase of the eclipse. Based on the results obtained, Abbe stated, "… the active or photographic power of the atmosphere, as illuminated by the light of the sun's corona and prominences, was very marked." (ibid.).

A small group of inhabitants gathered around at the time of the eclipse, and they and the eclipse party were able to see Baily's beads, some naked-eye prominences, stars and planets (Taylor 1869). Photometric observations demonstrated that at the time of totality the light of the zenith was less than a "… five-hundredth part of that 3 o'clock before the eclipse began …" yet only four planets and the star Regulus were visible. Seven satisfactory photographs of the event were obtained (ibid).

The time of first contact was reported by four of the party. All observers saw Baily's beads and numerous rosy prominences. Spectroscopic studies confirmed that these latter were gaseous, "… chiefly perhaps, hydrogen, shooting up from the sun's surface, sometimes to a height of 90,000 miles." (Professor Abbe's eclipse observation 1869). Each party member kept a journal with scientific data as well as personal comments and reminiscences. Warder's journal included a pencil sketch of totality (see Figure 16), while Taylor (1869) obtained a series of photographs of the eclipse (see Figure 17). As succinctly reported in the *Cincinnati Daily Gazette* (1869) this eclipse involved "A month of preparation, 2 h of observation, 3 min of swift activity, and the work of the astronomical expedition was over." Abbe went on to publish an account of his overall impressions of this, his first eclipse (see Abbe 1955: 264–267).

Iowa was the site of some important expeditions. Professors William Harkness, of the U.S. Naval Observatory, and Charles Young, of Dartmouth, were based near Des Moines and Burlington respectively (see Figure 11), and they obtained and studied spectra of the solar corona. They observed continuous spectra traversed by

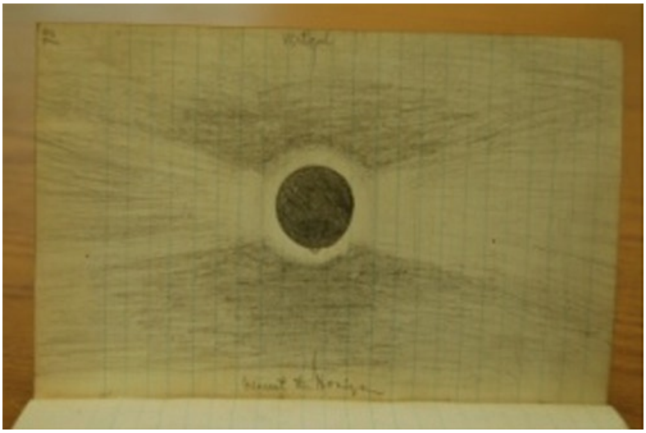

Fig. 16 Sketch of totality in the journal of R.B. Warder (courtesy: University of Cincinnati Archives).

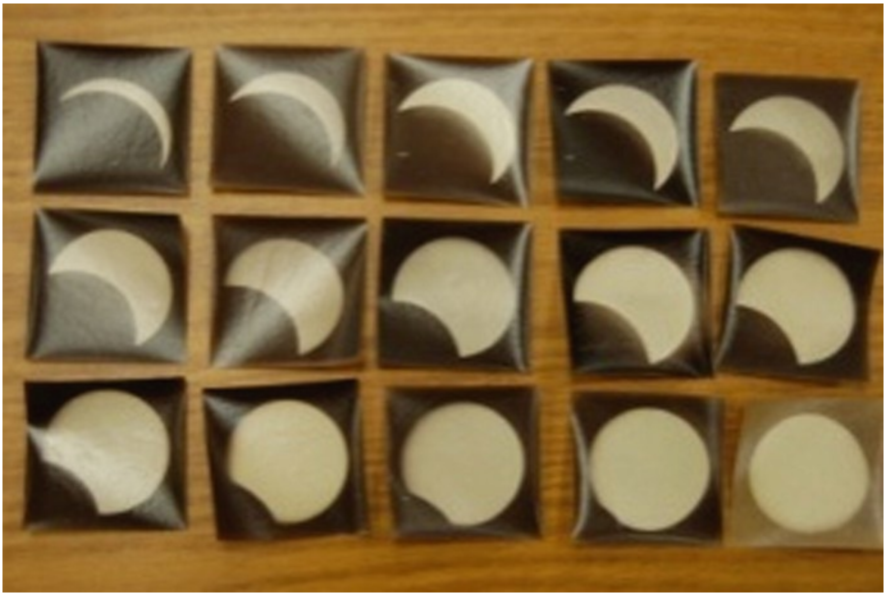

Fig. 17 The series of photographs obtained by W.C. Taylor at totality (courtesy: University of Cincinnati Archives).

a single bright green line which was initially associated with the newly-named element 'coronium' but would later be identified as a spectral line of highly-ionized iron (Clerke 1902; see, also, Golub and Pasachoff 1997). The Franklin Institute of Philadelphia sponsored three parties, authorized by Professor I.H.C. Coffin, U.S.N., Superintendent of the National Nautical Almanac, to Burlington, Mount Pleasant and Ottumwa (see Figure 11), all in the state of Iowa. These were strictly photographic expeditions (Webb 1869).

Besides these American parties, there was a Canadian party that published results in the *Monthly Notes of the Royal Astronomical Society*. They observed from Jefferson, Iowa (see Figure 11), where totality lasted 3 min and a few seconds. They took photographs but limited financial support precluded spectroscopic studies. In a letter to Warren De la Rue, E.D. Ashe (1869) wrote, "…I leave to the American astronomers the description of the results obtained by the spectroscope, &c."

4 The Total Solar Eclipse of 29 July 1878

This next eclipse visible in the United States would have a period of totality of about 2.5 min and was best visible in Wyoming, Colorado and Texas. Though these less-populated regions might lack some of the conveniences of civilization, the clearer skies would be an advantage for the eclipse parties. Professor William Harkness from the United States Naval Observatory published a 30-page document in 1878 titled "Instructions for Observing the Total Solar Eclipse of July 29th 1878."

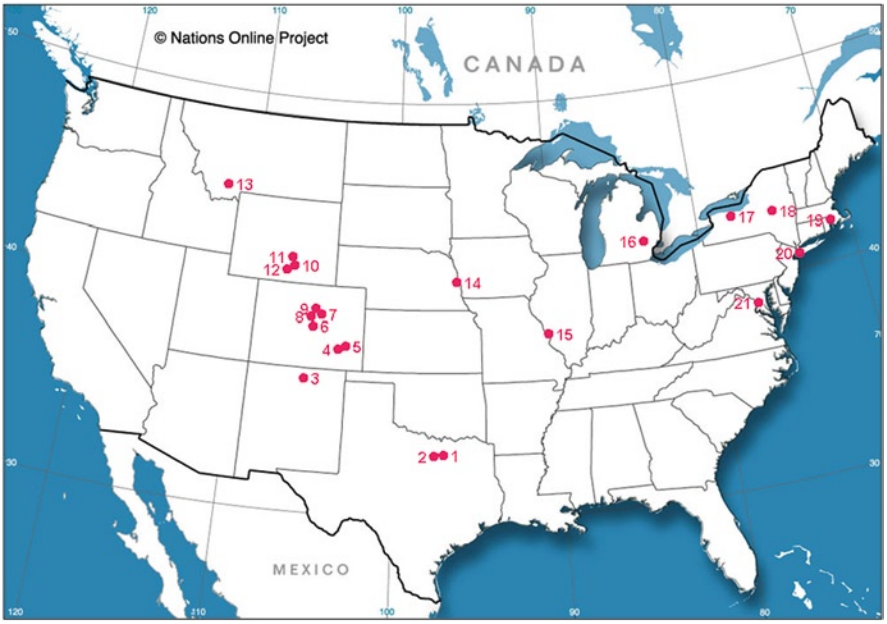

Fig. 18 Map showing the geographical distribution of U.S. localities mentioned in this paper relating to the 1878 eclipse. Key: 1 = Dallas; 2 = Fort Worth; 3 = Taos; 4 = La Junta; 5 = Las Animas; 6 = Pike's Peak; 7 = Denver & Cherry Creek; 8 = Idaho Springs; 9 = Central City; 10 = Rawlins; 11 = Separation Point; 12 = Creston; 13 = Virginia City; 14 = Omaha; 15 = St. Louis; 16 = Ann Arbor; 17 = Rochester; 18 = Utica; 19 = Providence; 20 = New York; 21 = Washington, D.C.

(cf. *Astronomical Register* 1878) which was divided into nine sections, and ranged from naked eye and telescopic observations to the use of the various new tools of solar physics. Several sections were useful to amateurs, who could contribute valuable observations.

At some eclipse sites (see Figure 18 for localities mentioned below) there was an unprecedented merging of British with American parties. The railroads provided reduced fares for scientists traveling to expedition sites, and decided to extend the same courtesy to Europeans. The British scientist F.C. Penrose (1878a, b) published results of his experiences in both *The Observatory* and *Monthly Notes of the Royal Astronomical Society*. His ultimate site was about 2.5 miles to the northwest of Denver, Colorado. During his travels there he would meet with leaders of several other parties, a veritable 'Who's Who' of the American scientific community, including Professors Eastman and Young and Cleveland Abbe, (Penrose 1878b). Penrose, himself, succeeded in his main goals of timing the four contacts and making a colored drawing of what he had seen. He commented, "I must not conclude without a word of recognition of the kindness we received from the American astronomers." (Penrose 1878a).

Dr Arthur Schuster, accompanied by his friend and fellow Briton, Mr Haskins, saw the eclipse from West Las Animas, South Colorado (see Figure 18). He was equipped to take advantage of the newer methodologies of spectroscopy and polariscopy. Haskins was mainly at the spectroscope and at totality noted a continuous spectrum for the corona (Schuster 1878a). Schuster concerned himself mainly with the polarization studies, and noted an initial increase in this effect with distance from the Sun, but after reaching a maximum there was a rapid decrease. He was led to conclude that at the farther distances, the particles were too large to polarize light, while this matter breaking up as it fell into the Sun became small enough to cause this effect (Schuster 1878b).

A British correspondent for the *Daily News* reported on several parties in Colorado. He noted that Professor Thorpe and Schuster were guests of Professor Hall at Las Animas. Lockyer received multiple invitations including those from General Myer at Pike's Peak (Colorado), Dr Draper at Rawlins (Wyoming), Professor Newcomb at Separation Point (Wyoming) and Professor Wright at Las Animas (Colorado). He opted for Rawlins (see Figures 18 and 19) where he and Draper took photographs of the coronal spectrum and determined that it was continuous. This same correspondent was impressed by the presence of the genius-inventor Thomas Edison who used his invention, the tasimeter, during the eclipse to determine "… the presence of heat waves in the radiation of the corona." (The eclipse of the Sun, 1878b: cf. Lockyer 1878c).

MIT student W.H. Pickering[1] observed at Cherry Creek, 2.25 miles southeast of Denver (Figure 18), where he used polariscopy. At totality he determined the corona

Fig. 19 Lockyer's eclipse station at Rawlins, Wyoming (courtesy: Mary Lea Shane Archives, Lick Observatory, Univ. of California-Santa Cruz).

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[1] It is interesting to note that this was Pickering's first flirtation with astronomy. William Henry Pickering (1858–1938) would later achieve international prominence at Harvard College Observatory before retiring in 1924 and moving to Mandeville, Jamaica, where he maintained a private observatory. After viewing the 1878 event his interest in total solar eclipses persisted, and he either led or participated in Harvard eclipse expeditions in 1886, 1889, 1893 and 1900 (Edwards 1939).

to be radially-polarized (Pickering 1878). Lockyer (1878a, b) had drawn the same conclusion in 1871 and recommended that for future expeditions a means be created to obtain permanent photographic records of this effect.

Maria Mitchell from Vassar College also participated in an expedition party. It consisted of six women who would observe from Denver (Figure 18). This all-woman expedition represented the only women – other than companion wives in other parties – to participate in the eclipse studies. They were equipped with chronometers and telescopes (Kendall 1896: 224–237).

Other successful parties included one at Forth Worth, Texas (Figure 18), consisting of L. Waldo and R.W. Willson from Harvard University, Professor J.K. Riles and W.H. Pulsifer from St. Louis and Mr F.E. Seagrave from Providence, Rhode Island. There were also numerous U.S. Naval Observatory expeditions led by the following Naval Professors: Asaph Hall at Las Junta, Colorado; W. Harkness at Creston, Wyoming; E.J. Holden at Central City, Colorado; S.P. Langley at Pike's Peak, Colorado; and D.P. Todd at Dallas, Texas (Notes 1878).

Cleveland Abbe who was now working for the Weather Bureau in Washington, D.C., would also lead a solar eclipse expedition to Pike's Peak in Colorado (see Figure 18), but this time he would miss the event. The summit of Pike's Peak lies at an altitude in excess of 14,000 feet, and Abbe suffered from altitude sickness and had to be carried down the mountain on a stretcher prior to the eclipse (The eclipse of the Sun 1878b). In 1889, however, he would have a third opportunity to observe a total solar eclipse, from Cape Ledo in West Africa (Abbe 1955).

There were non-American sites for some eclipse expeditions, including Havana (Cuba) and Quebec (Canada), from which positive reports were also obtained (The eclipse of the Sun 1878a).

5 Solar Eclipses and the *New York Times*

At the time of these various eclipses The *New York Times* was a daily publication, usually only eight pages in length. The first issue was published as the *New York Daily Times* and came out on 18 September 1851. Costing just one cent, it was intended as "… the paper for the masses." (Emery and Emery 1984: 152). The term *Daily* was dropped from the title in 1857. The first page in the *New York Times* was usually devoted to national and international news. The next two pages featured book reviews and general articles, while the fourth page was frequently editorial and might include late telegraphic news. The next three pages contained local news and advertisements and the final page financial news and advertising (Davis 1921). In such a publication, the placement and amount of space allocated to articles on astronomical topics would reflect the perceived public interest.

As we have seen in Sect. 2, 1868 was a particularly important year in the history of total solar eclipses as this was the first time that spectroscopy was applied to the study of the solar corona. However, in its limited reporting of this event the *New York Times* made little mention of this important advance in astronomy. On 26 April of that year the *New York Times* reprinted an article from *Mechanics Magazine* on the preparations to photograph the eclipse in India (Preparations to photograph the great eclipse 1868). On 2 August there was an article dealing with the likelihood of finding an intra-Mercurial planet during the event (The coming eclipse 1868). Later that month there was a paragraph reporting that the eclipse was observed satisfactorily in much of India, except at Bombay where the weather was uncooperative (Telegrams – India – The total eclipse of the Sun 1878). On September 20 a letter to the editor appeared which was signed by 'A.G.' and described the conditions and successes of visual observations made at Aden (European news – The solar eclipse 1868). A week later some findings were published on the nature of the prominences seen during eclipses, confirming recent conclusions that these were indeed derived from the Sun and not the Moon, as was once thought (Foreign news by mail – Science in Europe – The solar eclipse 1868). It was not until 6 December 1868, months after the event, that mention was made of the usefulness of the science of spectroscopy in solar studies during an eclipse. "The latest advance …" (1868) discusses the successes of Janssen and Lockyer in discovering that the prominences consisted of burning hydrogen gas. The concluding paragraph states: "… science has taken another step, and one which is worthy of popular recognition." Mention is also made of this eclipse on 1 January 1869 when it is listed as one of the significant events of 1868 (The old year 1869). On 18 July 1870, almost 2 years after the event, the *New York Times* printed its most extensive recognition of the significance of the 1868 eclipse. This article summarized what had been learned about the constitution of the Sun on the basis of spectroscopic analysis, and speculated that "… there really seems to be no reason for believing that we have as yet reached the limits of the knowledge which spectroscopic analysis is capable of supplying." (Recent solar researches 1870).

5.1 Reports on the Eclipse of 1869 in the New York Times

U.S. astronomers would have the opportunity to apply these new scientific approaches to the study of solar eclipses on their own 'turf' in 1869 when the line of totality cut right through the heartland of their nation. This eclipse was very much an American event as European astronomers waited to see how these relative newcomers to such scientific endeavors could contribute to a better understanding of the Sun and the solar corona. In 1869, articles in the *New York Times* would reflect a growing interest among the American public in solar eclipses. This time reports would enthusiastically be shared among those observing from many metropolitan areas as well as from more remote expedition sites, where observers had hoped to obtain better visibility.

5.1.1 The Preparations

On 19 May 1869 there was a report on the Government's preparations to establish a 'meridian line' in Springfield, Illinois (see Figure 4) where the eclipse would be seen as total. It was pointed out that "… this will be the most complete and interesting eclipse that will occur in this country during the century." (The new meridian line 1869). Four days later an article was reprinted from the *Springfield Journal* of 17 May with more specifics on the path of totality (The solar eclipse in August 1869).

A letter to the editor was published on 28 May which included an excerpt from a report by a Mr Crookes, Editor of the *Chemical News* and Co-editor of the *Quarterly Science Review* (The approaching total eclipse of the Sun 1869). Crookes recommended the use of multiple photographic methods during the eclipse, pointing out that both the daguerreotype and dry albumin processes were capable of yielding more detail than the wet colloidal process and they also had the logistical advantage of allowing some preparation beforehand and development afterwards, so that the photographer could maximize the number of plates exposed. He also recommended a system of lenses to magnify the image prior to development. Drawing upon the experience acquired from earlier European eclipse expeditions Crookes concluded that photographers of talent were necessary to guarantee success (The solar eclipse – The Litchfield expedition 1869).

On 17 June 1869 there was a paragraph in "Washington – The solar eclipse in August, 1869" describing the sites chosen and equipment to be used by the party of Professors Harkness and Newcomb of the U.S. Naval Observatory. At a site outside of Des Moines, Iowa (Figure 11) they planned to use three telescopes as well as photographic and spectroscopic equipment.

Suggestions by Commodore B.F. Sands, Superintendent of the U.S. Naval Observatory, about useful meteorological data to record during the eclipse were printed in the *New York Times* on 6 July 1869 (The solar eclipse – Arrangements by Commodore Sands 1869). The path of totality was to be approximately 140 miles wide and was to pass through a number of cities and towns that he listed. He described equipment to be used and a schedule of data collection for all participants. All were encouraged to share their observations with the Naval Observatory. The following day a paragraph appeared in the newspaper about Dr Edward Curtis from the United States Army who was to join the U.S. Naval Observatory party at Des Moines in order to photograph the progress of the eclipse (The coming solar eclipse 1869).

On 23 July an article titled "Massachusetts – Observers of the eclipse" (1869) described the two parties sent from Cambridge (Massachusetts) to observe the eclipse. Joseph Aimlock (a mis-spelling of Joseph Winlock) would lead a party to Shelbyville, Illinois (another error as Shelbyville was in Kentucky). Winlock's party included, among others, Charles Pierce, J.A. Whipple, Arthur Searle and Messrs. Clarke, "… the mathematical instrument makers …" of Cambridge, and "They are as finely equipped as any party of observation that ever went out, either in this country or in Europe, having a dozen powerful telescopes and every other instrument that could be serviceable to them which the country affords." The other party mentioned was that of the members of the Coast Survey, which included Professor Benjamin Peirce and photographer J.W. Black, who were going to Springfield, Illinois.

A letter dated 27 July from Dr C.H.F. Peters to the editor of the *Utica Herald* was reprinted in the *New York Times* on 28 July (see The solar eclipse – The Litchfield expedition, 1869). Peters was Director of the Litchfield Observatory, and he noted that since the eclipse would achieve approximately 7/8 totality there he would instead take a party to Des Moines in Iowa, where there would be totality lasting approximately 2 min and 45 s. He stated, "While observations for precising the times of beginning and end will not be neglected (though nowadays of comparatively little use) the principle object will be the investigation of certain questions regarding the physical constitution of the sun and its envelopes." (ibid.). He also noted that the newer methodology of spectroscopy would be important at this expedition site (ibid.).

The most remote expedition site was the subject of an article on 31 July. The party led by Professor George Davidson (Figure 20) from the United States Coast Survey had arrived safely at Sitka, *en route* to the Chilakahat's territory in Alaska where they would observe totality (The Pacific Coast – Arrival of the Davidson expedition at Sitka 1869).

On 2 August 1869 the *New York Times* published extracts from a paper by J. Fenimore Cooper on the eclipse of 1806. This eclipse was visible in parts of the United States, but prior to the scientific advantages of photography and spectroscopy. Born in 1789, Cooper was just a teenager in 1806, but his talents would later bring to reality this event of his youth. He described the sky, the weather and the surrounding responses of the animals and humans. He concluded:

> I shall only say that I have passed a varied and eventful life, that it has been my fortune to see earth, heavens, ocean, and man in most of these aspects; but never have I beheld any spectacle which so plainly manifested the majesty of the Creator, or so forcibly taught the lesson of humanity to man, as a total eclipse of the sun (Cooper 1869).

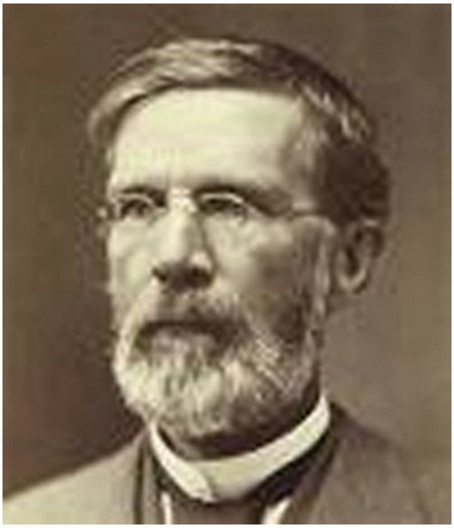

Fig. 20 George Davidson (source: www.history.noaa.gov).

5.1.2 The Experience

In early August 1869 the *New York Times* printed two articles designed to educate the public on the experience of the eclipse event. On the fifth the public was apprised of the best locations and the times for observing. They were also informed of some associated phenomena such as the corona, Baily's beads and prominences. The history of some of Janssen's spectroscopic successes was described. Some interesting comments were made regarding the use of calculated eclipse times in establishing the dates of associated historical events. The article ended with a list of cities and times for observing of the eclipse, which in some cases would only be seen as partial (The great solar eclipse – Where it begins and ends 1869). Then on 7 August 1869, the actual date of the eclipse, the *New York Times* published an article for the public on how they might best observe the eclipse. Two methods were suggested: using smoked glass or a card with a small round hole in the center that would permit passage of the image of the Sun onto a selected background. Mention was made of the fact that Professor Harkness at the Des Moines site would be employing spectroscopy which was first used during an eclipse in India the previous year. Included in this article were the somewhat disparaging words of a citizen predicting that an earthquake would occur during the eclipse, based on the coincidental eclipse-earthquake events in South America the previous year, a potential topic of discussion for the intrigued public (The eclipse to-day 1869). On this same day, a program of the usual Saturday musical concert to take place in Central Park was published. This was timed to accompany the eclipse, which would be partial from New York (The eclipse and music in Central Park today 1869).

On 8 August the *New York Times* printed their longest article regarding this eclipse. In New York the newspapers pointed out how the public was "… made aware in ample time to prepare for the show." (The eclipse – How it was seen in New-York and elsewhere 1869). Young street vendors had been selling colored glass for days. In Central Park the concert-goers, having been provided with pieces of colored glass, had their eyes turned to the sky. Representatives of the press were present at Daniel Draper's meteorological observatory in Central Park to observe the event. The report of Professor Thatcher, who made his observations from the top of the Astor House, was made here. He noted the times of contact and the meteorological conditions (ibid.).

5.1.3 The Results

Telegraphic reports from distant sites such as Washington D.C., Des Moines, Shelbyville, San Francisco, Cincinnati and Wilmington (North Carolina) were printed the day after the event. An interesting comment made here was that this well-predicted event did much to re-establish the public's confidence in the astronomical community (The eclipse – How it was seen in New-York and elsewhere 1869). The public had been much disappointed a year or two previously when the predicted Leonid meteor storm did not occur as promised.

Reports of results continued to be printed during the month. In its summary of the event as experienced in New York, on 9 August the *New York Times* noted, "… the exhibition amply gratified the curiosity of the spectators, and has doubtless led many to study, with a greater deal of interest than heretofore, the movements of celestial bodies …" in spite of the fact that the event was obscured much of the time by clouds (The great solar eclipse – City scenes 1869). In this article some results from other sites also were printed. Professor Peirce of Harvard had charge of the observations at Springfield, Illinois. One hundred photographs were taken by Mr Black of Boston and exceptional observations were made of the corona, prominences and Baily's beads. Meanwhile, members of the public filled the streets and rooftops in Wilmington, North Carolina. Included in this informative article were accounts of the scientific observations made by Winlock at Shelbyville and the various parties based at Des Moines. Briefer reports were printed from various other sites across the country and from Montreal in Canada.

On 11 August the *New York Times* included an article of just two paragraphs that was submitted by 'Our Own Correspondent' who witnessed the eclipse from the University Grove site in Chicago. The skies were ideal and the times provided precise. He mused, "But when shall science penetrate the mystery of the sun itself, and tell us the source of its light and heat?" (Chicago – The eclipse 1869). On that same date an article submitted by Daniel Draper was printed recounting his observations made from his meteorological observatory in Central Park (The eclipse – Its meteorological effects 1869). He reported on the variations in temperature, barometric pressure and various wind parameters as noticed during the eclipse. He anticipated making a future report of long-term effects several days later. On the following day there was a more extensive article by 'Our Own Correspondent' in Springfield, Illinois (The eclipse – Observations at Springfield and Illinois 1869). Here, after brief mention of the scientific parties present, he attempted to describe the experience from the viewpoint of an unscientific observer: "It was the grandest sight of a lifetime." He noted planets and stars observable by name, and commented on the effects that the eclipse had on the local fauna.

As the days passed more reports from further sites would be printed. On 21 August there was a short article containing news from Canada, which also mentioned the fact that Commander Ashe from the Royal Navy carried out successful observations from Iowa (Canada – Arrival of Prince Arthur's horses 1869). On 26 August an anecdote was recounted that would now be considered politically incorrect of how Dr Peters was amused by the reaction of an "old Negro's" observations of his chickens during the eclipse (The late eclipse – An old Negro and his chickens 1869). In 1867 Secretary of State, William Seward, had arranged the purchase of the future state of Alaska from the Russians for the sum of $7,200,000. On 28 August 1869 the *New York Times* reported his subsequent visit to Professor Davidson's camp in Alaska, where, during breaks in cloud cover, all were able to observe the various phases of the eclipse as well as "… the rose-colored flames and the corona." (The Pacific Coast – Arrival and reception of Mr. Seward 1869). The next day the newspaper carried the story of Davidson's serendipitous discovery of a mountain range of iron ore during his eclipse expedition (The Pacific Coast – Discovery of iron in Alaska 1869).

On 2 September 1869 an untitled article was published speculating on the possible relationship between the eclipse and four shipwrecks, all of which occurred on the same date (*New York Times* 1869). In the 5 September issue of the newspaper there was another account of the eclipse as viewed from Alaska, and of the visit of then Governor Seward to the expedition site (The eclipse in Alaska 1869). Comment was made of the fear experienced by the indigenous population during the event. Later that month, on the 14th, an article was reprinted from the San Francisco newspaper *Alla California*, another account of Seward's experiences in Alaska (Mr. Seward in Alaska 1869). The article began with a description of his reception upon arrival on the *Active* at the town of Sitka. He then continued to the eclipse site at the Indian village of Chilcat. It was actually during this trip up river that Seward and his party observed the eclipse. The subsequent reception and dinner parties were described, stylish but oftentimes tedious due to the complications of communication. Two interpreters were always needed to translate the English, Russian and Indian languages. A few days later Seward and his party were to return to San Francisco.

The 23 September issue of the *New York Times* reported on the total failure of the Siberian expedition led by Professors Hall and Rogers of the U.S. Naval Observatory (The Pacific Coast – The astronomical expedition to Siberia unsuccessful 1869), and on 2 October 1869 Hall responded to previous reports of failure (The eclipse – Observations at Behring Straits 1869). There were three stations and there was actually some success in seeing the eclipse through the clouds. The following day there was a front page article relating experiences in Siberia from Rear Admiral Turner who had transported Hall and Rogers to their sites. He noted the presence of predominantly overcast skies with occasional periods of good visibility. In his opinion he did "… not think that the weather was sufficiently clear to make the observations of the astronomer of value" (The eclipse in Siberia 1869).

On 8 November 1869 readers of the *New York Times* were informed of the return of the Behring Strait expedition party to San Francisco the previous day (The Pacific Coast – Return of an eclipse-observation party 1869).

5.2 Reports on the Eclipse of 1878 in the New York Times

In 1870 interest in solar eclipses seemed to wane as evidenced by the decreased number of articles on the subject in the *New York Times.* On 22 August 1870 – more than a year after the eclipse of 1869 – there was an article stating that reports were still expected from expeditions to some sites of the 1869 solar eclipse. Of the three government parties, those from the U.S. Naval Observatory, the Coast Survey and the Nautical Almanac Office, only the Naval Observatory had published its results (Washington – The last great eclipse 1870). The nature of the USNO publication was described on 7 October (Washington – Astronomical Observations 1870).

The *New York Times* also contained information about the total solar eclipse of 22 December 1870, which would be visible in parts of southern Europe. On 20 November was an article explaining how spectroscopy had solved the mystery of the nature of solar prominences, and it was expected that the upcoming eclipse might clarify the nature of the corona (The coming eclipse of the Sun 1870). Though this eclipse did not seem to intrigue the American public as much as the one that had just occurred at home, its scientists did send some expeditions, as related in an article on the day of the eclipse (Today's eclipse 1870). The American parties had invited eminent English physicists to join them (Foreign items 1870), thus Professor Peirce who led the main expedition to Syracuse was joined by Norman Lockyer, but unfortunately they had little success due to the poor weather conditions (General European news – The eclipse 1870), while another expedition, sited in Cadiz, obtained satisfactory photographs of the corona (The recent eclipse 1870).

In 1878 a total solar eclipse would again take place on American soil, though mainly to the west of the most populated areas. Again readers of the *New York Times* would be apprised of the preparations of the various observing parties and their locations. This time there was frequently an assumption of some scientific knowledge on the part of the readership, as terms like spectroscopy would be used without definition or explanation.

5.2.1 Preparations

Starting approximately 2 months before the eclipse the *New York Times* began reporting plans for the upcoming expeditions. On 30 May 1878 there was a special dispatch from Princeton College on preparations taking place there, including those of Professors Young and Brackett who were taking an expedition to Denver (Princeton College – The approaching commencement 1878). On 16 June in another special dispatch Princeton revealed the plans of these professors, who would leave for the expedition shortly. Another expedition of un-named membership had already left the previous week (The Princeton commencement 1878). On 11 July the public was notified of the plans of Professor Langley of the Allegheny Observatory to observe at Pike's Peak (The coming eclipse of the Sun 1878) and on 14 July of New York Professor Henry Draper's plans to observe at Rawlins in the Wyoming Territory. The following day the public was reminded of the plans of Young and Draper in the leading item in the regular feature "Scientific Gossip" (1878a).

On 18 July 1878 the *New York Times* printed a special dispatch on the progress of the Draper expedition which had just passed through Omaha, Nebraska (The Draper eclipse expedition 1878). Among the members of the party was Thomas Edison who would use his tasimeter to measure the heat of the Sun during the eclipse and who would also test his new 'carbon telephone' between Omaha and the site at Rawlins.

On 19 July 1878 a summary paragraph was printed listing parts of the country where the upcoming eclipse could be seen, and stating that totality would last on average for 2 min and 50 s (Topics of the season 1878). On 21 July there was an article by 'Our own correspondent' with an extensive list of expedition parties, their sites and some considerations regarding the likelihood of satisfactory weather conditions. On the same page of that issue was a short paragraph reporting the various locations of Professors Newcomb, Todd, Hall, Harkness and Holden, all representing government interests (*New York Times* 1878). On the 26th there was another progress report on the Draper expedition (Draper's eclipse expedition 1878). Having safely arrived at Rawlins the members were preparing their telescopes and equipment for the event. Specific details were provided of the photographic equipment for those interested. Professor and Mrs. Draper were to do the photographic work. Professor Barker would operate the analyzing spectroscope and Professor Morton the polariscope, while Mr Edison would use his tasimeter to measure the heat of the corona.

On the day before the actual eclipse the *New York Times* printed a nice summary of plans and expectations for the following day (The coming total eclipse 1878). As the "…earth is indebted to the sun for almost all of the manifestations of force which we find here … [one] … should seek to learn as much as possible about the sun …" It was total in western areas of the United States and its territories but a partial eclipse would be visible through the rest of the country. The approximate times for the beginning and the end were listed for many of the large cities. Scientists would be using photography, spectroscopy and polariscopy to gain understanding of the corona. They would search for a theorized intra-Mercurial planet. "Never before have preparations so elaborate been made to observe an eclipse" (ibid.).

5.2.2 The Experience

On the day of the eclipse the *New York Times* printed a description by General Henry E. Oliver of the eclipse of 1806 (The eclipse of 1806, 1878).

5.2.3 The Results

The day after the eclipse the *New York Times* printed several articles relating to the event. A brief untitled article stated that telegraphic reports were coming in indicating that all observers had good atmospheric conditions for their observations (Editorial article 1 – No title 1878). The 30 July issue of the newspaper contained a tongue-in-cheek article that theorized on some of the mysteries of the Sun (Solar mysteries 1878). For instance, since the heat of summer brings flies on Earth, an observer outside of our planet might see this fly-sphere as a homogeneous covering of the surface. A brushfire or hailstorm might cause movement within the fly-sphere giving the appearance of a spot. The writer offers this as an explanation for sunspots. On this same day the *New York Times* also published the interesting anecdote that an international baseball game in Utica, New York, ended at the first half of the tenth innings owing to the darkness caused by clouds and the eclipse (Base-ball 1878). However, it would seem that the effects of the eclipse were over-stated as Utica was so far from the line of totality. On this same date there was also an extensive article containing reports from various eclipse stations. This article began with a dispatch from New York's own Henry Draper:

> Totality just over. I have splendid photographs. Two are spectra of the corona, taken with a grating, and show the spectrum to be continuous. Two photographs of the corona are full of details. Edison's tasimeter showed the heat of the corona. (The eclipse of the Sun – Successful observations in the West 1878).

It was reported that Professor Watson, at the site of Separation Point, discovered an intra-Mercurial planet. In the city of Denver, the populace stood on their rooftops with smoked glass to best see the eclipse. Astronomers here made satisfactory spectroscopic observations but failed to find Watson's intra-Mercurial planet. At Idaho Springs, Professor Eaton of Packer Institute and S.V. White of Brooklyn, New York, had cloudless skies and they made numerous sketches of the corona as did Professors Holden and Compton at Central City. Brief reports of success and/or visibility were also received from 20 other sites. On 31 July 1878 three reports of successful observations made from Virginia City (Montana), Havana (Cuba) and Quebec (Canada) were printed (Monday's eclipse of the Sun 1878).

Over the following weeks reports would continue to be published as they were received. For instance, on 1 August there was a brief report from La Junta, Colorado, stating that "Rogers' photographs developed last night; they are excellent. Structure of corona well shown. – Hall" (The solar eclipse 1878a). The following day there was a report from Denver where astronomers from numerous parties met. Professor Watson felt certain he had discovered the intra-Mercurial planet Vulcan and Professor Draper got a photograph of the coronal spectrum (The solar eclipse 1878b).

On 3 August an article expressing the opinion that most astronomers were hiding an awful truth about the Sun (see The truth about the Sun 1878). Only Professor Lockyer would acknowledge that some noted changes in the Sun will have serious results. There had been a decrease in the number of sunspots, and recent eclipse studies noted a disappearance of hydrogen from the solar corona. It was argued that this must mean there was a decrease in solar activity and heat. Decreases in solar heat meant less heat on Earth which seemed to reflect the weather pattern noted over the previous several years.

The 4 August 1878 issue of the *New York Times* reprinted an educational item from the *Providence Journal* for readers with an interest in astronomy (The August Moon 1878), noting that the Moon was a star in the sky during this lunar cycle. Starting with the solar eclipse, she would within 2 weeks also be party to a partial lunar eclipse. She would further demonstrate a conjunction with the planets Jupiter, Mars, Uranus and Mercury. On this same day the *New York Times* also published a special dispatch stating that Professor Swift of Rochester had definitely observed the intra-Mercurial planet, thus agreeing with Professor Watson (The recent solar eclipse 1878).

On 8 August the newspaper included three mentions of the solar eclipse. One of these was a special dispatch from Professor Watson of Ann Arbor reporting his discovery of the intra-Mercurial planet Vulcan (The discovery of Vulcan 1878). Another report discussed Draper's expedition to Rawlins, Wyoming (The examiners of the Sun 1878). In his interview for this article he clarified a misconception that had been printed in various newspaper accounts that he was looking for oxygen in the Sun's corona, which he knew could not be present. His studies did, however, focus on photographic, spectroscopic and polariscopic observations of the corona, which led him to conclude that coronal light was reflected sunlight. One of the members of his party, Thomas Edison, used his very sensitive tasimeter to measure coronal heat. Finally, the 8 August issue of the *New York Times* also reprinted a story reported in the *Denver Tribune* that the popular actor, Joseph Jefferson, who was taking a rest in Colorado, had gone fishing during the solar eclipse (Joe Jefferson goes a-fishing 1878).

Professor Lockyer's non-eclipse research was the focus of an article that appeared in the 11 August issue of the *New York Times* where his nebular hypothesis – which reportedly accounted for the origin of worlds – was discussed (The nebular hypothesis 1878).

The 16 August issue of the newspaper printed a report from Princeton's Professor C.A. Young who was willing to accept the existence of the planet Vulcan, as advocated by Watson and Swift (Vulcan and the corona 1878). Young felt that this discovery and the apparent relationship between sunspot activity and the coronal atmosphere were the two most significant outcomes of the various expeditions sent to observe this eclipse. The next day the *New York Times* reprinted a fascinating human interest story that first appeared in the *Denver Tribune* and recounted the response of the Pueblo Indians of New Mexico to the solar eclipse (Their wrathful deity 1878). At the Pueblo village at Taos this was an un-expected event, and the darkening of the sky caused fear among the inhabitants. Their governor stated that this phenomenon was due to a grievous sin of one of their own and if proper penance was not paid crops would fail and certain death would result. The women of the community made penance by running naked on the fast-track until such time as the light grew stronger.

Watson's mooted intra-Mercurial planet was again the subject of attention in the *New York Times* on 15 September when Paris Observatory's Monsieur Gaillot noted that the object closely followed one of the potential paths predicted by Leverrier (Scientific Gossip 1878b).

A meeting of the National Academy of Science at Columbia College was featured in the 8 November 1878 issue of the newspaper. Among those who presented papers was Professor Draper who made significant observations during the recent solar eclipse (Science on the platform 1878). The next day there was an article on the last day of the meeting when Professor Alexander from Princeton College presented a paper requesting that observers of the up-coming solar eclipse in January 1880 direct their attention to the confirmation of the existence of the planet Vulcan (Miscellaneous city news – National Academy of Science 1878).

Rounding out the accounts of the eclipse published in the *New York Times* in 1878 was an article that appeared on 24 December about the many successes of Princeton College, including Professor Young's solar eclipse expedition which was "… one of the best equipped and one of the most successful." (Princeton College 1878).

6 Discussion

While there was little specific mention of the 1878 solar eclipse in 1879, various articles published in the *New York Times* on a variety of astronomical topics demonstrated that there was still a lingering public interest in astronomy.

For example, the 1 March issue of the newspaper included an article on lectures given by a Mr John Lockwood on astronomical subjects, ranging from the "… wonderful guesses of Kepler …" to the recent use of spectroscopy (Astronomical researches 1879). On 11 and 21 November 1879 there were two items describing a series of lectures on the progress of astronomy given at Chickering Hall (New York) by the distinguished British astronomer Richard Proctor to "… a cultured and refined audience, not composed of astronomers." (Worlds beyond the skies 1879). He discussed such topics of interest to the public as the habitability of the Moon and other planets. He described the use of spectroscopy as a tool to understanding the nature of the Sun and stars, presenting as examples photographs of several spectra collected by Henry Draper. He predicted a great future for the use of spectroscopy including "… how it might be applied to the determination of the question whether a star is advancing or receding." (Progress of astronomy 1879).

On 30 April 1879 the *New York Times* noted that Lewis Swift, a hardware dealer and amateur astronomer, had been elected as a Fellow of the Royal Astronomical Society of England (Astronomical researches rewarded 1879). Readers were reminded that Swift was one of the individuals who reputedly discovered the intra-Mercurial planet Vulcan during the 1878 total solar eclipse.

There also were a number of articles referring to the conflicting conclusions of Lockyer and Draper regarding their interpretations of spectra collected during the 1878 eclipse. The 7 January 1879 issue of the *New York Times* included a report on a paper that Lockyer presented at a meeting of the Royal Society in London (Nature of the elements 1879). Lockyer's comments were preceded by a paragraph on the basics of spectroscopy, provided for the benefit of readers. Lockyer explained to his audience how spectroscopy might be used to determine a number of parameters such as the presence and quantity of particular elements or compounds, as well as the temperature of a star. Exactly 1 week later the *New York Times* printed an article reporting on the conclusions drawn by Lockyer from spectra he collected during the 1878 eclipse (The new solar theory 1878). Lockyer concluded that "… so-called elements are really compound bodies." He inferred from his observations that the hottest stars have the simple spectra of thick hydrogen lines with very little metallic lines while cooler stars produce lines of "… compounds of metals with non-metals and of non-metals in a state of isolation." He proposed that heat led to the decomposition of the compounds. In the same article, Draper stated that he did not dispute Lockyer's theory but he felt it was at yet unproven. On 27 January 1879 the *New York Times* published an article describing Professor Draper's discovery of oxygen in the solar atmosphere (Professor Draper's discovery 1879). Lockyer's responses to this varied from skepticism to an allegation that he had found these spectral lines prior to Draper's revelation. When asked to document this claim Lockyer said that he had lost his photographs in the metro tunnel in London. At the time this article was published Draper was working on providing larger photographs that would make his claims indisputable. Included within the article was the interesting notion that science in America had finally become a force to contend with, and an unnamed distinguished American scientist was quoted as saying: "Germany to-day fears the physical experimentalists of the United States more than she fears those of any other country, and has long since practically adopted a protection tariff in the department of scientific discovery." Later that year, on 28 August

1879, the *New York Times* reported on a meeting of the American Association for the Advancement of Science where the President of the Association, Dr George F. Barker, agreed with Draper's claim that oxygen was present in the Sun (Scientists at Saratoga 1879).

Late in 1879 there was some discussion about Edison's tasimeter. The 3 December issue of the *New York Times* reported on an address that Professor Young delivered at the New York Academy of Science (Problems of solar eclipses 1879). He discussed various difficulties encountered during observations of the solar corona between 1869 and 1878, photographs his staff took during the 1878 eclipse and the failure of Edison's tasimeter. The following day there was an untitled editorial piece discussing the differences of opinion between Young and Proctor on the usefulness of the tasimeter (Editorial article 7 – No title 1879). Proctor suggested its application as a detector of icebergs! It was implied that Proctor was practicing 'platform astronomy'. The *New York Times* printed Proctor's response 4 days later (Edison's tasimeter 1879), where he was very gracious in his comments on Professor Young and agreed that the tasimeter was a failure in 1878. This new instrument was calibrated under the supposition that only delicate adjustments would be necessary. In fact, it was so sensitive that the indicator overshot the expected range. Calibration might indeed be set such that the tasimeter might indicate the nearing of a ship to an iceberg.

There were also two articles published in the *New York Times* in 1879 that dealt with historical solar eclipses. In an article that appeared on 11 May, Mr Hind calculated the occurrence of an eclipse on 15 June 763 B.C., thus confirming that the Assyrians took Sumaria in 721B.C. (Assyrian and Biblical history 1879), and on 3 August there was an article dealing with several historical events associated with 'sun-darkenings' which were usually solar eclipses in various stages of totality (Historical Sun-darkenings 1879).

Other articles published in 1879 mentioned eclipses in passing. In the 7 March issue of the newspaper there was an article about the United States Signal Service Station at Pike's Peak which included the following comment: "The best and most complete report of the last total eclipse of the sun received at Washington was the report of Professor Loud, of Colorado, from observations taken at Pike's Peak." (The highest inhabited point 1879). Then on 30 August Professor Stephen Langley from the Allegheny Observatory in Pennsylvania spoke about solar research and particularly the roles of photography and spectroscopy and the contributions made by certain astronomers (The study of the Sun 1879). He also spoke about the future of these studies, and referred to the possibility of making meteorological predictions and their significance for farmers. He also predicted the future of a 'solar engine' which man might employ "… to better advantage than we now use steam power."

It is apparent from the articles about solar eclipses published in the *New York Times* in 1878 and 1879 that some scientific knowledge on the part of the readers was assumed. However, on a number of occasions the newspaper also took responsibility for educating or re-educating the public by providing informational articles that would guarantee their readers' understanding of the astronomical articles that were published.

7 Concluding Remarks

The last three decades of the nineteenth century were years that saw great advances in American astronomy and America's scientists and the general public were very lucky that there were two total solar eclipses just a decade apart that were visible across the nation.

The year 1869 was significant in American history as the final spike was driven to complete the Transcontinental Railroad. This year's total eclipse occurred at a time when Americans desperately needed a diversion as the post-Civil War reconciliation of the individual states was still in progress. The eclipse expedition members, utilizing the free transcontinental rail transport provided for them, often witnessing first-hand the despair of former slaves and Native Americans seen abandoned along the railway's path. The stunning apparition of a total eclipse of the Sun and the arrival of expeditions with their busy camps, strange equipment and public lectures stimulated the general populace's interest and imagination in astronomy. Eclipses on faraway continents just did not hold the same level of US public attention as witnessed by the lack of general reporting by the news media.

The *New York Times* led the way as a consistent vehicle for the dissemination of eclipse expedition's events and scientific output to the general public.

At the time of the 1878 eclipse and thereafter, newsprint coverage of general topics in astronomy would occur on a more regular basis and with increasing frequency. Quite apart from the various accounts of the eclipse itself, Watson and Swift succeeded in stirring the public's imagination with their musings about that mysterious but yet to be discovered intra-Mercurial planet, Vulcan. These were well covered in the pages of the *New York Times*.

There would not be another total solar eclipse visible from the United States until a decade later when expeditions and numerous amateurs convened on the northwestern states in January of 1889. Accessibility to good viewing was limited to a small region of the northwest states that were not near major population centers. Just three significant American parties (Lick Observatory, Washington State University, and Harvard College Observatory) covered this eclipse, with the Harvard party being the only east coast institution. Although this level of participation paled in comparison to the 1869 and 1878 eclipse efforts, press coverage was good. This time, the west coast-based *San Francisco Chronicle* joined the *New York Times* in giving ample and somewhat voluminous eclipse coverage, providing instructions for viewers, accounts of the activities of the expedition parties and the results of their observations.

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Part V
The History of Australian Radio Astronomy

The Contribution of the Division of Radiophysics Potts Hill Field Station to International Radio Astronomy

Harry Wendt, Wayne Orchiston, and Bruce Slee

Abstract During the 1950s Australia was one of the world's foremost astronomical nations owing primarily to the work of the dynamic Radio Astronomy Group within the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics. Most of the observations were made at the network of field stations maintained by the Division in or near Sydney, and one of the most notable of these was located at Potts Hill, the site of Sydney's major water-distribution reservoirs.

This paper describes the amazing range of radio telescopes developed at Potts Hill; the types of solar, galactic and extragalactic research programs to which they were committed; and the pioneering young men and women who played a key role in the early development of radio astronomy.

1 Introduction

This paper provides a summary of the research carried out at the Potts Hill field station by the Division of Radiophysics, Commonwealth Scientific and Industrial Research Organization, Australia, during the seminal period of Australian radio astronomy prior to 1960.[1] While a number of histories of the early years of radio astronomy in Australia have been published (e.g. Orchiston and Slee 2005a, b; Robertson 1992; Sullivan 2005), there has not been a comprehensive review of the specific contribution made by the Potts Hill field station. This was arguably the most

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[1] For a more detailed discussion see Wendt 2008, and for reviews of the Potts Hill solar grating arrays and early H-line work see Wendt et al. 2008a and 2008b respectively.

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exciting and innovative era in the development of Australian radio astronomy. It was the era before 'big science' projects emerged, a period when small-scale projects dominated and radio engineers first entered the domain of the astronomers. This was a unique period when – along with Britain – Australia achieved world leadership in the new field of radio astronomy. As Hanbury-Brown (1993) remarked, "… golden ages in science are rare and should be recorded."

Under the leadership of Joseph Pawsey, 20 field stations and remote sites operated during the first 16 years (1945–1961) of Australian radio astronomy, or the 'pre-Parkes' era (see Orchiston and Slee 2005a). Potts Hill and the better historically-documented Dover Heights field station (e.g. see Bolton 1982; Kellermann et al. 2005; Orchiston and Slee 2002; Slee 1994; Stanley 1994; Westfold 1994) were the two major field stations operating during the early part of this period, and by 1952 Potts Hill had become the largest field station of the Division (Pawsey 1952).

The Potts Hill field station was located on vacant land adjacent to a water supply reservoir on the outskirts of suburban Sydney, some 16 km to the southwest of the central business district. A wide variety of instruments was used at Potts Hill and a number of the scientists who worked there emerged as leading researchers in Australian radio astronomy. For a period it was the focal site for Australian solar radio observations, and it was where the Australian confirmation of the 21-cm hydrogen emission spectral-line took place. Potts Hill was also the site of the discovery of the discrete source known as Sagittarius A at the centre of our Galaxy, although many histories incorrectly credit this to work carried out at Dover Heights (see Kerr 1983: 297; cf. Orchiston and Slee 2002: 30). The first use of Earth-rotational synthesis occurred at Potts Hill, but because it was not further developed, credit is now largely given to Cambridge for initiation of this technique (Christiansen 1989).

2 The Beginnings of Potts Hill Field Station

The suburb of Potts Hill was named after Joseph Hyde Potts, who bought the original allotment of land in 1834 from H.G. Douglas (Perrin 2006). To cope with the demands of the rapidly-growing city of Sydney, construction of a water supply reservoir was commenced at Potts Hill in 1880. Two reservoirs were ultimately constructed and these remain an integral part of Sydney's water supply system.

In 1947 R.F. Treharne and Alec Little were working at a Radiophysics leased site at Bankstown aerodrome on the construction of a new type of instrument that would become known as a Swept-Lobe Interferometer. In September 1947 the building they were working in was sold, requiring them to look for a new site to undertake construction as well as observations. At around the same time Treharne elected to leave the project and supervision was transferred to Ruby Payne-Scott who was concluding a program of solar observations at Hornsby Valley field station.

In April 1948, Payne-Scott and Little reported (Pawsey 1948) that a new site had been found on vacant land adjacent to the Potts Hill water supply reservoirs. Permission to operate the field station was granted by the Sydney Water Board.

Instrumental in this decision was the support of H.A. Stowe, the Head of Electrical Engineering at the Water Board. Stowe was himself an amateur radio operator and he maintained a close interest in the activities of the Division of Radiophysics.

At this time, also keen to find a new site for solar observations was W.N. 'Chris' Christiansen (see Wendt et al. 2011a). Christiansen had recently taken over as the lead researcher from Fred Lehany at the Georges Heights field station. This field station was located on military land at Middle Head and had been the site of early radar development. Having inspected the Potts Hill site, Christiansen took the opportunity to relocate his main instrument, a 16 × 18-ft paraboloid, to Potts Hill. Figure 1 shows the first sketch plan for the Potts Hill field station.

Thus, Potts Hill field station began operations in the later part of 1948 with two research teams. The first led by Payne-Scott intended to examine the active Sun using the newly-developed Swept-Lobe Interferometer, while Christiansen's team would also examine the Sun using the 16-ft by 18-ft paraboloid. Christiansen's first task would be to investigate the distribution of radiation across the solar disk using the opportunity presented by a partial solar eclipse that was due on 1 November 1948.

Over the next 10 years a great variety of different types of radio telescopes would be deployed at Potts Hill (see Table 1). These would be used in wide-ranging

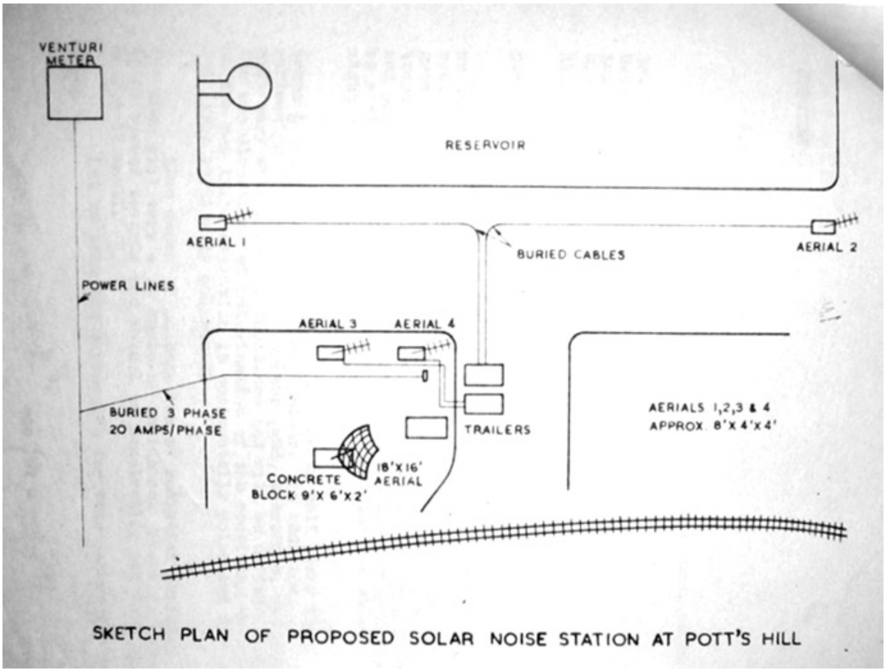

Fig. 1 A sketch plan for the Potts Hill field station from mid June 1948. At this stage only the Swept-Lobe Interferometer, the 16 × 18-ft and two Yagi arrays appear on the plan. The railway used to supply coal to the pumping station is evident at the *bottom of the plan*. In the sketch, South is up (courtesy: National Archives of Australian – 972098 - C3830 - A1/1/1 Part 3 Box 1).

Table 1 A summary of the 11 different radio telescopes operated at Potts Hill

Reference	Instrument	Frequency (MHz)	Wavelength (m)	Beamwidth[a] (°)	Research program(s)
A	16-ft × 18-ft Paraboloid	200	1.50	21	Solar
		600	0.50	7	Solar; cosmic
		1,200	0.25	3.5	Solar, cosmic
		1,420	0.21	2.3	H-line
B	10-ft Paraboloid	600	0.50	12	Solar
		1,200	0.25	6	Cosmic
C	44-in. Ex-Search Light Parabola	9,428	0.03	2	Solar
D	68-in. Parabola	3,000	0.10	3.4	Solar, cosmic
E	Swept Lobe Interferometer	97	3.09	0.03	Solar, cosmic
F(1)	E-W Grating Array	1,420	0.21	0.05	Solar
		500	0.60	0.14	Solar
F(2)	N-S Grating Array	1,420	0.21	0.05	solar
G	36-ft Transit Parabola	1,420	0.21	1.4	H-line
		600	0.50	3	Cosmic
		1,400	0.21	1.4	Cosmic
H	Mills Cross Prototype	97	3.09	8	Cosmic
I	Yagi Arrays	62	4.84	–	Solar
		98	3.06	–	Solar
J	Suspended Dipole	20	15.3	–	Jupiter

[a] The beamwidth (θ) is as stated in the published references, or where the resolution was not explicitly stated the beamwidth has been calculated using the formula $\theta = 1.2\lambda/D$, where λ = wavelength in metres and D = aerial diameter in metres

programs spanning solar, planetary, galactic and cosmic research. Figure 2 contains a site map of Potts Hill field station with the locations of the major instruments, while Figure 3 shows an aerial view of the field station in March 1954.

3 Investigating the Active Sun

3.1 Payne-Scott and the Swept-Lobe Interferometer

One of the first instruments deployed at Potts Hill was the Swept-Lobe Interferometer. This was a unique instrument that was developed specifically to investigate the accurate position of the origin of solar burst activity. Ruby Payne-Scott[2] had been involved in the very first Australian investigation of radio frequency radiation from the Sun using the sea-interferometry technique (McCready et al.

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[2] For a detailed review of Payne-Scott's career see Goss and McGee 2009.

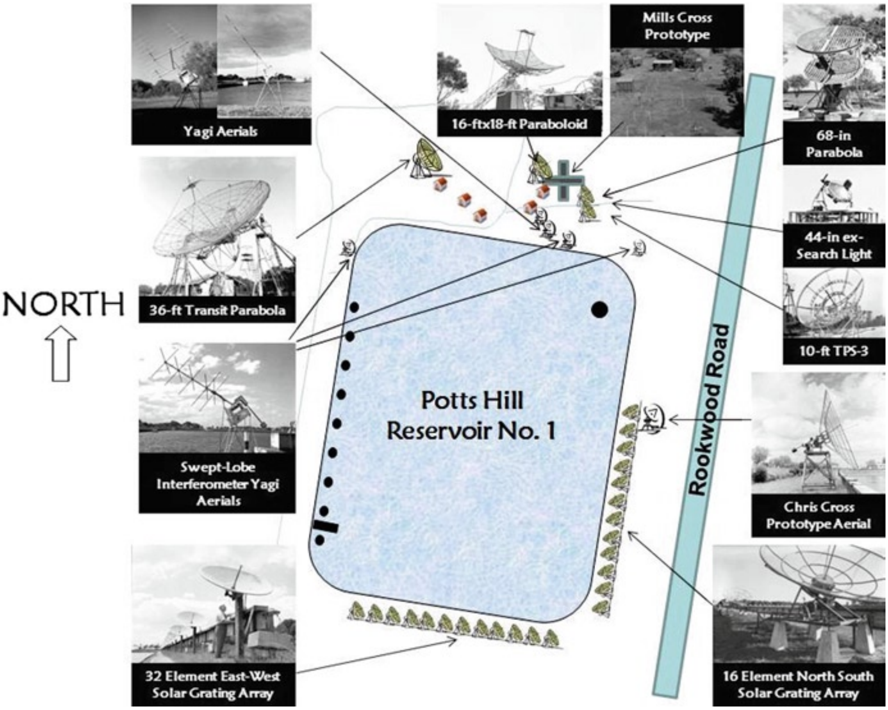


Fig. 2 A site map of Potts Hill field station showing the locations of the main instruments that operated at the field station from 1948 to 1961 (*inset* photographs courtesy: ATNF Historic Photographic Archive).

1947), but this technique was unsuited to accurate determination of the positions of the very short duration solar bursts. The Swept-Lobe Interferometer overcame these limitations by changing the phase of the local oscillator to sweep the interferometer lobes rather than waiting for the Earth's rotation to move the source through the lobes. In this way an interference pattern could be obtained from a very short duration source and hence an accurate position could be determined. By using two different baselines (see Figure 4) to eliminate the ambiguity of the location of the main lobe and operating at 98 MHz, the Swept-Lobe could determine a source position accurate to 2′.

The Swept-Lobe Interferometer used three Yagi aerials (see Figure 5) in a Michelson interferometer configuration. The key to the design was to feed the pre-amplified aerial outputs to a central phase-changing unit that changed the phase of the local oscillator. Here a 1,500 rpm synchronous motor produced a total relative phase change of twice the electrical length line length, 25 times per second. The output was a 25 Hz interference pattern which was displayed as a sine wave on a cathode-ray oscilloscope. The position of the sine wave minimum varied with the position of the detected source. Figure 6 shows a block diagram of the major components of the interferometer.

Fig. 3 An aerial view of the two Potts Hill water reservoirs taken on 19 March 1954 from the north, looking south. The main part of the radio astronomy field station is located in the foreground on the flat land immediately to the north of the reservoir (courtesy: ATNF Historic Photographic Archive: B3253-1).

A 16-mm cine camera was used to photograph the output signal together with a clock and frame counter record. The camera was triggered to take three consecutive photographs automatically when the signal reached a threshold level. In the first frame, the signal recorded was of the short spacing A1–A2 shown in Figure 4 and using the horizontal elements of the Yagi array. In the second frame the receiver was switched to the vertical elements and in the third, the long spacing A1–A3 was recorded. In this way not only could the position of the source be located, but an indication of the polarisation of the source could also be determined. Figure 7 gives an example of the recorded output.

Payne-Scott and Little were able to use the Swept-Lobe Interferometer to accurately determine the position and movement of radio sources across the solar disk and outwards through the corona. After initial test observations they conducted a systematic series of observations from May 1949 to July 1950. Their first published research paper dealt with a description of the equipment they used (Little and Payne-Scott 1951), and in the second paper (Payne-Scott and Little 1951) in their series of three, they described their findings on noise storm sources (later to be classified as Type I bursts). They found the Type I sources originated high in the corona above large sunspot groups and that there was an association of polarisation with the underlying sunspots. In the third paper

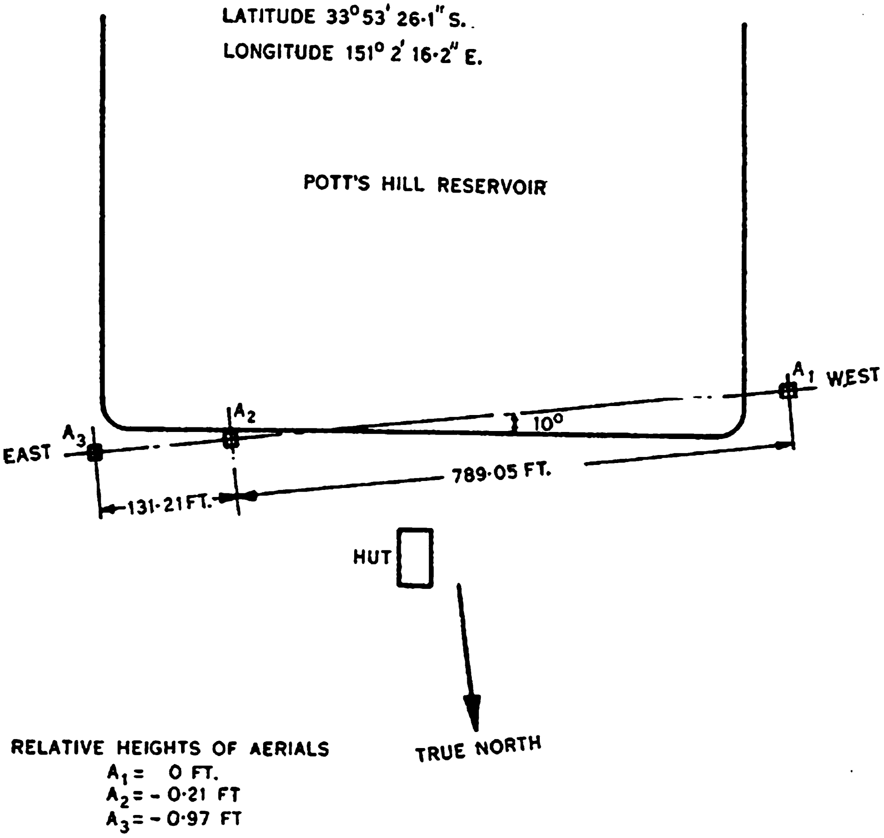


Fig. 4 A site map showing the locations of the Yagi aerials of the Swept-Lobe Interferometer. The use of three aerials allowed switching between two different baselines so that any ambiguity in the location of the main lobe relative to the solar noise source could be determined (after Payne-Scott and Little 1951: 494).

of the series (Payne-Scott and Little 1952), they examined the motion of outburst sources (later to be classified as Type II bursts). Their observations showed that the origin of the source was often associated with a solar flare event and that the source would move outwards through the corona as the result of an exciting agent, most likely a corpuscular stream believed to be associated with terrestrial magnetic storms. The velocity of the outward motion observed ranged from 500 to 3,000 km/sec. Figure 8 shows an example of a moving outburst source. These observations were the first direct observations of motions of radio sources in the solar corona.

In 1951, with the pending birth of her first child, Payne-Scott made the decision to resign from Radiophysics. Her resignation was a major loss not only to Radiophysics, but radio astronomy as a whole. Further work using the Swept-Lobe Interferometer was abandoned and Little joined Bernard Mills to help develop the prototype for his cross-type radio telescope.

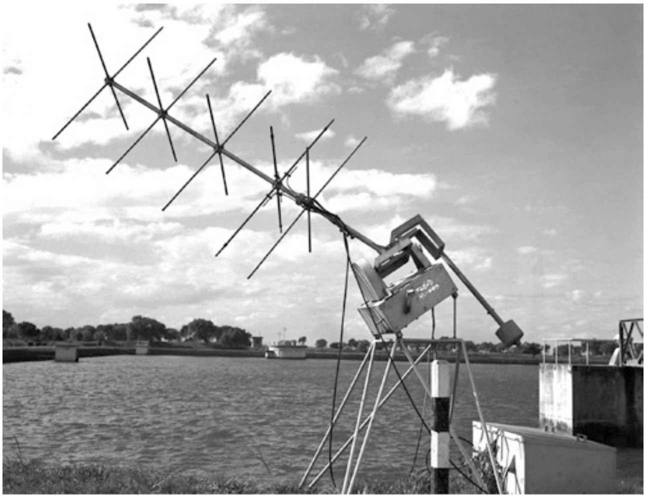


Fig. 5 The western Yagi aerial of the Swept-Lobe Interferometer at Potts Hill. The other two elements of the interferometer are directly to the east on the far left bank of the reservoir (courtesy: ATNF Historic Photographic Archive: 2217).

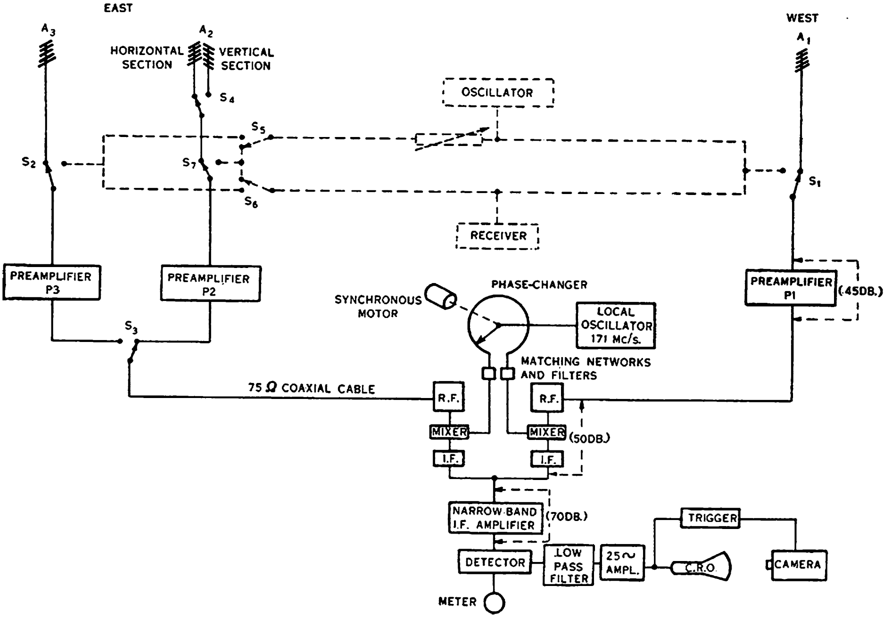
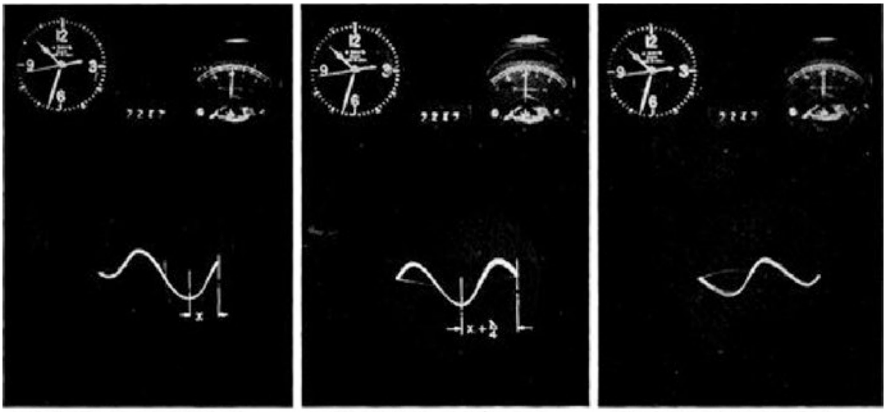


Fig. 6 A block diagram of the Swept-Lobe Interferometer (after Payne-Scott and Little 1951: 494).



(a) AERIAL A_1-HORIZONTAL
AERIAL A_2-HORIZONTAL

(b) AERIAL A_1-HORIZONTAL
AERIAL A_2-VERTICAL

(c) AERIAL A_1-HORIZONTAL
AERIAL A_3-HORIZONTAL

Fig. 7 A recording from the Swept-Lobe Interferometer showing the three photographed frames. The *left frame* shows the interference pattern from the short baseline, the *centre frame* shows the switch to the vertical Yagi array and the *final frame* is for the long baseline. The shift in the position of the minimum in the central frame is due to source radiation being circularly polarised. A quarter-lobe shift would be expected without a change in amplitude when switching between the horizontal and vertical elements (after Little and Payne-Scott 1951: Plate 4).

3.2 Other Observations of the Active Sun

While Payne-Scott's research was the major program of work examining the active Sun at Potts Hill, a number of other groups also made contributions.

In the lead up to the 1 November 1948 partial solar eclipse, Harry Minnett and Norman Labrum conducted a program of solar observations at 9,428 MHz using a 44-in. parabola that had been converted from a WWII searchlight. They noted that at this frequency, solar bursts were very rare with only 5 being recorded in some 230 h of observations (Minnett and Labrum 1950).

On 17 and 21–22 February 1950 two extremely large radio-frequency solar outbursts were observed across all of the frequencies being monitored at Potts Hill. This ranged from 62 MHz using a Yagi array, 98 MHz using the swept lobe interferometer, 600 MHz and 1,200 MHz using the 16 × 18-ft ex-Georges Heights paraboloid, 3,000 MHz using the 68-in. parabola and finally, 9,400 MHz using the ex-search light 44-in. parabola. In addition, 200 MHz observations were made using the 4-element Yagi at Mount Stromlo. Figure 9 shows the power flux levels recorded at the different frequencies for observations on both dates. These observations were supplemented by a range of other data and included measurement of the short-wave radio fade out in Sydney of the Brisbane radio station VLQ-3 broadcasting at 9.6 MHz, sunspot and solar flare observations from Mount Stromlo, flare observations from Carter Observatory in Wellington, New Zealand, and from Kodaikanal Observatory in India, and magnetogram records from the Watheroo Magnetic

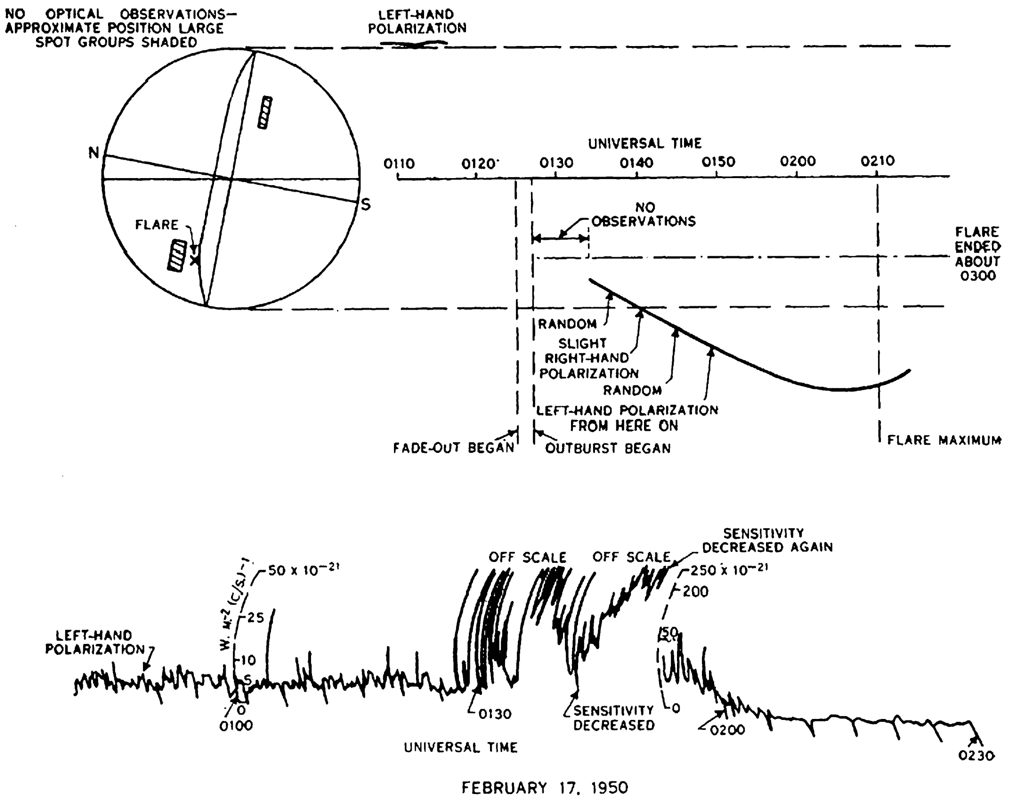


Fig. 8 The outburst of 17 February 1950 observed with the Swept-Lobe Interferometer. The *upper figure* shows the flare position on the solar disk, movement in the position of the outburst and polarisation measurements. The *lower chart record* shows the overall emission at 98 MHz, with 5-min timing marks indicated by the downward ticks (after Payne-Scott and Little 1952: 34).

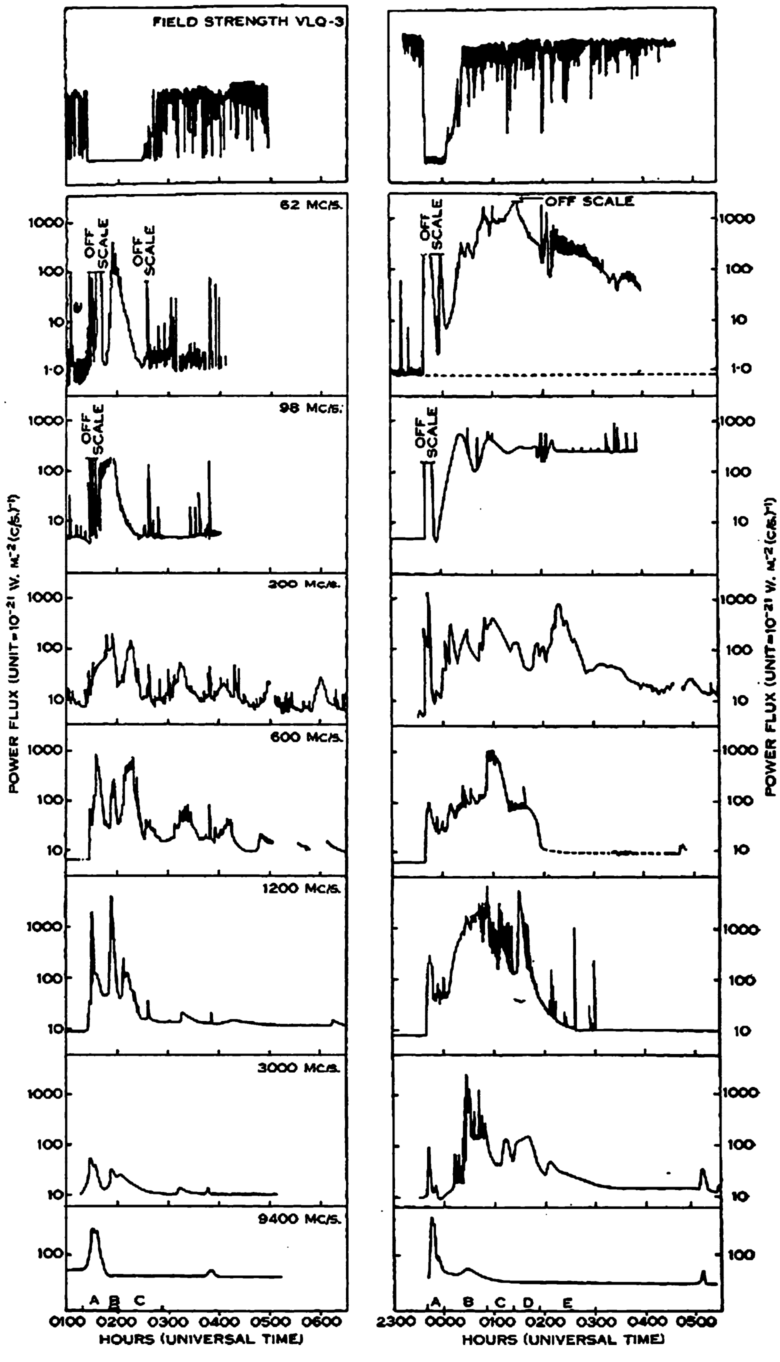


Fig. 9 Power flux records for the seven frequencies observed on 17 (*left*) and 21–22 (*right*) February 1950. The top record is of the field strength for the radio station VLQ-3 from Brisbane, measured at Sydney. The 200 MHz record is from Mt Stromlo (after Christiansen et al. 1951: 53).

Observatory in Western Australia. The combined observations were published in 1951 (Christiansen et al. 1951). This demonstrates the increasingly cooperative approach being undertaken with other solar astronomy groups both domestic and international.

The final published research based on the ongoing daily solar observation program at Potts Hill was an analysis of solar radio bursts over a period of 18 months from January 1950 to June 1951 (Davies 1954). Piddington and Davies had earlier tabulated data based on the daily records at 200, 600, 1,200, 3,000 and 9,400 MHz in an internal report. These were later extended to include the 62 and 98 MHz records. With the exception of the 200 MHz records which came from Mount Stromlo, all of the records were based on observations made at Potts Hill. Piddington was interested in tabulating the data to support his theoretical work on the origin of the solar corona (Davies 2005: 94).

Davies used the tabulated data to perform an analysis of some 400 bursts that were observed during the period and looked at their association with other solar events and with terrestrial magnetic crochets and radio fadeouts. The data for the magnetic crochet comparisons were drawn from the Toolangi Magnetic Observatory located near Melbourne, from the quarterly reports of the *Journal of Geophysical Research* and from the 1950 *Bulletin of International Association of Terrestrial Magnetism and Electricity*. The radio fadeout data were derived from 18 MHz measurements of galactic radiation made at the Hornsby Valley field station. It is interesting to note that these were the same records that contained the detection of Jovian radio bursts that remained unnoticed until the records were re-examined (Shain 1956) in light of the Jupiter emission discovery in the US (Burke and Franklin 1955). The solar flare and sunspot information were based on the *Quarterly Bulletin* of the International Astronomy Union and the *Monthly Bulletin* of the Tokyo Observatory.

The main aim of this analysis was to study the correlation of the radio bursts with other phenomena, therefore no attempt was made to classify burst types or examine the physical origins of the bursts. Given that the broadest definition of a burst, being any clear-cut solar radio emission rising above the daily level, was used, the analysis included all types of bursts without distinction. The broad characteristics of the bursts were described together with relationships between bursts at different frequencies.

The analysis showed the same time delays of onset of bursts at different frequencies as had earlier been observed (e.g. Payne-Scott et al. 1947), as well as supporting the observation of both outward and inward movement of sources through successive plasma levels in the solar atmosphere, as had been observed by Payne-Scott and Little (1952). All frequencies showed a tendency to lag 3,000 MHz, suggesting a simultaneous movement up and down from the level of zero refractive index at the frequency which occurred first.

In terms of correlations with other phenomena, the analysis showed that nearly all flares and their terrestrial effects (i.e. magnetic crochets and radio fadeouts) were associated with radio bursts. Only 1% of flares and fadeouts and 2% of crochets were not associated with bursts. There was also a rough correlation between the intensity of bursts, flares, fadeouts and crochets. The onset of the bursts appeared to coincide with the onset of flares and crochets, but preceded fadeouts by about 2 min.

As all types of bursts were included in the analysis there were many more bursts observed than flare, fadeouts and crochets.

This work effectively marked the end of research on the active Sun at Potts Hill. Through a prolonged period of regular observations, a solid base of radio data had been established. Payne-Scott and Little's accurate position measurements using the swept-lobe interferometer provided the first direct measurement of outward motions of radio sources through the corona. The focus of further measurements of the active Sun now moved to Paul Wild's group (see Stewart et al. 2011b) which had been measuring the dynamic spectra of solar bursts, first at the Penrith field station (Stewart et al. 2010) and subsequently at the Dapto field station (Stewart et al. 2011a).

4 Investigating the Quiet Sun

4.1 The 1948 and 1949 Solar Eclipse Observations

A partial solar eclipse was visible in Eastern Australia on 1 November 1948 and this provided an ideal opportunity for the Radiophysics teams to mount a major campaign to observe the Sun at a range of frequencies while it was eclipsed by the Moon's disk. This provided a relatively elegant means of obtaining very high resolution measurements of the distribution of radiation across the solar disk (Orchiston et al. 2005). Verifying the limb-brightening effect that had been predicted by Martyn (1946) was a major goal of these observations. Earlier efforts to mount an expedition to observe a total solar eclipse visible near Brazil in 1947 had been cancelled due to the logistical difficulties (see Wendt et al. 2008c).

Christiansen had re-located the 16 x 18-ft paraboloid (see Figure 10) from Georges Heights to Potts Hill to be ready in time to observe the 1948 eclipse. The relocation had also involved moving all of the other solar observation equipment to Potts Hill and this included an experiment being conducted by Don Yabsley to attempt to measure the Sun's one-dimensional brightness distribution using two portable ex-WWII AN/TPS-3 10-ft radar aerials in a Michelson interferometer configuration (see Figure 11). Although the preliminary results reported in the minutes of the Solar Noise Group indicated that Yabsley had been successful in detecting limb-brightening using this technique, no results were ever published and while further work was carried out at Potts Hill, it was given second priority to the eclipse observations and later abandoned altogether. This same technique would however be extensively developed at Cambridge (e.g. see Machin 1951; O'Brien 1953; Stanier 1950).

While the main eclipse observations were to occur at Potts Hill, two other teams were dispatched to two geographically disbursed locations in Strachan on the west coast of Tasmania and in Rockbank to the southwest of Melbourne in Victoria. Christiansen led the Victorian team while Yabsley led the Tasmanian team and the Potts Hill observations were led by Bernard Mills in his first foray into radio astronomy as a new member of Pawsey's group. The remote teams each used the

Fig. 10 The 16-ft × 18-ft Paraboloid at Potts Hill in May 1949 (courtesy: ATNF Historic Photographic Archive: B1803-4).

portable 10-ft TPS-3 aerials to observe the eclipse at 600 MHz. Observing at the three distributed locations allowed for the triangulation of the location and size of regions where there was a sudden change in radiation as the Moon's disk occulted an enhanced radio source. The team was able to use this technique to successfully identify sources of enhanced radiation as arising in the corona above or near some sunspot groups (see Figure 12). However, because of the presence of a number of these sources which were estimated to contribute 20% of the observed radiation, the measurement of the distribution of radiation across the solar disk was more problematic and the team could not reach a definitive conclusion on the detection of limb-brightening, although they were confident that the quiet-sun distribution at 600 MHz extended to some 1.4 solar radii. One interesting other point to come out of the analysis of the polarisation measurements by the resident Radiophysics solar theorist, Stefan Smerd, was that if the Sun had a general magnetic field, then its strength could not be greater than 11 Gauss (Smerd 1950a). At the time the generally-held view based on work by Hale et al (1918) was that the Sun had a general magnetic field of ~50 Gauss.

Fig. 11 An ex-WWII AN/TPS-3 aerial undergoing trials at Georges Heights on 13 August 1948 prior to being relocated to Potts Hill (courtesy: ATNF Historic Photographic Archive: B1511).

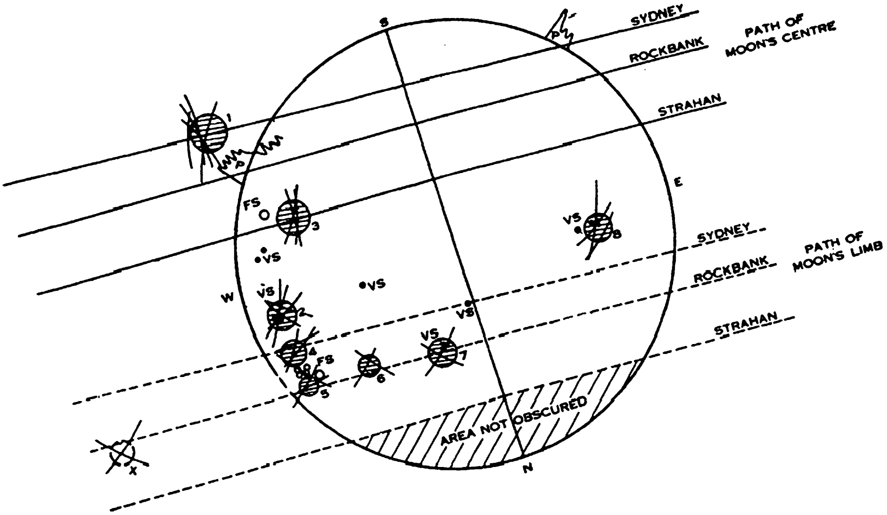


Fig. 12 The location of enhanced radiation (*hashed circles*) as measured from Potts Hill, Strachan and Rockbank during the 1 November 1948 eclipse. *VS* visible sunspot, *FS* position of a sunspot visible 27 days earlier, *P* solar prominence (after Christiansen et al. 1949: 513).

Two other groups within Radiophysics besides Christiansen's group also observed the 1948 eclipse from Potts Hill. Piddington and Hindman (1949) used a 68-in. parabola to observe at 3,000 MHz, while Harry Minnett and Norman Labrum (1950) used a 44-in. parabola which had been an ex-WWII search light to observe at 9,428 MHz (see Figure 13). In each case observations were conducted for an

Fig. 13 The 44-in. (*left*) and 68-in. (*right*) parabolas at Potts Hill used during the 1948 eclipse and for the ongoing solar monitoring program (courtesy: ATNF Historic Photographic Archive: B3171-1R).

extended period leading up to the eclipse and after it. Results of the daily measurements showed a correlation, strongest at the higher frequency, between the levels of enhanced radiation and the number of sunspot groups visible on the solar disk. Like Christiansen's eclipse result, the distribution measurements were again inconclusive although Piddington and Hindman argued that their result was most consistent with a model of the Sun with 32% of the radiation being concentrated in a ring near the limb of the Sun.

On 22 October 1949 another partial solar eclipse was visible from eastern Australia. Radiophysics again mounted a major observation program at Potts Hill, including observations from remote sites at East Sale in Victoria and Eaglehawk Neck in Tasmania. Despite a successful observation program, no results were ever published (see Wendt et al. 2008c for a detailed discussion).

4.2 The Solar Grating Arrays

Not long after these events Christiansen had the inspiration for development of what would become known as the solar grating array (see Wendt et al. 2008a for a detailed discussion). This unique instrument consisted of 32, 66-in. diameter dishes,

Fig. 14 The solar grating array in November 1951 on the southern bank of the Potts Hill No.1 reservoir (courtesy: ATNF Historic Photographic Archive: B2976-1).

each equatorially mounted along a 700-ft east-west baseline (see Figure 14). The array was located on the southern bank of the No. 1 reservoir at Potts Hill. Operating at 1,410 MHz the array produced a series of fan beams, each with a half-power beam width of 2.9′ and separated by 1.7°. This meant that at any one time the Sun would be located in a single fan-beam. With the development of this instrument, at last it was possible to obtain regular high resolution observations of solar radiation without the need to wait for the infrequent and fleeting opportunities presented by solar eclipses.

Construction of the solar grating array was completed in late 1951 and by 1952 a regular program of observations had begun. Figure 15 shows an example record of the one-dimensional brightness distribution of the Sun as it passed through one of the fan beam over consecutive 2-day intervals.

By examining the one-dimensional distributions over an extended period it became clear that strong limb-brightening was present at 1,410 MHz, in agreement with Smerd's (1950b) theoretical model for a 10^4 K chromosphere and a 0.3–3.0×10^6 K corona. Figure 16 shows an example of the derived radial distribution of brightness across the solar disk based on the one-dimensional scan observations compared with the theoretical predication.

Christiansen's next step was to build a north-south oriented grating array (Figure 17) so that he could explore how the brightness distribution varied with different orientations across the solar disk. This new array was a slightly different

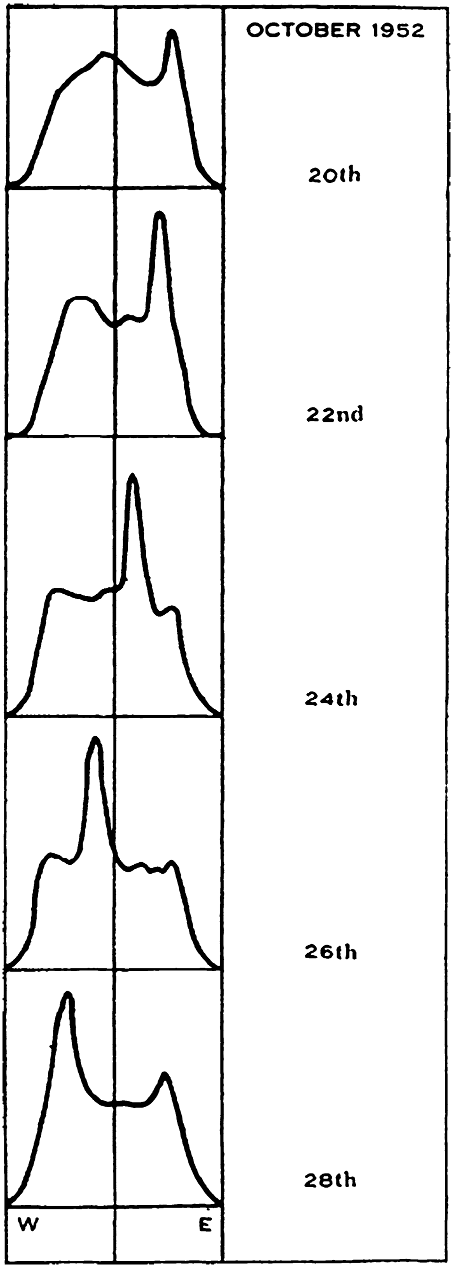


Fig. 15 Daily records of one-dimensional brightness distributions across the solar disk from 20 to 28 October 1952. The *image* shows an area of enhanced radiation on the Sun's eastern limb in the first chart. This area moves from east to west as the Sun rotates over consecutive days (after Christiansen and Warburton 1953: 198).

design consisting of 16 open mesh parabolas. It was also somewhat shorter than the east-west array being 760 wavelengths as opposed to the 1,028 wavelengths for the east-west array. The array produced fan beams with a half-power beamwidth of 4′.

Regular observations using the north-south array began in September 1953 and continued until April 1954. By observing over an extended period Christiansen and

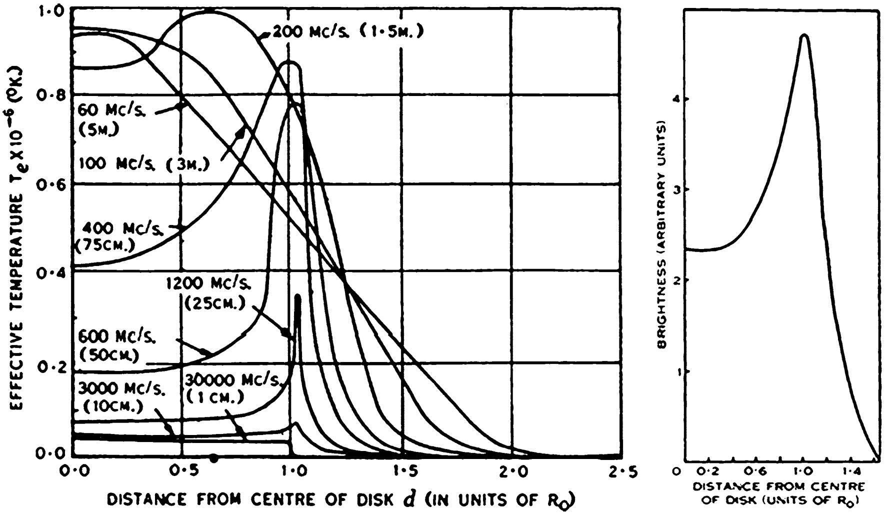


Fig. 16 The *left-hand chart* shows the theoretical distribution of temperature as a function of distance from the centre of the solar disk. Temperatures of 3×10^4 K and 10^6 K are assumed for the chromosphere and corona respectively (after Smerd 1950b: 46). The *right-hand chart* shows a radial brightness distribution across the solar disk based on one-dimensional scan observations at 1,410 MHz (after Christiansen and Warburton 1953: 268).

Fig. 17 The north-south grating array in July 1953 (courtesy: ATNF Historic Photographic Archive: 3116–1).

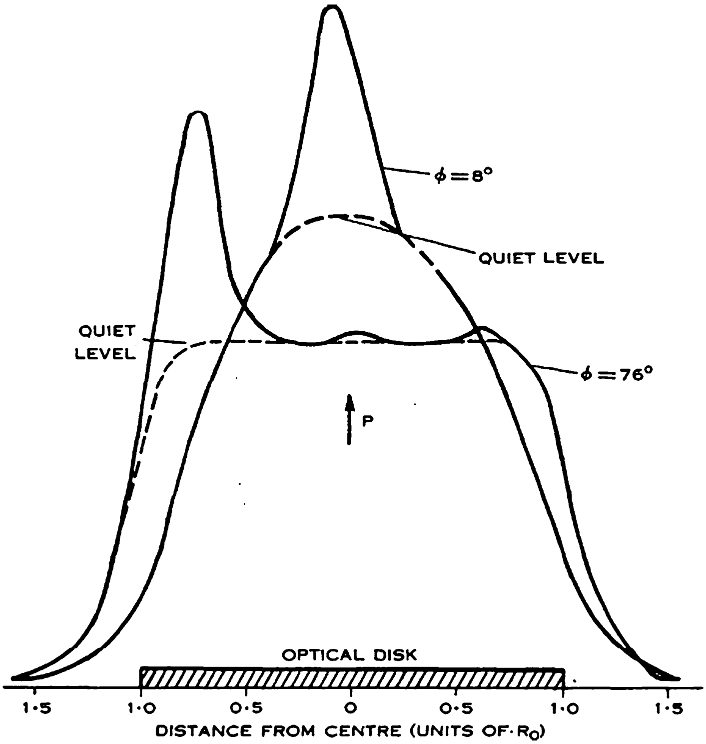


Fig. 18 An example of a one-dimensional scan taken for two different scanning angles by observing at different times on the same day. One scan is oriented at 76° while the other is at 8°. An area of enhanced radiation is evident on the western limb. Note that the distribution of the quiet level is clearly not symmetrical (after Christiansen and Warburton 1955: 478).

Warburton were able to make use in the seasonal variations in the orientation of the Sun with respect to the two arrays. This enabled them to achieve scanning angles coverage across the Sun's disk of 140° out of the full 180° scanning range (see Figure 18).

In order to produce a two dimensional image, a cosine Fourier analysis of the individual one-dimensional distributions for the different scanning angles was performed. It is important to note that by using the cosine Fourier analysis Christiansen assumed the Sun was symmetrical and phase was ignored. The numerical value for each scan was plotted radially corresponding to the direction of the scan and then strip integrated with the strip summations being perpendicular to the scan angle. The cosine Fourier transform of the strip integrals was then taken to give radial cross-sections of the brightness distribution. The final two-dimensional distribution was then constructed by plotting each of the radial cross sections and plotting contour lines joining points of equal intensity. This tedious process took months of calculation and plotting by hand to produce a single two-dimensional

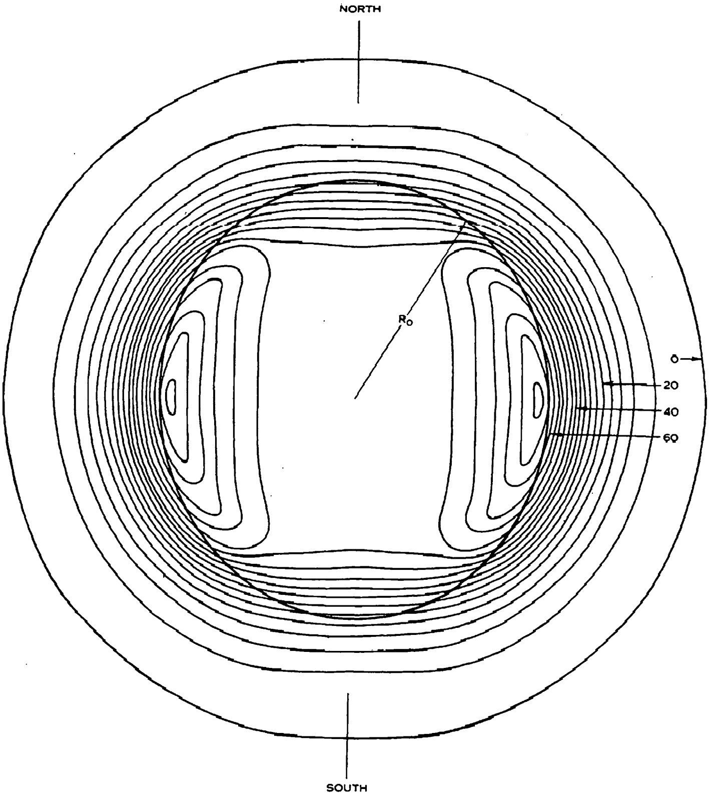


Fig. 19 An example of the derived two-dimensional image of the radio brightness distribution across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K. Contours are spaced at equal intervals of 4×10^3 K (after Christiansen and Warburton 1955: 482).

image as shown in Figure 19. This was the first application of earth rotational synthesis in radio astronomy (Christiansen 1989).

During 1954 Christiansen spent a year visiting the Meudon Observatory in France, so Swarup and Parthasarathy, who were visiting Radiophysics under a Colombo Fellowship, modified the east-west grating array to operate at 500 MHz. The primary purpose of their research was to check Stanier's earlier results at 500 MHz that had not found evidence of limb-brightening. From July 1954 to March 1955, they performed daily observations obtaining one-dimensional scans. Swarup and Parthasarathy found strong evidence of limb-brightening, in good agreement with the results of O'Brien and Tandberg-Hassen (1955). Figure 20 shows a comparison of Swarup and Parthasarathy's (1955a) results and those of Stanier (1950).

In 1957, Christiansen, Warburton and Davies (1957) published the fourth and final paper in their solar series based on observations from the solar grating array. This paper examined the slowly-varying component based on the observations during

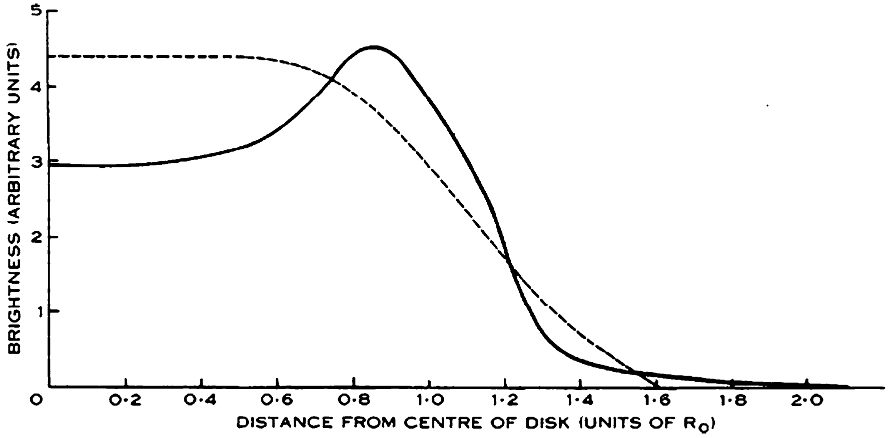


Fig. 20 Radial brightness distributions at 500 MHz comparing Stanier's result (*dashed*) and Swarup and Parthasarathy's observations (after Swarup and Parthasarathy 1955b: 493).

1952 and 1953. Part of their analysis concluded that the lag effect first suggested by Piddington and Davies (1953) was not sufficient to provide the sole explanation of the decline in base temperatures. They concluded that it was likely that both the quiet component and the slowly-varying component varied depending on the solar cycle. They also concluded that the original correlation method proposed by Pawsey and Yabsley (1949) gave results that were quantitatively correct. Christiansen, Warburton and Davies reached the conclusion that the radio emission associated with the slowly varying component appeared to be associated with plage faculiare rather than with sunspots themselves. The plage faculiare are the areas in the photosphere and chromosphere where sunspot groups grow and decay due to strong localised magnetic fields. Christiansen, Warburton and Davies based this on comparison of spectroheliograph observations from Mount Stromlo and the solar grating array observations. Figure 21 shows an example of the comparisons where the vertical lines indicate the maximum point of a one-dimensional scan. A similar conclusion had earlier been reached by Dodson (1954) based on a comparison of her optical observations with Covington's radio observations, and this was discussed with Pawsey following an introductory lecture during the August 1955 IAU symposium on Radio Astronomy at Jodrell Bank (Allen 1957: 262).

Using an analysis of the relative rates of rotation of the optical and radio sources, Christiansen, Warburton and Davies concluded that the 1,420 MHz radio emission emanated in a region about 24,000 km above the photosphere. They also found a correlation of $r = 0.85$ between the size of the plages and the sizes of the radio sources and noted that it appeared that the sources behaved like thin disks lying parallel to the photosphere.

Frustrated by the effort and time needed to produce a two-dimensional image of the Sun, Christiansen returned to an idea he had first discussed with Mills in 1953, the construction of a crossed grating array. Potts Hill did not have sufficient land for

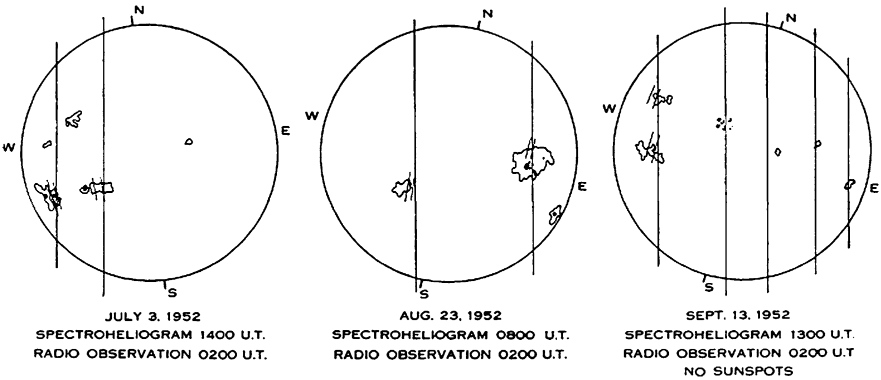


Fig. 21 Spectroheliograms showing plague faculiare (Ca *K*) regions with maximum 1,420 MHz emission position lines from one-dimensional scans shown as *vertical lines* (after Christiansen et al. 1957: 506).

an array with a common centre, so it was necessary to find a new site. However, a prototype of the new aerial for the cross-grating array was tested at Potts Hill. By 1957, Christiansen had constructed the new instrument at the Fleurs Field Station (see Orchiston and Mathewson 2009). This move effectively made the original grating arrays redundant. Swarup approached 'Taffy' Bowen, Chief of the Division of Radiophysics, with a proposal to donate one of the arrays to India (Swarup 2006). This was agreed to, and after many delays the east-west array was shipped to India and ultimately became the Kalyan Radio Telescope which began operations in April 1966 and produced the first research paper in *Nature* later that year (Swarup et al. 1966).

4.3 The 1959 Eclipse Observations

The final solar research paper from Potts Hill was based on observations of the 8 April 1959 partial solar eclipse (Krishnan and Labrum 1961). The eclipse was observed both at Potts Hill using the 16-ft × 18-ft parabola as a high sensitivity total power radiometer at 1,423 MHz and at Fleurs using the Chris-Cross array to help identify areas of enhanced radiation. No calcium spectroheliogram observations were available in Australia at the time, however one was provided by Dobson (now Dobson-Prince) working at the McMath Hulbert Solar Observatory in the U.S. This allowed Krishnan and Labrum to compare the distribution of plage faculaires seen in the K-line of calcium with their radio observations. They found a very close relationship between optical and radio plages, both in their intensity and their overall shape. Krishnan and Labrum were also able to test a number of quiet Sun models against the eclipse observations. They found that the best fit was achieved by a model based on Christiansen and Warburton's (1955) work for sunspot minimum which showed limb-brightening at the equator, but absent at the poles. After allowing for an overall increase in brightness temperature by a factor of two to allow for the sunspot maximum, Krishnan and Labrum found that a stepped-up gradient of limb-brightening (the ear component) provided the best fit. It is likely that the lower resolution of the grating arrays used by Christiansen and Warburton for measurements of limb-brightening would have washed out the steeper gradient and therefore the ear would not appear as pronounced. The higher resolution of the eclipse observation allowed the steeper gradient to be more accurately measured.

The 1959 eclipse observation effectively marked the end of the solar program at Potts Hill. Daily measurements of solar radiation continued for a time using single dish and Yagi aerials in support of observations at both Dapto and Fleurs, but the main focus of investigation had shifted to these field stations.

5 Investigating Discrete Radio Sources

The original reason for establishing the Potts Hill field station was to consolidate the solar observation programs. Solar research was therefore the major focus of the field station in its initial years. This focus began to change during 1949 as interest in discrete cosmic sources grew. Initially these investigations were made by using the solar instruments when solar observations were not possible, such as between sunset and sunrise (e.g. Mills and Thomas 1951; Piddington and Minnett 1951). In 1951 Ewen and Purcell (1951) working at Harvard detected the 1,420 MHz ($\lambda = 21$ cm) emission-line of hydrogen that had been predicted earlier by van de Hulst (1945). This discovery was quickly confirmed in Australia (Pawsey 1951) and led to a new branch of investigations at Potts Hill and to the construction of the first instrument there dedicated to cosmic research. In the second half of the life of the Potts Hill field station cosmic source investigations dominated the research program.

5.1 Discrete Sources in Cygnus

After a very short foray into solar research with Christiansen and Yabsley (1949), Mills turned his attention to the investigation of discrete cosmic sources. Together with Thomas, he used the Swept-lobe Interferometer in a conventional Michelson interferometer configuration to investigate the discrete radio source in Cygnus that had been discovered by Hey, Parsons and Phillips (1946). At Dover Heights significant progress had been made in identifying optical counterparts for three of eight discrete sources (Bolton et al. 1949). However, identification of Cygnus A remained problematic (Bolton and Stanley 1948a, b; Ryle and Smith 1948). After a number of further investigations (Little and Lovell 1950; Smith 1950; Stanley and Slee 1950) the fluctuations that had been observed from the source were determined to originate in the ionosphere and although accuracy of the positional estimates was improved, no optical identification of the source was able to be made.

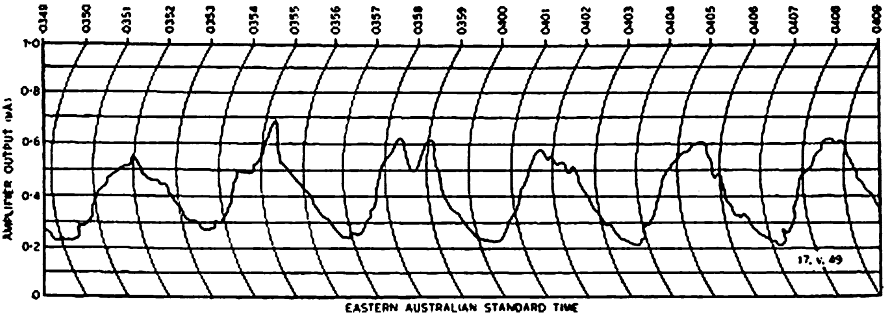


Fig. 22 A typical interference fringe record of Cygnus A as measured by the 97 MHz swept-lobe interferometer in its static lobe mode acting as a more traditional Michelson interferometer. Note the scintillations on the second and third fringe maxima (after Mills and Thomas 1951: 160).

It was with this background that Mills and Thomas undertook investigations of Cygnus A from May to December 1949. From Potts Hill, the source was relatively low in the northern sky rising to a maximum of only 16° above the horizon. This made positional measurements at the relatively low frequency of 97 MHz difficult and also subject to significant refraction and ground reflection errors. Figure 22 shows an example of the interference fringes from Cygnus A as measure from Potts Hill. In private communication with Rudolf Minkowski of Mount Wilson Observatory, Mills identified a 15th magnitude nebula at a distance of 10^7 parsec as being within the positional error box for their measured position of Cygnus A. It was one of the brightest galaxies in a cluster of galaxies; however nothing else appeared to distinguish this particular galaxy as the source of such strong radio emission. Minkowski wrote to Mills advising that he did not think it was permissible to identify the source with one of the faint extragalactic nebulae and therefore a more accurate position estimate was needed to unambiguously distinguish between the other faint nebulae (see Baade and Minkowski 1954). As it transpired the faint galaxy that was the subject of the discussion turned out to be the source of the extraordinary strong radio emission when a more accurate position was ultimately determined by the Cambridge group (Smith 1951).

Mills and Thomas also undertook a detailed analysis of the source fluctuations observed. They concluded that the source of the fluctuations was irregularities from ~5 to 100 km across in the F-region of the ionosphere.

The next investigation at Potts Hill of the Cygnus source was by Piddington and Minnett as part of a broader investigation they were making at 1,210 and 3,000 MHz using the ex-Georges Height 16-ft × 18-ft paraboloid (Piddington and Minnett 1952). This instrument's primary role had been solar investigations, but like Mills and Thomas, Piddington and Minnett were able to borrow the instrument and to use it for cosmic source investigations. Originally Piddington and Minnett commenced observations at Dover Heights (Christiansen 1950), but soon shifted their operations to Potts Hill when the opportunity arose for them to use the 16-ft × 18-ft paraboloid.

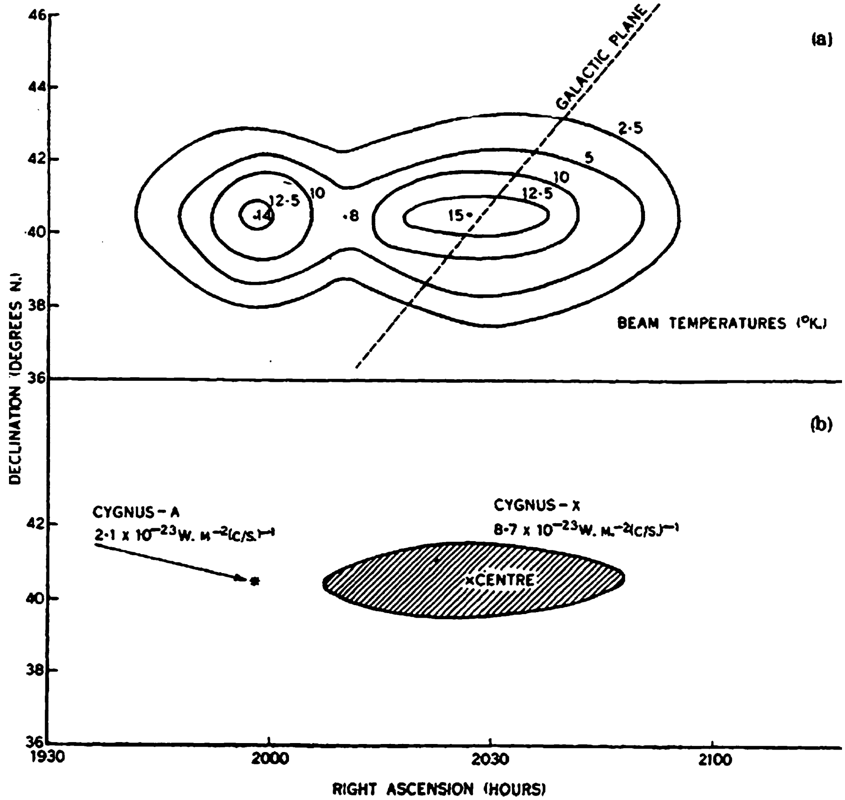


Fig. 23 The *upper plot* shows contours of equal aerial beam temperature at 1,210 MHz. The *lower chart* shows the derived flux density of the sources Cygnus A and X (after Piddington and Minnett 1952: 19).

The resolution of the 16-ft × 18-ft paraboloid was not sufficient to be useful for precise positional observations. Rather, the purpose of the observations had been to understand the broader disposition of sources at the higher frequencies of 1,210 and 3,000 MHz. Piddington and Minnett noted the detection of a new discrete, but diffuse source near Cygnus A which they designated Cygnus X (see Figure 23). They claimed in their published paper that it may be the first 'radio nebula' to be recognised having associated the Cygnus X source with the bright galactic nebulae surrounding the star γ Cygni. They determined its radio spectrum as consistent with thermal radiation from ionised gas, unlike the spectrum of Cygnus A. Due to the limited sensitivity of the equipment used at 3,000 MHz (the smaller 68-in. parabola), Piddington and Minnett were unable to detect either of the Cygnus sources. Therefore they could only establish an upper limit for the flux density at 3,000 MHz.

5.2 The Discovery of Sagittarius A

Piddington and Minnett's program of cosmic observations had begun in 1948 with some preliminary observations of the region of the Galactic Centre using a 10-ft parabola at 1,210 MHz. Later the opportunity arose to use the larger 16-ft × 18 ft paraboloid and the 68-in. Parabola. They used these for the Cygnus observations (discussed above) and for observations of the Galactic Centre, Taurus A (the Crab Nebula), Centaurus A, the Moon, M31 (the Andromeda Nebula and NGC 7293 (a large planetary nebula). The results of these observations were published in the *Australian Journal of Scientific Research* (Piddington and Minnett 1951). This was an important historical paper because it included the discovery of the discrete radio source at the Galactic Centre now known as Sagittarius A (see Figure 24). As discussed by Goss and McGee (1996) and Orchiston and Slee (2002), there are many misconceptions related to the discovery of Sagittarius A. Credit is often incorrectly given (e.g. Kerr 1983: 297) to McGee and Bolton, who in a paper published in the more widely-read journal *Nature* (1954), drew attention to the relationship of Sagittarius A to the Galactic Centre.

Piddington and Minnett (1951) investigated three other known discrete sources. However, only Centaurus A could be detected at 1,210 MHz with a flux density of 4.1×10^{-24} W m^{-2} Hz^{-1} and an uncertainty of 20%. The two other sources investigated, Virgo A and Hercules A, could not be detected and therefore it was assumed their flux densities were less than 1×10^{-24} W m^{-2} Hz^{-1}. No attempt was made to observe these sources at 3,000 MHz.

Attempts were also made to detect M31 and the large planetary nebula NGC 7293 (ibid.). Neither of these sources could be detected at 1,210 or 3,000 MHz.

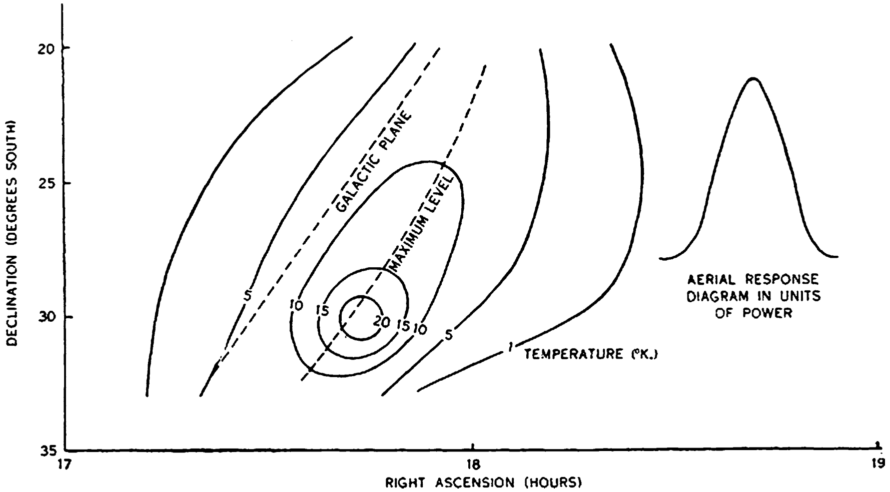


Fig. 24 Aerial temperature contours at 1,210 MHz showing the discrete source Sagittarius A (after Piddington and Minnett 1951: 465).

Subsequent to the observations, but prior to publication, Hanbury-Brown and Hazard (1950) detected radiation from M31 at 158 MHz with an observed flux density of 4×10^{-24} W m^{-2} Hz^{-1}. Piddington and Minnett noted that if the spectrum of M31 was similar to our own Galaxy then the flux density at 1,210 MHz would be 2×10^{-24} W m^{-2} Hz^{-1}, which was below the detection threshold of the equipment they were using.

5.3 The Mills Cross Prototype

After his experiences in using two-element and three-element interferometers, initially at Potts Hill and then more extensively at Badgerys Creek field station during 1950–1952, Mills was looking for a way in which he could overcome some of the limitations inherent in this type of interferometer. One of the main issues Mills had been dealing with at Badgerys Creek was the problem that the small spacing of the interferometer aerials required long periods of integration and therefore the measurements suffered from gain fluctuations in the receiver. It was while exploring a solution to overcome this problem that Mills recalled:

> I had begun to look for a better alternative when I received some unintended assistance from Cambridge. News came through the grapevine that a revolutionary system had been introduced there but it was all very hush-hush and no details were known; it was believed that it involved a modulation of the interference pattern. This seemed to be just what was needed. A little thought suggested modulation by interchanging maxima and minima on the interference pattern by switching phase and using a synchronous detector, as in the Dicke system. The necessary equipment was built and it worked very well. Later I found that this was precisely the system used at Cambridge, the only difference being their use of a hardware switch in the antenna feed lines whereas I had used an electronic switch following the preamplifier. (Mills 1984: 149).

Using the new phase-switched interferometer at Badgerys Creek Mills soon discovered another major issue with using spaced interferometers for survey work. Many of the sources resolved at the short spacing bore no resemblance to those detected at the longer spacing. Mills determined that this was most likely caused by the sources being extended in nature rather than being point sources. He concluded that this was causing the confusion of the interference patterns.

Mills believed that sensitivity was not the issue for the source survey work; rather, high resolution was the key requirement. As he has stated:

> By then, I knew that collecting area was relatively unimportant, the important thing was a large overall size to give high resolution. As a filled array seemed wasteful, I first looked at various passive configurations such as crosses and rings, but these all suffered from high side-lobe levels. Suddenly it occurred to me that by combining the phase-switch, which I had used on the interferometer, with a crossed array the side-lobe problem would be substantially reduced. (Mills 1984: 151).

It was determined that a prototype of the new array should first be constructed at Potts Hill to test the concept before moving to a full scale deployment. In hindsight

Fig. 25 A view of the Mills Cross prototype at Potts Hill in April 1953 (courtesy: ATNF Historic Photographic Archive: B3064-3).

this proved to be a useful undertaking as considerable experience was gained that was later applied to construction of the full-scale cross at the Fleurs field station.

The prototype array was built by Little in consultation with Mills (see Mills and Little 1953). Swarup (2006: 24) also spent 3 months working with Little and Mills on the development of a phase shifter for the array. The array was designed to operate at a frequency of 97 MHz and as such used an array of 24 folded dipoles. Each arm of the cross was 120-ft in length. The response of the combined arms produced a pencil beam with a beamwidth of 8°. The dipoles were backed by wire mesh suspended below the dipoles to act as a reflective surface as shown in Figure 25. Although the crossed array was constructed as a proof of the concept, it did produce the first radio detection of the Large Magellanic Cloud.

5.4 The 600 MHz Continuum Survey

In January 1955, as part of a joint project between the URSI and Commission 40 of the I.A.U., a catalogue of reliably-known discrete radio sources was published (Pawsey 1955). The catalogue was prepared in early 1954 based on surveys that had been published up to that time. This catalogue provides a good guide to the state of investigation of discrete sources in this period. A total of 38 sources was listed in the catalogue. Of these, only eight sources were definitively established, with accurate positions determined by a number of independent observers and optical identifications obtained. The remaining 30 sources were included in the catalogue on the basis that there was reasonable agreement of the source positions from at least two independent observations. Of these, nine had reasonable identification candidates proposed. Included in this list were both Sagittarius A and Cygnus X. These sources had first been proposed by Piddington and Minnett based on their Potts Hill observations. Thus, using Pawsey's (1955) review as an objective measure, as at 1954 5% of all known discrete radio sources had been determined based on research at Potts Hill.

The 1,210 MHz cosmic survey work by Piddington and Minnett was to be the last major program of observations using the 16-ft × 18-ft paraboloid. Having originally been designed as an experimental radar, it was far from ideal as a survey radio telescope. It suffered from sagging and distortion of the reflector surface and the multiple dipoles at the prime focus caused further losses in sensitivity (see Piddington and Trent 1956b: 490n).

The construction at Potts Hill of a 36-ft transit parabola for H-line survey work presented a new opportunity. Piddington and Trent modified the receiver design that had been used at 1,210 MHz on the 16-ft × 18-ft paraboloid to operate at 600 MHz, and, together with a 6-ft parabola operating as the reference aerial, they used the 36-ft transit parabola for a survey at 600 MHz covering the declination range 90° S to 51° N (Piddington and Trent 1956b). The reason for selecting 600 MHz was because surveys of the southern sky had already been conducted at 100 MHz (Bolton and Westfold 1950) and 200 MHz (Allen and Gum 1950). Instruments used for both of these surveys had low resolution, namely beamwidths of 17° and 25° respectively. Bracewell and Roberts (1954) had shown that all detail within an aerial beam could not be subsequently recovered by either graphical or other processing techniques and therefore is lost. This meant that the plots of brightness distribution, particularly in the area of the Galactic Plane, could not be even approximately accurate in terms of source structures. Piddington and Trent determined therefore to conduct a much higher-resolution survey using a pencil-beam instrument. The 36-ft transit parabola operating at 600 MHz had a beamwidth of 3.3°. The results of the full survey are shown in Figure 26. The main features of the survey were the strong source Sagittarius-A which had been associated with the Galactic Centre, the two sources in Cygnus, Cygnus-A and Cygnus-X, Centaurus-A, and Taurus-A the Crab Nebula. There was also a string of sources on or near the galactic plane which Piddington and Trent proposed were likely to be related to thermally-emitting HII regions.

By the mid 1950's the synchrotron process as a source of galactic radio emission had become fairly well accepted (Piddington and Trent 1956b: 489). Piddington and Trent observed that thermal emission from ionized hydrogen still remained a major component of the observed radiation, just as Piddington (1951) had earlier suggested. They proposed that the observations were consistent with a model of synchrotron emission constituting a single spheroidical system with a variable emission per unit volume that increased towards the Galactic Plane where thermal radiation was also concentrated. They concluded that the galactic concentration of thermal emission was consistent with the broad HII distribution of the Galaxy.

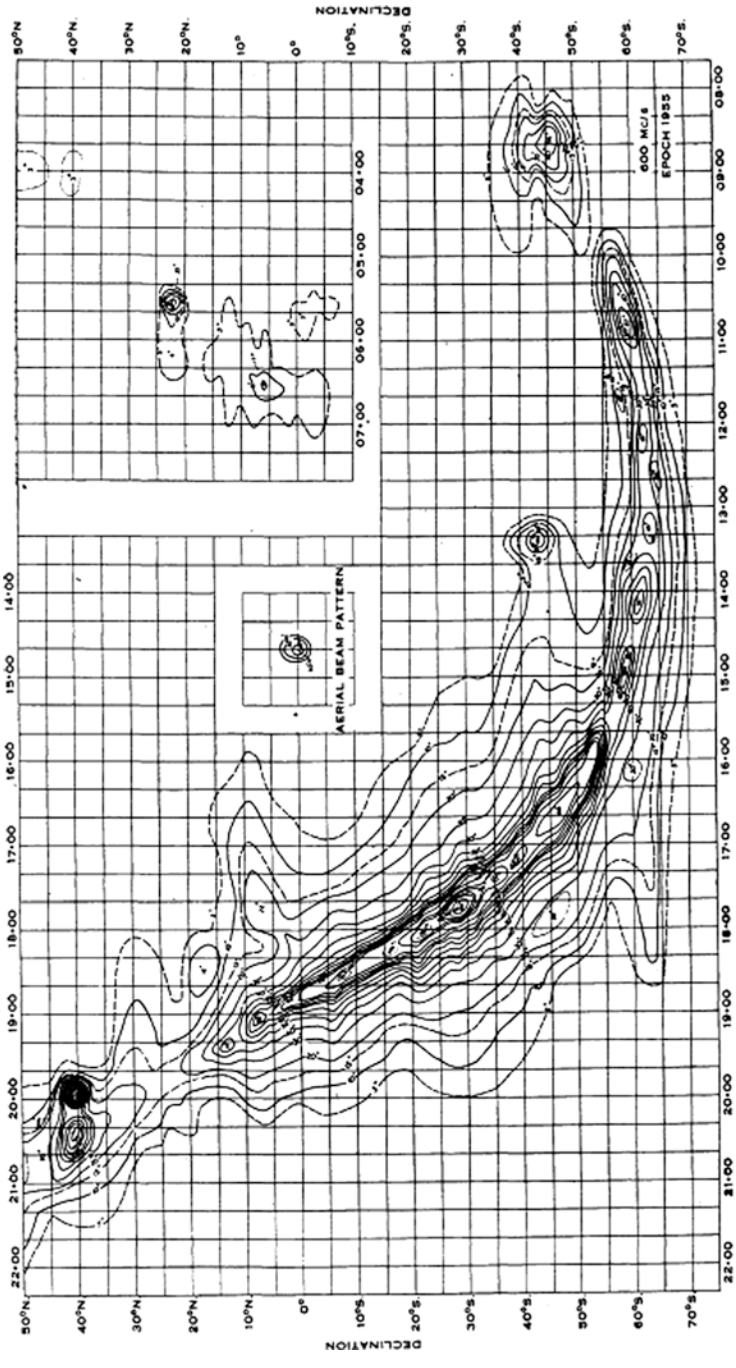


Fig. 26 The 600 MHz survey showing contours based on aerial beam temperature (Piddington and Trent 1956: 483).

Piddington and Trent (1956a) separately published a catalogue of 49 sources based on the 600 MHz survey. Of these sources, 31 appear to have been identified in previous radio surveys, with the remaining 18 being newly-identified sources. Of these 18 sources, 12 were located within ±2° of the Galactic Plane. For four of the sources optical identifications were proposed, all of these being with HII regions. No optical associations were proposed for the remaining 14 radio sources. A key conclusion of the examination of the sources was that many of those lying close to the Galactic Plane rather than being discrete sources appeared to have more complex structures and were often more akin to local maxima. Earlier interferometer surveys assumed many of these sources were discrete. The interferometers were unable to detect extended sources and their position estimates were confusion affected, as appeared to be the case for the later Cambridge 2C survey (Mills and Slee 1957).

5.5 1,400 MHz Observations

With the 36-ft transit parabola no longer being used for the H-line survey, Hindman and Wade modified the H-line receiver to measure the general radio continuum at 1,400 MHz rather than H-line emission. They used the modified equipment to observe a number of sources, but only published their observations of the Eta Carinae Nebula (NGC 3372) and Centaurus A (NGC 5128) (Hindman and Wade 1959). Eta Carinae was targeted because little was known of its physical properties. It was also the only important galactic HII emission nebula that had not been covered by Westerhout's (1958) 1,390 MHz survey because it was located too far south to be visible from the Netherlands. In a separate paper, Wade (1959) examined a physical model of the Nebula based on the Potts Hill observations and also drawing on the flux density measurement at 85.5 MHz (Mills et al. 1956) and some unpublished optical measurements that had been made by Gum. Wade's findings were largely consistent with previous studies on emission nebulae, confirming that the radio emission could be explained solely by the thermal mechanism of free-free transitions. Wade found that a relatively simple model of the emission nebula having a spherical distribution with an electron temperature of 10,000 ± 1,000 K, a dense core and a broad tenuous envelope, could provide a good account of both the radio and optical observations.

The other source observed at 1,400 MHz by Hindman and Wade (1959) was Centaurus A. Their findings were largely similar to the conclusions reached from earlier interferometric measurements (Bolton et al. 1954; Mills 1953) and confirmed by later pencil beam measurements at 19.7 MHz (Shain 1958) and 85.5 MHz (Sheridan 1958). They found that the source was composed of two components. One of these was a localised discrete source associated with the optical galaxy NGC 5128. The second component was a large extended source with no optical counterpart. Figure 27 shows the contour map of aerial temperature for Centaurus A. This was one of the first observations of an extra-galactic source to show the double lobe nature, now commonly associated with these radio sources.

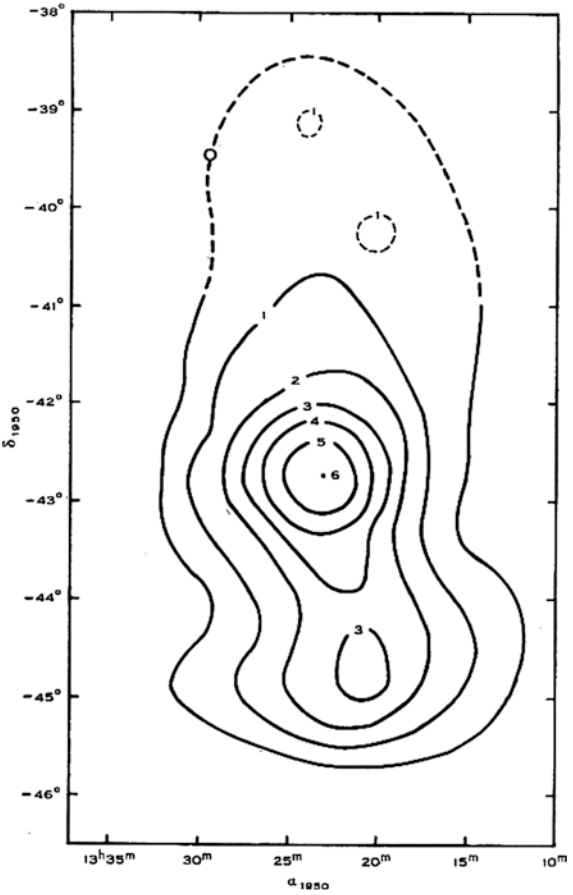


Fig. 27 A contour map of aerial temperature for Centaurus-A at 1,400 MHz. The *dotted lines* are estimates of the contour lines which were below the detection threshold of the equipment (after Hindman and Wade 1959: 268).

These observations marked the last major program of discrete source investigations at Potts Hill. With the Mills Cross now operating at the Fleurs field station and the construction of the 64-m Parkes Radio Telescope now committed, the focus of research shifted to these field stations.

6 The H-Line Investigations

Although some staff members were well aware of the potential that the detection of the predicted 1,420 MHz radio-frequency emission line from hydrogen would present astronomy, no attempt to detect the emission line was made at Radiophysics until the discovery at Harvard was announced (see Wendt et al. 2008b for a detailed discussion). At this point a crash program was launched which resulted in Christiansen and Hindman detecting the emission line on 6 July 1951 and in time to include a telegram announcing the confirmation of the detection in *Nature* together with the American and Dutch papers announcing the discovery (Ewen and Purcell 1951; Muller and Oort 1951; Pawsey 1951).

Christiansen and Hindman (1952b: 438) had been able to construct a ‘makeshift’ receiver in a very short period through a great deal of improvisation. The receiver was in principle similar to that used by Ewen, and by Muller and Oort in Holland. Coupling the receiver to the 16-ft × 18-ft paraboloid Christiansen and Hindman were able to confirm the H-line detection. Following the initial confirmation, between June and September 1951 they proceeded to make a preliminary survey of hydrogen emission in the southern sky. The detailed findings of their survey were published in the *Australian Journal of Scientific Research* (Christiansen and Hindman 1952b), and a summary paper also appeared in *The Observatory* (Christiansen and Hindman 1952a). By taking a series of measurements in progressive steps of right ascension they were able to obtain a series of profiles by declination and by combining these profiles a contour chart of peak brightness was constructed. A peak brightness corresponding to a brightness temperature of approximately 100 K was observed. Figure 28 shows the final contour map of hydrogen-line emission. From this map it was evident there were marked variations in the peak brightness along the Galactic Equator. Christiansen and Hindman noted that there were two likely causes of these variations. The first was that the variations were due to line broadening caused by rotation of the Galaxy and the second, and more interesting possibility, was they were the result of structural features such as the spiral arms.

Overall there were clear indications that the hydrogen-line emission occupied roughly the same distribution in the sky as the visible Milky Way. This association and the ability to penetrate the obscuring medium to discover galactic structure heralded the beginning of a very important branch of investigations in radio astronomy. It also marked the beginning of a major international collaboration, particularly with the Dutch group working at Leiden, and was characterised by close cooperation that started with the prepublication communications by Ewen and Purcell with both the Dutch and Australian groups. It is ironic that in the same year that the breakthrough discovery of a radio frequency emission line occurred, the first optical evidence for spiral arm structures in our Galaxy was also published (Morgan et al. 1952; Sheehan 2008).

Immediately following the Australian confirmation of the H-line, Paul Wild (1952) decided to update and publish the internal report he had written prior to the detection of the H-line (see Wendt 2010). This was a comprehensive review of the radio-frequency line spectrum of atomic hydrogen and is largely in accordance with modern theory. The report provided a very solid theoretical base for planning of further observations by the Australians. The one exception in this analysis was the conclusion that the 1,420 MHz emission would be the only detectable line emission, and that it would be unlikely that the higher order recombination lines would be detectable. It would be nearly two decades before the recombination lines were detected in the Soviet Union (Sullivan 1982: 300).

Following the initial H-line survey, Christiansen returned to his solar observation program. By this stage Kerr had returned from Harvard and, together with Hindman,

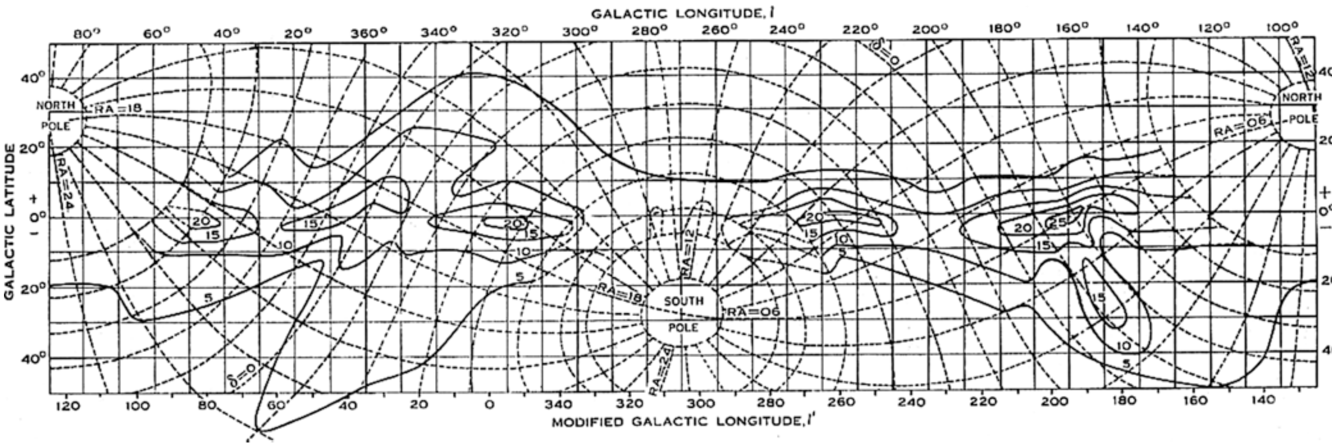


Fig. 28 A contour map of hydrogen-line emission. The peak brightness of 25 units corresponds to a brightness temperature of approximately 100 K (after Christiansen and Hindman 1952b: 446).

Fig. 29 The 36-ft Parabola at Potts Hill in June 1955 (courtesy: ATNF Historic Photographic Archive: 3679–1).

focused on the construction a new and more reliable receiver and on the new 36-ft transit parabola (see Figure 29) for use in a dedicated H-line survey of the southern sky. They were also joined by the new graduate student Brian Robinson, who would go on to lead the CSIRO's Radio Astronomy Group within the Division of Radiophysics during the 1970s (Whiteoak and Sim 2006: 265). The new receiver design had been devised by Pawsey and allowed for multi-channels, the first of its kind. Instead of using a narrow band that was swept over a line profile, a series of fixed frequency channels was used.

Preliminary observations began almost immediately upon completion of the aerial and while the new multi-channel receiver was still under development. The first observations made were of the Magellanic Clouds using only a single channel of the new receiver. These were the first ever observations of H-line emission from another galaxy. Kerr and Hindman presented their preliminary findings at a meeting of the American Astronomical Society, held at Boulder (Colorado) in August 1953. They also published a summary in the *Astronomical Journal* (Kerr and Hindman 1953), before presenting a more detailed account in the *Australian Journal of Physics* (Kerr et al. 1954). In late 1953, Robinson also unsuccessfully searched for H-line radiation from M31 (Pawsey 1954).

These preliminary observations quickly confirmed the value that radio astronomy could bring to the study of galactic structure through observation of neutral hydrogen (HI). Although the Magellanic Clouds had been extensively studied at optical wavelengths, the new radio frequency observations provided a range of new insights. The first of these was that the area of HI emission was much larger than the optical size determinations. Also, the Small Magellanic Cloud was nearly the same size as the Large Magellanic Cloud, which was a very different result from the optical view.

The large HI content of the Small Magellanic Cloud was not expected as it had been assumed that because of the low dust content of the Cloud there would also be a low concentration of HI. The HI emission showed that there was almost an equal mass present in both Magellanic Clouds. Assuming an optically-thin distribution, an estimate of 6×10^8 solar masses for the Large Magellanic Cloud and 4×10^8 solar masses the Small Magellanic Cloud was determined. The Small Magellanic Cloud also showed a very prominent wing extension toward the Large Cloud that was also faintly present in optical studies.

Optical determinations of velocities in the Magellanic Clouds had been limited to observations of 17 emission nebulae in the Large Cloud and only one in the Small Cloud (Wilson 1944). There was also some dispute as to whether motions in the clouds were due to rotation or translative motion of the Magellanic Clouds through space. The H-line radial velocities showed that both of the Magellanic Clouds appeared to be rotating about a common centre of gravity consistent with earlier suggestions from optical observations. After publishing their preliminary findings Kerr collaborated with G. de Vaucouleurs, who was a Visiting Fellow at Mount Stromlo Observatory as part of the Yale-Columbia Southern Station program. De Vaucouleurs had been studying the Magellanic Clouds, and like Oort, quickly realised the potential that collaboration with a radio astronomer could bring to an understanding of large scale structures of these galaxies. His optical observations had shown that both Clouds exhibited spiral structure in their outer regions and that the Clouds were flattened systems inclined to the line of sight and at a distance of approximately 46 kpc (De Vaucouleurs 1954a, b; 1955a, b, c, d).

The H-line observations generally supported the conclusions de Vaucouleurs had reached from optical observation. However, they also indicated some important differences. By examining the rotational curves of both of the Clouds it was clear that the radio centre of rotation was somewhat displaced from that derived from optical observations. The optical observations had suggested an asymmetrical rotation. This seemed physically unlikely and the radio observations supported a much more symmetrical rotation based on the displaced centre of radio emission. The Small Magellanic Cloud also showed a displaced HI centre of rotation compared to the optical observations and was tilted at a somewhat smaller angle (30°) than the Large Cloud.

While Potts Hill's location in the Southern Hemisphere provided an ideal opportunity to examine the Magellanic Clouds, the primary purpose of the H-line survey was to examine the southern Milky Way. This survey work commenced in earnest in 1954 with completion of the four-channel H-line receiver. Joining Kerr and Hindman was Martha Stahr Carpenter who was visiting Radiophysics from Cornell University. Although Christiansen and Hindman had published the first substantial survey of H-line radiation (Christiansen and Hindman 1952a, b), the Dutch group working at Leiden quickly made significant progress mapping the northern Milky Way and set the standard for galactic examinations based on H-line observations (Kwee et al. 1954; Oort 1953; van de Hulst et al. 1954). The leader of this group, Oort, had earlier established much of the theoretical underpinning for the study of galactic structure (Oort 1952). Oort (1927) was the first to propose that this phenomenon could be explained by galactic rotation. Building on their survey work of the northern sky the Dutch group soon developed a picture of the spiral structure of the Galaxy (Schmidt 1957; Westerhout 1957).

Although the Australian H-line survey began in 1954, it was not until 1959 that the full observational results of the survey were published in detail (Kerr et al. 1959). However, during this period there were many presentations and discussions on findings of the southern H-line survey at conferences (e.g. Carpenter 1957). In addition there were several publications of initial findings (Kerr 1957, 1958; Kerr et al. 1956) and a summary paper which appeared in *Nature* (Kerr et al. 1957).

The first published material to appear on the preliminary results of the Potts Hill southern galactic H-line survey was a short summary paper that appeared in the *Astronomical Journal* (Kerr et al. 1956). This paper reported on a tentative picture of the spiral structure of the southern portion of the Galactic Plane. The initial examination of the H-line profiles at longitudes between $l = 260°$ and $l = 275°$ showed that the outer spiral arms appeared to be trailing and showed an increasing southward shift in galactic latitude with distance in this region. These results were consistent with the Leiden observations and also showed that the hypothesis proposed by Edmondson (1955) – that the mean galactic motions would depart from a circular motion – was unlikely. These findings had first been reported by Carpenter in a paper summarising the work of the Potts Hill survey during an IAU meeting held at Jodrell Bank in August 1955. The paper was only published in 1957 as part of the conference proceedings (Carpenter 1957). It contained slightly more information on the provisional picture of the southern galactic spiral arm structure.

In May 1957 Kerr published a short note in the *Astrophysical Journal* noting that the southward shift of the spiral arms, which had been discussed in earlier results, appeared to indicate a warp in the galactic disk that coincided with the direction of the Magellanic Clouds (Kerr 1957). On face value the observation suggested a tidal influence from the Magellanic Clouds. However, the size of the warp was too large to be caused purely by a simple gravitational effect and Kerr suggested a more complex interaction effect was likely. This same effect was also independently noted by Burke (1957).

Finally, in October 1957, a full summary of the southern galactic survey was published in *Nature* (Kerr et al. 1957). Although the results of the northern sky survey had been known since 1954, this was the first time that the full southern and northern sky survey results appeared together. Even then, the analysis of the observations had not been fully reduced. No allowance in these results had been made for the smoothing effect of the aerial beam or for random motions within the interstellar

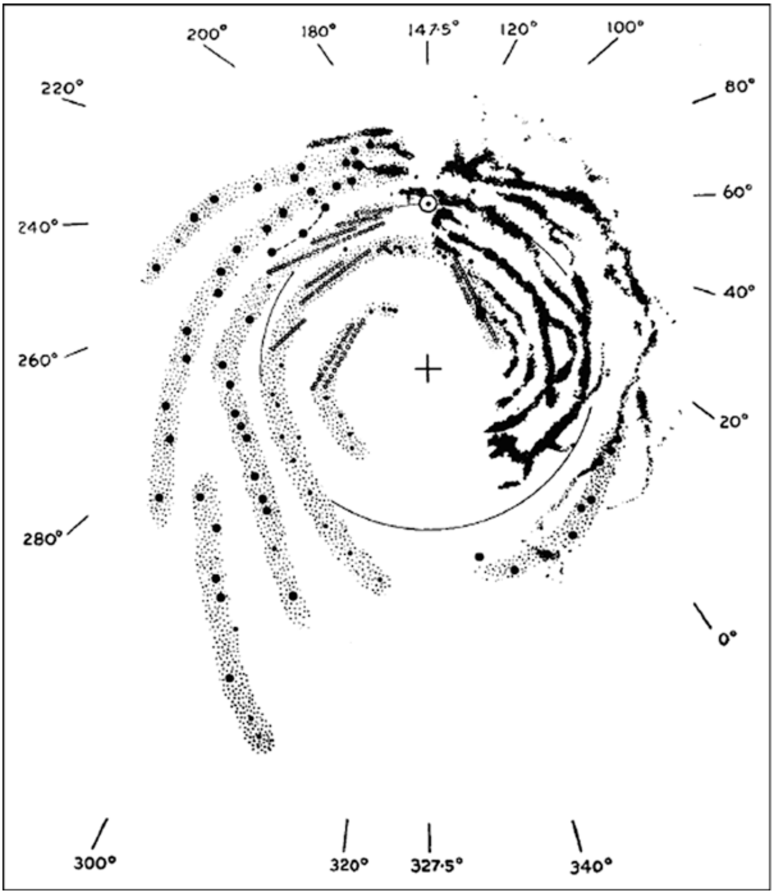


Fig. 30 Composite diagram of the spiral structure of the Galaxy based on observations from Potts Hill (*left half*) and Leiden (*right half*). The Galactic Centre is marked by a cross and the Sun's position and assumed circular orbit is also shown. A distance of 8.2 kpc from the Sun to the Galactic Centre is assumed (after Kerr et al. 1957: 677).

neutral hydrogen clouds. However, it was anticipated that these effects would not materially alter the preliminary results.

Drawing on the Leiden observations of the northern sky, for the first time a full-sky map of the structure of the galactic spiral arms could be made. Figure 30 shows the first composite map that combined the Potts Hill and Dutch results.

The southern side of the chart showed four distinct spiral arms, which were identified (moving outwards from the Galactic Centre) as the Scutum-Norma arm, the Sagittarius arm, the Orion arm and the Perseus arm. The Sun was believed to be located in the inner edge of the Orion arm. The outer boundary of the Galactic disk appeared to occur at approximately 15 kpc from the Galactic Centre. This identification of the spiral arms has fared well in modern times, the only difference being that the Scutum-Norma arm is now believed to be two separate arms (the Norma arm and the Scutum-Crux arm). The Orion arm is generally referred to as the Local arm. Although today the use of neutral hydrogen to map spiral arms is generally discounted in favour of other techniques, the general picture obtained was a remarkable achievement. It was not until 1976 (Georgelin and Georgelin 1976) that a more accurate representation of the spiral arms was produced.

It should be noted that the different appearance of the two sides of the diagram was due to the different techniques used. The shading in the Leiden results was an 'artist's impression' based on following the density contours. The Potts Hill result is a schematic representation based only on the well-defined features of the line-profiles. While these different techniques produced a different appearance there was still good general agreement between results. Overall the results clearly showed that the Galaxy has a multi-arm structure and that the arms have a general trailing tendency based on the clockwise direction of rotation used in the diagram.

The final detailed paper on the southern survey was published in the *Australian Journal of Physics* (Kerr et al. 1959). This paper contained a full set of line profiles together with a set of intensity contours plotted as a function of galactic latitude and radial velocity. During 1957, Kerr spent several months visiting the Dutch group at Leiden with the specific purpose of combining data on observations from the Southern Hemisphere. This work resulted in a joint paper between the Australian and Dutch groups summarising the understanding of the Galaxy as a spiral system (Oort et al. 1958). This included an update of the rotation curve derived from both the Leiden and Potts Hill observations. It is interesting to note that the two sets of data would actually produce two slightly different rotation curves if treated individually. This is something that Kerr would examine in a later review (Kerr 1962). For the first time Oort et al. (1958) also published a combined density map of neutral hydrogen, as shown in Figure 31.

In the inner 3 kpc of this map a tentative identification of a new 'expanding' arm was shown marked by a row of arrows. Within this inner region the team found evidence of an expanding motion of the neutral hydrogen with deviations from the expected circular rotation of up to 200 km/s. They named this arm the '3-kpc expanding arm', a name which is still used today (although generally the 'expanding' term has been dropped).

Given the growing body of evidence from the radio surveys at the 1955 General Assembly held at Dublin the International Astronomy Union appointed Sub-Commission 33b "… to investigate the desirability of a revision of the position of the galactic pole and of the zero point of galactic longitude." The members of the Sub-Commission were A. Blaauw, C.S. Gum (who was unfortunately killed in a skiing accident in Switzerland on 28 April 1960 shortly after the completion of the Sub-Commission's final report), J.L. Pawsey and G. Westerhout. Up until this time, the Galactic Pole had been located at right ascension 12h 40m, declination +28° (1,900.0) and was used as the basis for the standard conversion to galactic coordinates in the *Lund Observatory Conversion Tables* (Ohlsson 1932). By the time of the next General Assembly meeting in Moscow in 1958, enough preliminary evidence had been gathered, particularly from the neutral hydrogen surveys, to

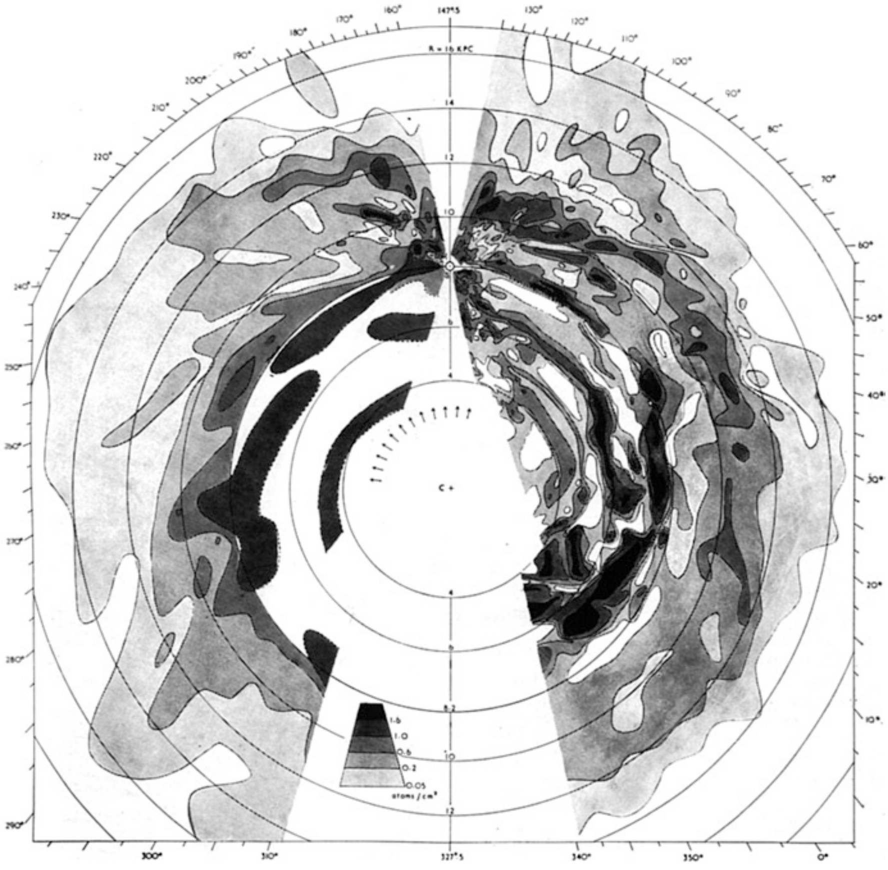


Fig. 31 The density distribution of neutral hydrogen in the Galactic Plane. The maximum densities in the z direction are plotted on the Galactic Plane and the points of common density are joined by contours (after Oort et al. 1958: Plate 6).

recommend that it would be opportune to adopt a new system of galactic coordinates and as such the General Assembly passed a resolution for the Sub-Commission to define and announce a new system of coordinates. In March 1959 the Sub-Commission completed its investigations and communicated its decision to the General Secretary of the I.A.U. and various astronomical journals. A series of five papers was published which together formed the final recommendations of the Sub-Commission (Blaauw 1960; Blaauw et al. 1960; Gum et al. 1960; Gum and Pawsey 1960; Oort and Rougoor 1960). The key paper out of the five that made up the Sub-Committee's final report was the analysis of the combined Leiden and Potts Hill neutral hydrogen observations (Gum et al. 1960). In this analysis, Gum, Kerr and Westerhout essentially conducted a new analysis of data from the two surveys. By selecting a number of points within the inner 7 kpc of the Galaxy, a least mean square analysis of different selection groups showed close agreement and indicated that this region was virtually indistinguishable from the principle plane of the Galaxy. The other Potts Hill contribution was in Paper III (Gum and Pawsey 1960), which examined the overall radio continuum and the position of the radio source Sagittarius A. A key set of observations were derived from the 600 MHz survey that was conducted at Potts Hill by Piddington and Trent (1956a, b).

By mid 1959 much of the research effort at Potts Hill had been completed, as noted in an internal report (Pawsey 1959). The 21-cm survey of the Milky Way had been completed although the research results were still being written up. It was decided that the 36-ft parabola and its equipment hut would be maintained at Potts Hill for receiver testing until such time as the new laboratory facilities, which were being constructed at Epping as part of the new headquarters of the Division of Radiophysics were completed. It was also noted that the continuing solar recording at Potts Hill, which was now the responsibility of Fairweather, would continue only as long as required to support observations using the Chris Cross at Fleurs and Wild's solar burst investigations at Dapto. A new 48-channel H-line receiver and fully steerable 21-ft parabola were constructed at a new field station at Murraybank in 1956 (see Wendt 2008; Wendt et al. 2011b) and were used to continue the H-line program of observations and to act as a test bed for equipment that would later be deployed for the Parkes Radio Telescope (Orchiston and Slee 2005a).

7 Jovian Burst Observations

During February and March 1956, Potts Hill was used as a secondary field station as part of the investigation of radio emissions from Jupiter by Gardner and Shain (1958). The main instruments were located at the Fleurs field station some 25 km to the west of Potts Hill.

Radio emission from Jupiter had first been detected in the U.S.A. by Burke and Franklin (1955) using a 'Mills Cross' operating at 22.3 MHz. It was only after this discovery that Shain found, by examining 18.3 MHz Hornsby Valley field station records, that he had in fact recorded Jovian burst emission in 1951 but that this had gone unnoticed at the time. In examining the 1951 records Shain (1955; 1956) found that the emission appeared to come from a localised region on the planet (Orchiston and Slee 2005b).

In order to compare results with those from Fleurs, at Potts Hill a simple dipole antenna was suspended between two wooden poles and connected to a receiver operating at 19.6 MHz. This formed part of a spaced-aerial experiment to determine if the scintillations in the radio emission were inherent in the source itself or caused by the ionosphere. The receivers at both sites were closely tuned to avoid discrepancies caused by sharp spectral variations in the burst signals. The high levels of radio interference at Potts Hill meant that only three pairs of results from the Potts Hill and Fleurs were available for comparison. Figure 32 shows an example of the spaced-receiver records taken simultaneously at Potts Hill and Fleurs.

An examination of the records showed significant differences between the two sites with some bursts observed at only one of the two sites. There also appeared to

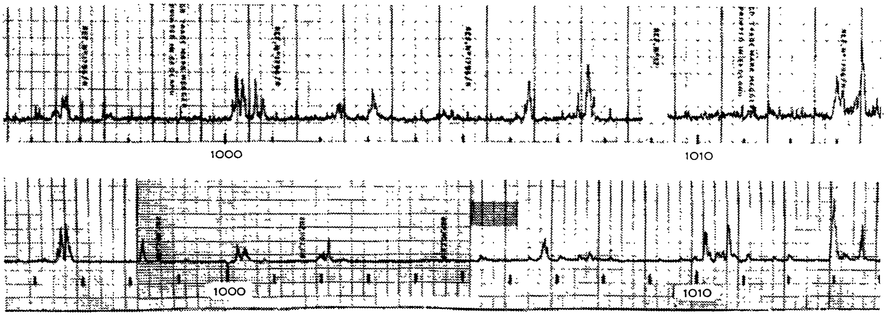


Fig. 32 The spaced-receiver records for Potts Hill (*top*) and Fleurs (*bottom*) taken at 19.6 MHz on 26 February 1956 (after Gardner and Shain 1958: 60).

be timing differences between the sites and some differences in the burst characteristics. Gardner and Shain (1958) concluded that these differences between the sites indicated that the terrestrial ionosphere must have a considerable effect on the time variations of the Jupiter radiation.

Jovian observations over a 200 km baseline by Slee and Higgins (1968) later showed that the so-called bursts are due to scintillations caused by diffraction in the solar wind.

8 Concluding Remarks

The seminal period of radio astronomy prior to 1960 was arguably the most exciting and innovative era in Australian radio astronomy (i.e. see Robertson 1992: 202). It marked the era before ‘big science’ projects emerged, a period when small scale projects dominated and radio engineers first entered the domain of the astronomers. For Australia this was a unique period in which it achieved a research leadership position in the new field of radio astronomy. This paper provides a summary of the activities at the Potts Hill field station, which operated for 12 years during this ‘golden age’ of radio astronomy, a period in which rich contributions to the emergent science of radio astronomy were made, both in terms of new instrumentation and scientific research.

Ten different types of radio telescope were operated at Potts Hill. Amongst these there were several examples of world-first instrumental developments.

The Swept-lobe Interferometer developed by Payne-Scott and Little used a continuously-variable path length between the two Yagi antennae to change the phase of the signal and hence sweep the aerial beam. This innovation removed the restriction of having to wait for the Earth’s rotation to move the source through the aerial beam to produce an interference pattern and was hence ideal for locating the position of short duration sources. At the time of its invention interferometry was being conducted either using the sea-interferometry technique (McCready et al. 1947), or using the Michelson interferometry technique that was first used by the

Cambridge group (Ryle and Vonberg 1946). Not only could the Swept-lobe Interferometer determine a position accurate to 2′ at 97 MHz, it could also measure the polarisation of the source. The swept or rotating lobe technique was later adapted by the Jodrell Bank group (Hanbury-Brown et al. 1955) and proved useful in their work on determining source sizes for high declination sources.

The E-W Solar Grating Array at Potts Hill was a unique instrument that provided the first regular one-dimensional images of the Sun at radio frequency. Earlier, Stanier (1950) working at Cambridge with a two element Michelson interferometer to obtain a brightness distribution across the solar disk, had failed to detect limb-brightening. The E-W Solar Grating Array provided clear evidence of limb-brightening and was able to produce a large data set of one-dimensional brightness distributions across the solar disk at 1,410 MHz. The Cambridge group went on to develop the aperture synthesis mapping technique, producing the first two-dimensional map of the Sun (O'Brien 1953; O'Brien and Tandberg-Hassen 1955). Meanwhile, with the construction of the N-S Solar Grating Array Christiansen and Warburton were also able to produce a two-dimensional distribution. However, in this instance they used the first application of Earth-rotational synthesis in radio astronomy to produce their image. The use of the Earth's rotation to provide a variety of scanning angles proved a much simpler method than relocating the elements of an interferometer as had been employed by O'Brien at Cambridge to obtain the wide variety of base-lines necessary to reconstruct a two dimensional image. The grating-style array proved very useful for solar observations; it was quickly adopted by a number of research groups throughout the world, such as the Carnegie Institute in the U.S., the Research Institute of Atmospherics in Nagoya, Japan and the Meudon Observatory in France.

The development of the Mills Cross was a major instrumental breakthrough and proved especially useful for source surveys. The use of a phase-switched interferometer was first introduced at Cambridge (Ryle 1952) and was one of the contributing factors for which Sir Martin Ryle was awarded the 1974 Nobel Prize in Physics. After gaining experience using a phase-switched interferometer at the Badgerys Creek field station, Mills struck on the idea of constructing a phase-switched crossed-array. This instrument produced a pencil beam response equivalent to the filled aperture of a parabola of the same diameter as the length of the cross arms. Unlike aperture synthesis techniques, it was not necessary to use a complex Fourier analysis to reconstruct the brightness distribution of the filled aperture. The prototype for the Mills Cross was constructed at Potts Hill and not only was the trial successful, but Mills and Little also achieved the first detection of the Large Magellanic Cloud at radio frequency. The 'Mills-Cross' design proved a very economical way to produce a high-resolution pencil beam instrument and its design was subsequently adopted by a number of other countries. It is interesting to note that at almost the same time the Jodrell Bank group had considered a similar cross design, but in view of their existing commitment to the construction of the 250-ft dish they did not develop the idea further (Hanbury-Brown 1953). The cross design also inspired Christiansen to build a new crossed-grating array at the Fleurs field station which became known as the ‘Chris-Cross’ (Orchiston and Mathewson 2009).

The Potts Hill 4-channel H-line receiver was the first proposed design of a multichannel receiver for H-line observations and the idea of using the multi-channel design was quickly adopted by other radio astronomy groups engaged in H-line research. By 1954 multi-channel receivers were under development at the Carnegie Institute in Washington and at Royal Radar Establishment at Malvern in the U.K.

Although research at Potts Hill initially focused on the Sun, in later years important contributions were also made to cosmic research and in particular the investigation of the distribution of neutral hydrogen in our Galaxy.

The solar research program provided an important contribution to knowledge of the quiet Sun and the slowly varying component. Although certainly not the first eclipse observations in radio astronomy, the 1948 partial solar eclipse observations provided an important confirmation of the association of enhanced sources of radiation with sunspot groups and the slowly varying component. The development of the grating arrays allowed regular daily determinations of brightness distributions across the solar disk, something which was not practical with any other instrument at the time. The grating array observations provided the most comprehensive dataset during the 1950s on the structure of the solar atmosphere at 1,410 MHz and later also at 500 MHz. The data provided confirmation that the quiet Sun component remained constant over prolonged periods and were used to show that the slowly varying component appeared to correspond with chromospheric plages, something that had first been suggested by Dodson (1954) working in the U.S. In a fitting end to the solar research program the final published work from Potts Hill was the observation of the 8 April 1959 partial solar eclipse. Thus 11 years of solar radio astronomy at Potts Hill began and ended with eclipse observations.

Payne-Scott and Little’s observations using the Swept-lobe Interferometer provided the first accurate positional information on solar bursts and evidence of the outward motion through the solar atmosphere of a number of sources. Unfortunately these investigations were cut short by Payne-Scott’s resignation. Had this work continued in conjunction with the work being conducted by Wild’s group at Dapto to include a spectral analysis, it seems likely that they would have discovered the Type IV sources later discovered by Boischot (1958) using the Nançay interferometer in France (Stewart 2009; Stewart et al. 2011a).

The initial neutral hydrogen survey conducted at Potts Hill by Christiansen and Hindman provided the first radio frequency indications of the spiral arm structure of our Galaxy. This was a remarkable achievement given that both the U.S. group at Harvard and the Dutch group at Leiden had been working in the field for a much longer period. The H-line program marked the beginning of a major international cooperative program. The Dutch group led by Oort soon overtook the Australians with their galactic mapping of the northern sky and they would have to wait some time for the Australians to complete the southern sky survey so their results could be combined to produce the famous ‘Leiden-Sydney’ H-line map (Oort et al. 1958). This combined work, together with the 600 MHz continuum survey conducted at Potts Hill, were key components in the redefinition of co-ordinates of the Galactic Plane. Australia's southern location provided access to the Magellanic Clouds something that was not possible for the northern hemisphere groups. It is natural therefore that the Australians dominated the early studies with the first neutral hydrogen maps of the clouds produced at Potts Hill. A later Murraybank survey detected the bridge of neutral hydrogen connecting the two clouds as well as finding the first evidence for 'splitting' of the Small Magellanic Cloud, suggesting an earlier interaction between the galaxies. Besides missing the opportunity to be the first to detect the 21-cm hydrogen line emission, the other aspect that escaped the Australian's early work was the discovery by Williams and Davies (1954) at Jodrell Bank that the hydrogen emission could also be studied in absorption. Hagen, Lilley and McClain (1955) working in the U.S. were also able to exploit this discovery to examine the properties of the interstellar medium and to determine the distance to galactic radio sources. This illustrates that while the Australians had made remarkable progress, there were also missed opportunities.

The most notable of the discrete sources discoveries at Potts Hill were made by Piddington and Minnett. Up to this time, work on discrete sources in Australia had been dominated by Bolton's group working at Dover Heights and later by Mills working first at Badgerys Creek and then at the Fleurs field station. There was intense competition and some disagreement during this period with the Cambridge group, although relationships with the Jodrell Bank group were more cordial. The two major discrete source discoveries at Potts Hill were Sagittarius A, which was associated with the Galactic Centre, and Cygnus X associated with a large Galactic HII region. While Piddington and Minnett attempted to detect M31 at radio frequencies they were unsuccessful and were soon scooped by the Jodrell Bank group who used a much more sensitive 218-ft transit telescope. Also of note during the early period of Potts Hill investigations was Mills' determination of the position of Cygnus A. Although discounted at the time, Mills had suggested an optical association of the Cygnus A source with an extra-galactic nebula. However, Smith (1951) working at Cambridge obtained a more accurate position that ultimately led to the optical identification of Cygnus-A with the faint extra-galactic nebula first suggested by Mills (Baade and Minkowski 1954).

As discussed above, British, Dutch and U.S. scientists were prominent in both solar and galactic research during the Potts Hill period. However, many other international groups also made contributions during this period. For example, Covington (1947), working in Canada, showed that strong solar emission was associated with a sunspot group that was occulted during the 23 November 1946 solar eclipse and went on to develop a slotted waveguide array capable of producing strip scans of the Sun at 10.7-cm wavelength. Khaykin and Chikhachev (1947) from the former Soviet Union observed the 20 May 1947 total solar eclipse from a ship near the Brazilian shore and demonstrated that the radio emission at 200 MHz came from the solar corona. The theoretical contribution of the Soviet astronomers, particularly V.L. Ginsberg and I.S. Shklovsky, was of great importance and included the independent explanation of the million degree temperature of the solar corona, synchrotron emission and predictions of a number of radio frequency spectral lines. The French were also particularly active in solar research (Orchiston et al. 2007, 2009) conducting a number of eclipse observations (Orchiston and Steinberg 2007) and constructing the 169 MHz Le Grande Interferometer de Nançay, which consisted of 32 × 5-m antennas on a 1,600-m east-west baseline and to which a north-south arm was added in 1959. This instrument was used by Boischot (1958) to discover the Type IV solar bursts. The Japanese had recognised solar radio emission as early as 1938 (Tanaka 1984). In 1949 they began regular solar monitoring and later constructed their own solar grating array. Yet, despite all of these developments, and others, Australia and Britain were widely regarded as the forefront radio astronomical nations at this time (Sullivan 2005), and Potts Hill played no small part in establishing and maintaining this reputation.

Many of the Australian pioneers of radio astronomy spent time at Potts Hill and by 1952 it was the major field station of the Division of Radiophysics. Ultimately the lack of space and the encroachment of the suburbs of Sydney (with a consequential increase in radio interference) meant that research was shifted to other field stations. In late 1961 the last of the solar monitoring was transferred to Fleurs field station and Potts Hill was decommissioned in 1962. These events signalled the end of an era in Australian radio astronomy. With the construction of the 64-m Parkes Radio Telescope and later the Culgoora Radioheliograph, Australian radio astronomy began a new era of ‘big science’ projects.

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The Contribution of the Division of Radiophysics Murraybank Field Station to International Radio Astronomy

Harry Wendt, Wayne Orchiston, and Bruce Slee

Abstract During the 1950s Australia was one of the world's foremost astronomical nations owing primarily to the work of the dynamic radio astronomy group within the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics. Most of the observations were made at the network of field stations maintained by the Division in or near Sydney, and one of these field stations was Murraybank in the north-western suburbs of Sydney.

This paper describes the research activities and equipment used at Murraybank for the investigation of neutral hydrogen emission from our Galaxy and the Magellanic Clouds.

1 Introduction

This paper provides a summary of the research carried out at the Murraybank field station, one of a number of radio astronomy field stations and sites maintained by the CSIRO's Division of Radiophysics between 1946 and the early 1960s (see Orchiston and Slee 2005).[1] The researchers at Murraybank field station had a close relationship with those from Potts Hill, this being the only other Australian site involved in investigating the 21 cm hydrogen line (henceforth H-line) emission from our Galaxy and the Magellanic Clouds in the late 1950s and early 1960s (see Wendt 2008; Wendt et al. 2011a, b). This paper examines the Murraybank field station, its researchers and the scientific contribution which they made.

Murraybank operated from 1956 to 1961 (ibid). The field station was established to test the operation of a new 48-channel H-line receiver in preparation for its

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[1] For a more detailed account of the Murraybank field station see Wendt 2008.

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potential installation at the 64-m Parkes Radio Telescope when it became operational in late 1961. This receiver (also known as the Murraybank Mk1 multi-channel line receiver) was one of the first operational observing systems to be installed on the Parkes Radio Telescope (Brooks and Sinclair 1994).

2 The Beginnings of the Murraybank Field Station

In June 1953 John Murray, who had been working at the Dapto field station south of Sydney, was summoned to the Radiophysics headquarters in the grounds of Sydney University to meet with Joseph Pawsey, the dynamic leader of the radio astronomy group at Radiophysics (John Murray, pers. comm., 5 August 2007).[2] Pawsey was unhappy with the progress being made on the development of the 4-channel H-line receiver at Potts Hill and asked if Murray would assist. Murray (ibid.) also recalled that while he was waiting to meet with Pawsey, John Bolton came storming out of Pawsey's office. This was the time when Bolton's proposal to construct a large interferometer at the Dover Heights field station was rejected in favour of constructing the Mills Cross. Bolton therefore decided to leave the radio astronomy group and to work in the Division's cloud physics group until January 1955 when he accepted the position as Professor of Physics and Astronomy at the California Institute of Technology (see Stanley 1994; Kellerman et al. 2005).

Murray worked with Frank Kerr, Jim Hindman and Brian Robinson at Potts Hill and after some time he concluded that it was very unlikely that the original receiver design could be improved and that it would be necessary to change to a switched system to overcome the issues associated with receiver drift that plagued the original design. Murray felt that it would be near impossible to get a stable bandwidth from vacuum tubes using the original design. While the filters were all on the same frequency the design worked well, but the further they were shifted apart in frequency, the more they drifted apart (John Murray, pers. comm., 8 February 2008). After Murray reported back, Pawsey decided that it would be prudent to launch a new project. The aim of this project was to design a new type of multi-channel receiver that addressed the limitations of the original 4-channel design then in used at Potts Hill (see Wendt (2008) for details). This decision would ultimately lead to the establishment of a new field station called Murraybank, which was located at West Pennant Hills in the northwestern suburbs of Sydney. To their credit, Kerr's team persisted and after many modifications to their receiver, managed to get it to a point where reliable observations were possible, first with a single channel, and later with all four channels.

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[2] At this time there were two main research groups within the Division of Radiophysics. One was the radio astronomy group, headed by Pawsey, and the other was the cloud physics and rainmaking group headed by Dr E.G. ('Taffy') Bowen, who also served as Chief of the Division. While Bowen never claimed to be a radio astronomer, it was he who was largely responsible for launching the Parkes Radio Telescope project and seeing this through to fruition.

By November 1953 three main streams of work were being undertaken within Radiophysics on radio frequency spectral lines (Kerr 1953):

1. Work led by Kerr at Potts Hill on the 4-channel H-line receiver and the subsequent survey of the Magellanic Clouds and the Galaxy.
2. Work by Gordon Stanley and Richard McGee (later joined by Price) at Dover Heights in an attempt to detect the red-shift in external galaxies and to search for the 327 MHz deuterium-line.
3. Work initially led by Murray at the Radiophysics Laboratory on the development of a new type of multi-channel H-line receiver.

The subsequent success of the Potts Hill H-line survey is discussed elsewhere in this volume (see Wendt et al. 2011a).

The search for the deuterium-line at Dover Heights ultimately proved unsuccessful and no evidence of absorption or emission from the Galactic Centre was found. Although the detection of high red-shifted HI in external galaxies had been proposed as an objective, no detection attempt was made after the negative deuterium-line result. The negative result was reported (Stanley and Price 1956) only after other search attempts began to appear in the literature. At I.A.U. Symposium No. 4 on Radio Astronomy held at Jodrell Bank from 25 to 27 August 1955, G.G. Getmanzev and K.S. Stankevitch from Gorky State University in the U.S.S.R reported that they had detected an absorption line from deuterium at 327.4 MHz using a 4-m paraboloid. The detection claim was met with some scepticism. In the discussion following the presentation Pawsey noted that Stanley and Price had been unsuccessful in 1954 using the 80-ft Dover Heights hole-in-the-ground aerial and Hey also noted his group had made an unsuccessful attempt at Malvern in the U.K. (Getmanzev et al. 1957: see discussion notes). The interest in pursuing the detection of deuterium was, and still is, that deuterium is believed to have been formed soon after the Big Bang and hence its abundance provides important information on the formation of the early Universe. Although the deuterium line at 327 MHz is well separated from other radio-frequency spectral lines, it is extremely weak. Most observers, like the Dover Heights team, were only able to establish an upper limit for detection. Although there have been many claims of a marginal detection, it is only quite recently that a detection seems likely (see Rodgers et al. 2005). The unsuccessful search for the deuterium-line by Stanley and Price also signalled the death knell for further research at Dover Heights, and the field station was decommissioned in 1954 (Orchiston and Slee 2002).

As an interesting aside, in an outline of the potential for spectral-line investigations, Kerr raised the possibility of not only searching for the deuterium line at 327 MHz, but also the 3 He line near 9,000 MHz (Christiansen 1952). Miller Goss (pers. comm., 20 January 2008) has noted that this appears to be one of the earliest references to the potential for the 3 He line being considered (e.g. compared to Goldwire and Goss 1967; Townes 1957).

The development of a new multi-channel H-line receiver was a major undertaking and, after some initial experimentation, a broad plan was drawn up by Murray in early 1954 outlining the steps necessary to complete the receiver design. In May

1954 in a letter to Oort, Pawsey noted that "We are working on the development of a multi-channel receiver (e.g. 30-channel) but, although I am happy about the objective, our equipment is not yet satisfactory."

By June 1954 more progress had been made on the power supplies and the first stage local oscillator, but many components including the channel filters remained on the drawing board and the question still remained as to when an operational receiver could be produced. The work on the receiver was being conducted in the Radiophysics laboratory workshops. Murray had to compete for resources with many other projects and with the other Radiophysics groups such as Air Navigation and Cloud Physics. While attempts were made to explore the possibility of outside groups such as A.W.A. constructing some of the components, no outside interest could be generated (Murray, pers. comm., 8 February 2008).

At the June meeting of the Hydrogen-Line Planning Committee the need for a "… Following Aerial …" for future H-line work was discussed. The Potts Hill 36-ft aerial was a transit instrument and therefore imposed limitations on examining fine structure and access to some parts of the southern sky. The idea of constructing a new paraboloid of approximately 25-ft diameter and re-using a mount from Dover Heights was suggested and Hindman was tasked with looking at the feasibility of upgrading the Dover Heights mount.

It was also at this stage that the question of a new site for the Division's H-line work was first raised:

> The question of a new site more free from interference than the present Potts Hill position was deferred until more evidence on the sources of interference and the future expansion of the same become available in this regard. It was noted that the Water Board is intending building a welding shop on the old Balt camp site at Potts Hill. (Note: This has since been confirmed with the engineer on the site and steel for the construction of buildings has commenced to arrive). (Kerr 1954).

With the likelihood of increased levels of electrical interference at Potts Hill, it was subsequently agreed that a new site would be necessary. The selection of the site was somewhat simplified when John Murray's father, who had an orchard called Rosebank at the outer north-western Sydney suburb of West Pennant Hills, offered to allow Radiophysics to set up a new field station on his property. This field station would become known as Murraybank, a concatenation and abbreviation of Murray's orchard and Rosebank. Murray (pers. comm., 8 February 2008) noted that there were also other radio astronomy 'bank' stations around at this time (e.g. Jodrell Bank and Green Bank), so the name was entirely appropriate.

The new Murraybank field station was in the corner of an approximately 2.5 hectare block of land that also contained the orchard, the Murray's home and an old weatherboard cottage in which John Murray lived for some time.

Meanwhile, the design of the multi-channel receiver continued to be a very complex undertaking. In a letter to Pawsey in August 1954, Lindsay McCready noted:

> I had to give John Murray extra T.O. [Technical Officer] assistance in the 1420 Mc/s Multi-channel Receiver. This was due entirely to the large amount of detail in it. It was a bit of a struggle to get him the right type of assistance but eventually got him a Diplomat-elect from the Rain Physics Group (Keith Weir). (McCready 1954).

Later, Richard McGee joined Murray on the project, following the unsuccessful search for the deuterium-line at Dover Heights. In a letter to Pawsey written in September 1955 McGee noted: "We hope to be moving into Murraybank at the beginning of next week and initial tests will be under way about the time of your return."

Although McGee's letter indicated that tests of the equipment at Murraybank would be commencing soon, this proved extremely optimistic. Upon Pawsey's return from the U.K. he undertook a review of progress. The review identified nine major tasks that remained to be completed on the receiver. Pawsey assigned these tasks between Murray, McGee and Joe Warburton (who had now been appointed to assist). McGee had earlier taken the opportunity to lobby Bowen for assignment to Murraybank of the 60-ft Kennedy Dish that was being considered for purchase and was ultimately installed at the Fleurs field station in 1959 (Orchiston 2004; Orchiston and Mathewson 2009). Pawsey discounted this idea and a specification was drawn up for a new aerial. It was agreed that this would be a modified Chris Cross aerial (Figure 1) with its diameter increased to 21-ft and with additional strengthening and greater depth. The design was assigned to Keith McAlister, the Division's Mechanical Engineer, and a target date for production of February 1956 was agreed.

Progress with the multi-channel receiver continued to be a problem. On 3 July 1957 Pawsey held another review meeting. After considering the progress that was being made, he decided to suspend any further work at Murraybank for a period of 5 months so that the team could properly replan their approach under the supervision of McCready. McGee prepared an internal review paper of their progress

Fig. 1 The central section of the Chris Cross at Fleurs, looking south along the N-S arm. The Murraybank aerial was based on the design of one of these aerials but with an increased diameter and strengthened structure (courtesy: ATNF Historic Photographic Archive).

where he implied that they would have been better off concentrating on improving the local oscillators and finishing off individual channels before attempting to take actual line profiles at Murraybank (McCready 1957). The first 20 filters of the Murraybank receiver had been constructed in the laboratory using high-quality 3 in. diameter ceramic coil formers that had been found in the Radiophysics store. The remaining filters were constructed by cannibalising surplus aerial tuning units intended for commercial aircraft radio units. These were not as good a quality as the original filters. The original 20 filters were configured around the central H-line frequency with the new filters making up the outer channels (Murray, pers. comm., 8 February 2008). Much of the wiring and fitting for the receiver was performed by Jack Ohlston and Mal Sinclair (Murray and McGee 1963).

Another source of delays was that the Chris Cross was then under construction at Fleurs field station immediately to the west of suburban Sydney and operated at the same frequency (see Orchiston and Mathewson 2009). This meant that the Murraybank team had to compete for access to test equipment. For some time they operated with a ‘wet-finger’ approach without access to a wavemeter to measure the local oscillator frequency. When they finally managed to get access to a wave-meter for a whole day, they found that they had been operating on the wrong harmonic and so had been trying to observe at 1,200 MHz instead of 1,400 MHz (Murray, pers. comm., 8 February 2008).

The refocus of activity on the multi-channel receiver development and access to test equipment finally proved successful, and the system became operational in mid-1958.

3 The Murraybank Equipment

As discussed in the earlier section, the Murraybank aerial was based on a modified Chris Cross design that had been increased in diameter to 21-ft and with increased structural rigidity. The ribs of the aerial were constructed of steel and the rings were made of aluminium (ibid.). The design was finalised by McAlister and construction was carried out in the Radiophysics workshops. The aerial was mounted on a simple alt-azimuth mount and installed at Murraybank in 1956 next to a comparatively large newly-fabricated equipment hut. The mounting was built on the ex-British Army 200 MHz gun-laying radar trailer (Figure 2) that Bolton and Stanley had taken to New Zealand in 1948 when investigating the positions of the earliest-known ‘radio stars’ (see Orchiston 1993, 1994), and which had since then been used on other Radiophysics projects (Murray, pers. comm., 8 February 2008).

In its original configuration the trailer weighed some 6–7 tons and hence had a very solid framework, including a set of elephant’s feet for stability. Figure 3 shows a close-up of the trailer at Murraybank. An aircraft propeller feather motor cannibalised from an ex-WWII Liberator Bomber located at Tocumwal airfield was used for the elevation drive on the aerial mount (ibid.), and although originally designed as a DC motor, it operated perfectly well on an AC supply. The azimuth control was provided by turning a hand crank which was part of the original gun-laying radar

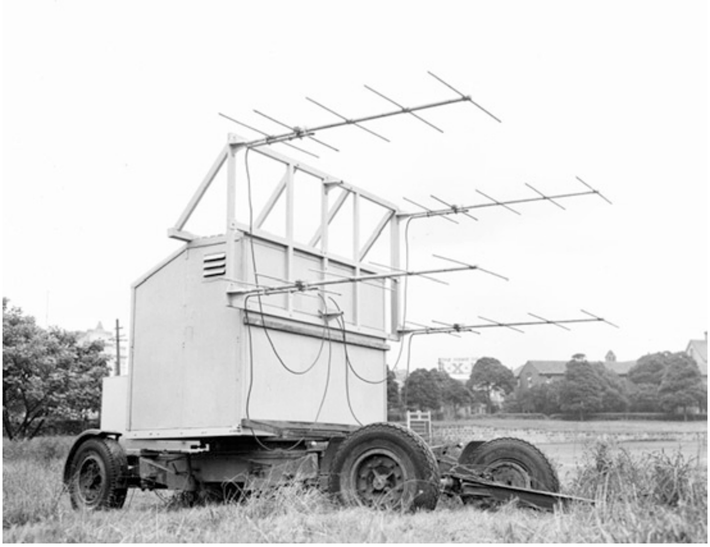

Fig. 2 The ex-British gun-laying trailer with the Yagi array used by Bolton and Stanley in New Zealand in 1948 (courtesy: ATNF Historic Photographic Archive B1351).

Fig. 3 The ex-British Army gun-laying 200 MHz radar trailer which was used for the alt-azimuth mounting ofthe Murraybank 21-ft aerial (adapted from ATNF Historic Photographic Archive B3973-1).

configuration and is visible just to the right of centre in the upper part of Figure 3. Figure 4 shows the 21-ft aerial being lowered onto the mounting at Murraybank.

In the original installation the primary feed was simply a long copper tube with a spilt bell and reflector, but this was soon abandoned and a new bipod feed mount was

Fig. 4 The 21-ft aerial being installed at Murraybank on 18 May 1956. The equipment hut is in the immediate background (courtesy: ATNF Historic Photographic Archive B3973-4).

constructed which was supported by nylon guide ropes. The new feed front-end box contained the mixer, the final stage of the local oscillator and a pre-amplifier (ibid.).

Figure 5 shows the aerial after installation at Murraybank and with the new feed mount. The aerial was tilted toward the equipment hut and a platform ladder was placed on a small wooden ramp so that the primary feed could be accessed. Also visible in the background is the small reference aerial. This aerial had been transferred from Potts Hill with Joe Warburton when the solar program wound down. At one stage consideration had been given to using this aerial to provide a reference signal, but this configuration was not pursued (ibid.). Warburton only stayed with the program for a short period before leaving the Division of Radiophysics.

In its initial configuration the Murraybank aerial had a half-power beamwidth of 2.8°. However, later changes to the primary feed of the aerial improved the beamwidth to 2.2°. Figure 6 shows McGee working on the primary feed of the aerial.

Fig. 5 The 21-ft aerial at Murraybank with its new feed system. The smaller reference aerial is also visible in the background (courtesy: ATNF Historic Photographic Archive).

Before discussing the multi-channel receiver in detail it is worth reflecting on the state of radio-frequency spectral-line receiver development when the Murraybank project commenced. By early 1954 there were only six other groups (excluding those in the Soviet Union) where spectral-line receivers were in use or being developed. Two of these were at the Division of Radiophysics in Sydney, being Kerr's team at Potts Hill with their 4-channel H-line receiver (see Wendt et al. 2011a) and the Dover Heights team that was attempting to detect the deuterium-line (see Orchiston and Slee 2002). Two groups were working in the U.S., at Harvard (Sullivan 2009) and the Carnegie Institute (see Burke 2005), while in the U.K. work was underway at Jodrell Bank (see Davies 2009: 5–6). In the Netherlands a major effort was underway at the Kootwijk station (see van Woerden and Strom 2006). Up until this time, none of the overseas groups had initiated projects to construct large multi-channel receivers. While the Potts Hill group had considered having up to 20 channels, ultimately their design could not support more than four concurrent channels, and even this resulted in many practical difficulties in observations. While most groups were not initially considering a multichannel receiver design, this position would change fairly quickly. A team from the Department of Terrestrial Magnetism (D.T.M.) at the Carnegie Institute in Washington developed a 54-channel H-line receiver which was operational

Fig. 6 Dick McGee working on the primary feed of the 21-ft Murraybank aerial (courtesy: ATNF Historic Photographic Archive R5695-8).

before the Murraybank one, and by early 1957 they were making observations using a 7.5-m Würzburg antenna (see Burke et al. 1959).

The first operating version of the Murraybank multi-channel receiver used as its first stage a crystal diode mounted in a tuned cavity. This signal was then passed to a double-conversion superheterodyne using intermediate frequencies of 31.8 and 6.74 MHz. The receiver output was switched at a rate of 385 Hz between the signal frequency of 1,420 MHz and a reference frequency of 1,424 MHz (Murray and McGee 1959: 127). The reference frequency was selected as being outside of the largest doppler shift expected in the Galaxy for the H-line. The output from the second intermediate frequency amplifier was passed into 48 double-tuned filters that were spaced at intervals of 32 KHz. The individual band pass filters had an approximately Gaussian response with a half-power bandwidth of 40 KHz which equates to a H-line radial velocity coverage of 8.4 kms^{-1}. A second detector was attached to each individual filter. The detected outputs, including contributions from the two switched frequencies, were then passed through audio amplifiers and synchronous detectors to produce the hydrogen-line signal. Signal fluctuations were smoothed by the using a 2 min time constant. A telephone-type uni-selector switch allowed sampling of each of the synchronous detector outputs once every 2 min. The noise temperature of the receiver was ~800 K. The output was recorded on a Speedomax chart-recorder as a 48-point profile with frequency on the x-axis and aerial temperature on the y-axis.

Figure 7 shows a view inside the receiver hut at Murraybank. On the left is the bank of 400 MHz amplifiers for the 48-channels. In the next rack to the right, starting from

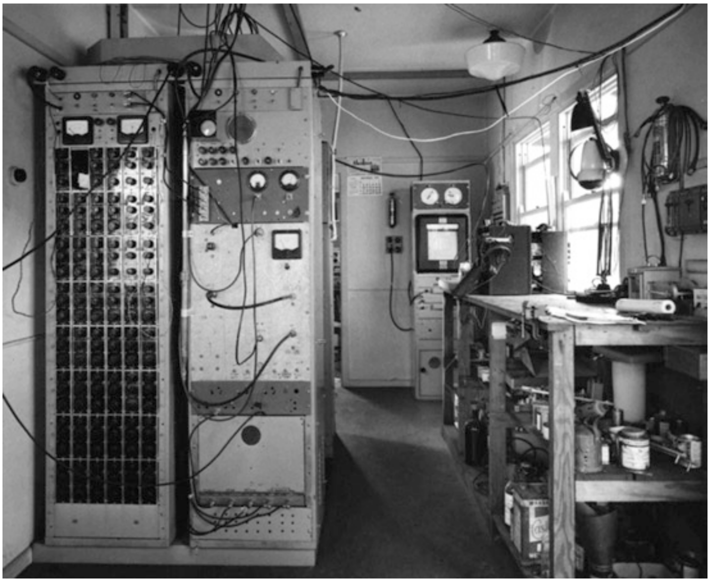

Fig. 7 A view of the multi-channel receiver equipment inside the receiver hut at Murraybank (courtesy: ATNF Historic Photographic Archive R5695-18).

the top is an oscilloscope and receiver used to check the frequency against the WWV signal. Below this are the main local oscillator multiplier chain, the local oscillators and the local oscillator switch. The chart-recorder is in the back right corner of the hut. The workbench visible in the right of Figure 7 was later moved and the chart-recorder was relocated next to the other equipment racks, as shown in Figure 8.

Given Murray's experiences with the problem of temperature control at Potts Hill, careful attention was paid to construction of the equipment hut which was heavily-insulated using 3-in. slag sheets on the walls, floor and ceiling. The roof had open eaves to allow airflow, but was shielded with netting to keep out animals and birds. The filters themselves were located inside another insulated area within the hut which was accessed through a butcher's cold-room store door.

Figure 9 shows a view of the filter bank. The filters were housed in heavy aluminium casings. To the left in Figure 9 is a large water tank which was used as a heat-sink. On top of this a recording thermometer can also be seen. With this set-up it was found that the temperature varied less than half a degree even on hot days (Murray, pers. comm., 8 February 2008).

Figure 10 shows John Murray standing at the chart-recorder inside the receiver hut at Murraybank. The clocks visible above the recorder show solar and sidereal time. All of this equipment was constructed in the Radiophysics workshop (ibid.). Meanwhile, Figure 11 shows an example of the raw output of seven successive 2-min profiles on the Speedomax recorder.

Figure 12 shows an example of a composite profile obtained from six successive 2-min scans while the aerial was held in a meridian transit position set at a declination of +14° and the profiles recorded from $03^h\ 44^m$ to $03^h\ 54^m$ as the Earth rotated.

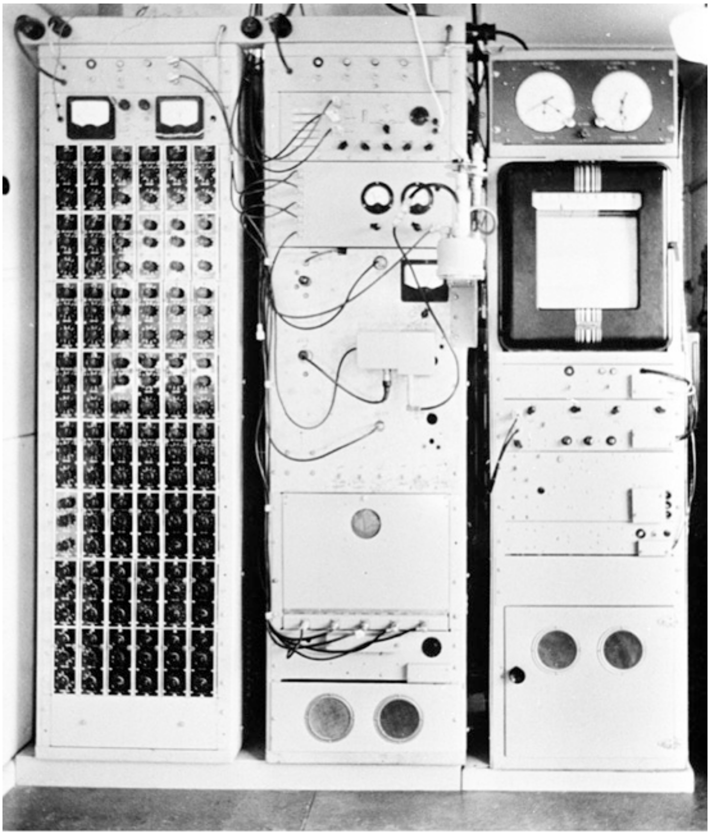

Fig. 8 A later view of the receiver and recording equipment following the relocation of the chart recorder (courtesy: ATNF Historic Photographic Archive B6222-1).

As can been seen from Figure 12, the baseline showed some inherent unevenness due to individual differences between channel filters. After some initial trial surveys, the receiver was modified by adding an additional two wide-band channels, taking the total to 50. These additional channels were added to each end of the existing 48-channel bank and were used as zero-line markers. The filters in each of these channels had a bandwidth 0.5 MHz between half-power points and were set up so that so that they covered the same frequency range as the first 24 and last 24 channels filters, so that complete coverage of the profile frequency range was provided.

A calibration system was also added to the multi-channel receiver. A switched noise source was located at the vertex of the main aerial paraboloid. The noise signal was generated from a dipole by switching alternatively on and off a high tension voltage supply to a noise diode mounted across the dipole feed point. This was used to provide a relative intensity calibration. The switching was performed in synchronisation with the frequency switching of the receiver so that the noise signal appeared only in the signal band of the receiver. In this way, the signal appeared

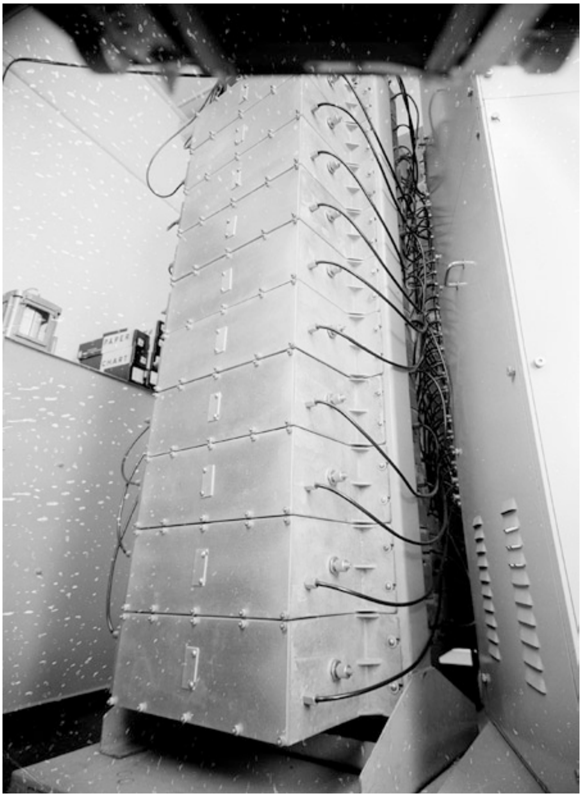

Fig. 9 The filters used in the Murraybank receiver (courtesy: ATNF Historic Photographic Archive B5985-1).

equally in all channels and served as a means of calibrating the relative gain of each channel. The system was capable of measuring deflections of up to 200 K aerial temperature. Frequency monitoring was made by comparison of the harmonics of the crystal-controlled local oscillator signals with signals from the radio station WWV. The team found that when a beat signal between WWV and another station JJY could be heard it was likely that propagation effects would impact on the quality of the recordings (ibid.). Later, tests were also performed using a laboratory frequency counter and these indicated that the local oscillators had frequency stability better than the equivalent of 0.03 km/s radial velocity.

For surveys the aerial was placed at a fixed declination in a meridian transit position. Recordings were then taken over a 24 h period. With a beamwidth of 2.2°, four complete profiles were produced per beamwidth and a total of 720 were produced in each 24 h declination strip observing run. It was clear that the multi-channel receiver would produce a very large body of data in a short period of time. As the multi-channel receiver was proving successful in operation, it also became clear that much larger amounts of data would be produced when the receiver was later installed on the 64-m Parkes Radio Telescope. To deal with these very large amounts of data, a new project was launched under Hindman's leadership to develop a digital recording and data reduction system.

Fig. 10 John Murray at the Speedomax recorder in the receiver hut at Murraybank (courtesy: ATNF Historic Photographic Archive R5695-9).

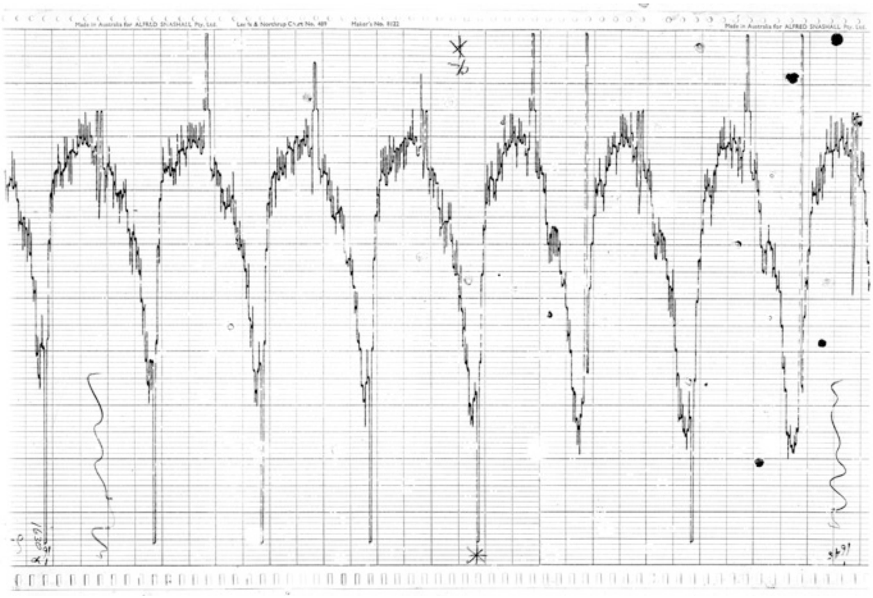

Fig. 11 An example of the 2-min H-line profiles produced as an output on the Speedomax chart-recorder (courtesy: ATNF Historic Photographic Archive B5849-1).

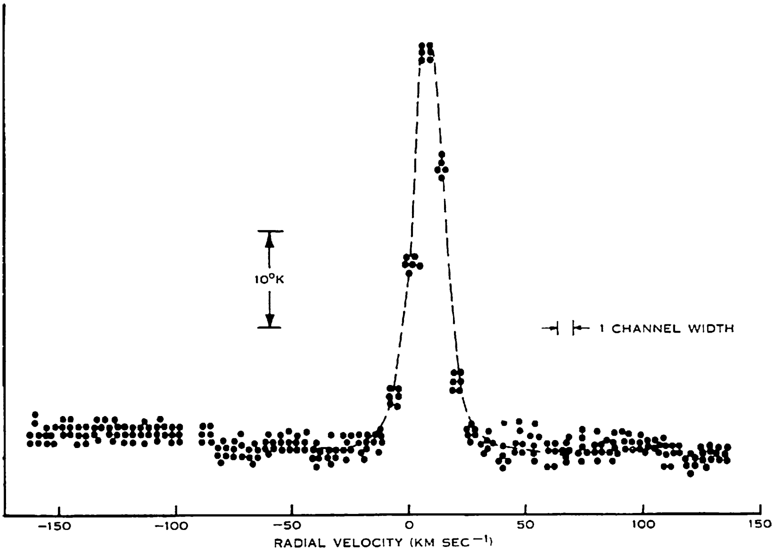

Fig. 12 An example of a composite H-line profile produced by the Murraybank multi-channel receiver. The profile consists of 6 two-minute profiles taken over a period of 12 min while the aerial was held at a fixed declination in a meridian transit position (after Murray and McGee 1959: 128).

Maston Beard, who had been involved with the development of the original Radiophysics' digital computer, joined the team to develop the Division's first digital recording system designed specifically for radio astronomy. This was also to be the Division's first application of digital computers to the reduction of observational data. This was viewed as a pilot project which would later be adapted for use with the Parkes Radio Telescope.

In the original pilot project the digital recording system used only 46 of the 48 channels. It consisted of five major components, namely: an analogue to digital converter; a ten binary digit data store; a paper hole-punch control unit; a paper tape hole-punch unit; and a program control unit with digital clock (Hindman et al. 1963b). Figure 13 shows a block diagram of the recorder system and an example of the paper hole-punch tape output.

The output produced by the digital recorder was a block of 53 pairs of characters representing the output of a single 2-min line profile together with the sidereal time of the observation, marker characters and check characters. In this example, the first pair of characters are blanks (or zeros) used to mark both the start and end of a single H-line profile block. This is immediately followed by 24-pairs of characters that record the relative intensity of each of the first 24 channels of the receiver, being channel numbers 0–23. A control symbol is then inserted represented by two-pairs of control characters, one pair with all holes punched and the other with no holes punched. This control symbol was used to check that the paper hole-punch was functioning correctly. Following the control symbol are the next 24 pairs of characters representing channels 24–47. This is immediately followed by a pair of characters recording the sidereal time of the observation, and finally by the blank character pair indicating the end of the block.

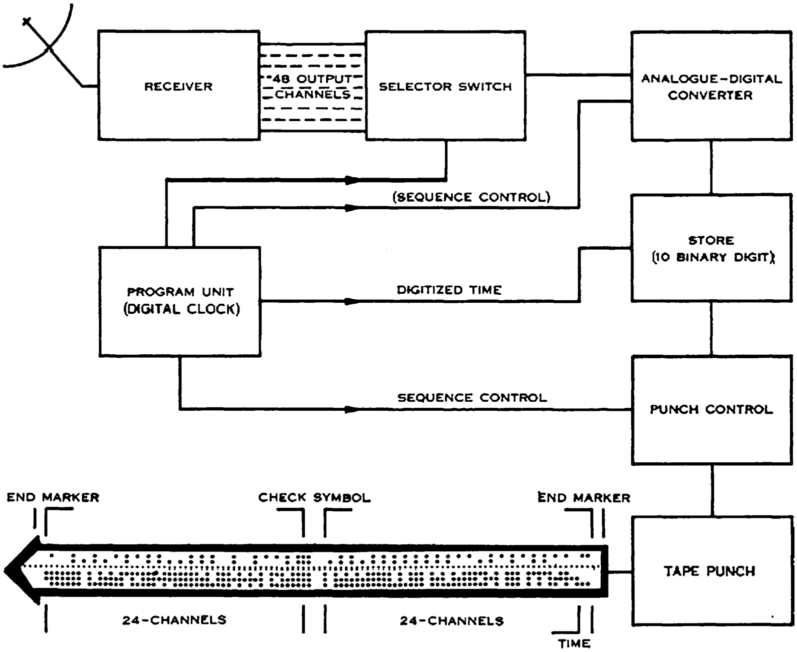

Fig. 13 A block diagram of the digital recording system used at Murraybank with the 48-channel hydrogen-line receiver (after Hindman et al. 1963b: 554).

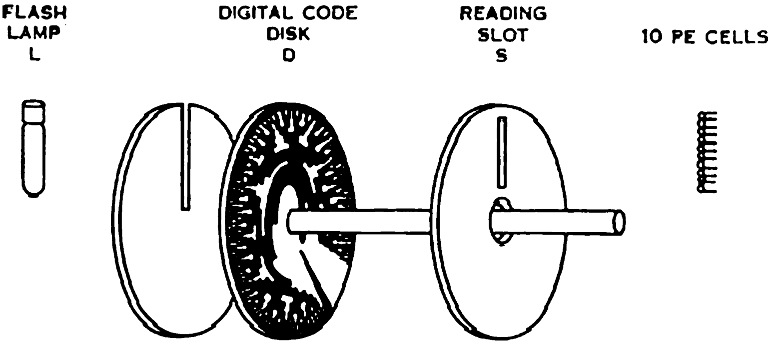

Fig. 14 A schematic diagram of the digital shaft encoder in the Murraybank digital recorder program control unit (after Hindman et al. 1963b: 556).

The program control unit contained a clock driven at a sidereal rate with a number of shafts to achieve four revolution rates: 52 revolutions in 2 min; 1 revolution in 2 min; 1 revolution in 1 h; and 1 revolution in 24 h. Figure 14 shows a schematic diagram of the digital shaft encoder that was used to convert the shaft rotation to digital signal using a flash lamp and photoelectric readout.

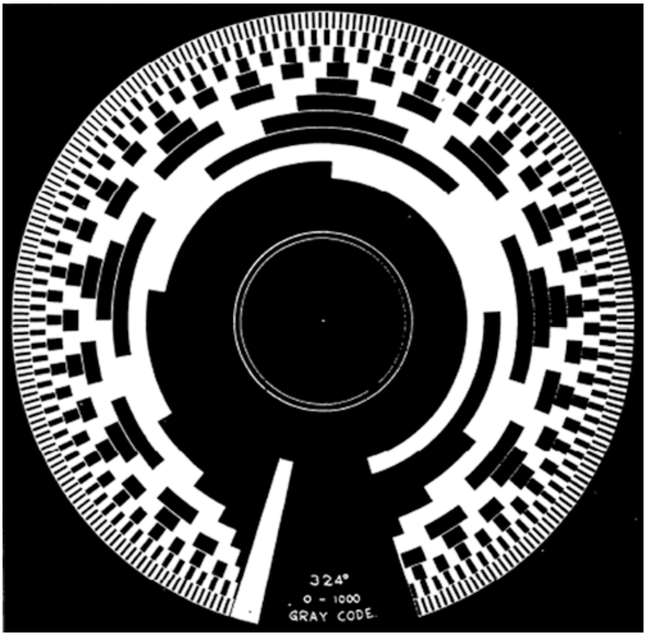

Fig. 15 A close-up view of the encoding disk pattern which divided the 324° of shaft rotation into 1,024 steps (after Hindman et al. 1963b: 557).

A reading from the digital converter was obtained by flashing the lamp and a number corresponding to the shaft position was detected through the disk reading slot by the ten photo-transistors. The 1-h and 24-h shafts were read every 2 min to record the sidereal time of the observation and recorded as two characters in the paper tape data block. Figure 15 shows a close-up of the digital code disk which gives 1,024 numbers from 324° of rotation.

Once a number had been read by the photo-transistor cells, it was stored in the binary store which consisted of ten bistable multivibrators. The program control unit then initiated a pulse which triggered the number to be punched on the five-hole paper tape, which used two characters to represent a number with the most significant digit being the first.

Before beginning any data reduction, each tape was checked visually to ensure that the block markers and central check characters were present. Further, each tape was passed through a reader as a check count of the number of characters per block. These checks were put in place to avoid more obvious downstream errors in the batch computer reductions. The usual chart record was recorded at the same time as digital encoding to provide a cross check.

Another feature of the digital recording method was that it made it possible to apply individual gain and zero level corrections to each individual channel. To do this a calibration tape was prepared for each data recording tape. The calibration tape had selected sections of the high and low level calibration and a base-level run that was usually the same as the low level. The calibration tape could then be fed into the computer at the beginning of the reduction process for each observation run. The calibration tape produced the base-level corrections and individual channel gain factors which were then stored in the working memory of the computer for use in reducing the observational data. Prior to the use of digital recording, manual data reductions were performed by estimating an average figure for gain corrections. In each calibration run, 10 or 12 blocks of data were averaged to produce a set of calibration factors which were substantially smoothed from the receiver noise fluctuations.

The data reductions were performed using SILLIAC (Sydney version of the Illinois Automatic Computer), the computer in the Adolph Basser Computing Laboratory, School of Physics, at the University of Sydney (which had entered service in July 1956). The Division of Radiophysics had abandoned its own computer-development program in 1955 so it therefore was necessary to purchase computing time from the University of Sydney and even after negotiating a special half-price rate a 'block' of 400 h of computing time on SILLIAC cost £16,000 (Deane 2006). As well as reducing the recorded data, the integrated brightness and median radial velocity of each profile was calculated, together with the first and third quartile median velocities as channel numbers. Finally, the average right ascension of the profile, corrected for the receiver time constant effect, was calculated and all the data were then recorded on an output tape. Velocity corrections to account for the Earth's rotation and its orbit around the Sun were not performed as part of the initial data reduction but were calculated in a separate run. The computer time required to reduce 250 h of observations was approximately 8 h, with a further 15 min required to calculate the velocity corrections. Plotting of the results was still performed by hand, but this was the next obvious step for automation. Figure 16 shows a simplified flow chart of the reduction program.

The use of digital recording not only greatly reduced the time necessary for reduction of the initial observations, but the more rigid application of calibration data led to the detection of a second-order receiver effect due to diurnal temperature variations which had not previously been detected. It also allowed the detection of lower level signals that had previously been averaged out in manual reductions. The pilot program was considered highly successful and allowed digital recording to be introduced when the Parkes Radio Telescope became operational.

4 The Murraybank Research Program

The first published research from Murraybank appeared in *The Observatory* (Murray and McGee 1958). This was based on a set of trial observations in the Pyxis-Hydra region in the mid-galactic latitudes between longitudes 210° and 230°. The observations were made prior to the adjustment of the aerial feed so that the beamwidth was still 2.8°. At this time no absolute brightness temperature calibration had been performed, so the temperature scale was based on a comparison with observations

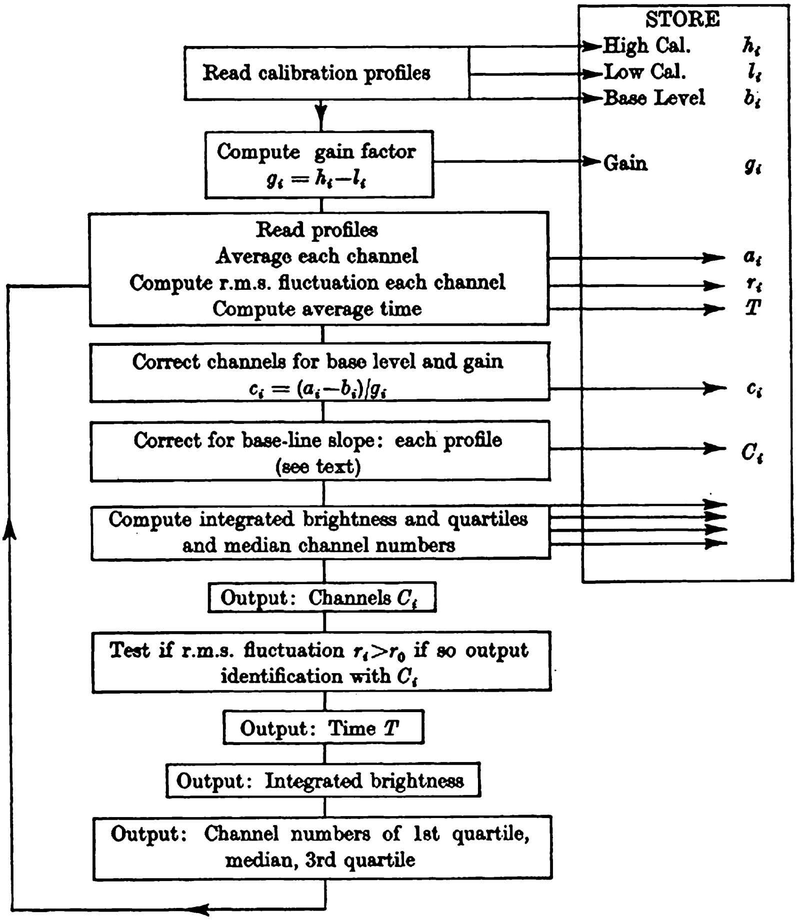

Fig. 16 A simplified flow chart of the reduction program run on the SILLIAC computer (after Hindman et al. 1963b: 562).

carried out by Muller and Westerhout (1957) in nearby regions. The Murraybank observations were made by holding the aerial at a constant declination with a spacing of two degrees or less between scans. Approximately 700 profiles were recorded covering an area of ~500 square degrees.

The profiles observed in the Pyxis-Hydra region were single-peaked and therefore the distribution of neutral hydrogen was reasonably represented by the peak profile brightness temperatures and the radial velocities at this point. Figure 17 shows a contour diagram of peak H-line brightness temperatures at intervals of 5 K, together with radial velocities and an indication of HII regions derived from optical observations.

Based on these observations, Murray and McGee deduced the presence of a large discrete neutral hydrogen cloud centred at right ascension 09^h 00^m and

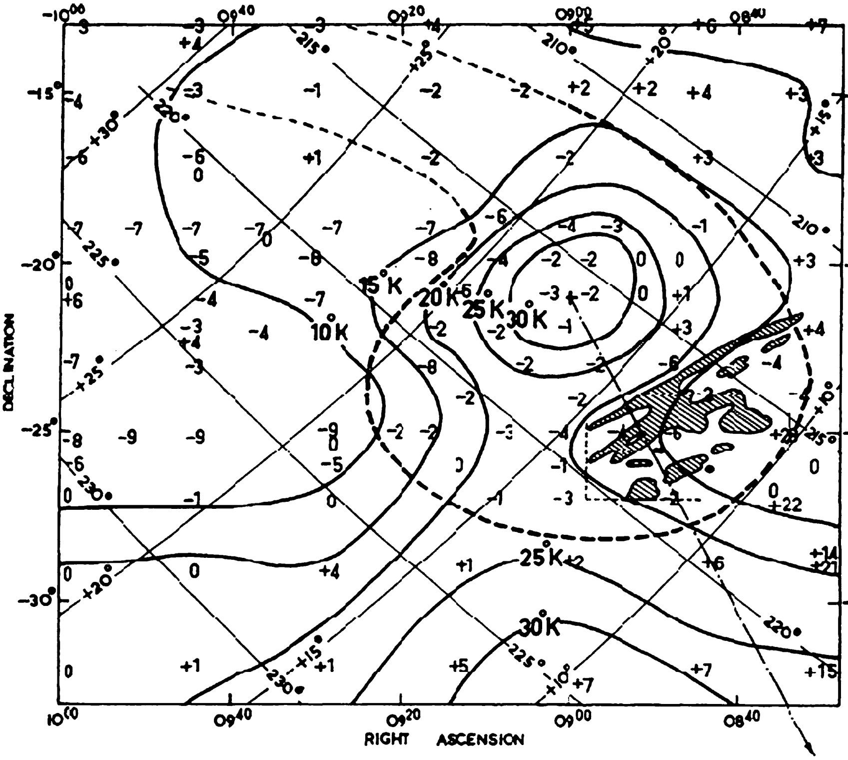

Fig. 17 A contour diagram of the H-line brightness temperature in the Pyxis-Hydra region. Contour spacing is 7.5° of peak temperature. The large numbers represent the mean radial velocity in kms^{-1} over areas 10° by 10°. Optical HII regions are indicated by hatching (after Murray and McGee 1958: 243).

declination −21°. This was supported not only by the peak brightness contours, but also by the fact that the radial velocities immediately to the cloud's left (east) in Figure 17 had a large step change in velocity indicating that the cloud appeared not to be associated with other HI in that region. The dashed line in the diagram encompasses the possible area of the cloud based on the radial velocity measurements. The extension in the upper left is speculative and based only on the velocity measurements. Gum (1956) had shown that the two stars γ^2 Vel and ζ Pup were the source of the ionisation radiation forming the HII region. The location of the HII region on the leading edge of the HI cloud facing these stars appeared to lend support to the idea that the two were indeed part of the same complex. Using a distance determination from Gum (1956) they derived the parameters listed below in Table 1.

The next preliminary survey was made of the Taurus and Orion complexes which covered approximately 3,500 square degrees. Again the survey was conducted by holding the aerial at a fixed declination and then the next scan taken with two degree spacing. Some 3,500 profiles were taken in this manner. Nearly all the line profiles were single peaked with an average half-width of 19 kms^{-1} with a standard deviation

Table 1 Some parameters of the Pyxis-Hydra neutral hydrogen cloud discovered by Murray and McGee (1958)

Position of the cloud centre (i.e. maximum H-line brightness)	$\alpha = 09^h\ 00^m$, $\delta = -21°$ $l = 216°$, $b = +17.5°$ (1950)
Cloud diameter	12°
Average peculiar radial velocity	-2.5 km s^{-1}
Maximum H-line brightness temperature	35 K
Average number of H atoms in line-of-sight column of 1 cm^2 section	1.0×10^{21} H atoms

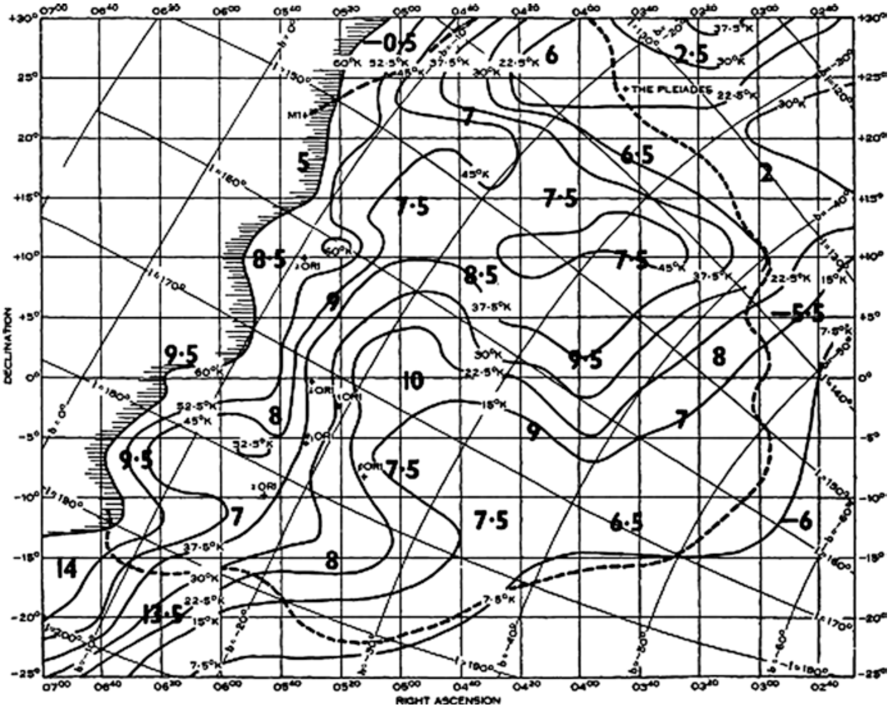

Fig. 18 A contour diagram of peak H-line brightness temperature at intervals of 5 K. Radial velocity in km/sec is indicated as integers on the chart. The shaded area represents an HII region sketched from the National Geographic-Palomar Sky Survey. The arrow indicates the direction from the centre of the contours of two stars believed to be responsible for the ionisation of the HII region (after Murray and McGee 1959: 130).

of 2 kms^{-1}. As no flattening of line profiles was observed it was concluded that the gas was optically thin at all points in the region.

To investigate the radial velocity distribution in the Taurus-Orion region, over 350 uniformly distributed velocity values, corrected to the local rest standard, were calculated. Figure 18 shows a contour diagram of brightness temperature and the mean radial velocities in a grid of 10° by 10°.

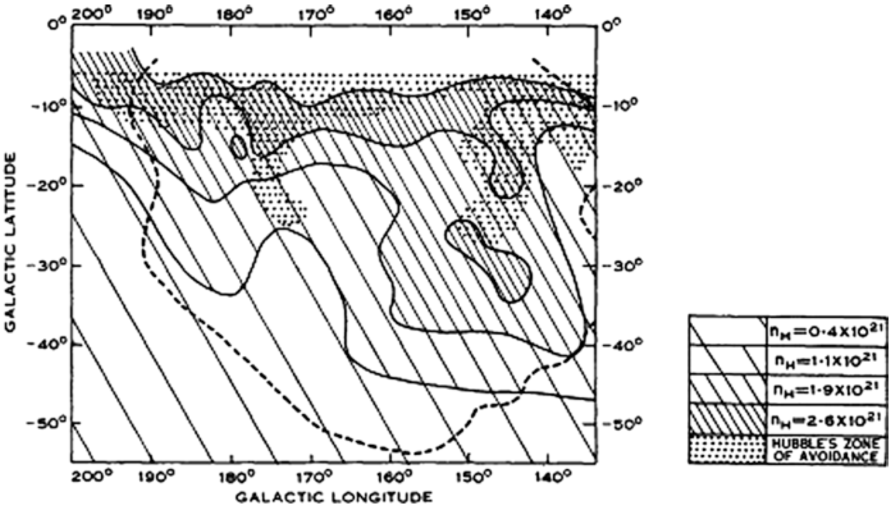

Fig. 19 A comparison of neutral hydrogen density and Hubble's zone of avoidance (after Murray and McGee 1959: 132).

As for the Pyxis-Hydra region, both the peak temperature contours and the radial velocity profiles supported the presence of a large cloud, or connected clouds, in the Taurus-Orion region. Figure 19 shows a comparison of neutral hydrogen density in a line-of-sight column compared to dust regions defined by Hubble's zone of avoidance where there are high levels of optical extinction.

The distance to the clouds estimated from a galactic rotation model (Kwee et al. 1954) was 430 parsec, however if the neutral hydrogen clouds were associated with the optically-observed dust clouds in the region, as suggested by Figure 18, then there was a large distance discrepancy as these had previously been determined to be at a distance of 145 parsecs (Greenstein 1937). A more recent VLBA measurement of the trigonometric parallax of several member stars in the Orion Nebula Cluster, showing non-thermal radio emission, has determined the distance to the cluster to be 414 ± 7 pc (Menten et al. 2007).

Both of the pilot surveys conducted by Murray and McGee demonstrated the viability of the multi-channel receiver coupled with the relatively low resolution 21-ft aerial. With this arrangement, large areas of the sky could be surveyed in relatively short periods. The initial surveys also demonstrated the value that could be gained in examining not only the large-scale structures of the Galaxy but also the more detailed study of specific regions.

With the pilot surveys completed, the focus now turned to a large-scale survey of the sky visible from Sydney. This survey was completed during 1960 and the first publication of results appeared in *Nature* and in the *Astronomical Journal* (McGee and Murray 1961a; McGee et al. 1961). These dealt with the large-scale streaming of neutral hydrogen in the vicinity of the Sun.

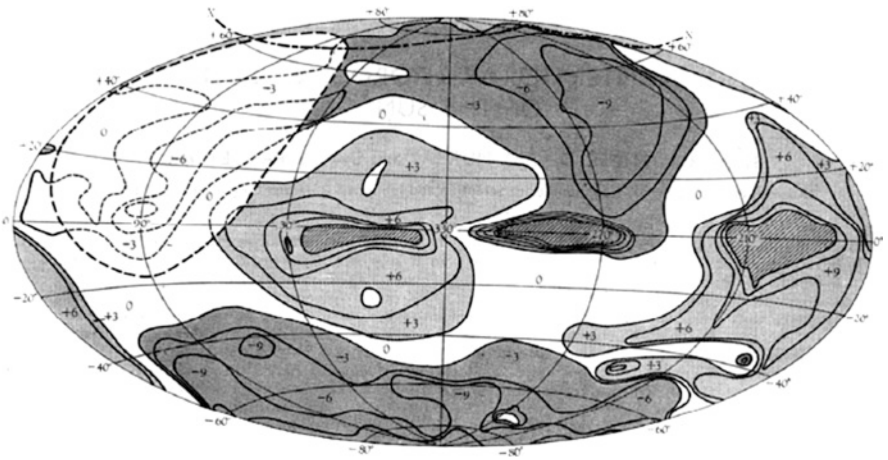

Fig. 20 A contour diagram of peak H-line radial velocities from the Murraybank southern sky survey. Dark grey areas represent negative velocities while light grey areas represent positive velocities. The hatching denotes areas where the radial velocity exceeds 15 km s^{-1}. Co-ordinates are in the old 1950 Ohlsson scheme (after McGee et al. 1961: 958).

Figure 20 shows a radial velocity contour diagram of the H-line peak profiles from the Murraybank survey. The diagram shows the positive and negative peak velocities along the Galactic Equator associated with differential rotation of neutral hydrogen in a disk about the Galactic Centre. However, the interesting features evident in the diagram are the large areas of negative velocity at high galactic latitudes. Areas of negative velocity near the Galactic Poles had previously been reported by Erickson et al. (1959), but they had not noted the overall disposition.

These areas appeared to be associated with a general in-streaming of neutral hydrogen, at least within the general area of the Sun, but possibly more generally. Figure 21 compares the observed peak velocities to a derived curve based on a differential galactic rotation model. The diagram shows areas of positive velocity toward the Galactic Centre where negative values would be expected, indicating that the gas in this region has an additional component of outwards motion.

Without being able to determine the distance of observed peaks, other than through an assumed differential rotation model, McGee et al. (1961) were unable to state whether the streaming was a more general phenomenon. However, they noted that if the observed flow was representative of the general flow over the galactic disk then the quantities of hydrogen involved would be sufficient to make this a major feature of galactic dynamics.

A further series of three detailed papers was published in the *Australian Journal of Physics* from 1961 to 1964 based upon the Murraybank southern sky survey (McGee and Milton 1964; McGee and Murray 1961b; McGee et al. 1963). For the analysis of the southern sky survey, McGee and Murray were joined by Janice A.

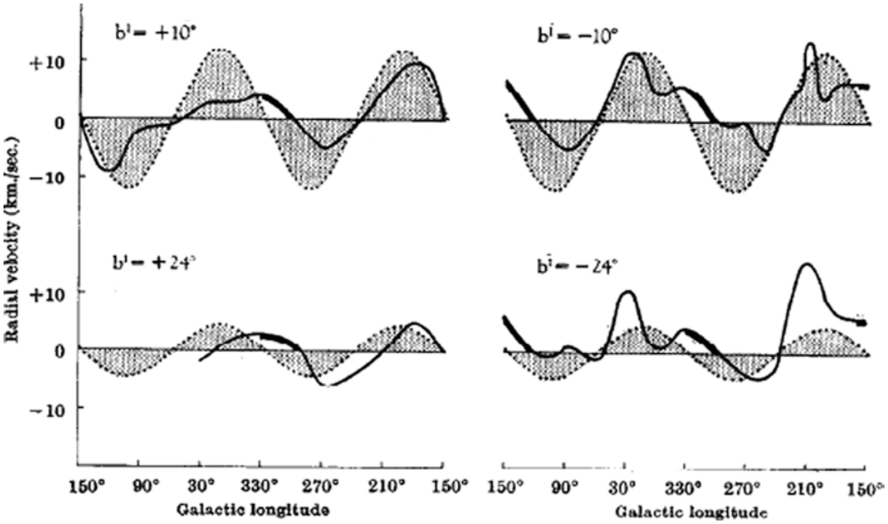

Fig. 21 A comparison of observed velocity curves to the predicted velocity curve assuming differential galactic rotation. The dotted line and shading represent the predicted curve. The solid line represents the actual observations. The thickened sections of the line represent the main deviations from the prediction (after McGee et al. 1961: 958).

Milton who conducted a major part of the data reduction. She was a co-author on the later two papers and was acknowledged for her contribution in the first paper. The third paper in the series was prepared solely by McGee and Milton as by this stage Murray was working in the Netherlands.

The Murraybank southern sky survey was performed by taking observations at meridian transit with intervals of one degree in declination from −90° to +42° over a period of 24 h for each observing run. The limit of sensitivity was believed to be set by an r.m.s. fluctuation level of the system of approximately 0.7 K. Prior to the Murraybank survey there had been only three extensive H-line surveys that dealt with the region away from the Galactic Plane. The first was the pioneering survey at Potts Hill by W.N. Christiansen and Hindman (1952) which included galactic latitudes of ±50° (see Wendt et al. 2008, 2011a, b). The second was by Bill Erickson et al. (1959) from the Department of Terrestrial Magnetism in Washington using a 54-channel receiver and covering galactic latitudes outside of ±20°. This survey was based on profiles taken at intervals of 10° in both galactic longitude and latitude. Finally, at Jodrell Bank Rod Davies (1960) had covered the same region and extended observations to include ±20°, with observations at 5° intervals.

In the first detailed paper in their series, McGee and Murray (1961b) dealt with the general distribution and motions of the local neutral hydrogen as had been reported in summary form in *Nature*. The paper established that in the vicinity of the Sun, neutral hydrogen was flowing outwards at a mean radial velocity of +6 kms^{-1} in those latitudes in the direction of the Galactic Centre and Anti-centre, and was flowing inwards at a mean velocity of −6 kms^{-1} from above and below in the high galactic latitudes.

McGee and Murray found that the recorded profiles could be divided into three broad classes. The first class was believed to be the local neutral hydrogen distributed over a wide area of the southern sky with line profile half-widths from the instrumental lower resolution limit of 12 kms^{-1} to a maximum observed value of 35 kms^{-1}. In most cases the profiles were single peaked with radial velocities not in excess of ±12 kms^{-1} and with maximum brightness temperature ~50 K. The second class was believed to emanate from the galactic spiral structure and fell within ±12° of the Galactic Equator. These profiles were wide and usually multi-peaked and of much greater intensity than those of any other regions. The third class mainly occurred in low intensity regions at high galactic latitudes. These had half-widths that ranged from 36 to 140 kms^{-1} and in some cases exhibited two or three distinct peaks. McGee and Murray considered the possibility that the wide profiles may be due to hydrogen from the galactic corona but discounted this idea, as a much greater dispersion would be expected from randomly-moving and highly-dispersed gas clouds.

Figure 22 shows the calculated local distribution of neutral hydrogen density as the number of atoms/cm^2 in a line-of-sight column.

The hatched area in Figure 22 indicates the area along the Galactic Plane where the neutral hydrogen density exceeds 2.0×10^{21} hydrogen atoms cm^{-2}. Also evident are a number of large-scale features. The northern galactic hemisphere showed two spurs, one in the Scorpius-Ophiuchus region and the second in the Sextans region. A weaker ridge is also visible in the southern hemisphere. McGee and Murray noted that the mean longitudes of the major northern spur, the southern galactic minimum, the northern minimum and southern spur were approximately the same. Erickson had also alerted McGee and Murray to the fact that the position of the northern minimum agreed exactly with that of the Department of Terrestrial Magnetism

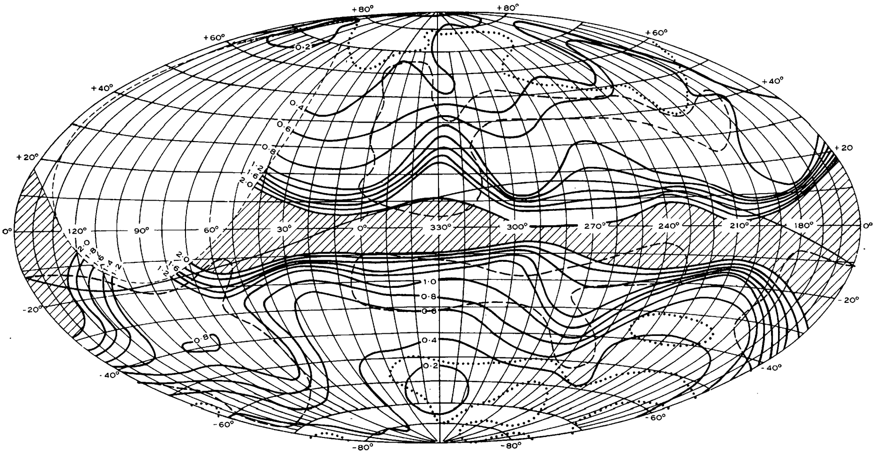

Fig. 22 A contour diagram of the local distribution of neutral hydrogen shown as the number of hydrogen atoms/cm3 in a line-of-sight column. The contour interval is 0.2×10^{21} H atoms cm^{-2}. The hatched area encloses regions where the profile half-widths were in the range 12–20 km/s. The galactic co-ordinates are from the old system of Ohlsson (after McGee and Murray 1961b: 264).

survey and was also the pole corresponding to the plane of the general magnetic field in the solar vicinity as derived by Shain (1957). No conclusion was drawn from the coincidence of this alignment.

McGee and Murray noted that if the neutral hydrogen is stratified parallel to the Galactic Plane, then the observed density should vary as the cosecant of the galactic latitude.

Figures 23 and 24 show the density of neutral hydrogen plotted against 12 galactic longitudes as a function of latitude. The conclusion drawn from these diagrams was that the neutral hydrogen was substantially horizontally stratified in the plane of the Galaxy and that there were a number of concentrations of neutral hydrogen embedded in the plane. The estimated density of neutral hydrogen in the solar vicinity was approximately 0.40×10^{21} hydrogen atoms cm^{-2}. Davies (1960) had found a variation in density in the southern galactic hemisphere, however McGee and Murray suggested that this discrepancy was most likely due to averaging effects over different areas of the sky. Their results suggested that there was little difference between hemispheres, indicating that the Sun lies at the centre of the hydrogen layer in the Galactic Plane.

Much of the data on the radial velocity distribution had been discussed in the *Nature* summary paper. In their paper that appeared in the *Australia Journal of Physics* a more detailed analysis was made of the departures of measured radial velocities from the predicted velocities due to differential galactic rotation.

Figure 25 shows a summary of these for both northern and southern galactic hemispheres from ±20° to ±60°. It is clear from this figure that at high galactic latitudes the velocity of neutral hydrogen is not influenced by differential rotation. Based on this evidence it was concluded that neutral hydrogen was flowing toward the Sun from above and below latitudes ±90° to ±40°.

The second paper in the series (McGee et al. 1963) dealt in detail with the low velocity gas observations. Some 95,000 H-line profiles were obtained in the survey, of which about 40,000 were redundant, being for the same region of the sky. The redundant profiles were however still useful for cross-checking of the observations. By this stage they were using the term ‘low velocity’ in place of ‘local’ as it became clear that the low velocity areas while predominantly local were not the only regions with low velocity characteristics. In the area of the Milky Way the observations showed a close adherence to the velocities of a simple double sine curve assuming differential galactic rotation. McGee et al. compared the neutral hydrogen measurements to ionised calcium optical observations reported by Feast et al. (1957) and found good agreement in radial velocities and distance estimates. However, as shown in Figure 26, it was apparent that a more reliable value for Oort’s constant $A = 19.5$ kms^{-1} kpc^{-1} was required. Adjustment of the value of A to 13.8 kms^{-1} kpc^{-1} and assuming a distance of 2 kpc brought the optical and radio observations into alignment. Over time the value for Oort’s constant has been refined, and the current value is $A = 14.8$ kms^{-1} kpc^{-1} (Sparke and Gallagher 2000: 81).

A detailed comparison was made between the neutral hydrogen distribution and the other radio-frequency emission distribution. A catalogue of concentrations, depression and column density deficiencies of low velocity neutral hydrogen was produced and this was compared to continuum surveys conducted by Westerhout

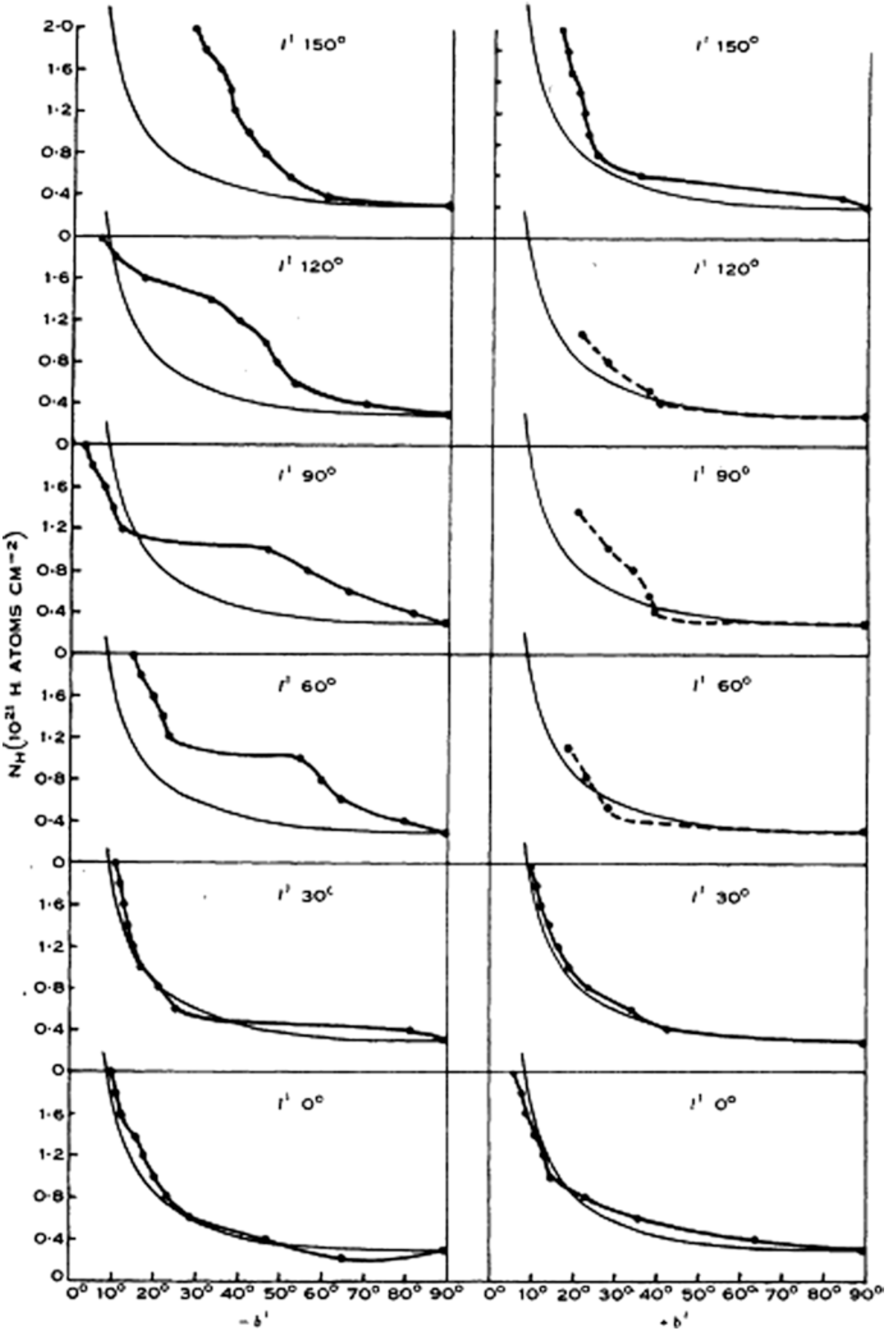

Fig. 23 The variation of neutral hydrogen (N_H) density compared to the cosecant curve $N_H = |0.3 \times 10^{21} \operatorname{cosec} b^I|$. The left-hand column are +ve latitudes and the right-hand column are −ve. Longitudes 0–150° (after McGee and Murray 1961b: 269).

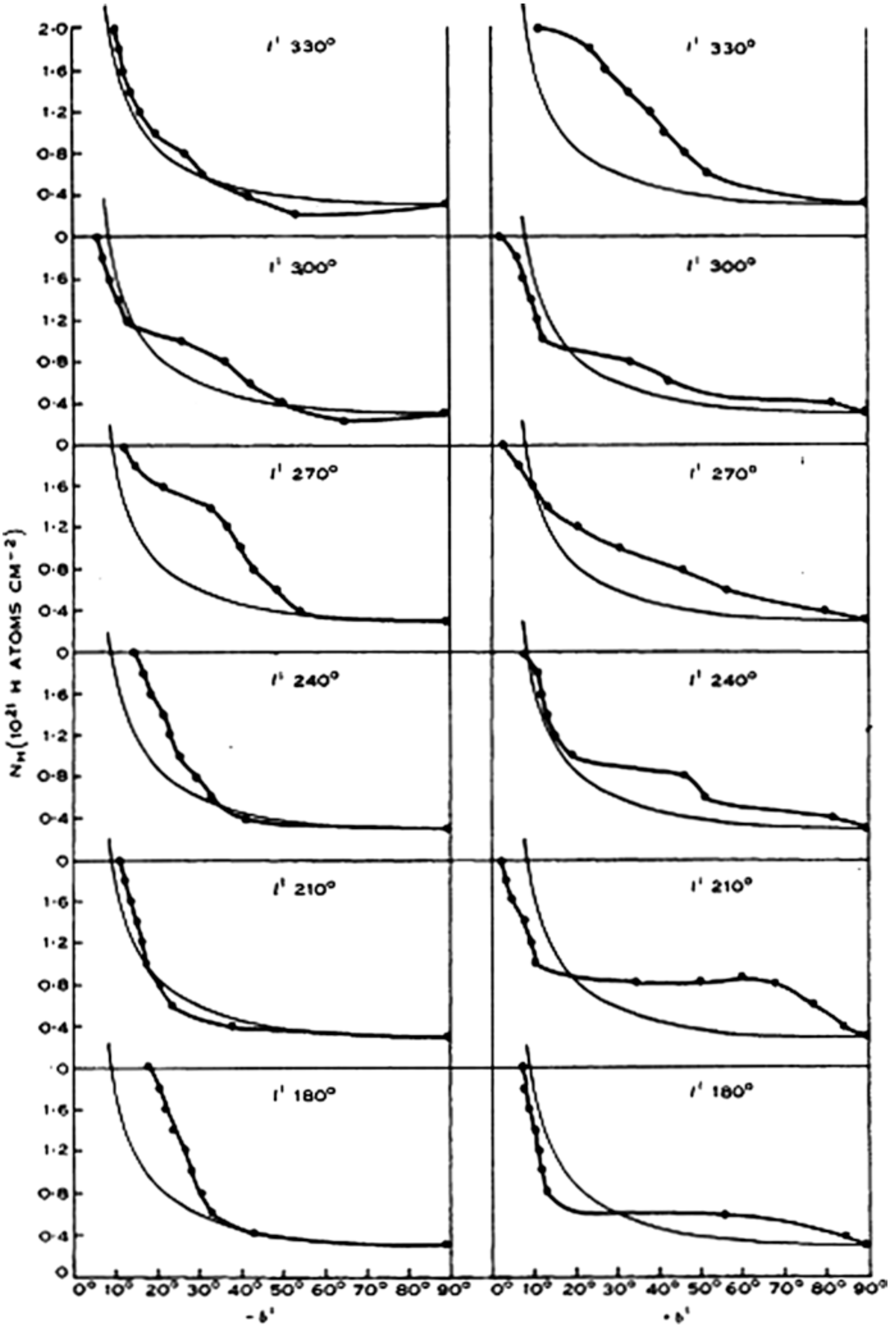

Fig. 24 The variation of neutral hydrogen (N_H) density compared to the cosecant curve $N_H = |0.3 \times 10^{21} \text{ cosec } b^I|$. The left-hand column are +ve latitudes and the right-hand column are −ve. Longitudes 180–330° (after McGee and Murray 1961b: 270).

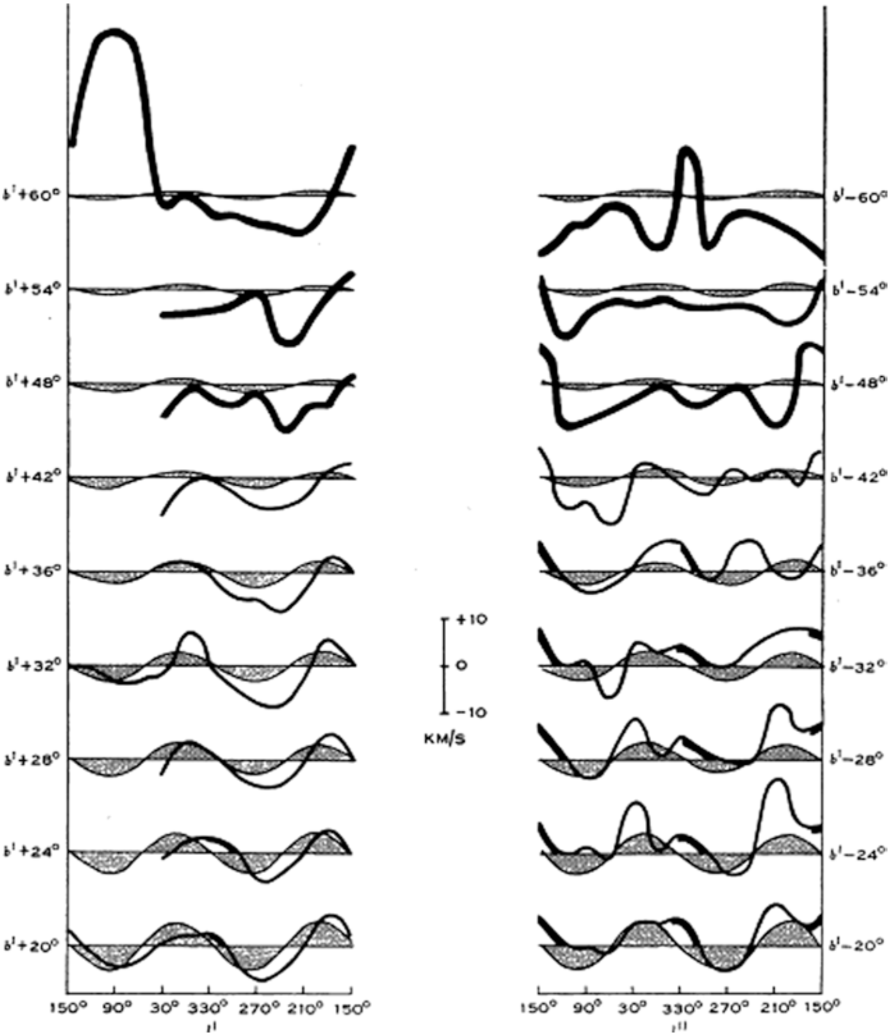

Fig. 25 Radial velocity as a function of galactic longitude compared to predicted velocities at points 11 kpc above and below the Galactic Plane. The thick lines indicate areas of major discrepancies between the prediction and observations (after McGee and Murray 1961b: 276).

(1958) at 1,390 MHz and by Mathewson et al. (1962) at 1,440 MHz. The general findings from this comparison were that there was evidence of absorption by neutral hydrogen from some intense and extended sources. For some nearby thermal radio sources, strong HI and HII emissions are related. The neutral hydrogen emission along the Galactic Plane on the other hand, can be very intense in places where the radio continuum drops to a negligible level. The survey also confirmed that Hα-emitting

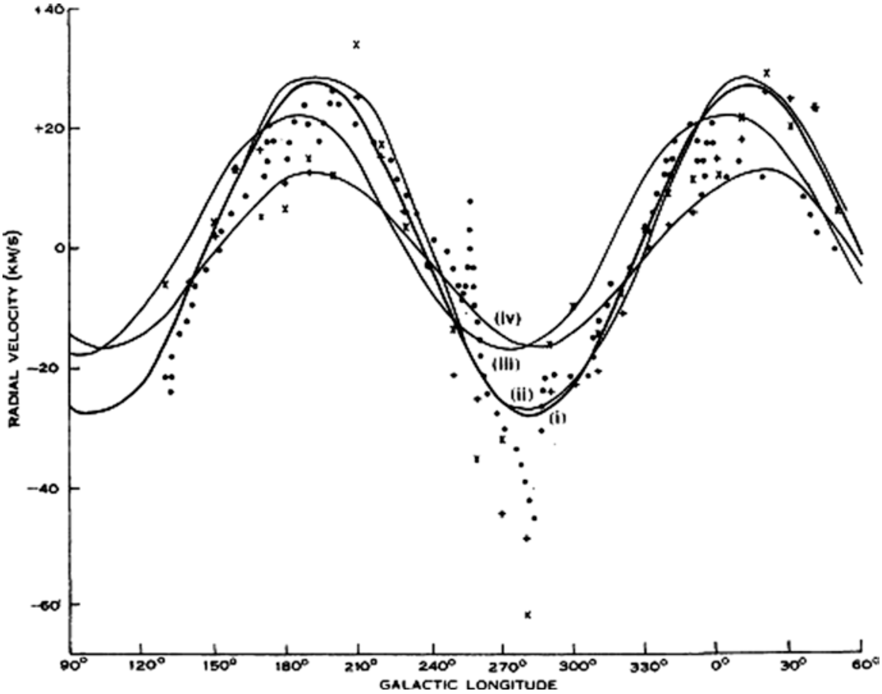

Fig. 26 Radial velocity observations as a function of galactic longitude. The dots represent neutral hydrogen observations. The + points and X points are derived radial velocities using the relation $v_g = 19.5r \sin 2(l^i - 238°)$. The + points are positive latitudes the X negative. Curve (i) is the theoretical differential rotation curve assuming a 1.4 kpc estimated mean distance of hydrogen in the Galactic Plane. Curves (ii), (iii) and (iv) are those derived by Feast and Thackeray based on ionised calcium (Ca II) absorption lines in the spectra of B-type stars reduced to mean distances of 2, 1.15 and 0.75 kpc respectively (after McGee et al. 1963: 154).

regions occur where there are areas of intense neutral hydrogen emission. It was noted that deficiencies in neutral hydrogen of about 8 K occur where their positions coincide with HII regions. Although the association of neutral hydrogen with dust had previously been demonstrated, the detailed survey provided very strong evidence to support this association. There were a number of outstanding examples of this correspondence in the regions of the Great Rift, the Ophiuchus Complex and the spurs in the Orion-Taurus-Perseus region, although this association was not present in all cases, for example in the Coal Sack region. Figures 27 and 28 are examples produced from the survey of the contour diagrams of peak temperatures and the corresponding radial velocities for similar areas of the Sky. Figure 29 shows a summary diagram of the peak temperature from declinations +42° to −80°. In this diagram the contours have been limited to 4, 8, 16, 32 and 64 K for simplicity.

The third paper published about the Murraybank H-line survey (McGee and Milton 1964) addressed the high velocity neutral hydrogen believed to be associated with the Galaxy's spiral arms. Again, the detailed data were presented with a

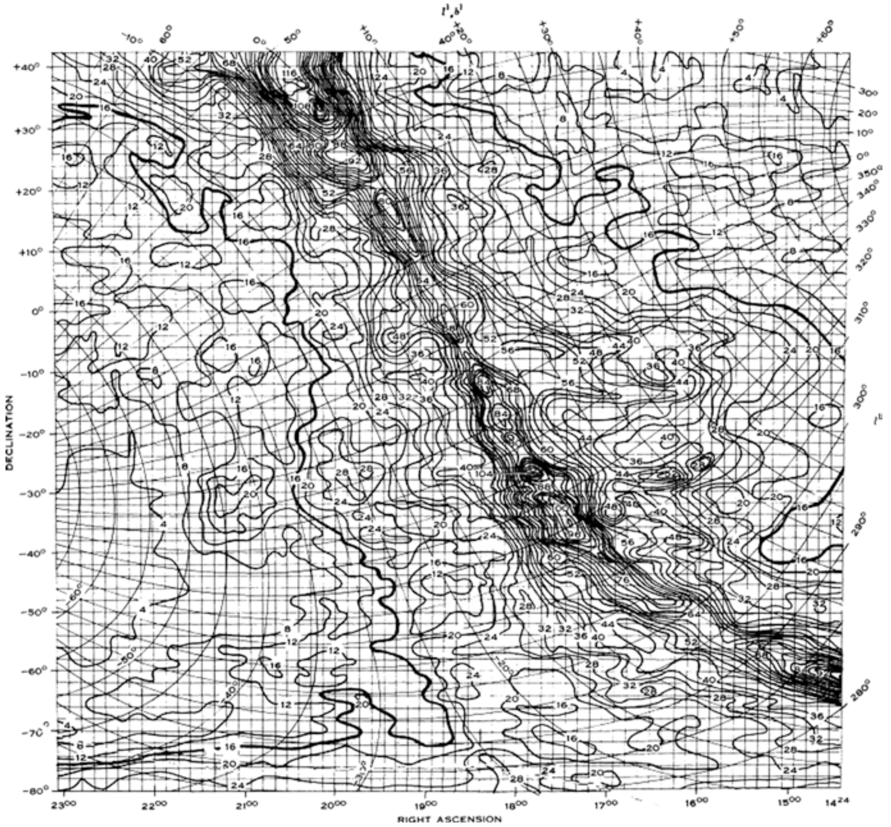

Fig. 27 An example of the peak temperature of neutral hydrogen contour diagram produced in the Murraybank survey (after McGee et al. 1963: 139).

minimal amount of reduction and correction. The distribution of neutral hydrogen in the Milky Way had previously been extensively studied in Leiden (see Muller and Westerhout 1957; Ollongren and van de Hulst 1957; Schmidt 1957; van de Hulst et al. 1954) and at Potts Hill. The new IAU System of galactic coordinates (Blaauw et al. 1960) had been determined principally from neutral hydrogen observations in the inner part of the Galaxy. The third paper in the Murraybank series therefore dealt mainly with the outer parts of the Galaxy, beyond the solar orbit and within galactic latitudes of ±10°. In this region the H-line profiles exhibited multiple peaks. Figure 30 shows examples of some triple-peaked profiles.

Figure 31 shows an example of the contour diagrams produced for both peak brightness temperature and radial velocity of the peak.

To enable comparisons with previous surveys, McGee and Milton adopted the radial velocity-distance model used by Kerr (1962). This included adjustments for both the northern and southern sets of data to include the galactic rotation and an expansion component. For positions inside the solar orbit, an ambiguity of position

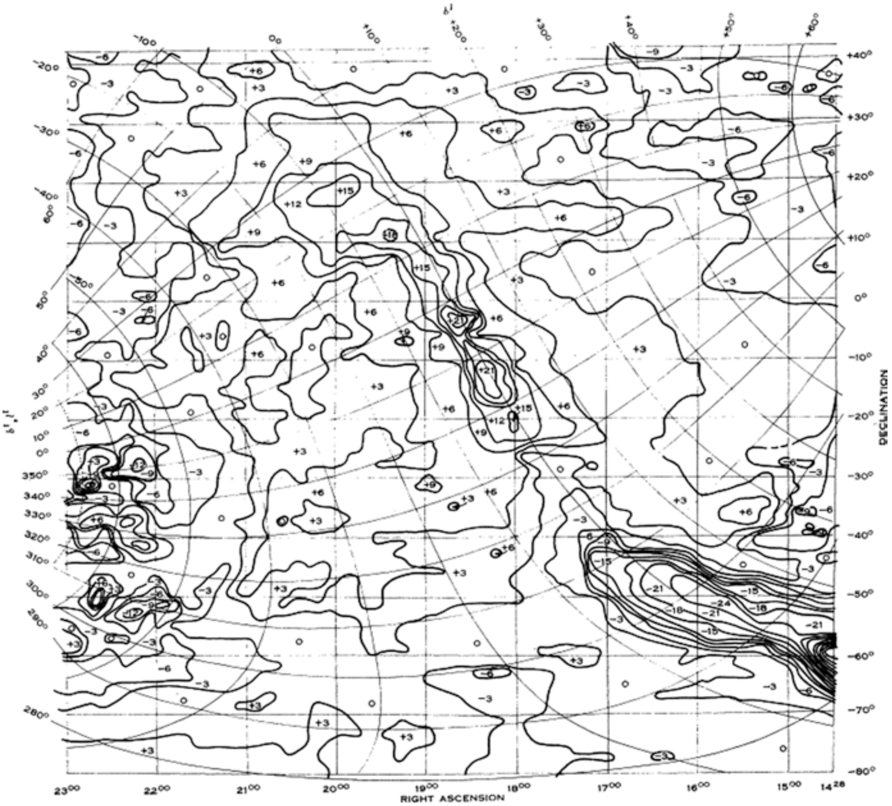

Fig. 28 An example of the radial velocity contour diagram corresponding to the brightness peak of neutral hydrogen from the Murraybank survey (after McGee et al. 1963: 147).

exists and therefore no general comparisons were made for this region. Figure 32 shows the overlay of their positions of maxima (open circles) and minima (crosses) of hydrogen concentrations on Kerr's (1962) map of the distribution of neutral hydrogen. The dark line joining the positions marks the ridges of maximum intensity of four spiral arms.

Van de Hulst (1958) had earlier published estimates for hydrogen cloud sizes as summarised in Table 2.

McGee (1964) had drawn attention to the existence of two further classes based on the Murraybank observations. The first of these was typically of 100–150 parsec and contained two or more of van de Hulst's 'typical clouds, 21-cm emission'. They were generally observed in the solar vicinity. The second class was HI clouds that were several times larger and are found in the region outside of the solar orbit. Twenty-nine examples of these clouds were recorded and these ranged in size from 350 to 1,330 parsecs. The average mass of these clouds was estimated to be ~10^7 solar masses.

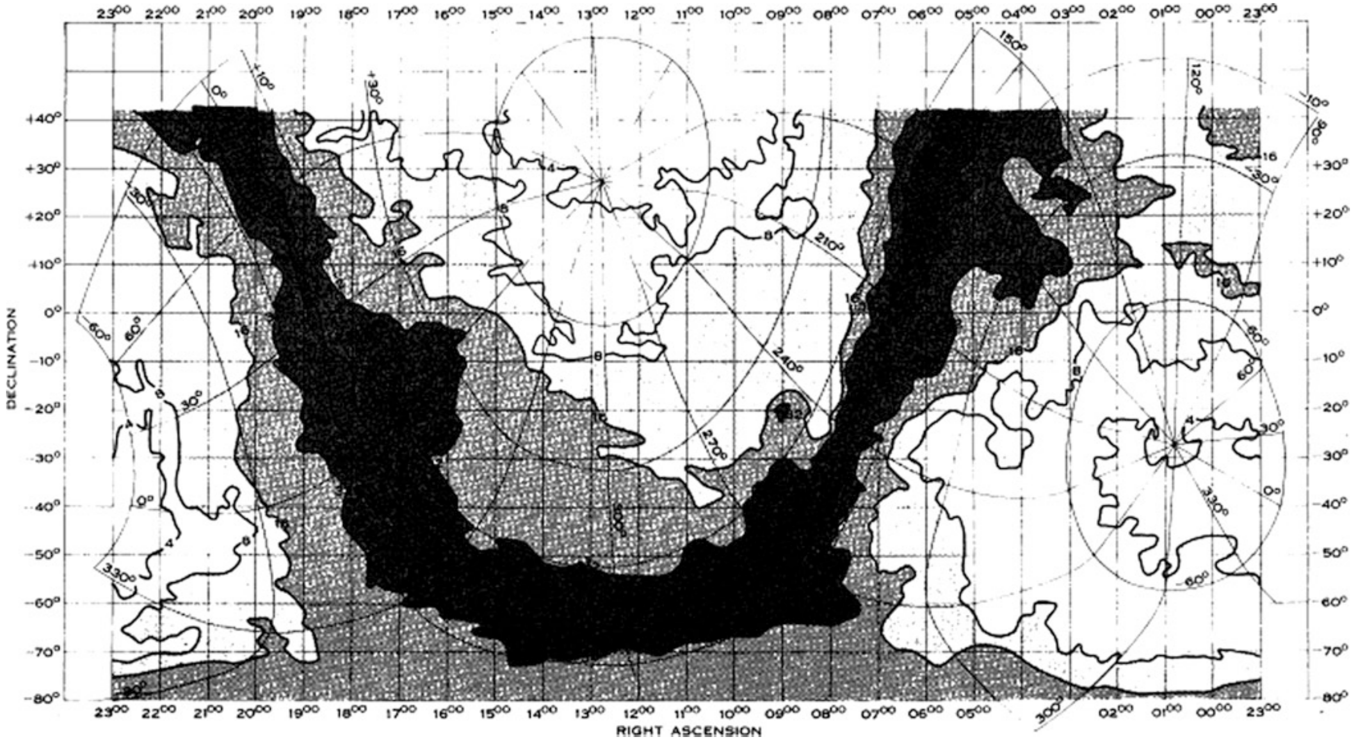

Fig. 29 A composite contour diagram of peak temperature with contours limited to 4, 8, 16 and >32 K (after McGee et al. 1963: 156).

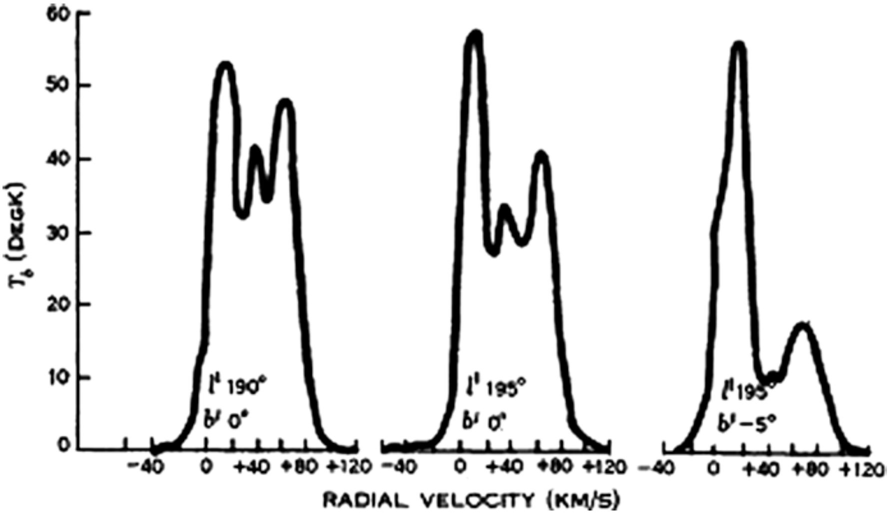

Fig. 30 Examples of triple-peaked H-line profiles from the Murraybank survey (after McGee and Milton 1964: 129).

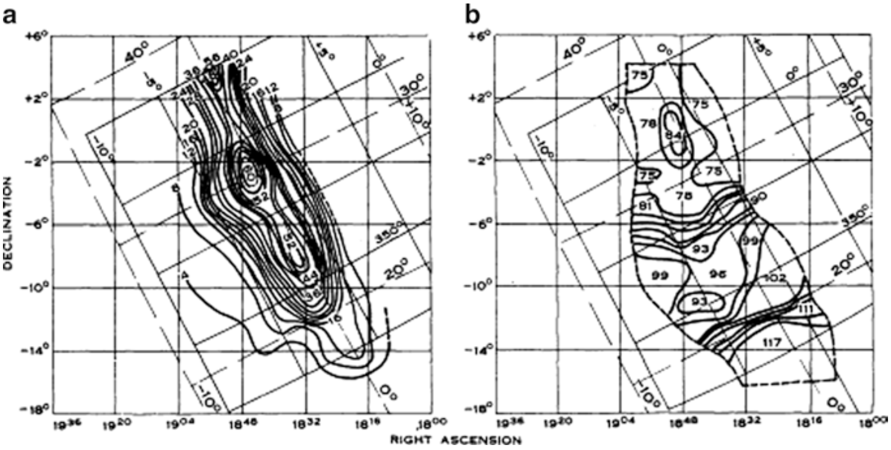

Fig. 31 Examples of the peak brightness temperature (left) and radial velocity (right) contour diagrams along the galactic equator from the Murraybank survey (after McGee and Milton 1964: 143).

McGee and Milton noted that the hydrogen in our own local neighbourhood could well be considered to form one of the large clouds with the major components being of the 100–150 parsec class, such as the Scorpius-Ophiuchus, Pupis-Vela and Orion-Taurus-Perseus clouds.

One of the major findings from this section of the Murraybank survey was that although there was good agreement with earlier surveys on the possible thickness of the hydrogen layer in the Galactic Plane, outside of the radius of the Sun's galactic

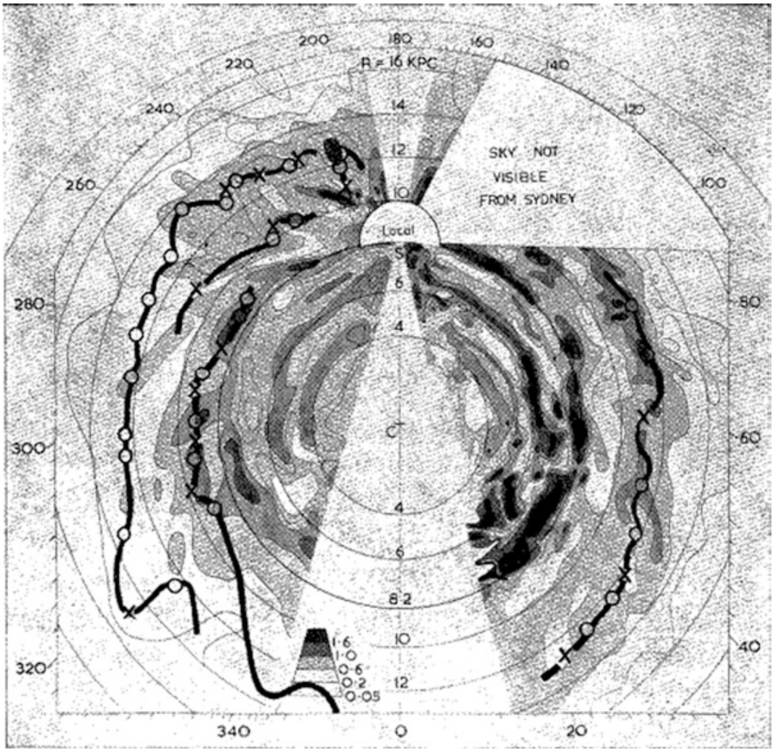

Fig. 32 The ridges of maximum intensity of neutral hydrogen for four spiral arm outside of the Sun's galactic orbit over-laid on Kerr's (1962) map of hydrogen distribution (after McGee and Milton 1964: 149).

Table 2 Some parameters for galactic hydrogen clouds (after van de Hulst 1958)

Class	Size in pc
Diameter of spiral arms in the plane of the Galaxy	500–1,000
Diameter of spiral arms 90° to the plane of the Galaxy	200
Condensations in spiral arms	100
Large emission regions	60
Typical cloud, Ca^+ absorption	30
Typical cloud, 21-cm emission	20–70

orbit the thickness of four of the spiral arms increases with increasing distance from the Galactic Centre. At a radius of 13 kpc the half-power thickness of the arms was estimated to be 1,300 parsecs. This phenomenon had not previously received a great deal of attention. Van de Hulst et al. (1954) had found "… a distant arm … [which had a] … true half-thickness of 750 parsecs." and in discussing a "… faint outer arm …" Westerhout (1957) stated that "… its mean height between +500 and +1,000 parsecs is very peculiar." In discussing their result with the Potts Hill team, Hindman "… informed us that he had noticed the great increase in the thickness of outer arms …" (McGee and Milton 1964) however this interpretation was discounted at the time. Figure 33 illustrates the observed rapid increase in cloud thickness outside of the radius of the Sun's galactic orbit.

This third paper was the final one in the Murraybank H-line galactic survey series, although McGee also co-authored a paper that studied the correlation between radial velocities derived from optical Ca II and H-line observations (Howard et al. 1963).

The next step for the Murraybank program was a trial of the new digital recording system. For this purpose it was decided to conduct a survey of the Magellanic Clouds to test the recording system prior to its use at Parkes. This survey was conducted in late 1960. For this work McGee was joined by Jim Hindman from Potts Hill (as by this time Murray had moved to the Netherlands and was working on the design of the Benelux Cross).

The introduction of digital recording and data reduction was the first time that Radiophysics staff had used a digital computer in this role. The Murraybank team consisted of Hindman, McGee, Beard, Alan Carter and Eric Holmes. The survey of the Magellanic Clouds was chosen as it represented a self-contained project, but

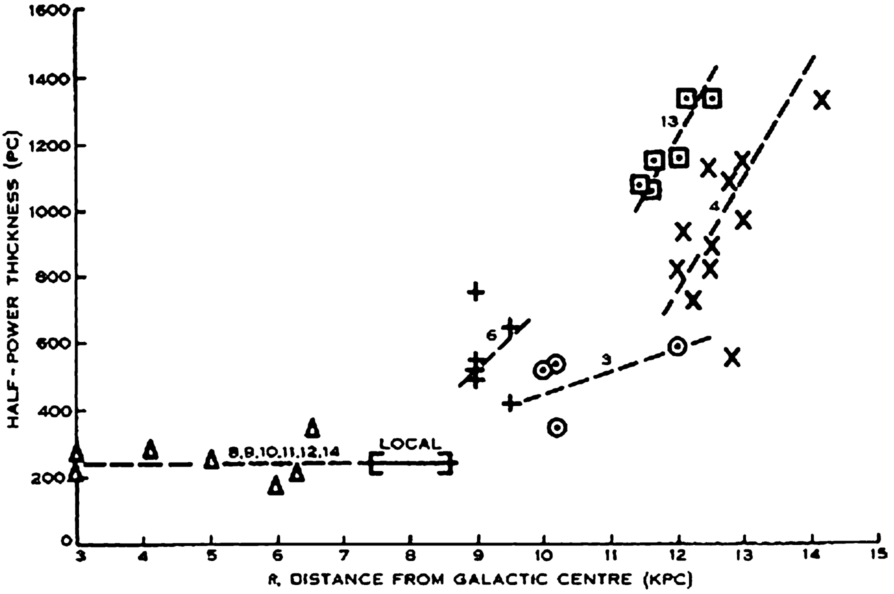

Fig. 33 HI cloud thickness at half-power points plotted as a function of distance from the Galactic Centre. The different symbols and associated numbers refer to the groups of observations. The triangles are from within the solar orbit. The other symbols represent the four different spiral arms (after McGee and Milton 1964: 152).

with the increased sensitivity of the 48-channel receiver it also provided a worthwhile extension of the earlier Potts Hill work by Kerr et al. (1954).

The low resolution survey of the Magellanic Clouds proved extremely successful, not only demonstrating the value of the digital recording and computer-based reduction techniques, but also resulting in two major discoveries about the Magellanic Cloud system. Two papers on the survey were published in the *Australian Journal of Physics* (Hindman et al. 1963a, b). The first of these covered the observations and a description of the digital recording technique, reduction procedure and equipment. The second paper provided an interpretation of the results. This latter paper was the first research effort that formally bought together the Potts Hill and Murraybank H-line teams prior to their transfer to Parkes.

The first of the major discoveries produced by the Murraybank survey is clearly evident in the contour diagram of integrated brightness of the neutral hydrogen in the Magellanic system (Figure 34). The brightness distribution showed that the two Magellanic Clouds were joined by a bridge of neutral hydrogen gas, and that they were also within a common envelope of this gas. This detection was made possible by the increased sensitivity of the Murraybank receiver, coupled with the effect of digital integration which raised the sensitivity to a level where the low density region between the clouds could be detected. The system was estimated to be some three times more sensitive than the Potts Hill equipment. The team ruled out the possibility that the effect was caused by overlapping clouds in the line-of-sight at different distances by observing the continuity of the general radial velocity gradient across the cloud system. Although the observations had no sign of a link between the

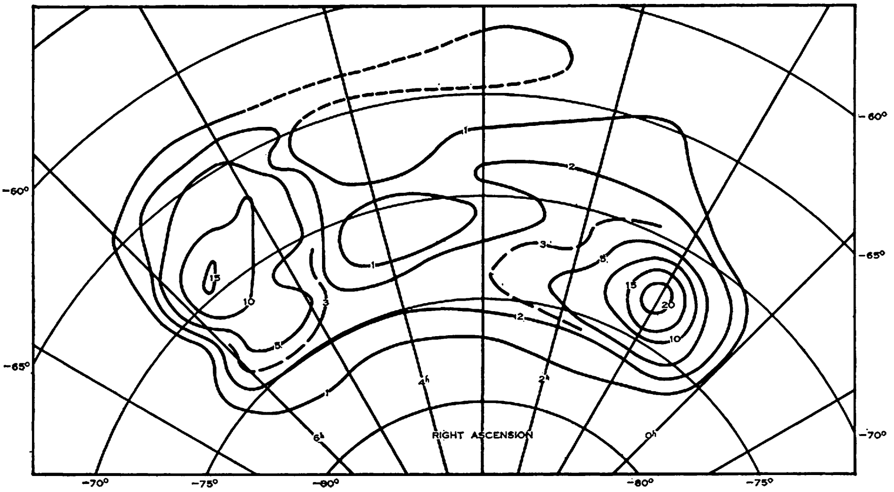

Fig. 34 The contours of integrated brightness of neutral hydrogen in the Magellanic system from the Murraybank survey. The contour units = 2×10^{-16} Wm^{-2} sr^{-1} (after Hindman et al. 1963a: 572).

Magellanic Clouds and the Galaxy, the team noted that “Such a link would, however, be quite difficult to detect, because it would probably be spread widely on the sky and in velocity, and a different observing technique would be desirable in searching for it.” (Hindman et al. 1963a: 577).

With the benefit of hindsight this statement proved insightful, with the Magellanic Stream (Figure 35) being discovered by a team, including Murray, using observations from Parkes (Mathewson et al. 1974). HI velocity anomalies near the South Galactic Pole had been noted as early as 1965 (Deiter 1965) and subsequently van Kuilenburg (1972) and Wannier and Wrixon (1972) noted a large area of HI emission, but it was Mathewson et al. (1974) who recognised its full extent and associated the stream with the Magellanic Clouds (see Figure 35). De Vaucouleurs (1954a, b) had been the first to propose a link between the Magellanic Clouds and our Galaxy some 20 years before the discovery of the Magellanic Stream. More recent studies by McClure-Griffiths et al. (2008) have shown that the leading arm of the Stream is intersecting the disk of our Galaxy approximately 21 kpc from Earth at a point in the sky near the Southern Cross.

Using Wild’s (1952) method for estimating the number of atoms in a line-of-sight column of optically thin gas, Hindman et al. came up with the values listed below in Table 3 for different parts of the Magellanic system. A comparison also was made

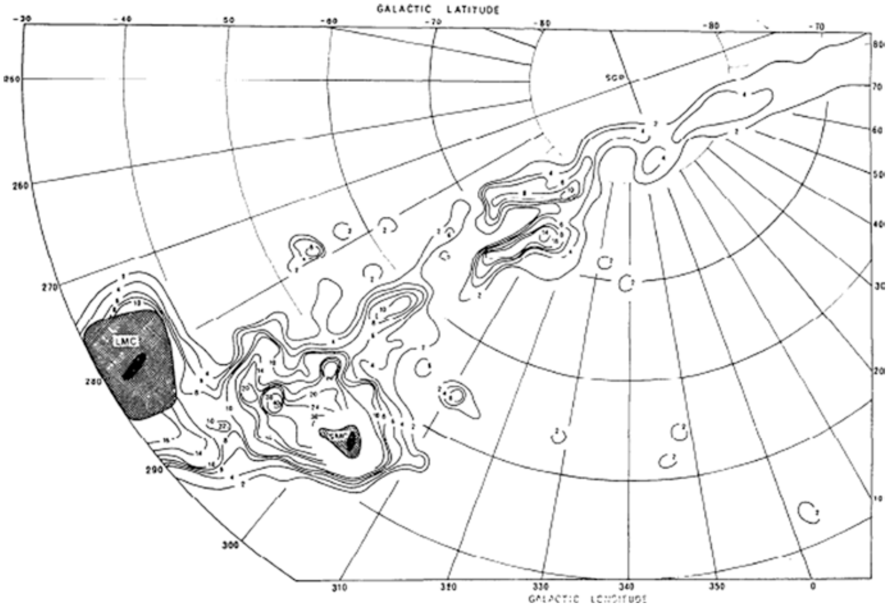

Fig. 35 Contours of surface density of neutral hydrogen from Parkes 18-m (ex-Kennedy dish). The Magellanic Stream is seen extending from the Magellanic Clouds (left) across the sky (after Mathewson et al. 1974: Plate 6).

Table 3 The estimated mass of different parts of the Magellanic system (after Hindman et al. 1963)

Region	Solar Masses
Large Cloud (inside contour 3 in Figure 34)	3.2×10^8
Small Could (inside contour 3 in Figure 34)	2.8×10^8
Whole Magellanic System	1×10^9

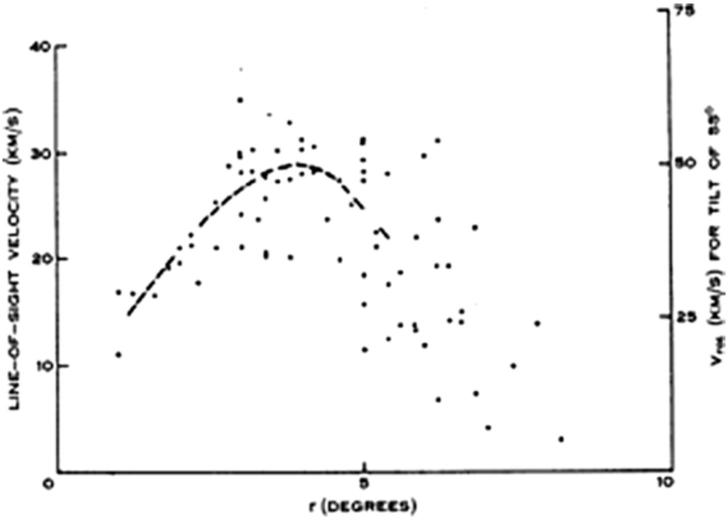

Fig. 36 The rotation curve for the Large Magellanic Cloud derived from median velocities of neutral hydrogen profiles. The centre of rotation was R.A. 05:25, Dec. –68° (1960). The position angle of major axis: 5–185°. A tilt of 55° was assumed. Note that both sides of the curve are plotted together (after Hindman et al. 1963a: 580).

between the neutral hydrogen distribution and the distribution of HII regions (Henize 1956), globular clusters (Hodge 1960, 1961), SMC clusters (Lindsay 1958) and SMC emission-line objects (Lindsay 1961), but no significant conclusion was drawn other than that all the objects tended to be concentrated in the main bodies of the two Clouds.

Based on the Murraybank observations, a rotation curve for the Large Magellanic Cloud was derived (Figure 36) which was very similar to the findings of the earlier survey by Kerr et al. (1954). No clear curve could be derived for the Small Cloud. Based upon this rotation curve the mass of the Large Magellanic Cloud was estimated to be in the range 7–10×10^9 solar masses. Note that this is a factor of ten larger than the mass derived from Wild's method and could have been

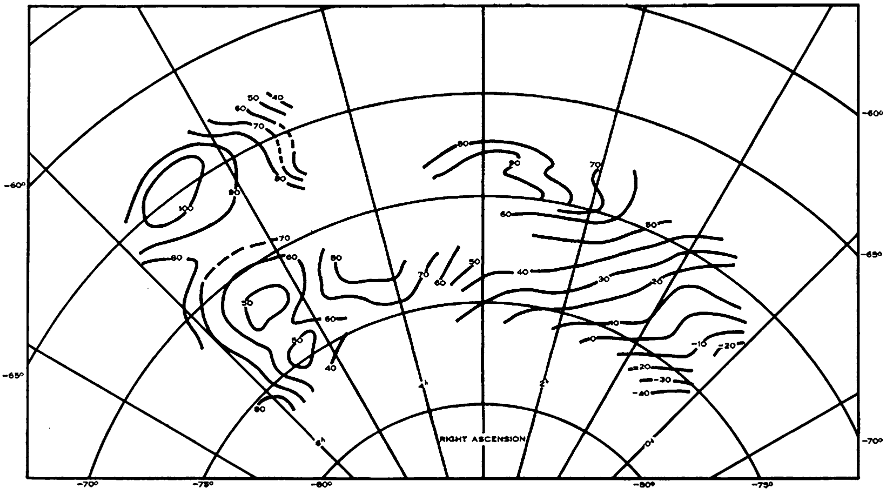

Fig. 37 The contours of median radial velocity of the Magellanic System. The contour interval is 10 km/s (after Hindman et al. 1963a: 579).

another of the early clues to the 'missing mass problem' generally identified with galaxies and examined in detail in the late 1960s (e.g. see Freeman 1970; Rubin and Ford 1970).

The second major discovery came from the radial velocity measurements of the Small Magellanic Cloud. Figure 37 shows the contours of median radial velocity of the neutral hydrogen profiles from the Magellanic System that has been corrected for both the motion of the Earth's orbit and the Sun's orbit about the Galaxy. To allow for correction due to the Sun's orbital motion, a velocity of 216 km/s was assumed. This figure was adopted in order to simplify the comparison with the earlier survey which used this value but by this time evidence was building for a much higher value (i.e. 300 km/s; see de Vaucouleurs 1961).

Figures 38 and 39 show a summary of H-line profiles for the Large and Small Magellanic Clouds respectively. The Small Cloud shows large areas where double-peaked line profiles are evident, a feature which had previously been noted by Johnson (1961) based upon an examination of the original survey data published by Kerr et al. (1954), although at the time few conclusions could be drawn due to the quality of these records.

The splitting of the H-line profiles into two distinct groups is best illustrated in Figure 40. The difference between peaks is consistently between 25 and 30 km/s over a large area. This 'splitting' of the Small Magellanic Cloud had not been observed in any other optical or radio observations before this time. Many years later the 'splitting' of the Small Cloud was seen as providing an important clue to the origin of the Magellanic Stream. Mathewson et al. (1987) found that by integrating backward in time, the Small Cloud could have collided with the Large Cloud $\sim 4 \times 10^8$

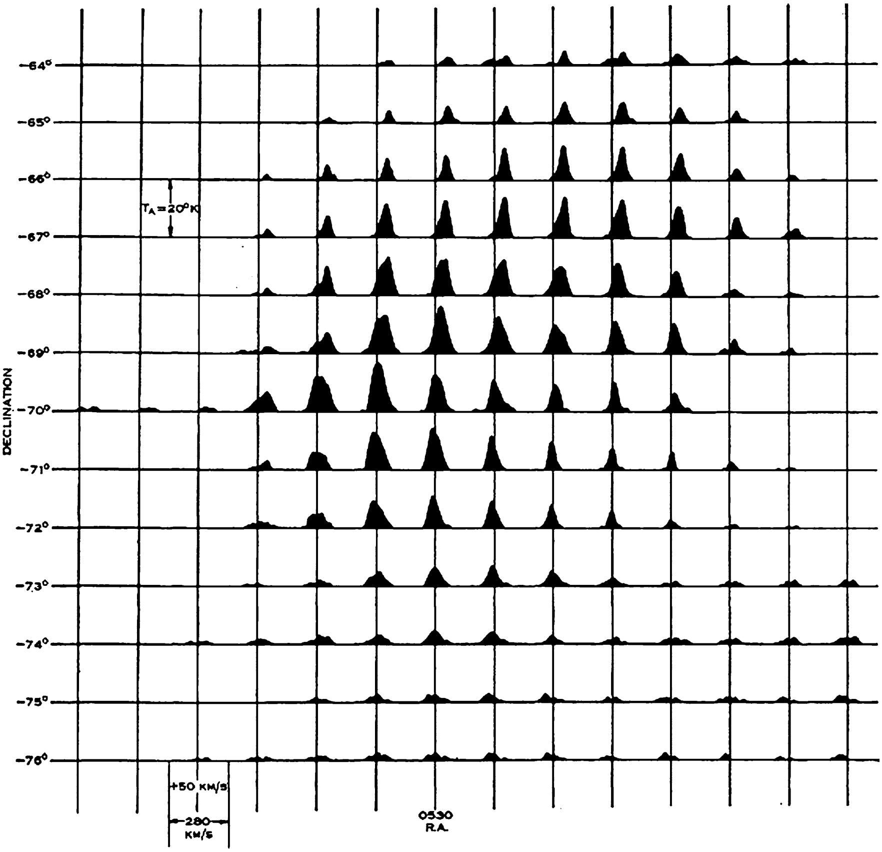

Fig. 38 Line profile per square degree of sky from the Large Magellanic Cloud. The *vertical line* on each profile is +50 km/s (after Hindman et al. 1963b: 568).

years ago. This could mean that the Stream originated from this collision and the split of the Small Cloud indicated it was breaking up following the interaction with the Large Cloud.

Over the period 1962–1964, Hindman (1967) used the 64-m Parkes telescope together with the Murraybank multi-channel receiver for a high resolution (~15" at 1,420 MHz) survey of the Small Magellanic Cloud. At this much higher resolution, Hindman concluded that the double-peaked profiles that had earlier been observed were related to at least three broad structural features which may represent expanding shells of gas within the main body of the Cloud, which itself appeared to be a flattened system, rotating in a plane observed near edge-on to the observer. This conclusion was supported some years later when data from Parkes and the Australia Telescope Compact Array were combined in a detailed study of the Small Magellanic Cloud (Stanimirovic et al. 1999).

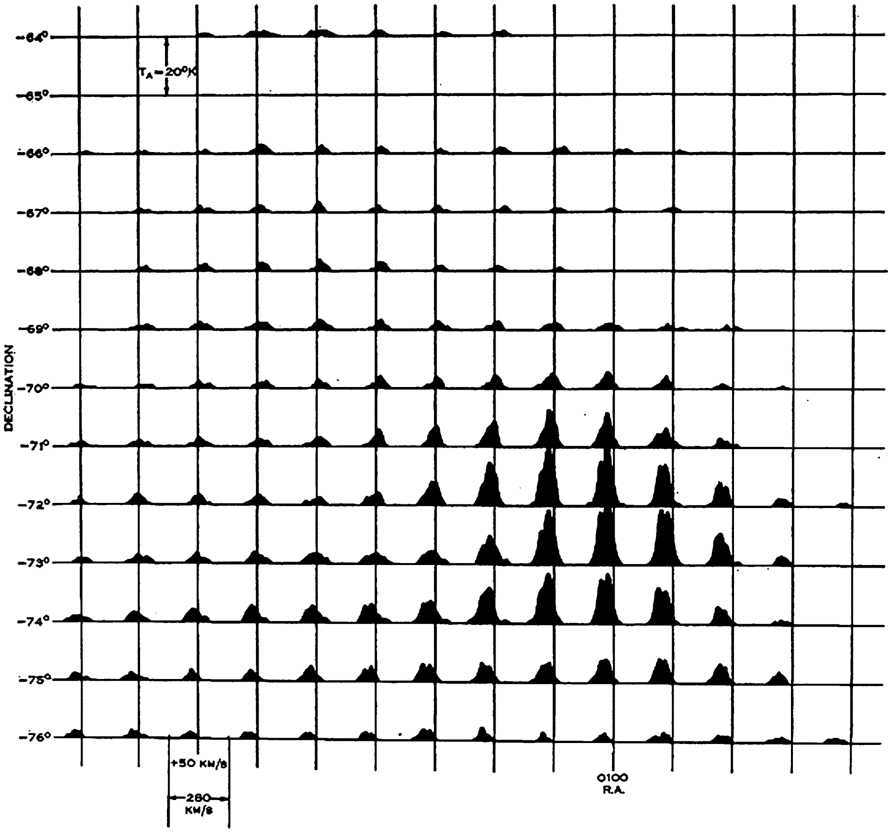

Fig. 39 Line profile per square degree of sky from the Small Magellanic Cloud. The *vertical line* on each profile is +50 km/s. Note the large area of double-peaks (after Hindman et al. 1963b: 567).

5 Concluding Remarks

With the completion of the Magellanic Clouds survey in late 1960 the Murraybank research program drew to a close. Some testing activity was carried out at Murraybank during 1961 when new feeds for the Parkes Radio Telescope were tested (Murray, pers. comm., 8 February 2008), but the field station ceased to be used for radio astronomy by the end of 1961.

Although it was only in operation for a comparatively short period, the Division of Radiophysics' Murraybank field station made important contributions to both galactic and extragalactic H-line studies. The field station continued to be used by the Radiophysics Cloud Physics group for many years and a wind tunnel was even constructed on this site. The field station was eventually closed after the land was sold to developers in the 1970s and John Murray's parents returned to Tasmania (ibid.).

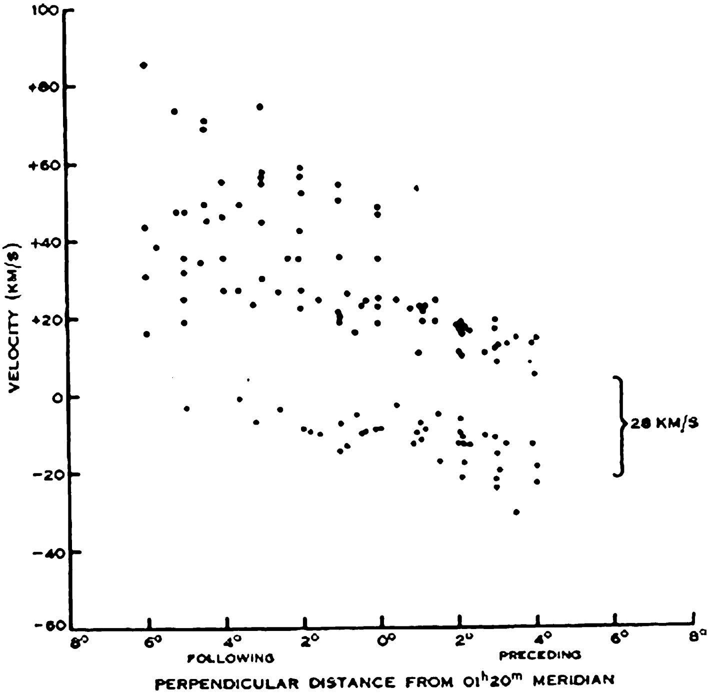

Fig. 40 Velocities of the main peaks of neutral hydrogen in the Small Magellanic Cloud showing the systematic separation into two groups separated consistently by ~28 km/s (after Hindman et al. 1963a: 581).

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The Contribution of the Division of Radiophysics Dapto Field Station to Solar Radio Astronomy, 1952–1964

Ronald Stewart, Wayne Orchiston, and Bruce Slee

Abstract By the early 1960s the Solar Group within the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics had established an international reputation for solar research, largely through the achievements of Paul Wild and his collaborators at the Division's Dapto field station south of Sydney. This paper describes the innovative instruments found at this field station, the ways in which they were used to unravel many of the mysteries surrounding different types of radio bursts from the Sun, and some of the reasons for the success of the Dapto team.

1 Introduction

By the early 1960s, the CSIRO's Division of Radiophysics in Sydney (Australia) had earned a worldwide reputation as a leader in solar radio astronomy (Orchiston and Slee 2005; Sullivan 2005). By this stage the highly-successful Dover Heights, Dapto, Potts Hill, Murraybank and Fleurs field stations had been closed as efforts concentrated on the newly-commissioned 64-m Radio Telescope at Parkes. W.N. "Chris" Christiansen, who had led investigations of the quiet Sun (see Orchiston and Mathewson 2009; Wendt et al. 2009; 2011), had left to pursue his interests at the School of Electrical Engineering at the University of Sydney. The leader of the group investigating the active Sun, Paul Wild (see Stewart et al. 2010; 2011), was soon to be the awarded the prestigious Hendryk Arctowski Gold Medal of the US National Academy of Science and the Balthasar van der Pol Gold Medal of the International Union of Radio Science for his metre wavelength studies of solar radio bursts. Radiophysics had been awarded a large grant by the Ford Foundation to cover half of the cost of constructing the world's first radioheliograph at Culgoora, in north western New South Wales.

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This paper examines the success of the Division's solar radio astronomy program carried out at the Dapto field station south of Sydney, which was set up to house an improved radiospectrograph following the successful operation of the world's first radiospectrograph at the Division's Penrith field station on the outskirts of Sydney in 1949 (Wild and McCready 1950). This latter instrument recorded the intensity of solar radio bursts over the frequency range 70–130 MHz and led to the first spectral classification of solar bursts. Recently its development was described by Stewart et al. (2010).

The new spectrograph at Dapto had an expanded frequency range, from 40 to 240 MHz, with the capability of measuring burst polarization as well as intensity. It soon led to the important discovery of fundamental and second harmonic structure in Type II and Type III bursts (Wild et al. 1954a, b). This observation gave credence to the "plasma hypothesis" of Wild (1950a), which assumed that the radio emission was generated at the local plasma level in the solar corona, and led to the discovery of fast particle streams and shock wave disturbances moving outwards through the corona.

The "plasma hypothesis" was finally confirmed with the construction at Dapto of a swept-frequency interferometer, the first of its kind in the world, which operated over the 40–70 MHz frequency range (Wild et al. 1959a, b).

This paper examines the development of these instruments at Dapto (Sheridan 1963) and the discoveries which were made, as well as placing the research in an international context.[1] A more detailed account of the contribution that this field station made to international solar radio astronomy can be found in Stewart (2009).

2 Development of the Dapto Radiospectrograph

The idea of a radio spectrum analyser operating over the 40–240 MHz range was first mentioned in a letter that Lindsay McCready wrote to Joe Pawsey in December 1947. At the time McCready was head of the Division's Receiver Group, while Pawsey was the charismatic leader of the Division's over-all radio astronomy program. At the time Pawsey was on a visit to England and McCready (1947) provided the following information in order to keep him appraised of developments back in Sydney:

> The spectrum analyser is proceeding slowly. It is impossible for me to do much or rather have any continuity. Always some interruption. Nevertheless there is progress. Rhombics & their mounts are in the shop & satisfactory experimental results obtained with a 200–600

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[1] All three authors of this paper were very familiar with the developments that occurred at Dapto during the life of this field station. Stewart and Orchiston were members of the CSIRO's Division of Radiophysics Solar Group from 1965 to 1988 and 1962 to 1968, respectively, and worked on Dapto projects. Slee joined the Division of Radiophysics in 1946 and subsequently transferred to the Australia Telescope National Facility and later the Division of Astronomy and Space Sciences when these groups were formed in 1988 and 2009, respectively. Today he continues to conduct research as an Honorary Fellow of the latter group. Whilst never a member of the Solar Group, he maintained an interest in the work of this group and published a number of papers on the nature of the outer corona.

> Mc/s Rhombic (SWR > 2/1 over the range). The required 70–140 aerial will give no troubles. Work now proceeding on the receiver. Wild is a good man & good balance between theory & experiment but inclined to be too much of a perfectionist in the matter of detail.

In his next letter to Pawsey, written early 1948, McCready (1948a) provided a further progress report:

> My own job is progressing slowly but I am unable to spend much time on it. It will be different when Chris [Christiansen] finds his feet and you return. Rhombic is under construction and the motor tuned R.F. unit (MkI) is almost ready. The remainder of the show is straight forward & the new chap Murray is very useful and appears to be able to handle it, in good engineering fashion at any rate. My eventual aim is to have two analysers covering 1. 50–200 Mc/s and 2. 200–600 Mc/s. I think it can be done with good butterfly type tuned circuits and attention to engineering details. Owing to the sunspot max now almost past and the difficulty of polar axis mounting of large rhombics I think it would be risky impairing receiver sensitivity by taking the easy course of omitting an r.f. stage (on the 20–200 Mc/s range at any rate). Should you come across any suitable butterfly type condensers over there we could use them. Even drawings would save time. Such things will have to be made in our own workshop. At the moment we are using a semi-butterfly [unreadable word] type pinched from some P58 English Search receivers (B.T.H) and only attempting to cover 70–140 Mc/s …

Further information is provided in a letter McCready (1948b) wrote Pawsey on 6 June 1948 (his underlining):

> As far as the spectrum analyser is concerned I am sorry I did not express myself clearly in my last. I was originally interested in extending the range as a long term project if the position warranted it later & thought it could be done very quickly later on. [some unreadable lines] … getting respectable coverage above 100 Mc/s. We are pushing ahead with the simple scheme & have a r.f. unit now covering 80–130 Mc/s with almost the theoretical noise factor over the range. The rhombic is nearly out of the shop & most of the display ancillary development is completed, but still a bit to be done on the recording & calibration techniques. F.M. is becoming a curse & we must choose a site that does not merely tell us what F.M. stations are on the air around Sydney …

FM interference had become a problem at the Radiophysics field stations near Sydney so Wild went in search of a more suitable site. One of those who accompanied him on the trip was Gordon Stanley, who had been working on discrete sources with John Bolton and Bruce Slee at the Division's Dover Heights field station (see Kellermann et al. 2005). Many years later Stanley (1994:511) wrote about this field trip:

> Paul Wild invited me to join him on a trip down the south coast of New South Wales in September 1950, as he was looking for a new site for a solar telescope … We borrowed an old ambulance from the military and Paul, John Murray, Steve Smerd and I, as the only driver set off on our missions. The trip is an epic story in itself and full of the unexpected problems peculiar to neglected army vehicles. Following a major breakdown, Paul and Steve left us at Berry whilst John Murray and I travelled down the coast, close to the Victorian border. I chose a site at Jervis Bay and although it was never used, the idea of the interferometer was the genesis of the one built at Owens Valley in California.

The most significant outcome of this field trip was that Wild found an ideal site for a new solar field station. It was on a dairy farm at Dapto, near Wollongong, which was readily accessible from Sydney by train. But more importantly, the site was protected from Sydney's radio interference by nearby Mt Kembla.

On 11 June 1951 the *Wollongong Times* newspaper reported under the title "RADAR EXPERIMENTAL STATION AT DAPTO WEST":

> Part of the land at West Dapto which Council proposed to resume for a sanitary depot had been acquired for use for radar experiments, Ald. H.A Graham told Greater Wollongong Council last Wednesday night.

The article went on to include earlier questions from councillors such as:

> Is council aware that the Commonwealth Scientific and Industrial Research organization has resumed 80 acres in that area and is going ahead with further development of the land in connection with radar research?
>
> Is Council aware that this land was once used as a piggery and that the Health Department served notices on the owner that it had to be closed owing to contamination of the creeks running into Lake Illawarra?

Thus the birth of the Dapto field station began in a less than salubrious fashion.

Planning for the new spectrograph had began as early as 1950 (Murray pers. comm. 2007). In the minutes of the Radiophysics Radio Astronomy Committee on 27 July 1950 Christiansen (1950) recorded:

> Mr.Wild. The new model spectrum analyser (35–240 Mc/s) is under construction. Four papers have been written on solar spectroscopy in the range 70–130 Mc/s. Two papers have been accepted by the Aust. J. Sci. Res. and a third has been sent off. Some particular conclusions of these papers are:
>
> 1. The spectrum of flare-accompanying "outbursts" supports the hypothesis of an outward-moving disturbance in the solar atmosphere.
> 2. The frequency drift observed in some of the short duration "isolated bursts" cannot be explained solely on the basis of group retardation from a fixed transient disturbance, but may be due to an outward-moving disturbance (~3×10^4 km/s).
> 3. The background continuum, present during noise storms may be explained in terms of the resultant of a large number of "storm bursts" if a plausible amplitude distribution is secured.

2.1 The Principle of the Dapto Radiospectrograph

The Dapto Radiospectrograph was an improved engineered version of the Penrith spectrograph (see Stewart et al. 2010; 2011) and consisted of three swept-frequency receivers and wideband rhombic aerials (Figure 1) rather than one.

The wooden aerials (Figure 2), designed by Paul Wild and constructed by the Divisional engineer, Keith MacAlister, were crossed rhombics, thereby permitting polarization studies (described later), and were on equatorial mounts and motor-driven to allow remote tracking of the Sun.

The receivers, designed and built by Bill Rowe and John Murray, were tuned by ganged butterfly capacitors which were motor driven to produce a swept-frequency spectrum twice per second. A photograph of the condensers is reproduced in Figure 3. These condensers are reminiscent of the tuning condensers used in early wireless sets and were modelled on those used in WWII P78 radar spectrum analysers (see reference to butterfly condensers in the second letter from McCready to Pawsey mentioned above).

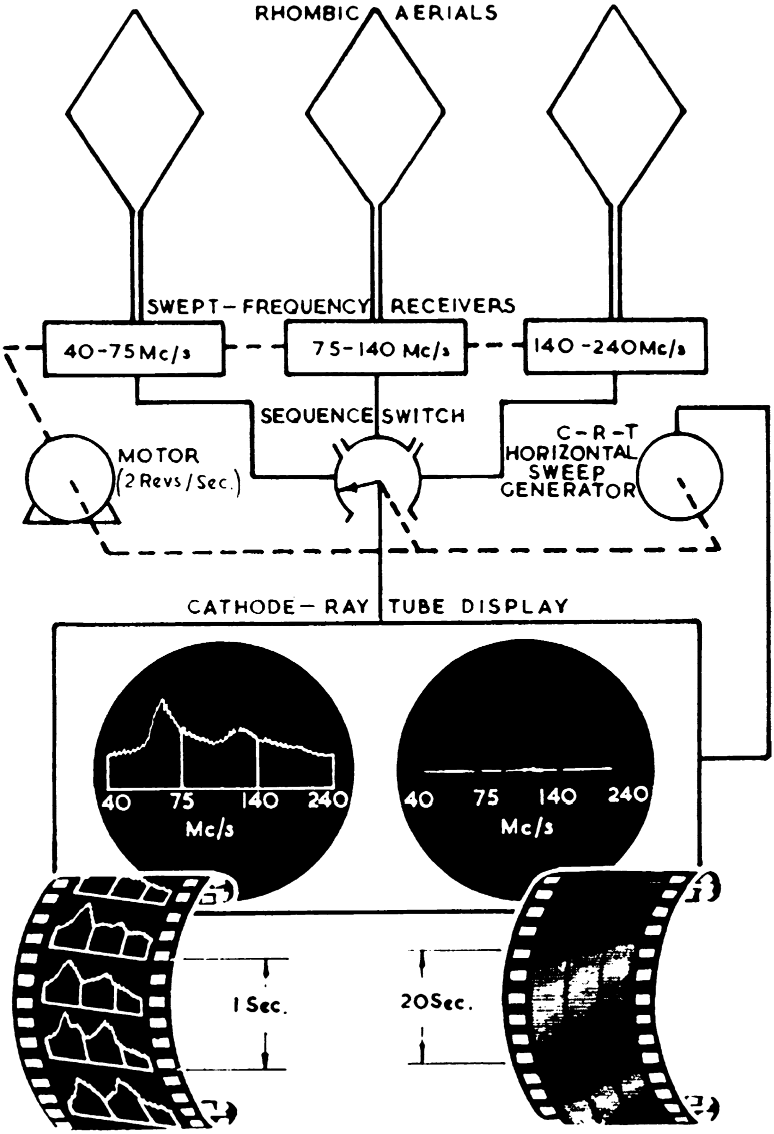

Fig. 1 Block diagram of the three aerials and receivers of the Dapto Radiospectrograph, excluding polarization arrangements (after Wild, Murray and Rowe 1954: 441).

The photographic display (see Figure 1) was of two kinds: an A-scan display of intensity-versus-frequency as used in the original Penrith Radiospectrograph, and an intensity-modulated display of frequency-versus-time, known as a dynamic spectrum. The display system (Figure 4) was designed by Murray.

Fig. 2 Photograph of the three Dapto crossed rhombic aerials on their mounting towers, with the receiver hut in the background (courtesy: ATNF Historic Photographic Archive).

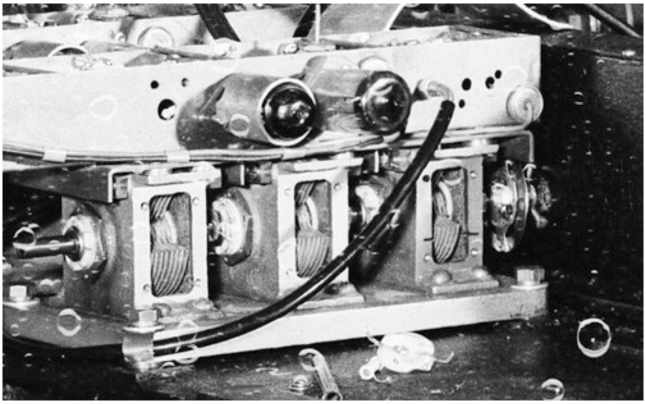

Fig. 3 Photograph showing one set of the three tuning condensers in each spectrograph receiver, connected to a common motor-driven shaft (courtesy: ATNF Historic Photographic Archive).

2.2 Initial Results: 1952–1953

The initial results were spectacular. The wider frequency coverage led to the discovery of both fundamental and second harmonic structure in Type II and Type III bursts. The original dynamic spectra are reproduced in Figure 5.

Murray (pers. comm., 2007) recalls that he was the one on duty when the first harmonic Type II burst was recorded. He was of the opinion that earlier records from Penrith may have contained evidence of harmonic structure but were missed because of the restricted frequency range of the earlier instrument. This is more than likely to be true as the dynamic spectra of one of the earlier Type II bursts analysed by Wild (1950a) and reproduced here in Figure 6 shows what is probably a low

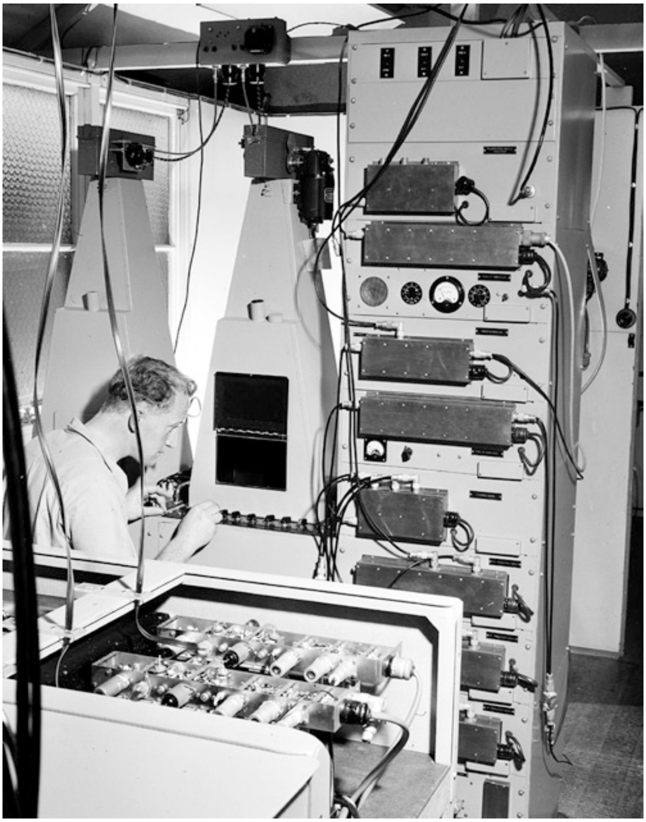

Fig. 4 Photograph of John Murray adjusting one of the two display units of the Dapto Radio-spectrograph, with the receivers in the foreground unit and mounted on the panel to Murray's right (courtesy: ATNF Historic Photographic Archive).

frequency edge of a second harmonic band. (Note that time runs from right to left and frequency increases from top to bottom in these figures).

The most likely explanation for the harmonic structure was that the radio emission was generated at both the fundamental and second harmonic plasma frequencies which lent support to the "plasma hypothesis" previously used by Wild (1950a, b) to convert the frequency drifts of the Type II and Type III bursts into height-time plots, derived by converting plasma frequency to height using a standard electron density model for the corona.

Emission at the fundamental plasma frequency, f_0, occurs when the refractive index is zero. The refractive index of the solar corona, in the absence of a magnetic field, is given by the Lorentz formula:

$$\mu^2 = 1 - Ne^2/\pi m f^2 \tag{1}$$

where N is the electron density and m is the electron mass. Substituting $\mu=0$ gives

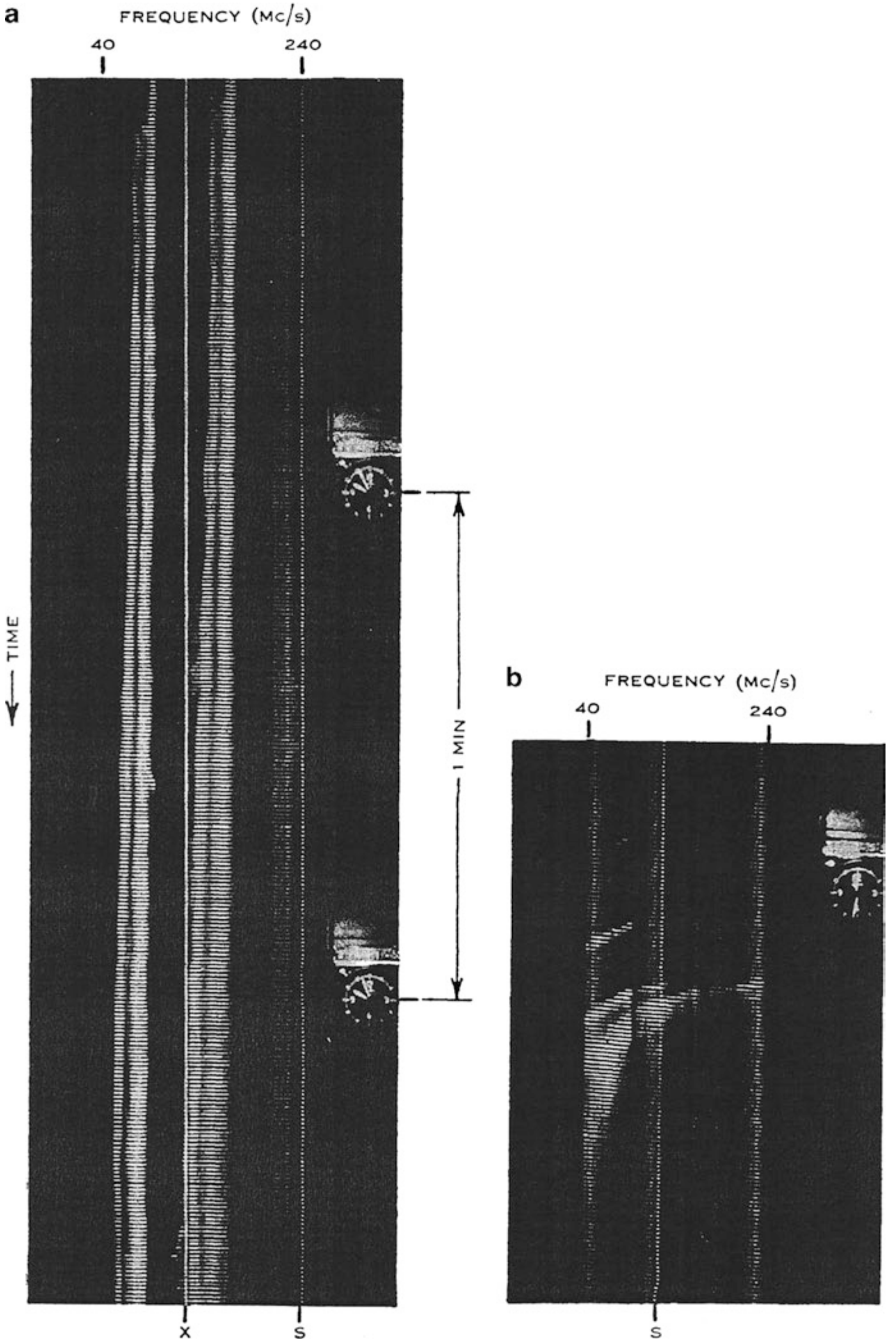

Fig. 5 (**a**) Intensity-modulated record of the first identified fundamental and second harmonic Type II burst recorded on 21 November 1952 at 2350 UT (**b**) Harmonic Type III burst recorded on 5 June 1953 at 0132 UT (after Wild, Murray and Rowe 1954: Plate 1).

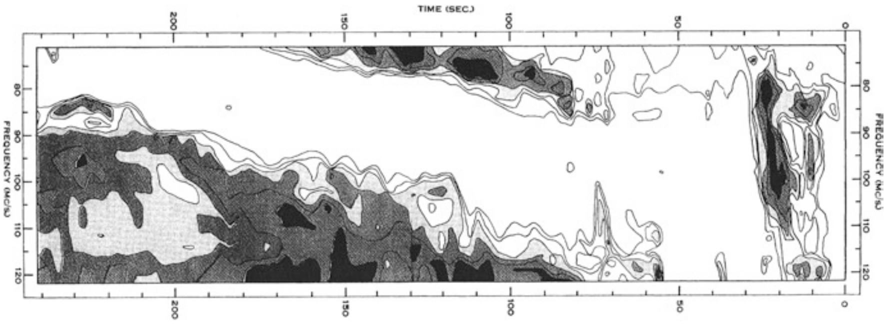

Fig. 6 Dynamic spectrum of the Type II burst of 14 February 1949 (after Wild 1950a: Plate 2B).

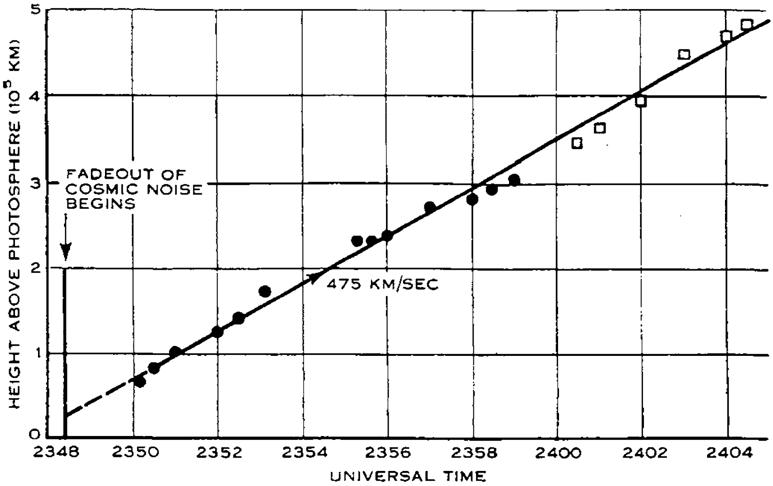

Fig. 7 Derived height plot for the outburst of 21 November 1952. Where possible the heights are derived from the fundamental frequency band (*dots*). The range is extended to greater heights by using half the frequency of the second harmonic (*squares*) (after Wild, Murray and Rowe 1954: 456).

$$f_0 = (e^2 N / \pi m)^{1/2} = 9 \times 10^{-2} N_{(cm^{-3})}{}^{1/2}\ \text{MHz} \tag{2}$$

where *e* and *m* are the electronic charge and mass (*e.s.u.*).

The recording of a second harmonic meant that the plots could now be extended to greater heights. An example is shown in Figure 7.

Wild et al. (1954a, b) discussed several mechanisms which could explain this phenomenon, including a disturbance of some kind which gives rise to the combination of a fast corpuscular ejection and a shock wave. It is noteworthy that the typical slow (Type II) velocity is of the order of the mean speed of thermal protons in the corona, which may be identified with the velocity of sound. This was the first time

Fig. 8 Paul Wild (*right*), F. Graham Smith (*centre*) and Harry Minnett (*left*) visiting Dapto during the 1952 URSI Congress (courtesy: ATNF Historic Photographic Archive).

a shock wave origin for Type II bursts was considered. Later it was shown by Uchida (1960) and others that the shock wave was not a gas-shock but more likely a magneto-hydrodynamic disturbance (m.h.d. shock).

It was at this time – when the Dapto field station was producing its first significant scientific results – that it received an impressive assemblage of international visitors. This was in connection with the congress of URSI, which was held in Sydney in 1952 (see Robinson 2002), and because of its emerging role in solar radio astronomy Dapto was one of those field stations selected by the organisers for a field strip (see Figure 8).

3 Radio Scintillation Studies, 1952–1954

On 17 April 1953 Wild submitted a report to Pawsey, McCready and E.G. ("Taffy") Bowen (Chief of the Division of Radiophysics) titled "Investigation of Cygnus Fluctuations at Dapto" in which he wrote:

> Although the main long-term programme of work at Dapto is concerned with the sun, it has seemed desirable to find a supplementary line of research to enable the equipment to be put to maximum use during the sunspot minimum. With this in view, exploratory observations of the spectrum of Cygnus fluctuations in the frequency range 40–70 Mc/s have been carried out since September 1952. These observations and conclusions are summarised below:
>
> Records show intense ridges.
>
> Records apparently show interference patterns.
>
> During the approaching winter period in which Cygnus fluctuations reach a maximum (say June to August inclusive), it is proposed to carry out an intensive programme of observations. Subsequently observations may be continued, but at less pressure, to January 1954 so as to include the summer maximum. It may then be appropriate to wind up the investigation completely.

Wild and Roberts (1956a: 56) showed that the introduction of spectral records led to a remarkable simplification in the interpretation of scintillations, which previously had been made at discrete frequencies only, and noted that:

> The complete specification of a diffraction pattern on the ground requires measurement of both intensity and phase as functions of frequency and position on the ground. With these considerations in view, apparatus was built to record radio-star scintillations simultaneously in the following three ways:
>
> 1. The recording of intensity at one point as a function of time and frequency, using a 40–70 Mc/s spectroscope.
> 2. The recording of the phase gradient along one direction as a function of time and frequency, using a 40–70 Mc/s "swept-frequency interferometer."
> 3. The recording of intensity at a fixed frequency (45 Mc/s) as a function of time at three points on the ground, arranged at the corners of an approximate equilateral triangle.

3.1 Principles of the Three Instruments

The three instruments installed at Dapto are illustrated in Figure 9. Murray and Rowe were involved with the instrumental development and installation while Roberts, Jack Joisce, Max Komesaroff and Govind Swarup (during a visit from India) assisted with the observations.

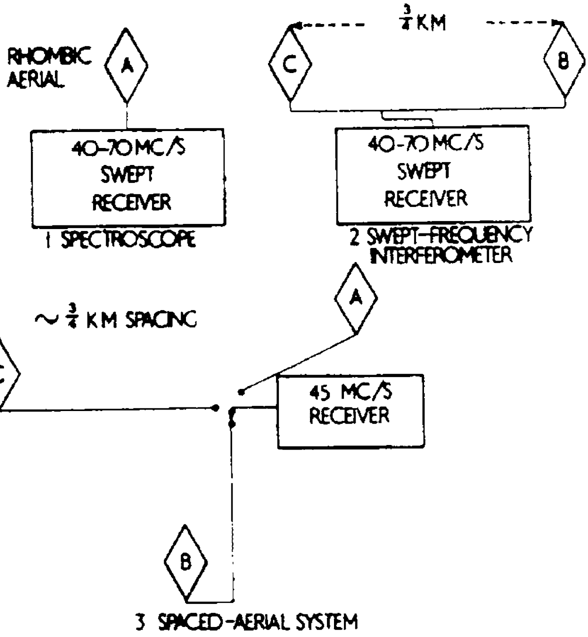

Fig. 9 Principles of the three instruments used for observing radio-star scintillations (after Wild and Roberts 1956a: Figure 1).

3.1.1 The Modified Spectroscope

The spectroscope consisted of a broad-band aerial connected to a tuneable receiver which was part of the original Dapto Radiospectrograph receiver described above. The aerial (as well as the other two aerials mentioned below) was a fixed horizontal rhombic arranged for maximum acceptance from the north with dimensions as follows:

Length of each side .... 31.1 m
Angle between wires at side corners........... 148°
Height from ground............................. 4.2 m

3.1.2 The Experimental Swept-Frequency Interferometer

This was the first time a swept-frequency interferometer was used in radio astronomy. It was highly experimental and led to the development of the first working swept-frequency interferometer installed at Dapto in 1957 (Wild and Sheridan 1958), which is discussed below in Section 6.

The two rhombic aerials (A and B in Figure 9) were located ¾ km apart on a baseline 118.5° E of N (i.e. approximately east–west) and connected to the 40–70 MHz spectrograph receiver by 700-ohm transmission line. The aerial spacing was such that the angular separation of adjacent lobes was 33′ at 40 MHz and 19′ at 70 MHz allowing angular deviations of about one-fifth of a lobe-width to be recognized, giving a positional accuracy of about 4′ at 70 MHz. By varying the length of each aerial path the source could be observed in higher-order fringes near transit. Sudden changes in source position could then be seen as kinks in the lines of maximum intensity in the interference pattern.

An important advantage of using a swept-frequency interferometer rather than a single frequency one was that directional data could be obtained at a number of frequencies simultaneously. By using higher order fringes sudden movements in the source pattern could be observed across the 40–70 MHz frequency band.

Despite the novelty of this interferometer the results were never published, probably due to the difficulty of reliable phase calibration (Roberts, pers. comm. 2007).

3.1.3 The Spaced-Aerial System

For measuring the scale size and movement of the diffraction pattern on the ground, the intensity was recorded almost simultaneously at three corner points of an equilateral triangle with sides of ¾ km. The three aerials (A, B and C in Figure 9) were connected to a 40–70 MHz swept-frequency receiver by long lengths of open wire and the resulting signals displayed on a common cathode-ray tube once per second.

At first the whole spectrum at A, B and C was recorded but because similar features showed time-delays that were independent of frequency it was decided to record only at 45 MHz.

3.1.4 Combined Operation of the Three Instruments

To accommodate these additions modifications were made to the motor and gearbox driving the tuning condensers of the 40–70 MHz receiver and to the two displays of the Dapto spectrograph (Murray, pers. comm., 2007). The sequence of switching for the aerial signals to the receiver was as follows:

1. 0 to ⅛ second – Aerials B and C in to form an interferometer.
2. ⅛ to ¼ second – Aerial A only.
3. ½ to ⅝ second – Aerial B only.
4. ⅝ to ¾ second – Aerial C only.

4 Results

Dynamic spectra of ridge patterns in scintillation records are shown in Figure 10. According to Wild and Roberts (1956a: 61):

> It was found that the three spectra (recorded simultaneously at each of the three spaced aerials) were normally similar, the systematic time delays between the same frequency at different positions being independent of frequency. Evidently the frequencies are dispersed across the ground in the nature of a rainbow, and the whole pattern drifts coherently past the aerials. The phenomenon is attributed to dispersion by horizontal gradients of electron content in the ionosphere which act like huge prisms.

Sometimes the ridge patterns showed interference effects as well as dispersion, as illustrated by the idealised sketch of the ribbed interference pattern in the fourth panel in Figure 11.

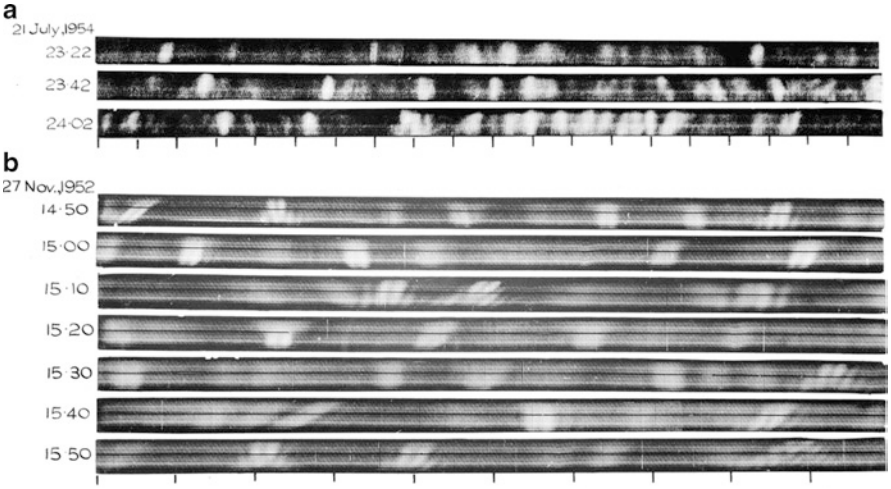

Fig. 10 Dynamic spectra of ridge-type scintillations (**a**) recorded on 21 July 1954 is typical of night time (winter) records and (**b**) recorded on 27 November 1952 day time (summer), many of the ridges are seen to show an internal fine structure; frequency increases vertically from 40 to 70 MHz, time horizontally (courtesy: ATNF Historic Photographic Archives, B3607-5).

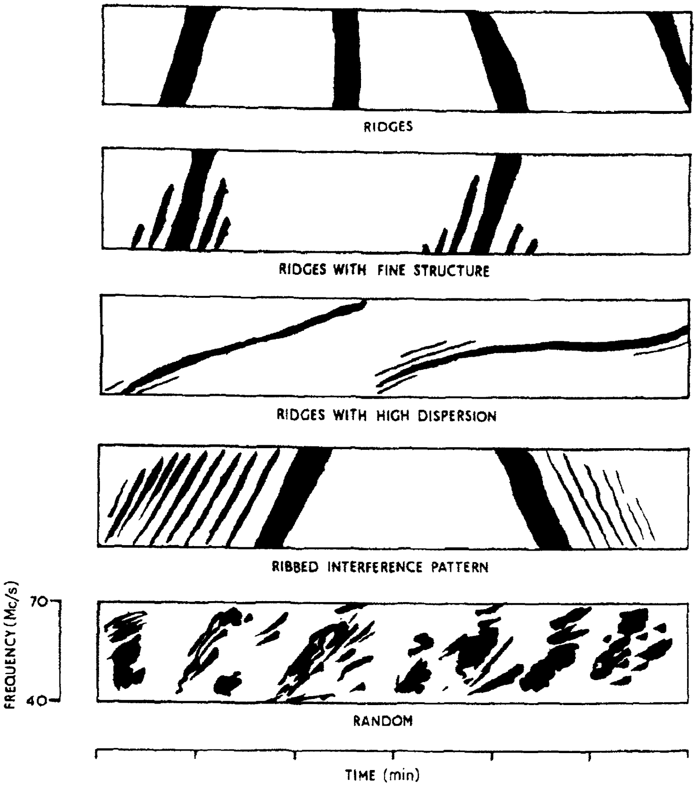

Fig. 11 Idealized sketches of dynamic spectra (after Wild and Roberts 1956a: 60).

Again, according to Wild and Roberts (1956a: 62),

> Ribbed patterns are believed to arise when rays pass through a region of the ionosphere in which the large-scale horizontal gradient of ionization changes abruptly. Rays passing through the two gradients are bent towards each other and interfere. An optical analogy may be found in the Fresnel biprism.

Wild and Roberts (1956a: 72) summarized their findings as follows:

1. Observations of dynamic spectra indicate that the commonest type of fluctuation is produced by the focusing effect of a single ionospheric irregularity.
2. The "focused" pattern is often dispersed across the ground like a rainbow. This effect is attributed to large-scale gradients in the ionosphere.
3. The pattern on the ground is usually highly elongated.
4. The degree of fluctuation shows a marked diurnal or annual variation, exhibiting maxima near midnight (winter observations) and midday (summer observations).

Mills and Thomas (1951) observed Cygnus A at an elevation of 15° and found a correlation between scintillations and spread F echoes whilst Bolton et al. (1953) observed other sources at an elevation of 10° and found a correlation with sporadic

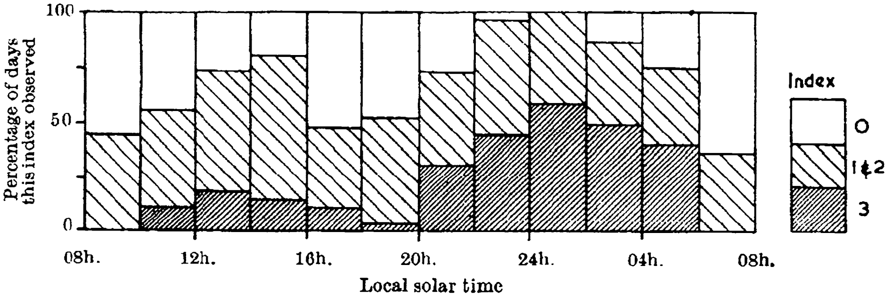

Fig. 12 Solar time variation of the fluctuation index. Observations were made on 227 days during September 1952–February 1955 (Wild and Roberts 1956b: 378).

E only. In a second paper, Wild and Roberts (1956b) resolved this discrepancy by showing that scintillations from Cygnus A observed during the night correlated with spread F but daytime observations correlated with sporadic E (Figure 12).

In reminiscences of his time at Dapto, Roberts (pers. comm., 2007) says that Wild asked him to write another paper on Cygnus A where the swept-frequency interferometer records would be discussed, along with a mathematical model to explain the observed ridge pattern. He wrote:

> I was to produce Paper II, reporting and discussing the interferometer results, and presenting Paul's theoretical calculations. Other matters intervened and the paper was never completed. As a result neither Paul's calculations of the focusing by a density wave, nor the interference results were ever published. Perhaps this has contributed to the fact that what I believe to be important conclusions from these observations never seem to have been accepted by some of the other workers in this field.

5 The Swept-Frequency Polarimeter, 1953–1955

The polarization measurements were conducted by Komesaroff using the Dapto Radiospectrograph mainly from January to October 1955 near the start of the new solar cycle. According to Murray (pers. comm., 2007), the polarization equipment was available from 1953 but the absence of burst activity prevented any study occurring earlier. Observations included bursts of Types I, II and III.

5.1 Principle of the Dapto Polarimeter

Komesaroff (1958: 202) wrote:

> The method of polarization measurement is a variant on the crossed-aerial technique, adapted to a swept-frequency instrument … Each of the three pairs of rhombic aerials has a corresponding receiver and the individual aerials of each pair were connected to the common receiver by twin-wire transmission lines of different lengths [as shown in

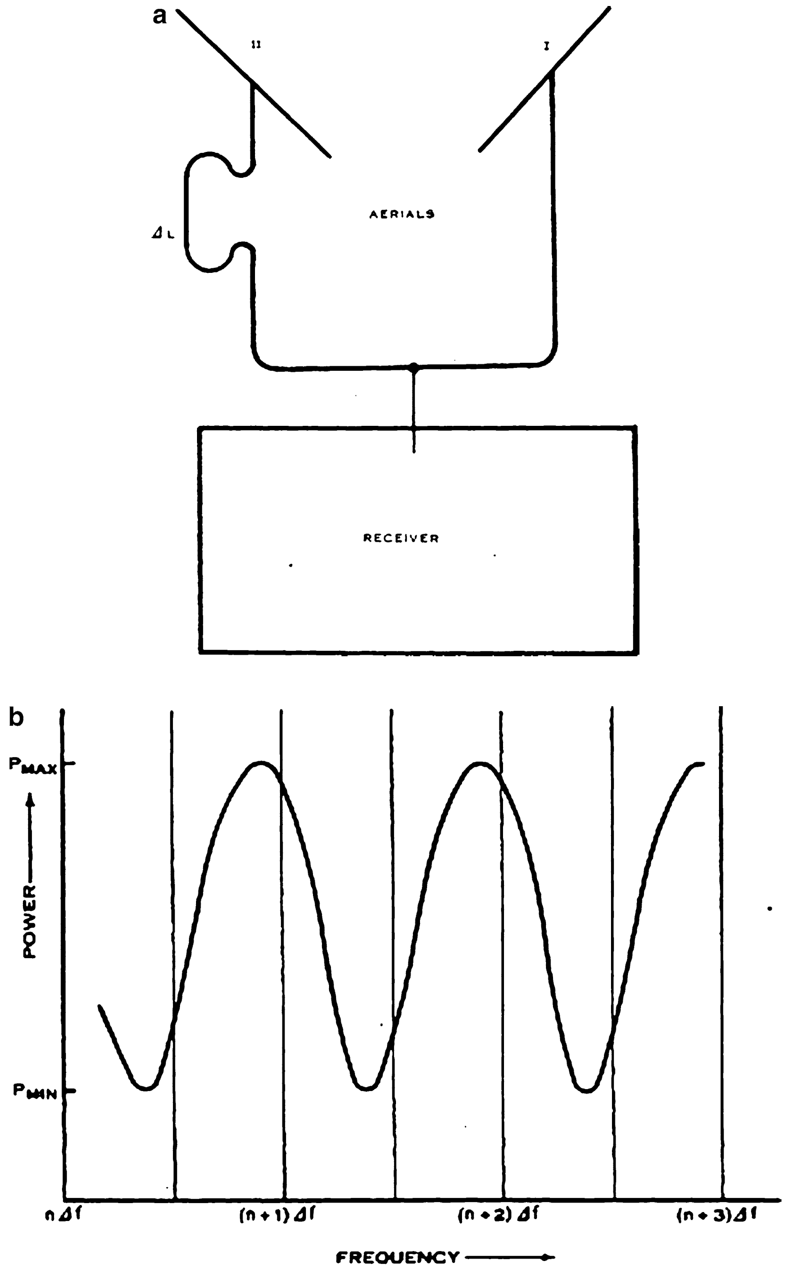

Fig. 13 (**a**) Block diagram of the Dapto Swept-frequency Polarimeter. One unit of this type was used for each of the three frequency ranges of the Dapto Radiospectrograph (after Komesaroff 1958: 202). (**b**) Schematic representation of a record of polarized radiation having a flat spectrum (after Komesaroff 1958: 204).

> Figure 13a]. If ΔL is the difference in line length, the system accepts one circularly polarized component when the receiver is tuned to a wavelength λ such that $\Delta L = (2n \pm 1/4)\,\lambda$, where n is an integer, the sign being determined by the sense of rotation of the electric vector. As the receiver tuning is varied the output goes through a series of maxima and minima [as shown in Figure 13b].

The following equations apply:

$$\Delta L = (2n \pm \tfrac{1}{4})\lambda \tag{3}$$

phase angle of the polarization ellipse

$$\theta = 2\pi(n - f_n / \Delta f) \tag{4}$$

and

$$\Delta f = c / \Delta L \tag{5}$$

where c is the velocity of light. For LH circular polarization $\theta = \pi/2$ and for RH polarization $\theta = 3\pi/2$.

The degree of circular polarization

$$\%circ = 100(P_{max} - P_{min}) / (P_{max} + P_{min}) \tag{6}$$

is given by the modulation pattern of the power spectrum where P_{max} and P_{min} are indicated in Figure 13b.

6 Results

Altogether, 13 days of Type I activity were studied and it was found, in agreement with earlier investigations, that the radiation was highly circularly polarized (>50%) at all frequencies and usually showed the same sense of polarization throughout the frequency range and during any one day. Examples of the modulation pattern of polarization in the spectra of Type I noise storms are shown in Figure 14.

Polarization measurements were obtained for thirteen Type II bursts. Eight of these were completely unpolarized, three showed weak modulation and two were indeterminate because of their narrow bandwidth. Only one record was polarized for a short period but the modulation at maximum was not greater than 30%.

Over 500 Type III bursts were observed and about 50% of these showed the modulation pattern of fairly strong circular polarization. Examples of the spectral records of polarized and unpolarized Type III bursts are shown in Figure 15.

Komesaroff noted that Type III bursts previously were thought to be always unpolarized (Payne-Scott 1949). However, this misconception was mainly due to terminology as Payne-Scott had labelled all short duration bursts as noise storm

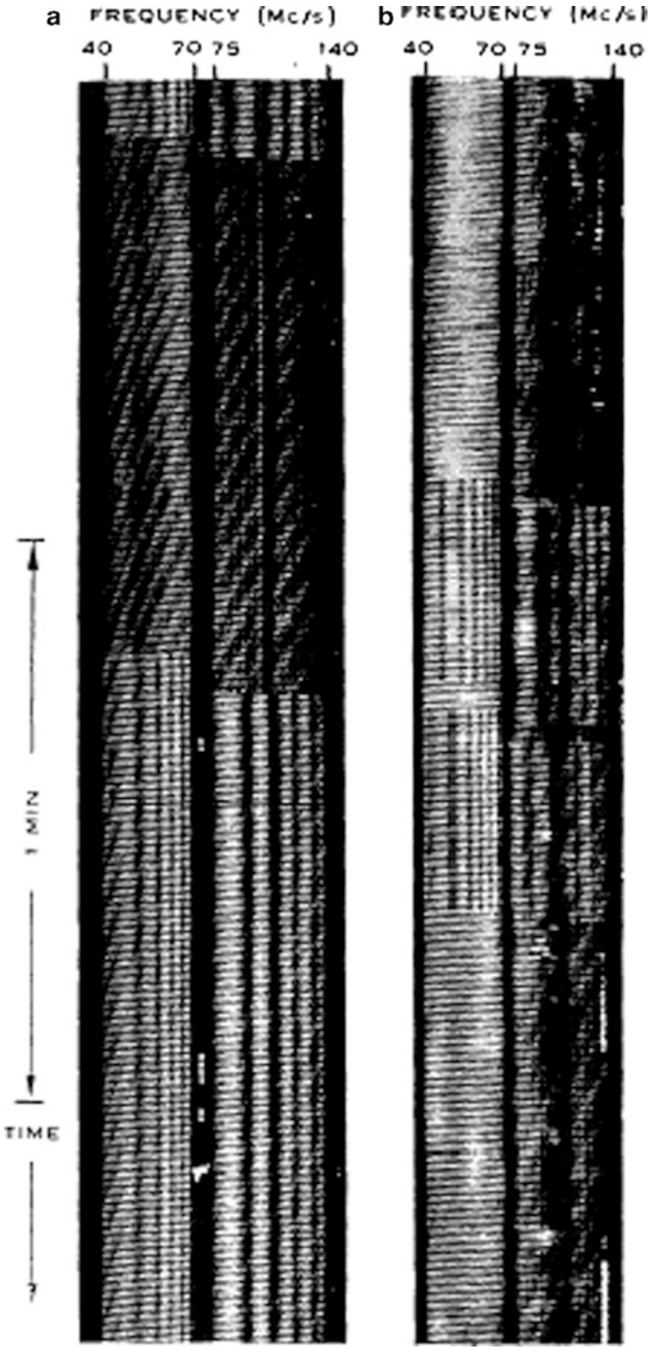

Fig. 14 Single records of strongly polarized Type I radiation. The bright streaks parallel with the time axis are the maxima of the modulation pattern. Unpolarized sections obtained with single aerials are included. The faint sloping lines on the records are due to power lines producing a 50 Hz modulation (after Komesaroff 1958: Plate 1).

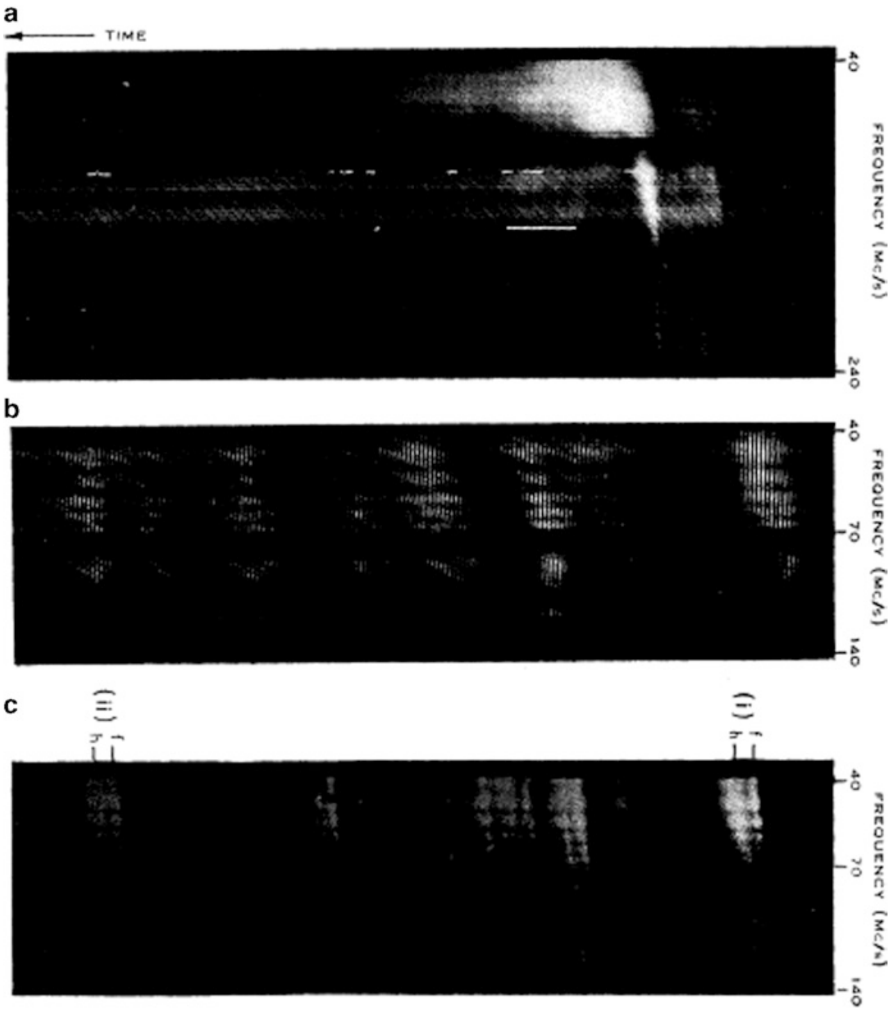

Fig. 15 (**a**) Record of an unpolarized Type III burst observed on 15 August 1955 at 0155 U.T. (**b**) Polarized Type III bursts on 12 January 1955 at 0749 U.T. (**c**) Cluster of polarized Type III bursts observed on 9 June 1955 between 0246 and 0250 U.T. (after Komesaroff 1958: Plate 2).

(Type I) bursts. However, a closer examination of a number of those bursts occurring almost simultaneously at 85 and 60 MHz (which were clearly Type III bursts) were found to be polarized (see Table 2 in Komesaroff 1958).

Despite the difficulties incurred with this type of measurement, Komesaroff's conclusions were essentially correct and vindicated when Rao (1965) found examples of strong circular polarization in some Type III bursts using the 40–70 MHz swept-frequency interferometer. Even the observation of weak polarization in several Type II bursts might have been a real effect caused by the undetected presence of herring-bone structure, which Stewart (1966) found to be also circularly polarized.

7 Further Studies, 1955–1959

7.1 Correlation of Type III Bursts with Solar Flares

Following Wild et al.'s (1954a, b) suggestion that Type III bursts might be caused by solar cosmic rays it was decided that a joint investigation by the CSIRO Divisions of Physics and Radiophysics be undertaken to study the association of solar flares with Type III bursts. Using the Dapto Radiospectrograph and the Hα flare patrol telescope at Fleurs, Loughhead et al. (1957) undertook an investigation from November 1955 to July 1956 in which over 300 flares were investigated, of which 85% were sub-flares (of importance class 1-). About 20% of the flares were associated with Type III bursts, while more than 60% of the Type III bursts recorded occurred during the lifetime of a flare.

An association was said to occur if a burst occurred within 2 min of the flare. Further evidence for an association was obtained on 3 days during the period of investigation when the east–west positions of Type III bursts were measured to an

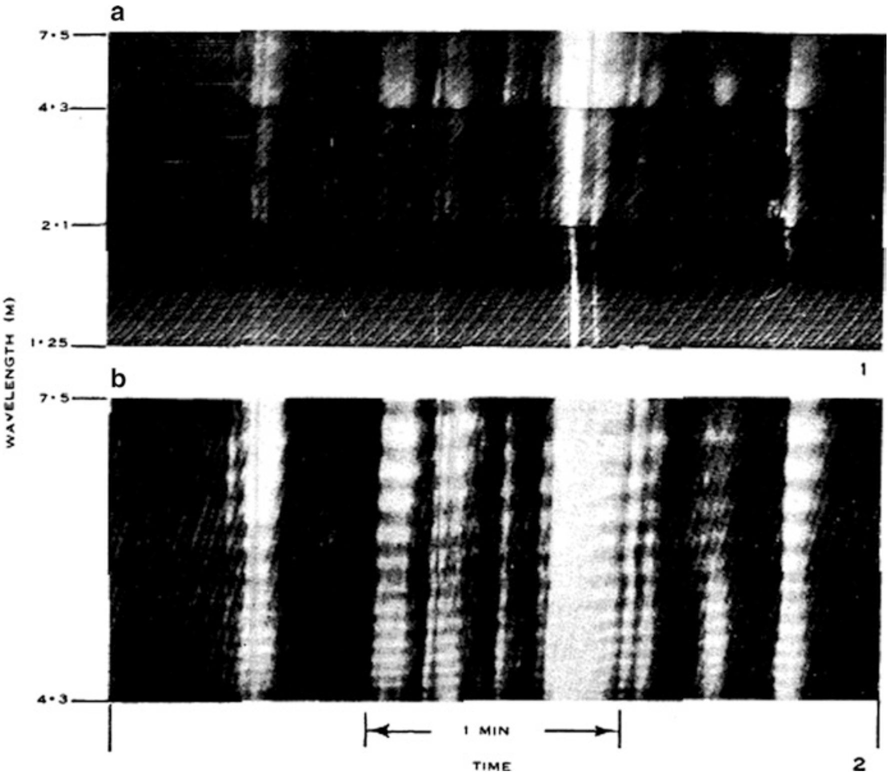

Fig. 16 (**a**) Spectral record and (**b**) interferometer record of Type III bursts on 9 November 1955. Interference fringes are evident in (**b**) (after Loughhead et al. 1957: Plate 1).

accuracy of 4′ by examining the interference fringe pattern of the experimental Dapto 40–70 MHz Swept-frequency Interferometer records (which had been constructed to study ionospheric scintillations from Cygnus A). Examples of the interferometer fringe patterns recorded by the interferometer on 9 November 1955 are shown in Figure 16 along with their spectra.

Loughhead et al. (1957) concluded that the radio bursts on metre wavelengths, which are associated with solar flares, are found to be mainly of spectral Type III with over 60% of the bursts occurring during solar flares, but not all flares or active regions on the Sun produce Type III bursts.

7.2 Echo Hypothesis for Reverse Drift Pairs

Observations over the previous five years with the Dapto 40–240 MHz Radiospectrograph had shown that the majority of recorded bursts fell naturally into the three spectral classes Type I, II and III. However, on rare occasions a new type of burst was observed termed a “reverse drift pair” (RDP) because of its spectral characteristics (Roberts 1958).

The RDP burst is characterized by two narrow bands drifting from lower to higher frequencies at rates typically between 2 and 8 MHz/s. The two elements of the pair are remarkably similar in form, although their intensities are sometimes very different. Often the pair begins at about same frequency but with a delay of 1.5–2.0 s and often terminate at about the same frequency. Examples are shown in Figure 17.

According to Roberts, the RDP is quite rare only occurring on 38 out of the 250 days of records obtained from November 1955 to July 1957. About 10% of the hundreds of RDP observed occurred during Type III bursts and were easily recognized because of their greater intensity. The bursts have shorter durations and instantaneous bandwidths than Type III bursts and drift in the opposition direction hence their name. The bursts appear to be restricted mainly to the 40–80 MHz frequency band.

On 12 and 13 March 1957 some reverse pairs were observed with the experimental 40–70 MHz Swept-frequency Interferometer described earlier by Wild and Roberts (1956b). Although not enough frequencies were observed to give an unambiguous position it was clear that at the declination of the Sun the burst positions would occur on the solar disk. The solar origin is supported by the close association of reverse pairs with Type III bursts.

Roberts (1958) showed that the second element of the reverse pair is an approximate repetition of the first element with a time delay typically 1.5–2.0 s. This suggests that a single band is emitted but received via two paths with different propagation times. The most straight forward explanation for Roberts was to consider the possibility that emission occurred above the fundamental plasma level and that the radiation was received as both a direct and a reflected ray as shown in Figure 18.

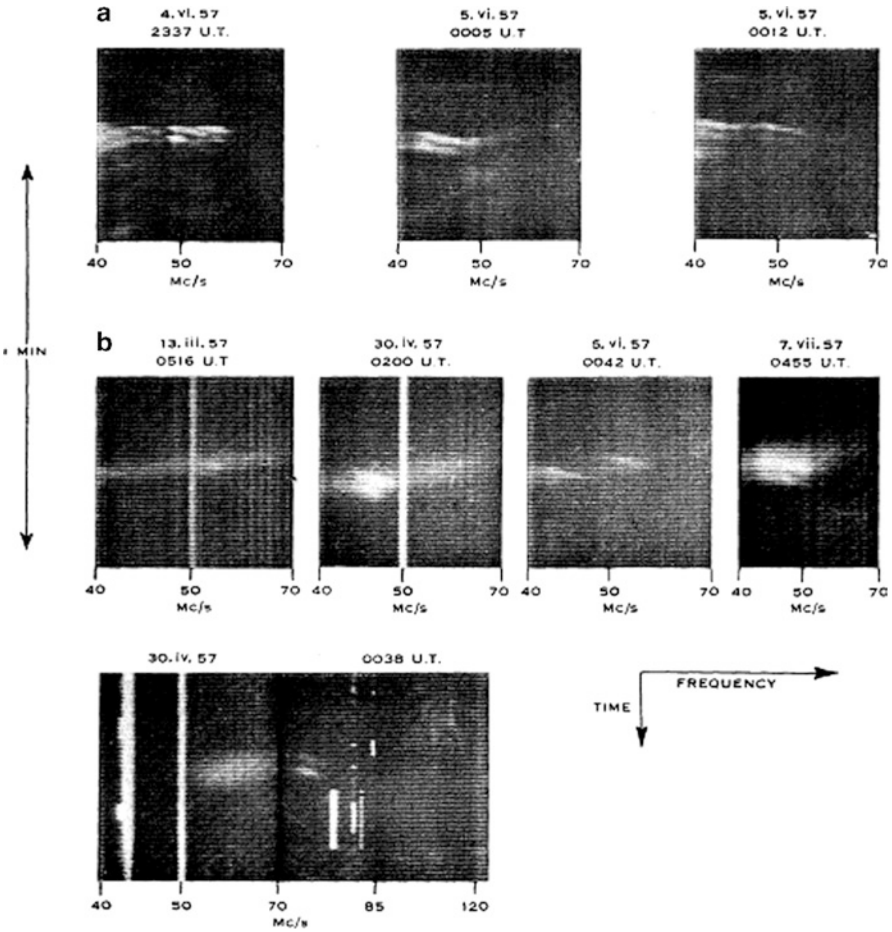

Fig. 17 Examples of reverse drift pairs (**a**) showing sudden changes in the rates of frequency drift; (**b**) occurring within bursts of spectral Type III (after Roberts 1958: Plate 2).

Jaeger and Westfold (1950) had first suggested that the "double- humped" unpolarized bursts observed by Ruby Payne-Scott (1949) were due to echoes from a regular corona and had shown that such echoes should have time delays of several seconds at frequencies near 60 MHz. However, these double bursts were later identified as fundamental and second harmonic components of Type III bursts by Wild, Roberts and Murray (1954).

Roberts (1958) extended these ideas by assuming that in the case of the reverse drift pair the radiation only occurred at the second harmonic of the local plasma frequency. He then calculated the centre to limb variation in the echo time delay for a source at the 30 MHz plasma level in a Baumbach-Allen coronal density model by using the refraction equations developed by Jaeger and Westfold (1950).

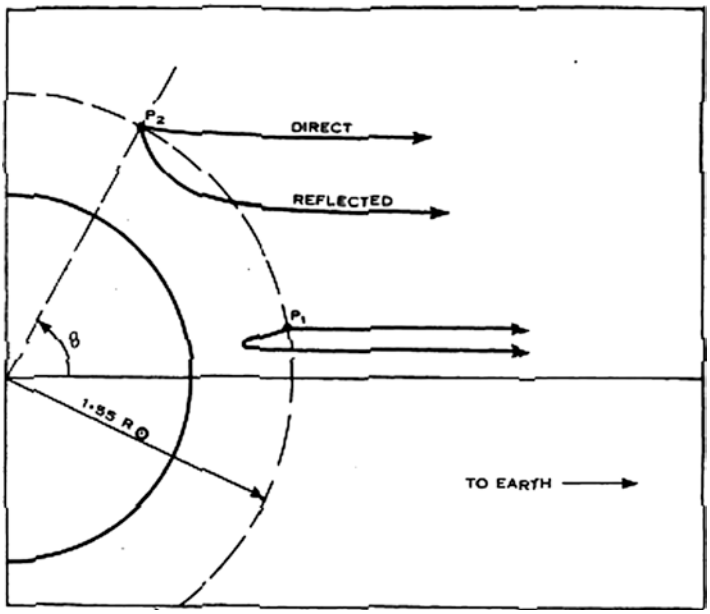

Fig. 18 Diagram showing the paths of direct and reflected rays in the corona for a source located at the 30 MHz plasma level and radiating at 60 MHz. (after Roberts 1958: 227).

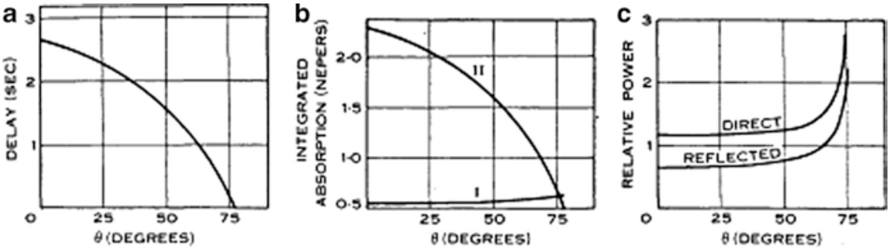

Fig. 19 Centre to limb variation for a source at the 30 MHz plasma level radiating at a frequency of 60 MHz. The source position angle θ is defined in Figure 19. (**a**) Time delay of the reflected ray after the direct ray. (**b**) Integrated absorption in the direct (curve I) and reflected (curve II) ray (after Roberts 1958: 229).

Roberts' results are given in Figure 19 where it can be seen that the echo time delay for 60 MHz radiation varies from about 3 s at a viewing angle $\theta = 0^0$ to zero at an angle $\theta = 75^0$. As there were no measured positions for the reverse pairs in this study, this theory could not be verified by examining the variation of delay times with position on the disk. Indeed, to our knowledge, this theory has never been tested by any subsequent observations.

7.3 Association of Type II Bursts with Solar Flares

A collaborative program by the two CSIRO Divisions during 1956–1957 investigated the optical disturbances which could be responsible for Type II outbursts (Giovanelli and Roberts 1958). Fifteen Type II bursts were recorded during Hα flare patrol observations. All bursts were found to be associated with optical disturbances which produced Hα particle ejections.

Of the thirteen definite identifications, nine were with flares on the disk, two with surges at the limb, and two with ejected prominences at the limb. The other two flares followed disappearing filaments which are the manifestation of eruptive prominences on the solar disk. The linear velocities of all the eruptive events were supersonic and >200 km/s but somewhat lower than the radial velocities derived from the Type II drift rates, assuming a Baumbach-Allen spherically-symmetric coronal density model.

The distribution of solar flare positions indicated that fundamental Type II bursts could be seen out to radial distances of 0.8 $R_\odot$ suggesting a much wider cone of emission than expected from the theoretical calculations of refraction effects in a spherical corona (Jaeger and Westfold 1950).

7.4 Statistical Study of Type II Bursts

In 1958, Roberts presented a preliminary account of a statistical study of all Type II bursts recorded at Dapto between 1949 and 1957 (Roberts 1959b) and subsequently published a more detailed account (Roberts 1959a).

Roberts found that about 50% of the bursts contained harmonic structure and confirmed that fundamental Type II bursts could be observed near the solar limb (Figure 20).

This result conflicted with an earlier explanation by Wild et al. (1954a, b) who showed that the harmonic ratio of Type II bursts was slightly less than 2.0 and

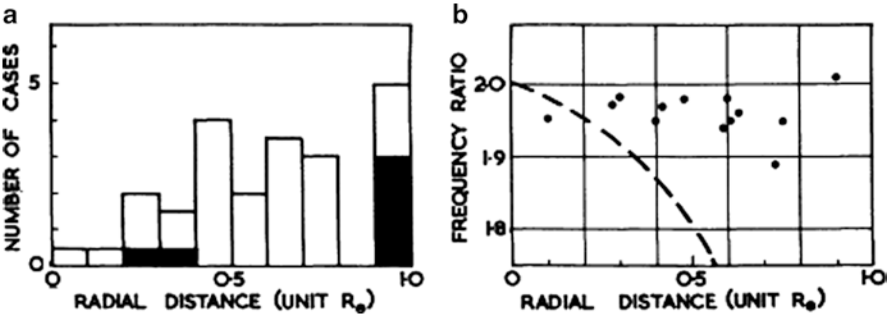

Fig. 20 (**a**) Distribution of Type II bursts associated with a solar flare. Unshaded regions refer to bursts showing both fundamental and harmonic bands. Shaded regions refer to bursts where a harmonic was not observed. (**b**) Disk distribution of observed harmonic ratios (*dots*) compared with the predicted curve from Wild et al. (1954a, b) (after Roberts 1959b: 197).

explained this in terms of absorption of the lower part of the fundamental band. They suggested that more of the fundamental band would be prevented from escaping from the corona at larger angles to the line of sight by refraction and absorption effects in a spherically-symmetric corona.

To explain this new result Roberts (1959b: 197) suggested that:

> Quantitative agreement may be possible if radiation in the fundamental band is strongly scattered by irregularities near the level of origin, so that it emerges in a wide cone and not in the very narrow beam predicted on the basis of [refraction in] a regular spherical corona. Since the refractive index for the fundamental band is close to zero at the level of origin, small variations in the electron density could produce considerable scattering.

The lack of agreement between simple refraction theory and observed solar radio burst positions remained an absorbing but unsolved problem for many years.

Roberts' study also revealed two new features in Type II bursts. In some bursts a "split-band" structure occurs in both the fundamental and second harmonic. Examples are shown in Figure 21. Often similar features are reproduced in both portions of the split-band suggesting radiation from a single source. The magnitude of the separation conforms with the splitting being a Zeeman effect as suggested by Wild (1950a, b). However, Roberts (1959b) concluded that there was no general

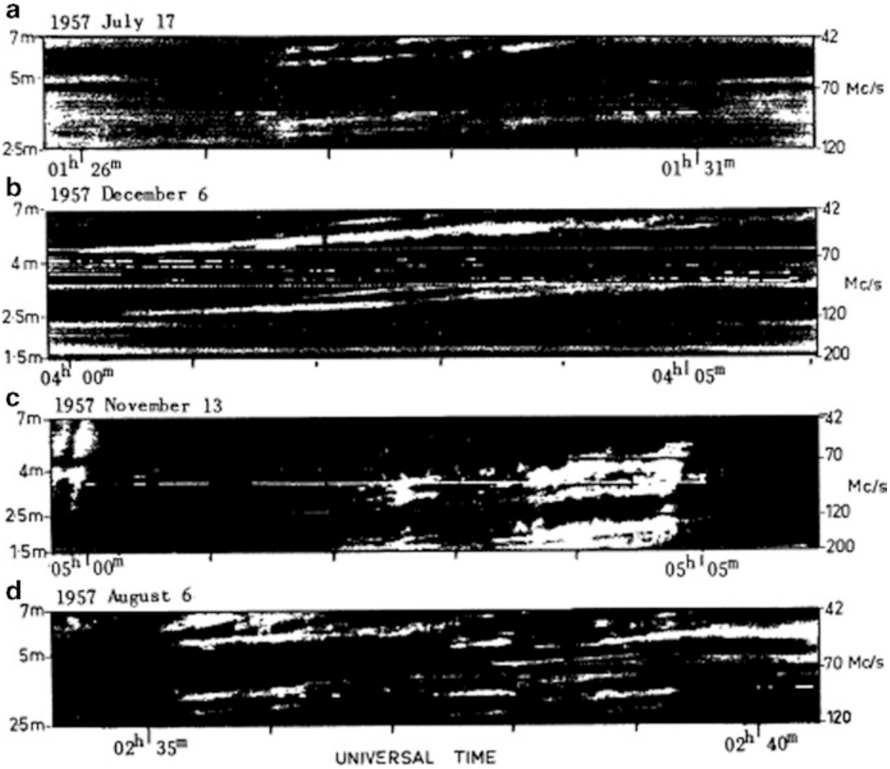

Fig. 21 Examples of Type II bursts showing split-band structure (after Roberts 1959b: 196).

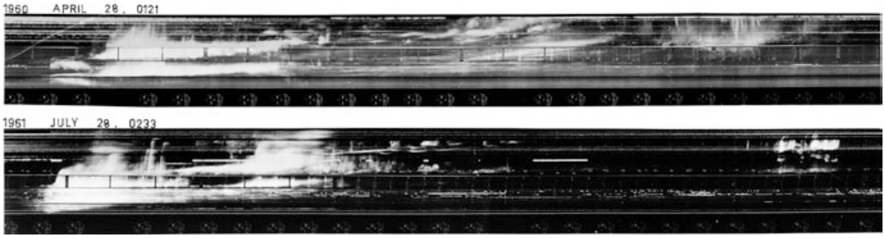

Fig. 22 Examples of herringbone structure in two Type II bursts (courtesy: ATNF Historic Photographic Archive).

agreement between existing theory and observation on the excitation of radiation near the plasma level in the presence of a magnetic field.

Roberts (1959b) reported that in some cases the drifting bands of the Type II burst contain considerable fine structure. Sometimes, the fine-structure elements are of broad bandwidth and short duration and drift at rates similar to Type III bursts (Haddock 1958). An interesting form of this appears on the record as a “herringbone” pattern. Some examples are shown in Figure 22. Here the slowly drifting and of the Type II burst appears to be a source from which rapidly drifting elements extend toward both high and low frequencies. Sometimes the pattern is not so pronounced extending over only a small range of frequencies. This may occur in about 20% of all Type II bursts.

Roberts (op. cit.) interpreted the herringbone structure in terms of the theory for Type III bursts and concluded that the Type II disturbances are sometimes the source of high speed particle ejections travelling both towards and away from the Sun. Such secondary ejections are most likely generated by the Type II shock wave.

Roberts (ibid.) also found that there is a greater tendency for the geomagnetic field to be disturbed in a few days following flares accompanied by Type II bursts than there is for flares without Type II bursts (Figure 23).

The time delays suggest that whatever causes the geomagnetic storm travels outwards from the Sun with a mean speed of about 1,000 km/s. In a subsequent paper McLean (1959) associates the disturbance with a combined Type II – IV burst (see below).

7.5 Model of a Type IV Burst

To distinguish between Type I and Type IV continuum bursts McLean (1959) used criterion based on Boischot’s (1959) original classification of a Type IV burst; a long duration (~½ to 6 h), very smooth increase in intensity of solar radio emission extending through metre and decimetre wavelengths preceded by a Type II outburst. Boischot (1958) used the 169 MHz multi-element interferometer at Nançay (France) and found that these bursts showed rapid source motion away from the solar disk with speeds of ~1,000 km/s. during the first few minutes of their existence.

McLean (op. cit.) also found that the low frequency cut-off of the spectral record of some Type IV storms drifted from high to low frequencies over an initial period of

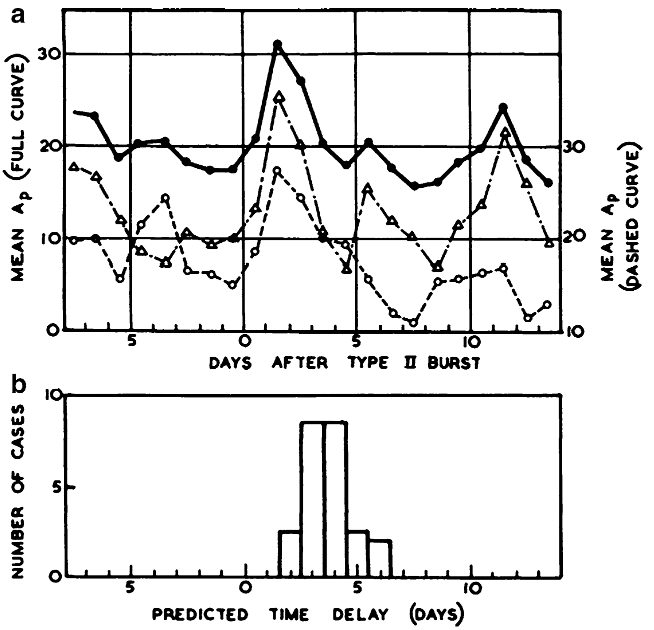

Fig. 23 (**a**) Superposed epoch diagram showing the mean value of the geomagnetic index A_p on days before and after 60 type II bursts recorded in the period January 1955 to March 1958. The dashed curves give the corresponding diagrams for the first 30 and second 30 bursts, respectively. (**b**) The predicted time delays inferred from the frequency drift of 24 of the Type II bursts (after Roberts 1959a: 199).

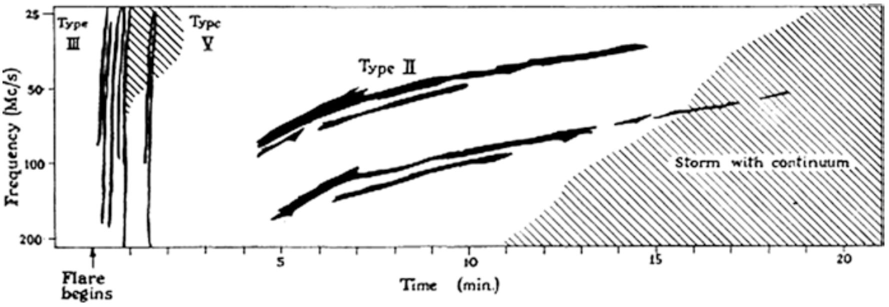

Fig. 24 Idealized sketch of spectral record showing the metre wavelength components of a complete major radio event (after Boorman et al. 1961: 87).

10 min or so suggesting an outward-moving source. McLean distinguished Type I from Type IV storms by dividing the events into "burst" continuum which contained many short-lived bursts, which he called Type I storms, and those which showed "smooth" continuum which he called Type IV. A schematic of the various metre wavelength components of a large flare event is reproduced in Figure 24. The Type IV continuum is not indicated but would occur at the beginning of the storm continuum.

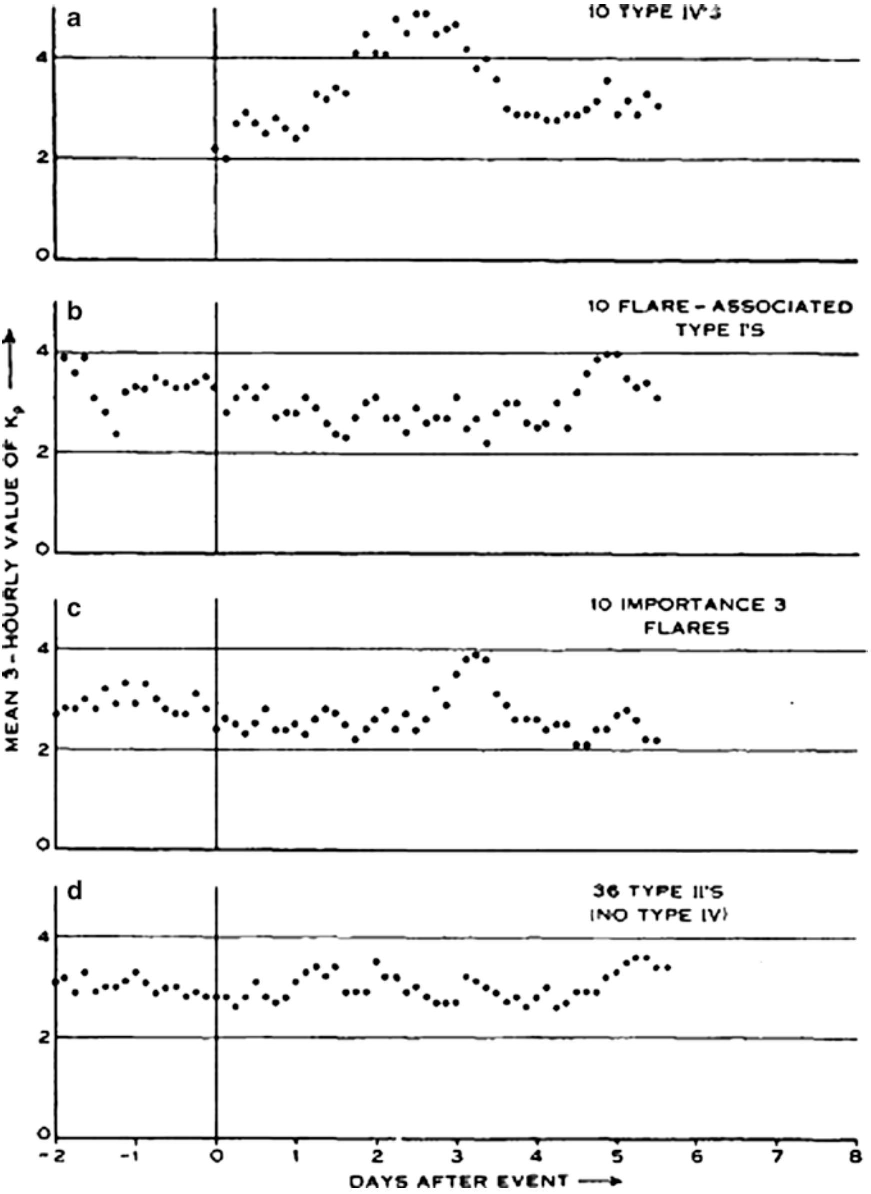

Fig. 25 Mean K_p index for each 3-hourly period before and after (**a**) ten Type IV storms (**b**) ten Type I storms (**c**) ten importance 3 flares (**d**) thirty-six Type II bursts (after McLean 1959: 412).

To show the association of Type IV storms with geomagnetic storms McLean (ibid.) plotted in Figure 25, noting:

> As can be seen [from Figure 25] the correlation of geomagnetic storms with type IV storms is outstanding and is probably the only significant one; certainly type II bursts without type IV storms following them, do not appear to be associated in any but a small percentage of cases.

McLean (ibid.) then presented a model of the Type IV burst which included all the known features. The sequence of events is envisaged:

> *First phase* [Figure 26a]. A flare occurs low in the solar atmosphere in a region of high magnetic field associated with a sunspot group. The explosion ejects a column of gas which moves radially outwards.
>
> *Second phase* [Figure 26b]. As the gas column moves outwards at a velocity ~1,000 km/s it is preceded by a shock front which excites the type II burst. Particles accelerated in the explosion are tapped in "frozen in" magnetic fields travelling along with the compressed gas behind the shock front. The spiralling charged particles emit synchrotron radiation over a wide frequency range (Schwinger 1952) to produce the type IV burst.
>
> *Third phase* [Figure 26c]. The gas behind the shock front will be at a higher density and a higher plasma frequency than that ahead of the front, where the type II burst is assumed to be generated. Consequently, the type II emission at say 40 MHz will escape from its plasma level earlier than the type IV radiation at the same frequency. This explains why the type IV storm commences several minutes after the type II burst.
>
> *Fourth phase* [Figure 26d]. Eventually the type IV emission stops while the gas cloud with its frozen-in magnetic field continues outward to become the magnetic storm cloud reaching the Earth 1 or 2 days later.

Further investigations using the Dapto Swept-frequency Interferometer (see below) were to show that not all the smooth continuum events observed during large solar flares were associated with moving sources but rather that there were two components, one moving and one stationary, which became known as the "moving" and the "stationary" Type IV bursts. This complicated the picture and also restricted the number of genuine moving continuum events observed and made it difficult to undertake meaningful statistical analysis of the correlation of moving Type IV bursts with geomagnetic storms. However, McLean's model remained in vogue for some time before the discovery of coronal mass ejection events in the 1970s.

8 The Swept-Frequency Interferometer, 1957–1964

The principle of the interferometer is illustrated in Figure 27 and was first trialled in 1955 for radio scintillation studies (Section 3). In 1957 an improved version was installed at Dapto for regular solar observations (Wild and Sheridan 1958). Radio waves incident at an angle θ with the normal travel through the antennas along paths which differ by $a \sin\theta + l$, where a is the spacing between antennas and l is the extra feeder length in one side.

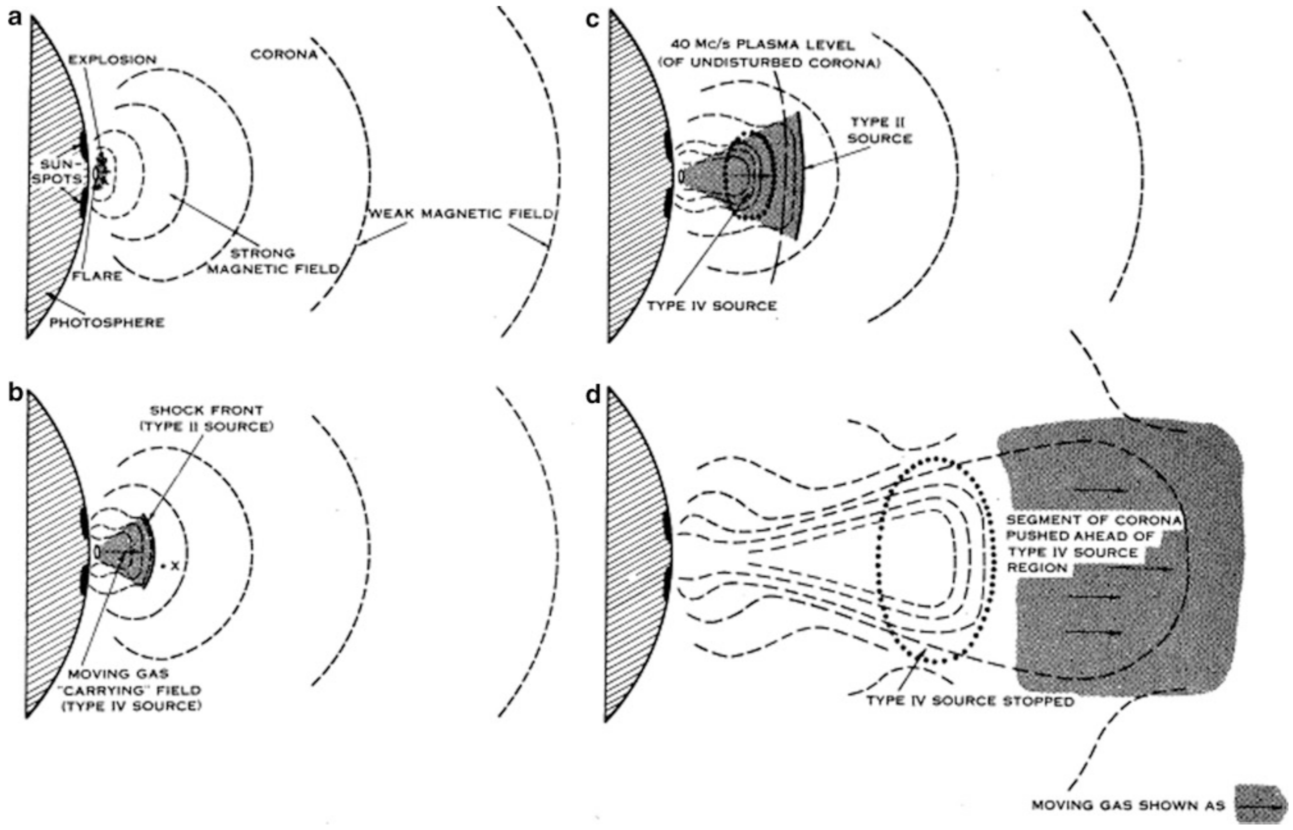

Fig. 26 Proposed model of a Type IV storm; see text for details (after McLean 1959: 414).

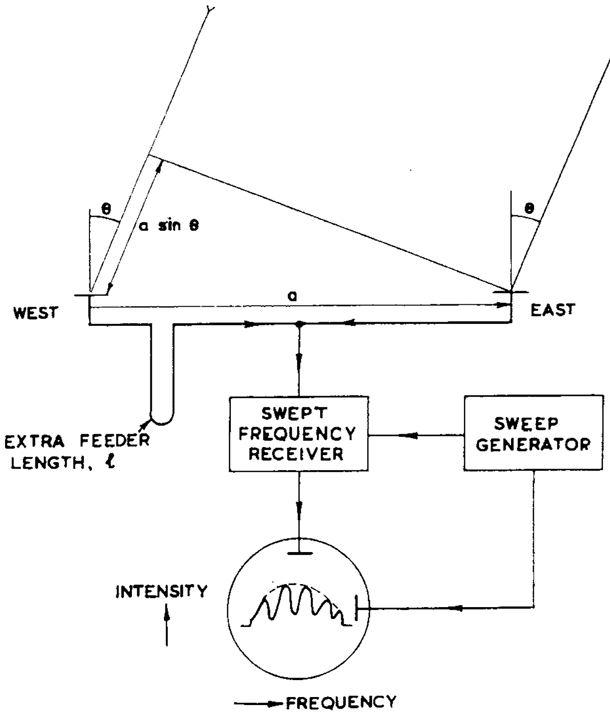

Fig. 27 Block diagram of the Dapto Swept-frequency Interferometer (after Wild and Sheridan 1958: Figure 1).

The interfering signals were received in a swept-frequency receiver and displayed on a cathode-ray tube which traced the pattern of intensity versus frequency. The pattern is just the spectrum of the source modulated with an interference pattern having maxima for which

$$a \sin\theta + l = n\lambda \tag{7}$$

and minima for which

$$a \sin\theta + l = (n + 1/2)\lambda \tag{8}$$

where n is an integer. If all frequencies arrive from the same direction, such maxima occur at equal intervals, Δf, in the frequency scale, given by

$$\Delta f = c/(a\, sin\theta + l)(\theta < \pi) \tag{9}$$

where c is the velocity of light.

Fig. 28 Paul Wild standing near one of the interferometer rhombic antennas (courtesy: ATNF Historic Photographic Archive).

The value of Δf can be adjusted to any desired value by varying the length of the variable line l. In practice, a value of Δf ~5 MHz was found to be most suitable. This required the difference in path length to the two antennas to be approximately 60 m. The Dapto interferometer was designed to operate ±2 h from noon, during which time the rotation of the Earth caused the path length difference to vary by about ±480 m. The path length was compensated by a variable line, consisting of 5 loops of open-wire line of length 15, 30, 60, 120 and 240 m, which were automatically inserted in the feeder line and adjusted to the correct length to keep l ~60 m.

The spaced antennas of the interferometer were single wire rhombics (Figure 28), each mounted on a wooden cross in the vertical north-south direction and pivoted to allow two declination settings (summer and winter); no azimuth movement was necessary because the beamwidth was wide enough to accommodate the Sun's daily motion during operation. The antennas were designed for uniform effective area of 9 m^2 over the 40–70 MHz operating band with a characteristic impedance of 700 ohms. The antenna was connected to a 700 ohms open-wire transmission line which was tapered near the receiving end to an impedance of 300 ohms.

As a result of operating experience two major features were added to the interferometer. Firstly, an additional interferometer system with a shorter baseline of ¼ km was added for lobe identification. Secondly, a more convenient display was used and an automatic system of calibration installed (Wild et al. 1959a, b). The latter facilities resulted in a reduction, by an order of magnitude, in the time to analyse the records.

Fig. 29 Kevin Sheridan in front of the facsimile recorder (courtesy: ATNF Historic Photographic Archive).

In the new system, each swept-frequency modulated pattern was converted into a square waveform and displayed as a single intensity-modulated line on paper records using a facsimile recorder (Figure 29). Wild et al. (1959a, b: 373) wrote:

> In the method used to analyse the records a reference pattern is generated corresponding to a source at the centre of the sun. To do this, the pair of aerial feeders at appropriate times are automatically disconnected from their receiver terminals and replaced for a few seconds by a pair of calibration lines connected to a broad-band noise generator. One line contains an additional loop of length *l* appropriate to the position of the centre of the sun at that time. In practice, four standard *l* values are used for calibration, namely 60, 55, 50 and 45 m. The times are calculated by a clock-driven computer … To produce the desired sequence of pulses a small commercially available hand calculator (*Curta*) is used as it is capable of adding a number *m* times, with an accuracy exceeding 1 in 10^7.

To our knowledge, this was the first time that a computer was used in radio astronomy.

9 Interferometer Results, 1957–1964

9.1 The Moving Type IV Burst

Wild et al. (1959a, b: 181) acknowledged that:

> It now seems probably that at least some of the earlier observations of transverse motions, which were made by Payne-Scott and Little (1952) at 97 Mc/s, referred to this class of event. Haddock (1958) and Maxwell et al. (1958) have also reported phenomena that they believe to be type IV bursts in the frequency range 100–600 Mc/s.

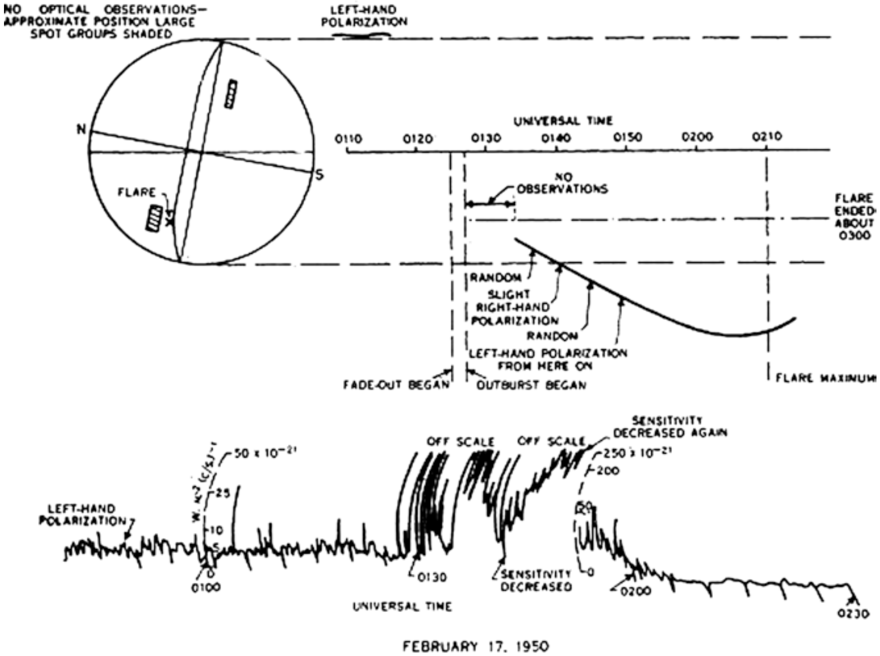

Fig. 30 Observations of source position, polarization and intensity during the outburst of 17 February 1950 (after Payne-Scott and Little 1952: 34).

One of Payne-Scott and Little's (1952) events is shown in Figure 30 for comparison with the swept-frequency interferometer event of Figure 31. It is immediately clear that the transverse motions in each of these two cases refer to examples of Boischot's (1958) Type IV burst. It was unfortunate that Little and Payne-Scott's Swept-phase Interferometer was operating at Potts Hill field station without the support of a radiospectrograph otherwise it seems quite likely that the Type IV burst would have been discovered earlier.

Further Dapto interferometer studies by Weiss (1963b) distinguished between two phases in this metre wavelength event; an initial moving phase and a later stationary phase as shown in the four examples of Figure 32.

Weiss (1963b: 541) concluded that:

1. Two varieties of the type IV burst have been recognized. They appear to be distinct phenomenon. On the basis of position measurements, these two varieties have been designated "moving" and "stationary" type IV bursts.
2. The moving type IV burst is characterized by fairly short duration, ill-defined spectral features, rapid outward movement, broad cone of emission, and polarization in the extraordinary mode.
3. The stationary type IV burst is characterized by long duration, broad continuous spectrum, a height close to the plasma level, and strong polarization in the ordinary mode. It includes the long-lived continuum storms. It may occur with or without a moving type IV burst.

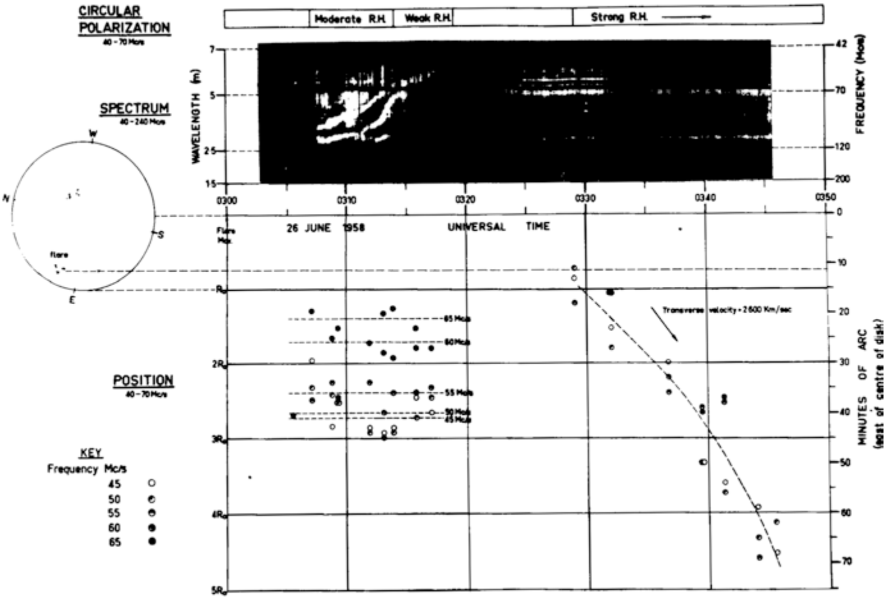

Fig. 31 Polarization, spectrum and position data recorded during an outburst at the time of a solar flare of importance 2. The earlier section of the outburst is a Type II burst, the later a Type IV (after Wild, Sheridan and Trent, 1959: 180).

9.2 *Confirmation of the Plasma Hypothesis*

The plasma hypothesis for Type II and Type III bursts was confirmed by interferometer results when (Wild et al. 1959a, b: Figure 7) showed that the dispersion of source heights with frequency for events near the solar limb (Figure 33) was in reasonable agreement with the plasma level heights derived from electron density models for the corona (see Weiss 1963a).

9.3 *Relative Positions of Fundamental and Harmonic*

During the period May 1958 to November 1960 four Type II bursts and six independent groups of Type III bursts with both fundamental and second harmonic bands were recorded on both the swept-frequency interferometer and the Dapto Radiospectrograph. The positions of these burst sources are reproduced here in Figure 34.

Jaeger and Westfold (1950) have shown that radiation can escape the corona along a direct and also a reflected path provided the frequency exceeds f_0. In 1958, Ginzburg and Zhelezniakov suggested that the second harmonic of solar bursts arises from the combination scattering of pairs of plasma waves of frequency f_0 to produce an electrodynamic wave of frequency $2f_0$. Smerd et al. (1962) used this process to calculate the direction of the resulting electrodynamic wave and its angular power spectrum as

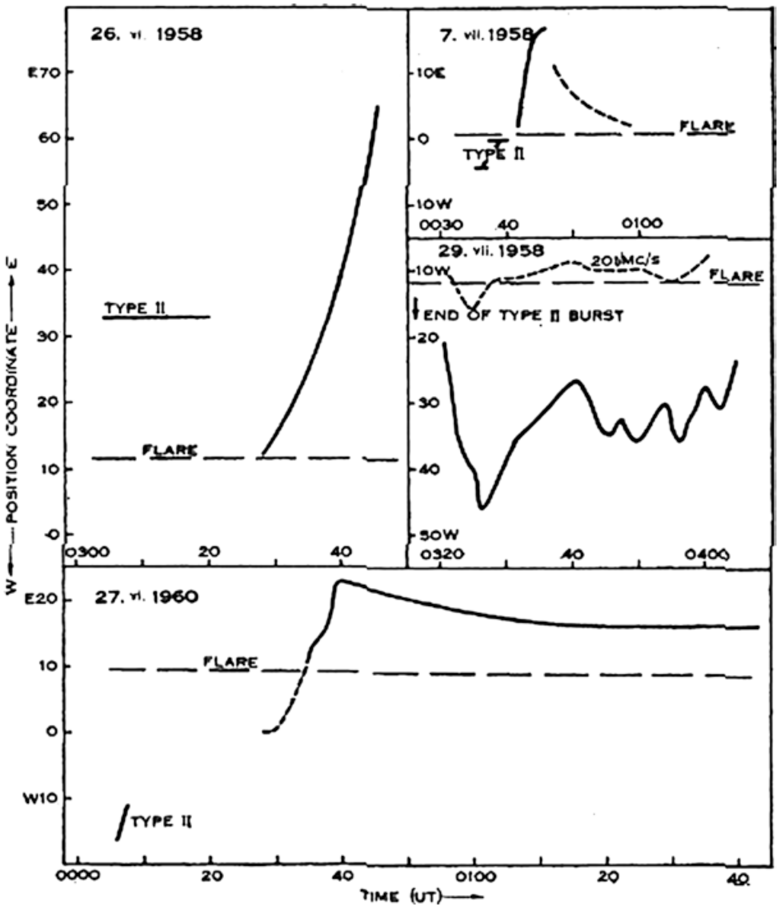

Fig. 32 Type IV bursts which show initial rapid movement. For the event of 29 July 1958 (Tokyo) the movement is partly suppressed by blending with a coexisting stationary Type I source (after Weiss 1963b: 533).

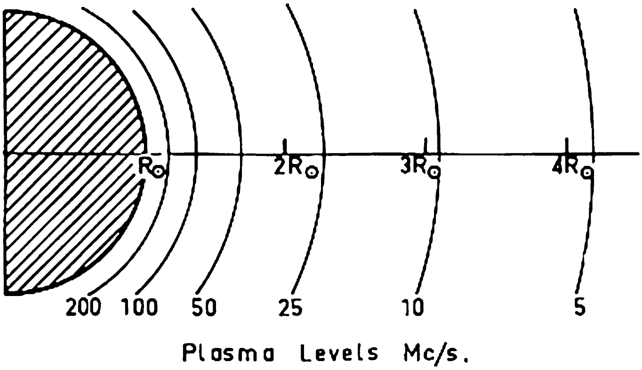

Fig. 33 Plasma levels in the solar corona (after Sheridan 1963: 175).

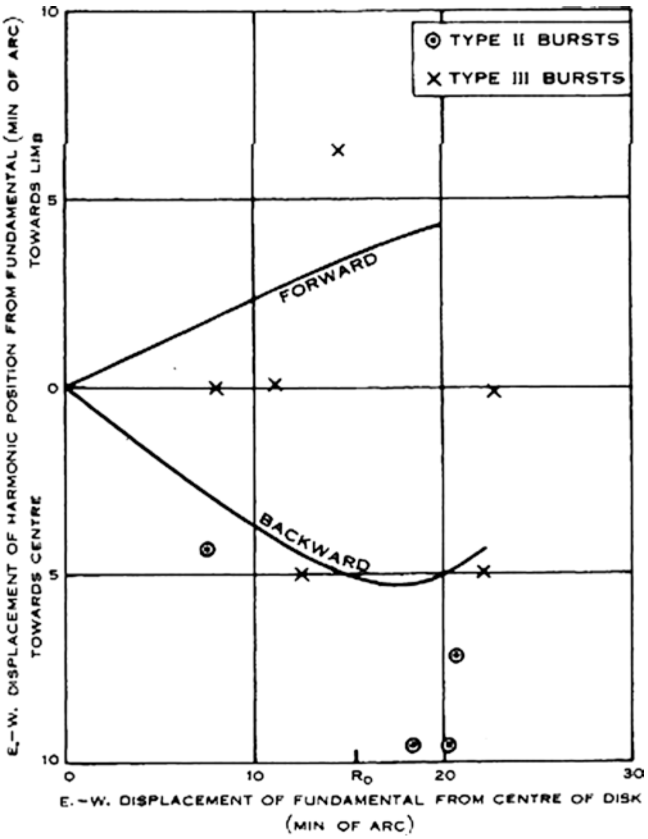

Fig. 34 Plot showing the relative displacements of fundamental and harmonic Type II and Type II bursts. The full lines show theoretical curves on which the points would lie according to a simple model discussed below with propagation of the harmonic along forward and backward rays, respectively (after Smerd et al. 1962: 185).

$$F(\theta) \sim \sin^3\theta[1+3(v/c)^2 - 2(3(v/c)cos\theta]^{\frac{1}{2}} \qquad (10)$$

giving the distribution shown in Figure 35 (below). Smerd et al. (1962: 191) wrote that Figure 35.

> … implies that the harmonic radiation will be emitted most strongly in a direction backwards of the transverse direction. The higher the radial velocity v_r, of the plasma wave, the more backwards the beaming becomes, and when $v_r > c/2$, the backward emission exceeds the forward by an order of magnitude. Hence under these conditions much more radiation will escape along the reflected ray than the direct.

They concluded that for Type III bursts where $v_r \sim c/2$, the reflected source of harmonic radiation should dominate the direct source as observed. For Type II bursts where $v_r \sim 1{,}000$ km/s, this could not happen unless the shock wave disturbance accelerates c/2 electrons which travel outwards through the corona. Support for this idea comes from the observation of "herringbone structure"; in some Type II bursts.

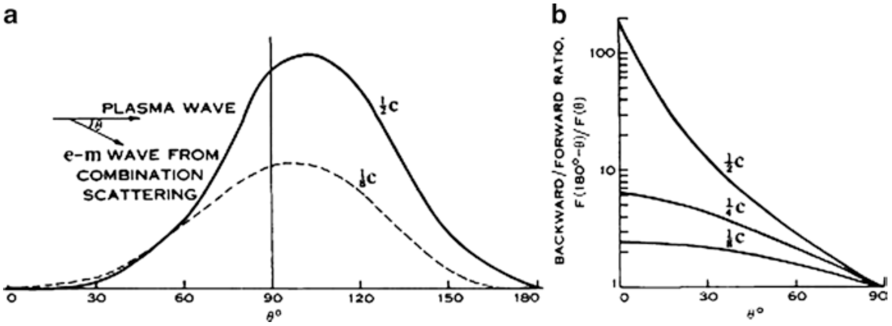

Fig. 35 (**a**) Calculated angular power spectrum for radiation at the second harmonic of the plasma frequency (**b**) The backward/forward ratio of intensities (after Smerd et al. 1962: 191).

9.4 The Type V Burst

Wild et al. (1959a, b: 181–182) noted that

> In the course of this investigation we have recorded positions of a number of broad-band enhancements that are often observed at the time of, or shortly after, the occurrence of type III bursts. Such enhancements can last from 30 s to 3 min and can reach very high intensities (comparable to the type III burst) with a peak frequency usually below 100 MHz. The complete frequency range of the enhancement is not known but Neylan (1959) has found a correlation with centimetre wavelength bursts. This suggests the possibility of extremely broadband emission … It is possible that they are initiated high in the corona by the type III disturbance.

These authors suggested that the Type V burst was synchrotron emission from relativistic electrons. However Stewart (1965) showed that the velocity of Type III bursts accompanied by Type V emission was ~c/3 and argued that this meant that the energy of the electrons exciting Type V emission was too low for the synchrotron process.

Examples showing the broadband nature of Type V bursts recorded by the Dapto radiospectrograph are shown in Figure 36. The Type V follows the Type III and can extend from 200 MHz down to 7 MHz (the cut-off imposed by the ionosphere).

Further investigations by Weiss and Stewart (1965) led to the proposal of the model illustrated in Figure 37 in which the Type V burst arises from plasma wave emission from electrons trapped in a magnetic field displaced from the path of the Type III disturbance.

9.5 "Herringbone Structure" in Type II Bursts

An example of a Type II burst containing "herringbone structure" is reproduced in Figure 38 together with a plot of the degree of polarization measured at 40 MHz (full line) and 60 MHz (dashed line). The herringbone is present in the early stages

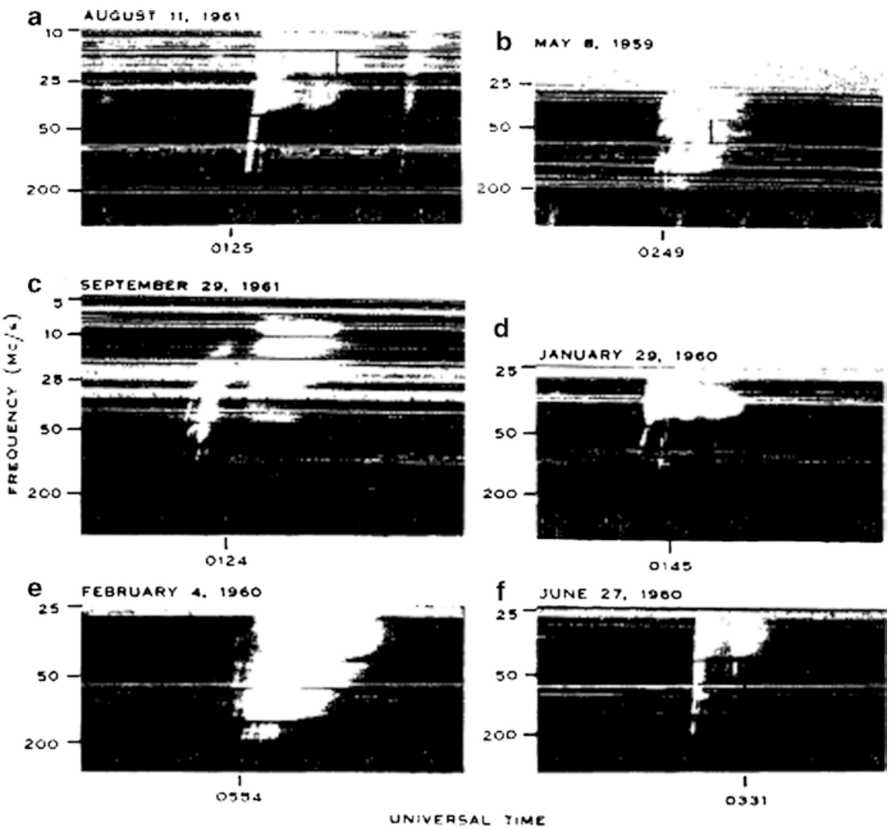

Fig. 36 Examples of Type V bursts (after Weiss and Stewart 1965: Plate 1).

of the Type II burst (0424 to 0429 U.T). During this period the polarization reaches a higher value at 40 MHz (40–60%) than at 60 MHz (20 to 40%). However, the 60 MHz readings are closer to the core of the Type II burst and may be lessened by contributions from the much weaker polarized emission from the core. Later in the event, when the herringbone structure is no longer present, the polarization at both frequencies drops below 10%. From these results it is concluded that the Type II burst is only weakly polarized, if at all, but when the herringbone structure is present features far from the core are highly polarized (Stewart 1966).

The source of the herringbone feature, though similar to type III bursts, appears to be initiated in the disturbance responsible for the Type II burst. This disturbance is thought to be a magnetohydrodynamic shock front, driven by a cloud of ions and electrons ejected from the flare region and capable of exciting plasma oscillations in the corona (Wild et al. 1963).

Wild (1964) suggested that the herringbone structure arises when the disturbance travels across a radially-directed magnetic field. Some of the fast electrons produced

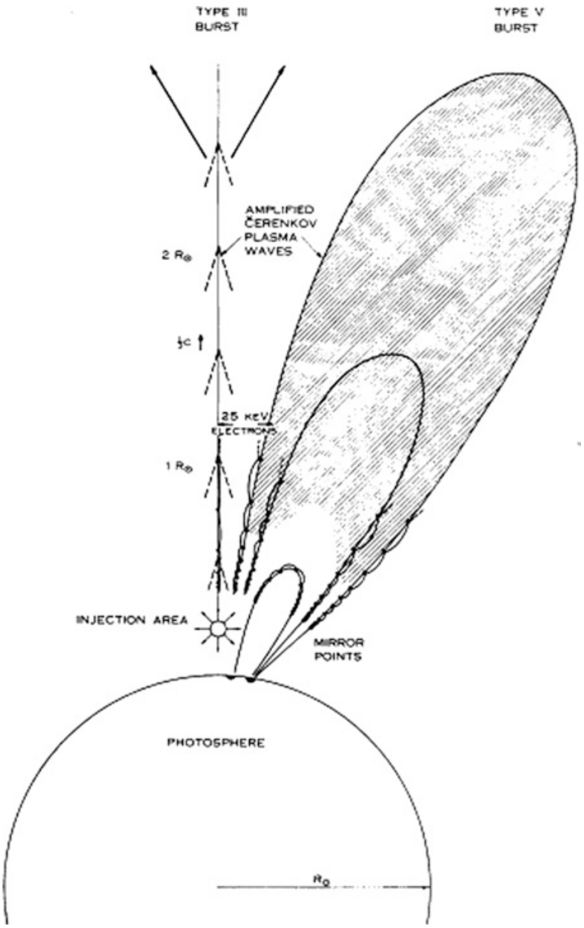

Fig. 37 Proposed model for the physical state of the corona at the time of a Type V burst. The magnetic configuration is such that some of the fast (~25 keV) electrons ejected during the flare are trapped in the corona for a minute or longer. It is suggested that the fast electrons generate plasma waves which, after conversion to electromagnetic radiation, produce the Type V burst (after Weiss and Stewart 1965: 161).

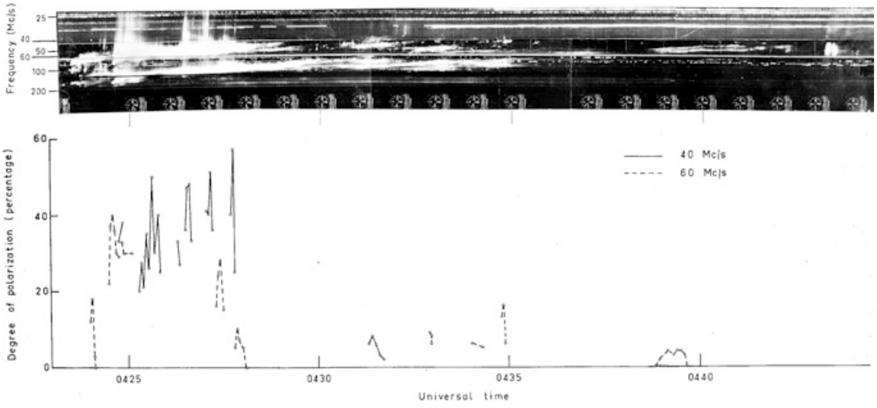

Fig. 38 An example of the spectrum and degree of polarization at 40 and 60 MHz of a type II burst containing herring-bone structure (after Stewart 1966: Plate 1).

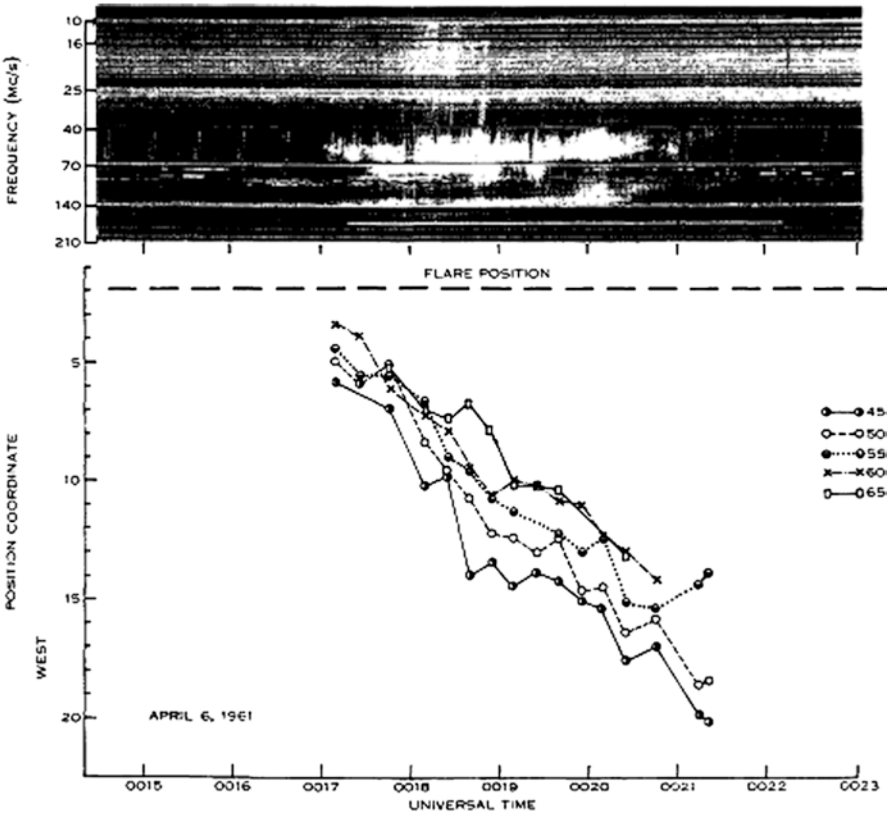

Fig. 39 The herringbone event of 6 April 1961 showing low drift rate and systematic transverse motion and "herringbone structure" (after Weiss 1963a: Plate 3).

by the disturbance could then escape from the Type II source region along radial field lines to both higher and lower regions of the corona and set up plasma waves. This model is very appealing as it explains not only the appearance of both positive and negative frequency drifts in herring-bone features but also the unusually slow drift rates often observed in Type II bursts with herringbone structure. Evidence for tangential source motion in herringbone events has been given by Weiss (1963a). An example is shown in Figure 39.

10 Extensions to the Dapto Radiospectrograph, 1958–1963

As a first step in exploring the decametric frequency range, the Dapto equipment was extended downwards in frequency by adding a 25–40 MHz spectrograph in October 1958 to supplement the 40–210 MHz spectrograph. The new spectrograph

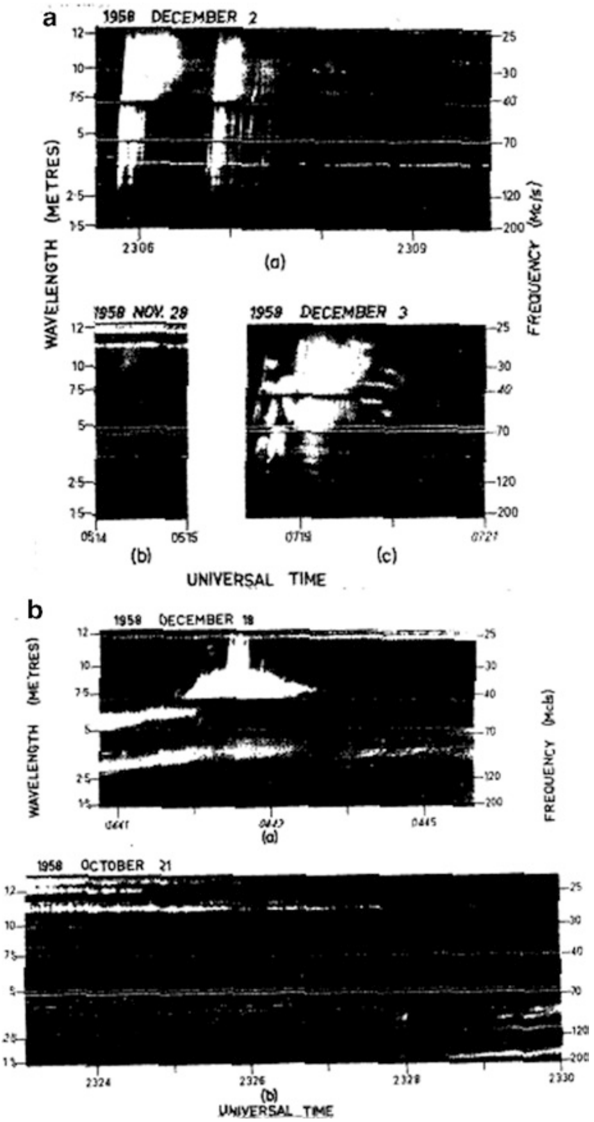

Fig. 40 Examples of dynamic spectra recorded over the full frequency range of 25–210 MHz (after Sheridan et al. 1959: 51a).

employed a conventional swept-frequency receiver connected to a simple steerable rhombic aerial. A receiver bandwidth of 100 kHz was found to be sufficiently narrow to minimize most interference effects. Examples of dynamic spectra recorded with the 25–210 MHz spectrograph are reproduced here as Figure 40 (Sheridan et al. 1959).

Further extensions down to 15 MHz followed in 1960 (Sheridan and Trent 1961) and down to 5 MHz in 1961 (Sheridan and Attwood 1962). No further low frequency extensions were warranted because of the cut-off frequency of the ionosphere. A study of spectral records by Stewart (1965) showed that the radial velocities of Type III bursts remained constant out to heights of at least 3 $R_\odot$, suggesting that the electron streams responsible for these bursts continued unimpeded into the interplanetary space. This was confirmed by subsequent spacecraft observations.

The final modification to the Dapto Radiospectrograph was made in 1963 with a high frequency extension from 200 to 2,000 MHz (Suzuki et al. 1963).

11 Concluding Remarks

On 1 March 1964 the Dapto Observatory was handed over to the Wollongong University College and a new radiospectrograph was installed at the CSIRO Culgoora site of the radioheliograph (Sheridan 1967). A continuous coverage of solar spectra was maintained by CSIRO until 1986 when the radiospectrograph was handed over to the Ionospheric Prediction Service and the Culgoora Radioheliograph was closed down to make way for the Australia Telescope, thus ended almost 40 years of outstanding observations of solar bursts by the CSIRO Division of Radiophysics Solar Group.

Acknowledgements We are grateful to the CSIRO Astronomy and Space Science Division for supplying images from the ATNF Historic Photographic Archive.

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The Sun Has Set on a Brilliant Mind: John Paul Wild (1923–2008), Solar Radio Astronomer Extraordinaire

Ronald Stewart, Wayne Orchiston, and Bruce Slee

Abstract In this short paper we pay tribute to our long-time colleague, mentor and good friend, Paul Wild (FAA, FRS, FTSE) and briefly review his major contributions to solar radio astronomy from 1941 when he joined the CSIRO's Division of Radiophysics until 1971 when he became Chief of the Division. During this period he made important contributions to our understanding of solar physics with his development of the Penrith and Dapto radiospectrographs, the Dapto Swept-frequency Interferometer and the Culgoora Radioheliograph. These instruments revealed for the first time the presence of charged particles and shock waves travelling through the solar corona, and their potential effects on 'space weather.'

1 Introduction

In October 1947 John Paul Wild, 1923–2008 (Figure 1), took up a position as a Research Scientist at the CSIRO's Division of Radiophysics in Sydney after serving time as a radar gunnery officer with the Royal Navy in WWII. During 1948 he helped Lindsay McCready design the world's first radiospectrograph for the study of solar bursts in the 70–140 MHz frequency range.

Although the techniques used in spectrum analysers had been developed for search radars during WWII (Bowen 1984) the available equipment (P78 search receivers) were found to be too noisy for solar studies (McCready 1948) and Wild was given the task of designing a new receiver. He also designed the broadband antenna (see Figure 2).

With the help of Bill Rowe and Keith McAlister these two pieces of equipment were constructed, while John Murray assembled the display system (see Figure 3).

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Fig. 1 Paul Wild in 1952 (adapted from an ATNF Photographic Archive group photograph).

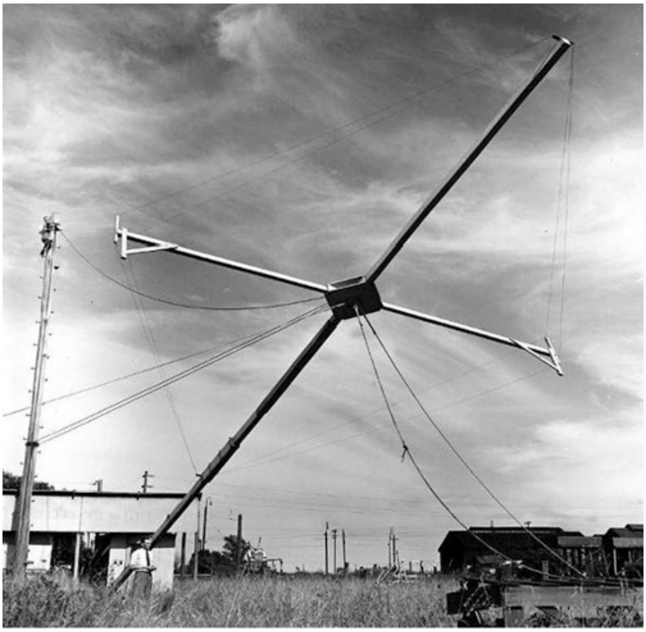

Fig. 2 The rhombic aerial and pulley system with Bill Rowe standing nearby. In the background, on the right hand side, can be seen the Penrith railway locomotive shunting sheds (courtesy: ATNF Historical Photographic Archive).

Fig. 3 Paul Wild (*left*) and John Murray (*right*) working on the Dapto Radiospectrograph display (courtesy: ATNF Historical Photographic Archive).

Paul was always the systems designer not the engineer as John Murray (pers. comm. 2007) recalls: "Paul would fiddle with cables and connectors while Bill Rowe and I worked on the receiver and display." Paul also liked to joke about his lack of technical skill, as recounted by Jim Roberts (pers. comm. 2007): "Whenever he needed John Murray to do work on the equipment he only had to pick up a soldering iron."

Solar observations were conducted at a 'radio quiet' site near the Penrith railway station during 1949 and the results were written up by Wild and Lindsay McCready (1950) and by Wild (1950a, b; 1951).

The observations exceeded all expectations (see Stewart et al. 2010), resulting in the spectral classification of three distinctly different types of solar bursts which Wild and McCready (1950) called Type I, II and III (Figure 4), thereby clarifying the confused state of earlier single frequency observations (Stewart 2009).

Much later, Wild (1985: 7) reflected on these formative years:

> The situation around 1948, when I joined the Sydney group of investigators led by Joe Pawsey, was one characterized by mystery, incredulity and intense interest. A whole new field of research lay ahead with obvious objectives: to disentangle the conglomeration of phenomena; to interpret and understand them; and to put the results to use in the mainstream of research for solar physics, astronomy and physics.

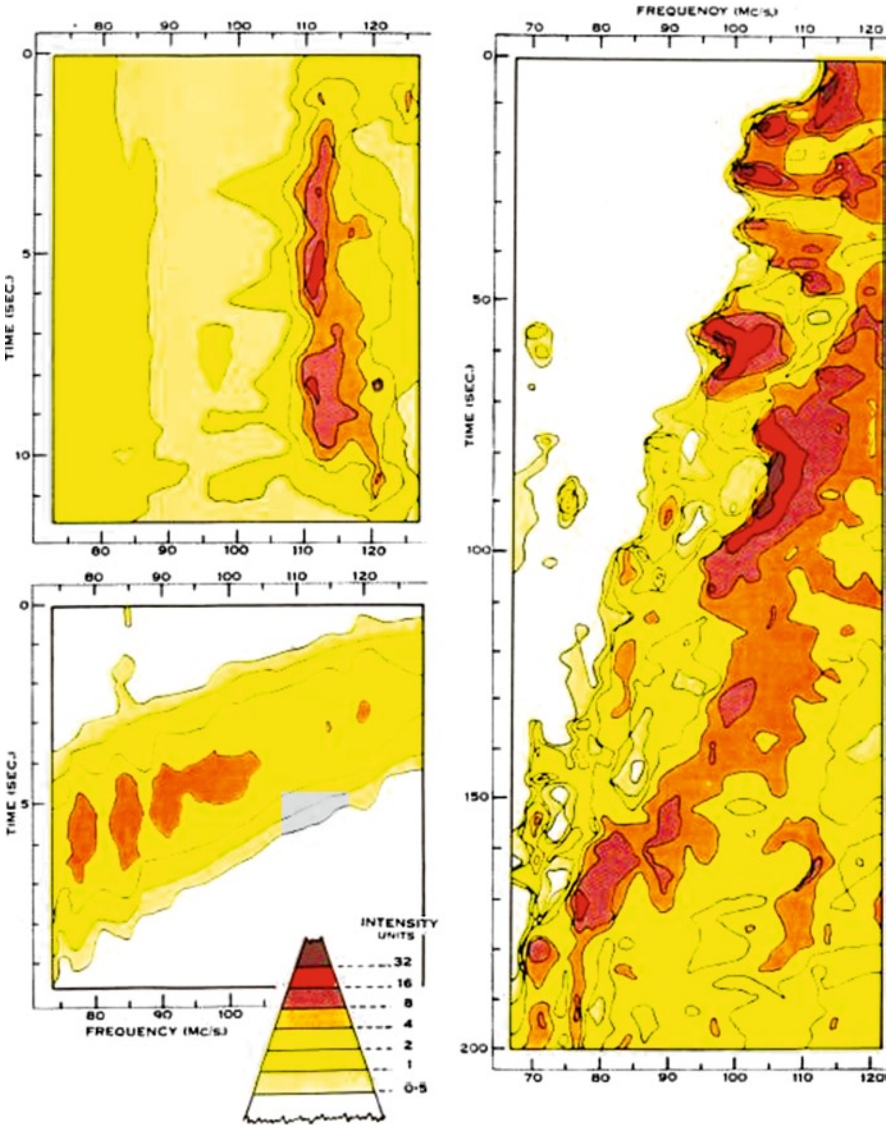

Fig. 4 Dynamic spectra of Type I (*top left*), Type III (*bottom left*) and Type II (*right*) bursts (adapted from Wild and McCready 1950: Plate 2).

Wild (1985: 7–8) also recollected:

> Before the 'origin of species' could be identified there had to be an exercise in taxonomy. Already Pawsey and his colleagues at Sydney had found that, in addition to the polarized storm radiation, there were different kinds of unpolarized bursts: there were large *outbursts* lasting 10 or 20 min which accompanied large flares, and there were short, sharp 'isolated' bursts lasting a few seconds …
>
> A new clue was discovered when Payne-Scott et al. (1947) noted systematic time delays in the starting time of bursts, high frequency preceding low. In the case of the isolated bursts

> these delays were typically a few seconds and were thought to be due to the difference in travel time … In the case of outbursts, one event was recorded with long delays (a few minutes) between frequencies, and the possibility was suggested that the delay was due to the outward movement of the source. However, in a subsequent extended series of observations Payne-Scott (1949) found no further evidence of similar delays and was inclined to believe that the long delays of that one event was fortuitous. She stressed the difficulty of identifying corresponding features of a complex burst at different frequencies … An obvious next step, therefore, was to develop a radiospectrograph to record the intensity of the solar emission as a continuous function of frequency and time.

Wild speculated that the Type II and Type III bursts were excited as plasma oscillations in the corona by the outwards passage of fast particles at speeds of the order of 500 and 10^4–10^5 km/s respectively and that on arrival at the Earth these particles were responsible for geomagnetic storms and solar cosmic rays.

2 Dapto Sunrise

Following the success in 1953 of the Penrith observations an improved Radiospectrograph was built by Wild et al. (1953) covering the extended frequency range from 40 to 240 MHz and was installed at Dapto, south of Sydney (Figure 5).

Fig. 5 The three crossed-rhombic aerials of the 40–240 MHz Dapto Radiospectrograph (courtesy: ATNF Historic Photographic Archive).

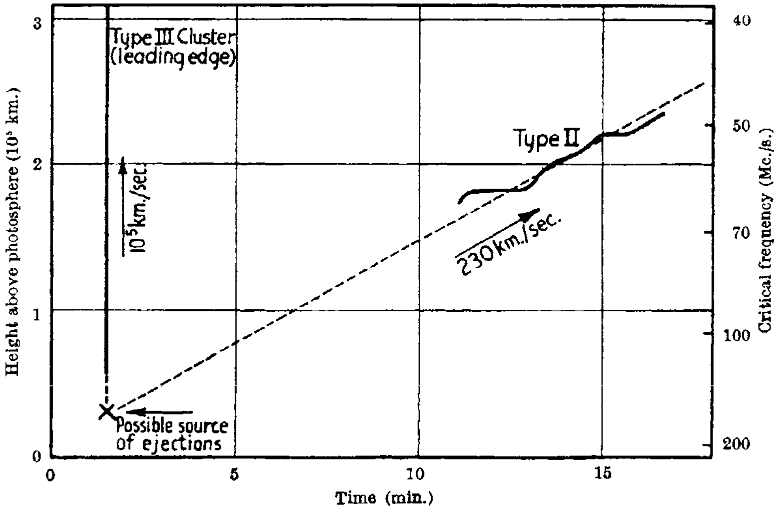

Fig. 6 Derived height-time plots of a Type III-II event (after Wild, Roberts, and Murray 1954: 533).

Observations revealed the presence of fundamental and second harmonic structure in both Type II and Type III bursts (Wild et al. 1953; Wild, Murray, and Rowe 1954), giving support to Wild's earlier 'plasma hypothesis' and extending the heights attained by these disturbances (see Figure 6).

Roberts joined Wild's Dapto group in 1953, and he recollects (pers. comm. 2007):

> The weekly 3-day visits to the Dapto field station allowed Paul to see to general supervision, and provided a great environment for examining the observational results, and attempting an interpretation. At the same time Paul gently educated this new recruit on subjects such as *aerial temperature* and *available power*, in sessions over extended morning teas, taken sitting at a table out in the sunshine. Discussion would be accompanied by Paul repeatedly stabbing his teaspoon into his teacup, trying to dissolve all the sugar he had added!
>
> It was at one of those leisurely morning teas that Paul mused, "I wonder if Type III bursts really are caused by particles travelling out from the Sun at close to the speed of light", which led to the first Radiophysics publication including my name as an author, a letter to the journal *Nature*, with authors Wild, Roberts and Murray, dated December 14, 1953, and entitled "Radio evidence of the ejection of very fast particles from the Sun."

This paper also mentions for the first time the possibility that the Type II disturbance might be a shock wave travelling through the corona.

Wild and Sheridan (1958) then designed the first swept-frequency interferometer to measure the source positions of solar bursts at frequencies between 40 and 70 MHz (Figure 7).

The source heights were found to be consistent with optically-derived electron density models (Wild et al. 1959), providing convincing confirmation for Wild's plasma hypothesis (Figure 8).

Over the next 3 years Sheridan et al. (1959), Sheridan and Trent (1961) and Sheridan and Attwood (1962) extended the operation of the Dapto Radiospectrograph in

Fig. 7 Paul Wild with one of the Dapto interferometer aerials (courtesy: ATNF Historic Photographic Archive).

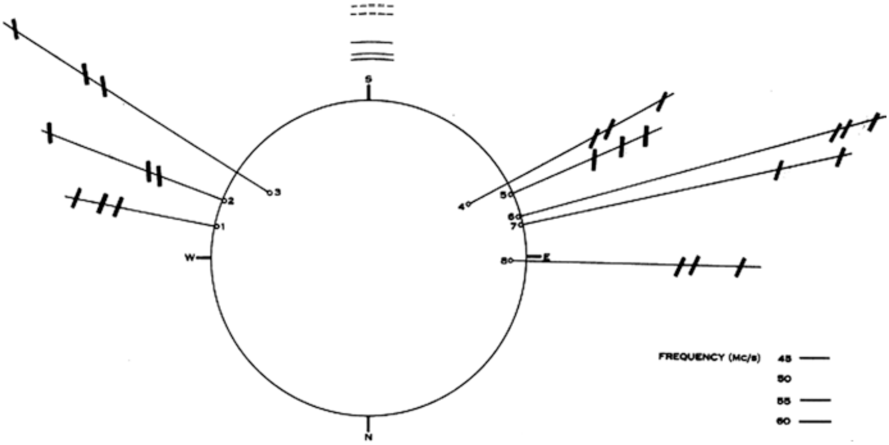

Fig. 8 Dapto Swept-frequency Interferometer observations of the source heights of Type III bursts (after Wild et al. 1959: 382).

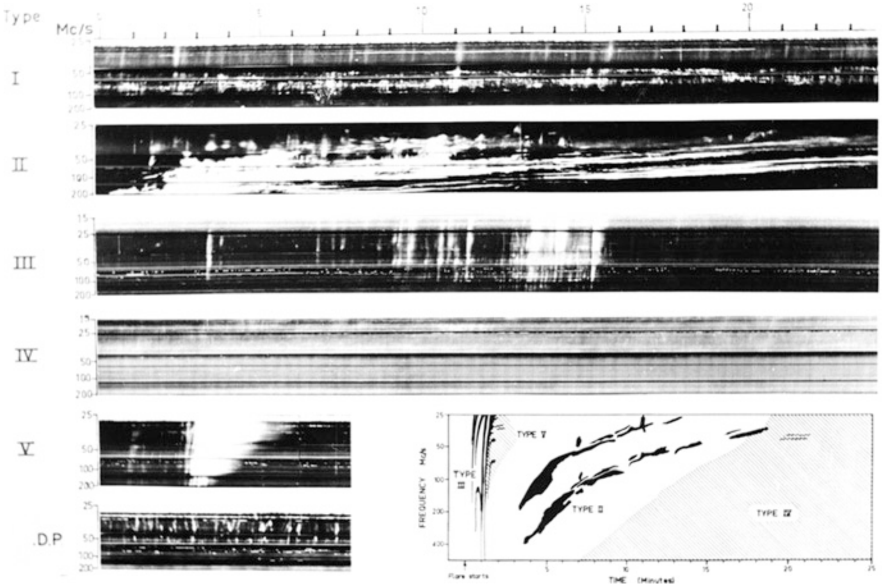

Fig. 9 Typical dynamic spectra of the five different types of solar bursts (courtesy: ATNF Historic Photographic Archive).

steps down to 5 MHz, close to the lower limit imposed by the ionosphere for the reception of radio signals from space.

This meant that Type II and Type III disturbances could be traced out to heights of ~3 $R_\odot$ above the photosphere (Stewart 1965), a remarkable achievement for ground-based observations. Later, spacecraft observations confirmed the existence of Type III electron streams and Type II shock waves travelling from the Sun to the Earth.

Typical examples of dynamic spectra of the five different types of solar bursts observed by the Dapto Radiospectrograph are shown in Figure 9.

3 Culgoora Noon

In 1962 Paul Wild was awarded a grant of $600,000 from the Ford Foundation (USA) for the construction of a radioheliograph. CSIRO reciprocated with funding to acquire a site on flat land at Culgoora, in north western NSW (near the town of Narrabri) and to support the operating cost of this innovative new radio telescope.

The Culgoora Radioheliograph comprised a circular array of 96 antennas each 13 m in diameter spread round the circumference of a circle 3 km in diameter (see Figure 10). Each antenna was equatorially-mounted and could track the Sun. The Culgoora Radioheliograph was designed to produce a real-time, TV-like picture of 80 MHz solar emission every second.

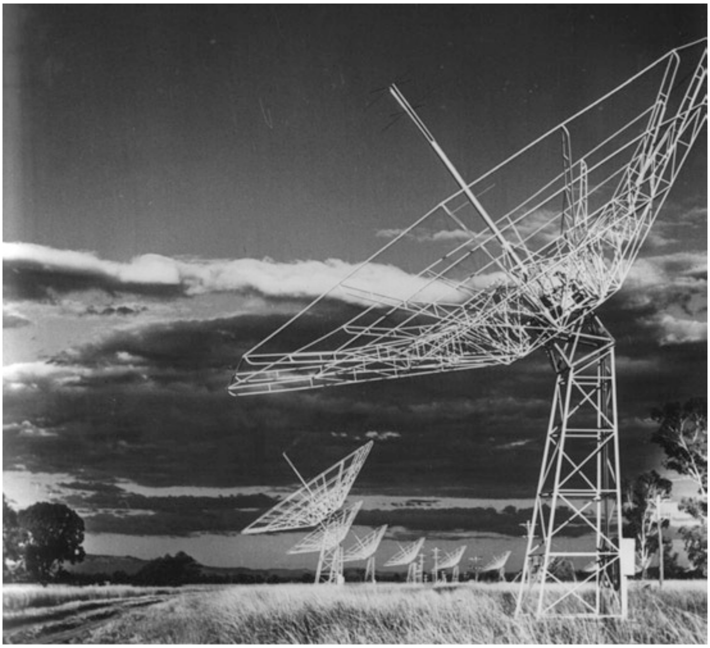

Fig. 10 A section of the Culgoora Radioheliograph showing the design of the individual antennas (courtesy: ATNF Historic Photographic Archive).

The Radiophysics Solar Group was greatly expanded and construction began in 1963 with all components being built in-house. Figure 11 was prepared at the end of 1967 to mark the up-coming departure of one of the authors of this paper (WO) and showcases the scientific and technical support staff in the Solar Group at this time. Youthful images of two of the authors of this paper (RS and WO) appear in the outer ring of Group members, third from the top on the right and fifth from the top on the left, respectively.[1] Group leader, Paul Wild, features by himself near the top of the photograph, adjacent to the dipole feed.

Observations at Culgoora began in 1967 (Wild 1967) and the results were spectacular with one moving source being tracked out to heights of at least 7 $R_\odot$ (see Figure 12).

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[1] All three authors have suitable credentials to pen this paper, spending time on the payroll of the Division of Radiophysics while Paul Wild was there. Bruce Slee joined the staff in 1946 and remained there until the Division was wound up and he transferred to the Australia Telescope National Facility (ATNF). He retired from the ATNF in 1988, long after Wild had left radio astronomy. While never a formal member of the Solar Group, he did use occultations of discrete radio sources to investigate the outer solar corona and adapted the Culgoora Radioheliograph so that it could be used for non-solar research of an evening (in the guise of the 'Culgoora Circular Array').

Ron Stewart joined Radiophysics and the Solar Group in 1963 and after transferring to the ATNF in 1986 remained there until 1996.

Wayne Orchiston joined Radiophysics in November 1961 and early in 1962 was appointed to the Solar Group, remaining there until February 1968 when he left to pursue full-time university studies.

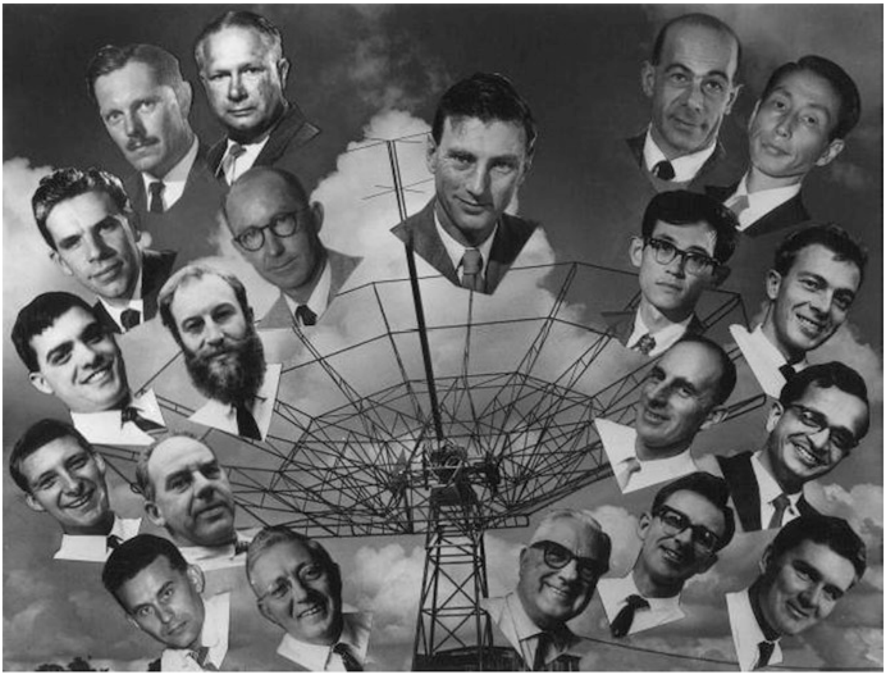

Fig. 11 Members of the Culgoora Solar Group at the end of 1967. The isolated portrait, top centre, is team leader, Paul Wild. The *outer ring of portraits*, from *top right running clockwise*, are: Steve Smerd, Shigamasa Suzuki, Ron Stewart, U.V. Gopala Rao, Len Binskin, then a gap to Joe Mack, Wayne Orchiston, Nick Fourikis, Warren Payten, Norm Labrum and Alan Weiss. The *inner ring of portraits*, from *top right running clockwise*, are: Masaki Morimoto, Charlie Attwood, John Sparks, Jack Palmer, Bill Bowie, Les Clague, Geoff Chandler and Kevin Sheridan (courtesy: ATNF Historic Photographic Archive).

Later, in 1977, after the Culgoora Radioheliograph had been extended to 160 and 43 MHz, the event shown in Figure 13 was recorded at the time of an eruptive prominence.

These moving Type IV sources as they are called were found to be associated with enormous eruptions of mass ejected from the lower corona during very large solar flares (Figure 14). These are now thought to be the cause of the magnetic storms we experience here on Earth when the entangled magnetic fields of these major solar events impinge on our magnetosphere. Often coronal mass ejections are preceded by Type II bursts, which are still used today to forecast space weather.

4 Afternoon Reflections

In 1971 Paul Wild succeeded E.G. (‘Taffy’) Bowen as Chief of the Division of Radiophysics and directed his efforts to the design of the Interscan aircraft landing system which was subsequently adopted internationally. Then in 1978 he became

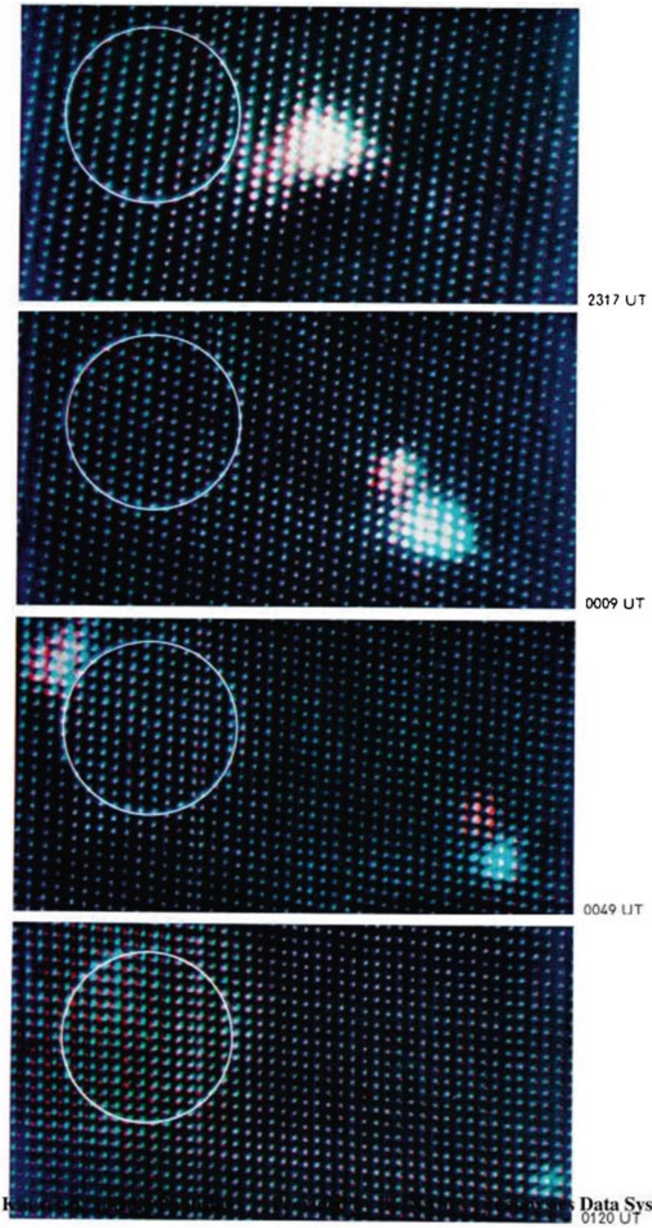

Fig. 12 Observations of a moving Type IV burst which split into two polarized sources observed on 1969 March 1. *Blue* denotes LH polarization and red denotes RH polarization (after Riddle 1970: 450).

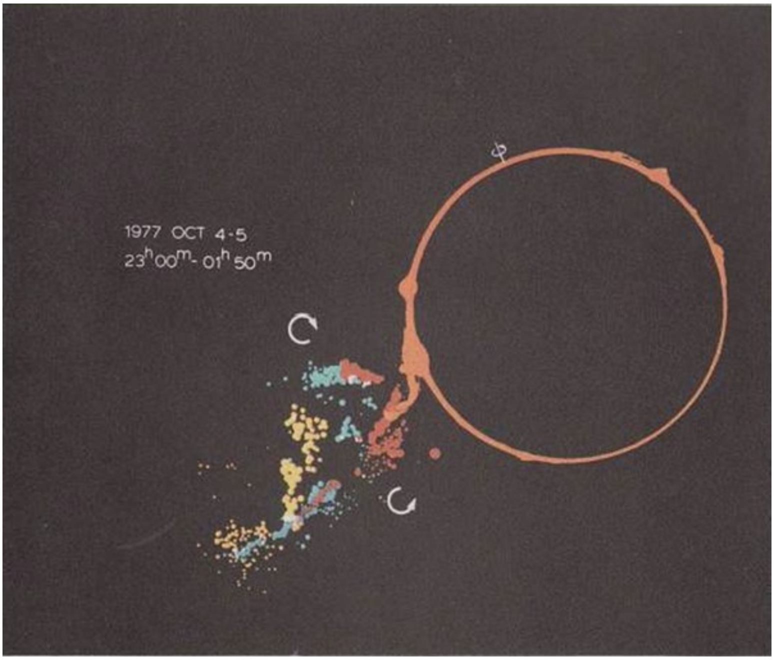

Fig. 13 *Coloured dots* show the outward displacement of a moving Type IV source (*red* 160, *blue* 80, *yellow* 32 MHz) above an eruptive prominence (*orange*) on 4–5 October 1977 (after Stewart et al. 1979).

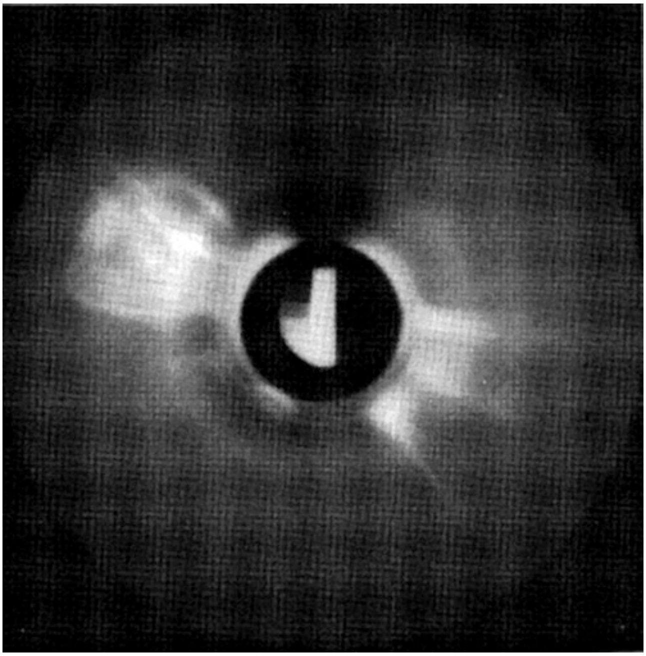

Fig. 14 Skylab coronagraph photograph (using a central occulting disk) which shows a coronal mass ejection event (courtesy: High Altitude Observatory, Boulder, Colorado).

Chief of the CSIRO, and moved from Sydney to Canberra. He retired in 1985, and it was no coincidence that the Culgoora Radioheliograph was decommissioned in that same year to make way for the Australia Telescope Compact Array. However, the Culgoora site was fittingly renamed ‘The Paul Wild Observatory.’

Paul was not only a fine physicist but also a gifted mathematician. One of us (RS) recalls him saying in the early 1960s that it was a pity that I was not stronger in mathematics – a reference no doubt to his command of mathematics which led to his keen insight into radiophysics.

On another occasion when Paul was giving a talk at Radiophysics on his plans for the Culgoora Radioheliograph he was asked by Bernie Mills, inventor of the Mills Cross, why he preferred a circle to a cross. Paul simply replied: “Because of the more elegant mathematics …”, referring to his recent paper (Wild 1961) in which he used Bessel functions to correct the side lobes of a dilute circular array.

Like his good friend Steve Smerd, Paul had a passion for understanding radio emission theories and in 1963 along with Smerd and Alan Weiss he reviewed the state of solar burst emission theory for the first addition of the *Annual Review of Astronomy and Astrophysics* (see Wild et al. 1963). Then in a memorial lecture entitled “The Sun of Stephan Smerd” he discussed the progress that had been made by Smerd and others in understanding how Type III electron streams propagated through the corona at constant speed without losing energy – what Paul referred to as ‘Sturroch’s Dilemna’ (Wild 1980).

No doubt his time in the Royal Navy as a gunnery officer was good training for what lay ahead at Radiophysics. Not only did he possess a brilliant mind but he also displayed from very early in his career leadership qualities which greatly endeared him to his colleagues and demanded respect from all he met.

5 Sunset

Paul passed away in July 2008, and will be sadly missed. His legacy includes amongst other things a list of impressive publications and inventions which positioned Australia at the forefront of solar radio astronomy from 1949 to 1984, a period that spanned more than three cycles of solar activity.

He also was largely responsible for founding the Astronomical Society of Australia in 1967, with help from Steve Smerd, Kevin Sheridan, Harley Wood and Ben Gascoigne.

All three authors of this paper knew Paul Wild personally, and two of us worked in his Solar Group. We will always remember how he could light up a room with his wit, intelligence and charm. He loved a party and a few beers, and would amuse the audience with his impressions of Churchill and Hitler at parties such as the one shown in Figure 15.

Fig. 15 One of the famous Dapto parties. Paul Wild is standing in the front row with beer in hand next to his wife, Elaine, and his close friend, Steve Smerd (with the *guitar*) (courtesy: ATNF Historic Photographic Archive).

In bringing this celebratory paper to an end we can do no better than to reproduce the following excerpt which is taken from The Australian Academy of Science Archives and lists many of Paul's accomplishments and honours:

> Born Sheffield, England 17 May 1923. CBE 1978; AC 1985. Educated University of Cambridge (BA 1943, MA 1950, ScD 1962). Radar Officer, Royal Navy 1943–47; Research Officer, CSIRO Division of Radiophysics 1947–53, Senior Research Officer 1953–56, Principal Research Officer 1956–58, Senior Principal Research Officer 1958–61, Chief Research Officer 1961–66, Director, CSIRO Solar Observatory, Culgoora 1966–71, Chief, CSIRO Division of Radiophysics 1971–77, Member, CSIRO Executive 1978, Chairman, CSIRO 1978–85; Chairman, Very Fast Train Joint Venture 1986–91. Edgeworth David Medal, Royal Society of New South Wales 1958; Foreign Honorary Member, American Academy of Arts and Sciences 1961; Foreign Member, American Philosophical Society 1962; Fellow, Australian Academy of Science 1964; Corresponding Member, Royal Society of Liege 1969; Hendryk Arctowski Gold Medal, US National Academy of Sciences 1969; Balthasar van der Pol Gold Medal, International Union of Radio Science 1969; Fellow, Royal Society 1970; first Herschel Medal, Royal Astronomical Society 1974; Matthew Flinders Lecturer, Australian Academy of Science 1974; Thomas Ranken Lyle Medal, Australian Academy of Science 1975; Fellow, Australian Academy of Technological Sciences and Engineering 1977; Hale Prize for Solar Astronomy, American Astronomical Society 1980; ANZAAS Medal 1984; Hartnet Medal, Royal Society of Arts London 1988. President, Radio Astronomy Commission, International Astronomical Union 1967–70; Foreign Secretary, Australian Academy of Science 1973–77. (Biographical material on John Paul Wild n.d.).

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Paul Wild and His Investigation of the H-Line

Harry Wendt

Abstract Paul Wild is best remembered for the major contributions he made to solar radio astronomy. Less well known is his contribution to the Australian work on the 1,420 MHz hydrogen emission line. This short communication draws attention to this work, in the context of the early research on the H-line carried out by staff from the C.S.I.R.O.'s Division of Radiophysics.

1 Introduction

On 25 March 1951, Harold Ewen was working on his doctoral thesis at Harvard University when he detected the 21-cm emission line of hydrogen (the H-line) which had first been predicted by van de Hulst in 1945. Frank Kerr from the CSIRO's Division of Radiophysics was at Harvard at this time, and he immediately relayed this information to J.L. Pawsey, the leader of the Radiophysics' Radio Astronomy Group in Sydney. This led to a frantic program at the Division's Potts Hill field station (see Wendt et al. 2008), and by July 1951 Pawsey was able to cable a confirmation of the detection to *Nature*. This was published alongside papers by Ewen and Purcell (1951) and Muller and Oort (1951).

Although no attempt had been made at the Division of Radiophysics to detect the H-line prior to Kerr's airmail letter to Pawsey, knowledge of the potential for its detection was well known, as the following account indicates.

2 Radiophysics Alerted

During a visit by Pawsey to the U.S.A. in early 1948, Grote Reber alerted Pawsey to the theoretical prediction that had been made by van de Hulst. Reber (1984: 64) had met van de Hulst in 1945, and he subsequently promoted the possibility of

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detecting the H-line in emission (see Reber and Greenstein 1947: 19). Pawsey (1948a) passed these details on to E.G. (Taffy) Bowen, Chief of the Division of Radiophysics, in a letter dated 23 January 1948, and he also included a specific section on ‘Atomic Spectral Lines’ in his visit report dated 15 April 1948, although he concluded that the potential for detection was “… quite uncertain.” (Pawsey 1948b).

Bowen (1948) agreed that the mooted H-line was certainly an interesting possibility, but he felt that it did not warrant diverting the Division’s attention from other research programs that were already underway.

3 Wild’s Contribution

Although both Bowen and Pawsey did not support diverting resources to search for the H-line (i.e. Pawsey 1948b; Bowen 1948), there was a good deal of activity and discussion within the Division. Sullivan (2005: 14) has noted Bernard Mills considered taking on the search for the H-line as an independent research project. John Bolton and Kevin Westfold had also considered searching for the line (Robertson 1992) and Murray (2007) recalled that Ruby Payne-Scott raised the potential for conducting a search.

In early 1949, J. Paul Wild (Figure 1), who had been working on the spectral analysis of solar bursts at radio frequencies, prepared an internal report that provided a comprehensive review of the earlier theoretical H-line predications. His report was titled, “The Radio Frequency Line-Spectrum of Atomic Hydrogen. I. The Calculation

Fig. 1 Paul Wild during the 1952 U.S.R.I. meeting in Sydney (adapted from an original in the ATNF Historic Photographic Archive).

of Frequencies of Possible Transmissions." Wild (1949) concluded that there was a prospect of detecting radio emission at 1,420.4 MHz from the spin-flip transition of a hydrogen electron to the ground state due to the hyperfine structure transition of 5.9×10^{-6} eV. It is likely that Wild was motivated to conduct the review as he had identified this as being one of the possible applications for the spectrum analyser he was developing. In the minutes of the Propagation Committee Meeting held on 7 March 1949 (Kerr 1949), Wild noted that the spectrum analyser could possibly be used to detect the "… line spectrum of polarised radiation."

Wild's report impressed Bowen enough for him to send a copy to the Chief Executive of the C.S.I.R.O., F.W.G. White on 21 March 1949 (Bowen 1949), and White replied on 28 March 1949 noting that:

> I have looked through it [the report] and find that, even to one who is not a spectroscopist, it is relatively easy to follow. The end results are certainly very interesting, and I hope that experimental data can now be found to which these can be related. (White 1949).

Despite this positive review no search for the H-line was undertaken at Radiophysics at that time. It is likely that the Group's early success in both solar and cosmic research and the wealth of discoveries that were still being made meant that they were reluctant to pursue a new and more speculative area of research.

Immediately after he was advised of Ewen's detection of the H-line at Harvard, Wild determined to update and publish his theoretical overview, and this appeared the following year in the *Astrophysical Journal* (Wild 1952) and was used thereafter as a standard reference for Australian H-line work. Much of the content of Wild's paper remains in accordance with modern theory. Perhaps the one exception to this, as noted by Sullivan (1982: 300), is that Wild concluded that the 21-cm emission would be the only detectable hydrogen emission-line and that it would be unlikely that the higher-order recombination lines would be detectable.

4 Concluding Remarks

Although well known for his contribution to solar radio astronomy (Stewart et al. 2011), Paul Wild also made a significant theoretical contribution through his review of the atomic structure of hydrogen and the potential for radio frequency emission lines. This theoretical work provided a solid foundation for the future exploration of the H-line by scientists from the Division of Radiophysics, first at Potts Hill field station (see Wendt et al. 2011b), then at Murraybank field station (Wendt et al. 2011a) and finally with the 64-m Parkes Radio Telescope (e.g. see Robertson 1992).

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An Overview of W.N. Christiansen's Contribution to Australian Radio Astronomy, 1948–1960

Harry Wendt, Wayne Orchiston, and Bruce Slee

Abstract In 1948, an accomplished industrial physicist who had harboured a long-term ambition to become an astronomer joined the newly-formed Radio Astronomy Group in the CSIR's Division of Radiophysics in Sydney, Australia. Thus, W.N. ('Chris') Christiansen (1913–2007) began a new career in the fledgling field of radio astronomy. This paper reviews Christiansen's contribution to both instrumentation development and scientific research during the first phase of his career in radio astronomy, covering his work at the Potts Hill and Fleurs field stations prior to his resignation from the Division of Radiophysics in 1960.

1 Introduction

The beginnings of radio astronomy in Australia has been described by a number of authors (e.g. Bowen 1984, 1988; Christiansen 1984; Mills 1988; Orchiston and Slee 2005; Pawsey 1956, 1961; Roberts 1954; Robertson 1992; Sullivan 2005; Wild 1972). The post-war application of the CSIRO Division of Radiophysics to peace-time research included the investigation of "… extra-thunderstorm sources of noise (thermal and cosmic)." (Bowen 1945: Section 1.2). The team within Radiophysics undertaking this research was lead by J.L. (Joe) Pawsey. They made significant early progress and by 1948 were known as the Solar Noise Group. It was this group that W.N. (Chris) Christiansen joined in 1948 after a successful career as an industrial physicist who had worked most notably on broadcast aerial design.

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This paper reviews Christiansen's contribution to radio astronomy over the period he worked at Radiophysics (1948–1960).[1]

2 Background

Wilber Norman Christiansen was born in Melbourne, Australia on 9 August 1913 (Chrompton 1997). He attended the University of Melbourne where he graduated with an M.Sc. (First Class Honours) in Physics in 1935. After graduation he worked for 2 years at the Commonwealth X-ray and Radium Laboratory before joining Australian Wireless (Australasia) Ltd. (AWA) in 1937. During his time at AWA he became expert in antennae design.

In 1948, Christiansen was recruited into a senior role within Radiophysics, filling a vacancy created by Fred Lehany's transfer to the Division of Electro-technology (Bowen 1948). Christiansen had long harboured a desire to be an astronomer (Sullivan 2005: 14) and had earlier expressed an interest in joining the Solar Noise Group (Chrompton 1997).

Prior to his transfer, Lehany had been working with Don Yabsley at the Georges Heights field station (Figure 1: Location 8) on daily 200, 600 and 1,200 MHz measurement of solar radiation using a 16×18-ft ex-experimental radar aerial (Figure 2). This equipment had been constructed for the cancelled 1947 solar eclipse expedition to Brazil (see Wendt et al. 2008a). In late 1947, Lehany and Yabsley had also become interested in exploring the limb-brightening effect that had been predicted by D.F. Martyn (1946). Verification of limb-brightening had been one of the original objectives of the eclipse expedition. Lehany and Yabsley had decided to use a pair of WWII surplus TPS-3 antennas (Figure 3) in a Michelson interferometer configuration operating at 600 MHz to try and detect the limb-brightening effect (Kerr 1948a).

Christiansen joined the Solar Noise Group as a Senior Research Officer replacing Lehany. He entered Radiophysics on the same level as Lindsey McCready who had been the senior member of the Solar Noise Group until this time, and was second only in seniority to Jack Piddington who had been a wartime member of the Division of Radiophysics (see Minnett 1999).

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[1] One of the authors of this paper (B.S.) working at the Division of Radiophysics throughout the period that Christiansen was there, and was familiar with his work, although he was never a member of the Solar Group. Another author of this paper (W.O.) joined Radiophysics a year after Christiansen had transferred to the University of Sydney, but as a member of the Solar Group, and through operating the Chris Cross, he soon became aware of Christiansen's seminal role in developing solar radio astronomy between 1948 and 1960.

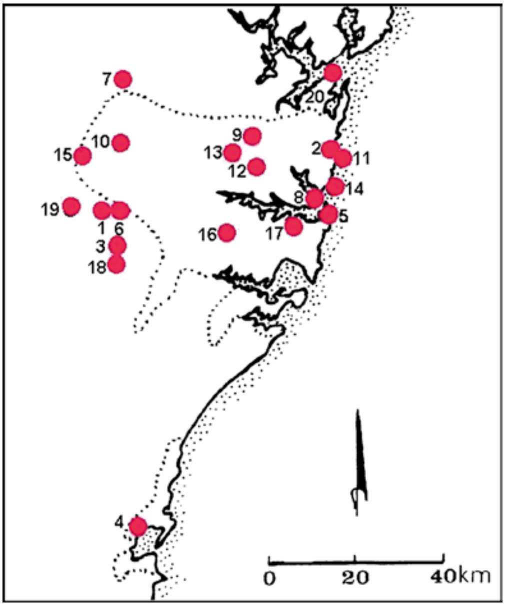


Fig. 1 The Radiophysics field station sites in the Greater Sydney-Wollongong regions. These were Badgerys Creek (1), Collaroy (2), Cumberland Park (3), Dapto (4), Dover Heights (5), Fleurs (6), Freeman's Reach (7), Georges Heights (8), Hornsby Valley (9), Llandilo (10), Long Reef (11), Marsfield (12), Murraybank (13), North Head (14), Penrith (15), Potts Hill (16), the Radiophysics Laboratory in the grounds of the University of Sydney (17), Rossmore (18), Wallacia (19), West Head (20). The *dotted outline* shows the current approximate boundaries of Greater Sydney and Greater Wollongong (after Orchiston and Slee 2005: 121).

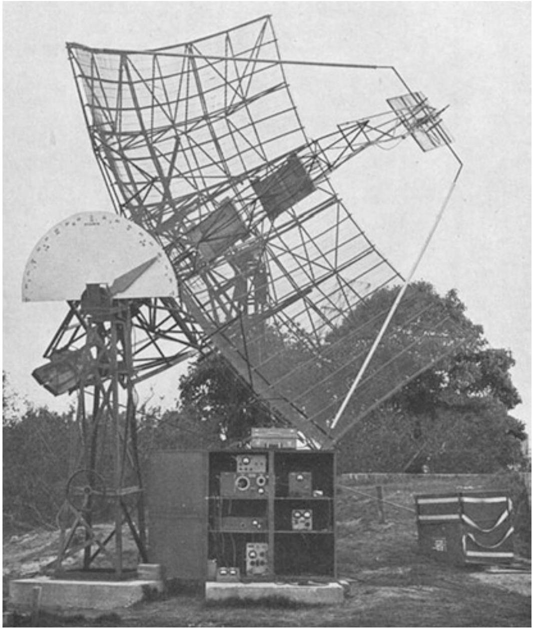


Fig. 2 The ex-experimental 16 × 18-ft radar aerial at Georges Heights field station (courtesy: ATNF Historic Photographic Archive).

Fig. 3 A TPS-3 aerial on an improvised mount at Georges Heights field station in 1948 (courtesy: ATNF Historic Photographic Archive).

3 Georges Heights Field Station

Christiansen's immediate task on joining Radiophysics was to take over the solar monitoring program at Georges Heights (see Lehany and Yabsley 1949; Orchiston 2004a). The original mounting of the 16×18-ft aerial was not suitable for daily tracking of the Sun and it was decided it would be necessary to construct a new equatorial mount.

Yabsley continued with the experiments to look for limb-brightening using the TPS-3 aerials. In February 1948, he reported that measurements using two different aerial spacings had begun using the two TPS-3 aerials. These had been recovered in 'chicken-wire' and installed on improvised mounts (Kerr 1948b). By July 1948 he reported that he was still working on the calibration of the system and had now also started work on a 1,200 MHz feed system for the TPS-3 (Kerr 1948c). By August 1948, Yabsley reported that good progress had been made observing at 600 MHz and 1,200 MHz using the spaced TPS-3 aerials. He proposed a "… very tentative …" abstract for future publication:

> It is shown that the form of distribution of the intensity of radiation from different parts of the Sun can be deduced from the degree of interference between rays received at the two aerials as the Sun moves relative to them. It is concluded that a pronounced limb-brightening effect is present at these frequencies, the bulk of the energy originating from the rim of the solar disk. It is also shown that there is a change in the depth of interference pattern when sunspot groups are present on the face of the Sun and it is concluded that this is due to enhanced thermal radiation from the region of the sunspots. (Yabsley 1948).

Yabsley noted that considerable experimental work was still necessary to support these conclusions. He also noted that it might be possible to use the 1 November

1948 partial solar eclipse to help confirm these results although his preference was to continue with the spaced-aerial experiment.

At the September 1948 meeting of the Radiophysics Propagation Committee (the forerunner to the Radio Astronomy Committee), it was decided to take advantage of the opportunity presented by the upcoming partial solar eclipse that would be visible in south-eastern Australia on 1 November 1948. It was agreed at this meeting to mount a series of experiments. Piddington proposed conducting high frequency measurements from the roof of the Radiophysics Laboratory and from the newly-established field station at Potts Hill (Figure 3: Location 16) where Payne-Scott and Little had set up their Swept-lobe Interferometer (see Little and Payne-Scott 1951). Bolton proposed measuring the intensity distribution and polarisation at 100 MHz with two crossed pairs of Yagi aerials at a remote site in Strahan in Tasmania, and Christiansen proposed that as the eclipse would occur close to sunset in Sydney, observations from other remote sites should be considered. He favoured performing measurements at 600 MHz at two remote sites while simultaneously observing at 600 and 1,200 MHz using the 16 × 18-ft aerial in Sydney. At the same time a decision was made to close down observations at the Georges Heights field station and to relocate the 16 × 18-ft aerial to Potts Hill and to use the TPS-3 aerials for the 600 MHz measurement at the remote sites. This effectively put a hold on further work by Yabsley on trying to use spaced interferometer measurements to determine limb-brightening.

4 Potts Hill Field Station

4.1 The 1948 Solar Eclipse

The Potts Hill field station was established in 1948 (Wendt 2008; Wendt et al. 2011), and later that year when Christiansen relocated the 16 × 18-ft aerial there and installed it on a newly-constructed equatorial mount (Figure 4) in time for observation of the 1 November 1948 eclipse.

The eclipse observations at Potts Hill were undertaken by Bernard Mills who had also recently joined the Solar Noise Group. This was his first, and as it turned out, his last experiment in solar radio astronomy. Christiansen led observations at a remote site in Rockbank in Victoria and Yabsley led a team at Strahan in Tasmania where he was joined by Bolton and Stanley.

The primary goals of the observations at 600 MHz were:

1. To determine the accurate distribution of radio brightness over the solar disk;
2. To pin point the location of localised radio-emitting regions; and
3. To look for possible polarisation effects that were predicted to be associated with the Sun's magnetic field.

By conducting observations at three dispersed sites it was possible to triangulate position estimates for sources on the solar disk. The three sites gave six possible intersecting arc solutions for any observation, three on entry and three on exit from

Fig. 4 The 16 × 18-ft antenna on its new equatorial mount at Potts Hill field station. A TPS-3 aerial is visible in the *right* foreground (courtesy: ATNF Historic Photographic Archive).

the eclipse. Both Strahan and Rockbank had full visibility of the eclipse. At Potts Hill, sunset occurred before the last contact of the Moon's disk (i.e. the fourth contact point). Based on the observations it was found that in a number of cases the radio sources accurately corresponded with the location of sunspot groups (Figure 5).

No definitive results were achieved for detection of limb-brightening or any possible effect of a general magnetic field.

The detailed results of the eclipse observations were published in the *Australian Journal of Scientific Research* (Christiansen et al. 1949a), but a summary also appeared in *Nature* (Christiansen et al. 1949b). The success of these observations in his first major research program helped quickly establish Christiansen's reputation within Radiophysics, but also enhanced Radiophysics' reputation worldwide (see Orchiston 2004c; Orchiston et al. 2006; Wendt et al. 2008a).

4.2 The Inspiration for the Grating Array

In April 1949 Christiansen was appointed Secretary of the Solar Noise Committee and at the same meeting the Committee's name was formally changed to the Radio

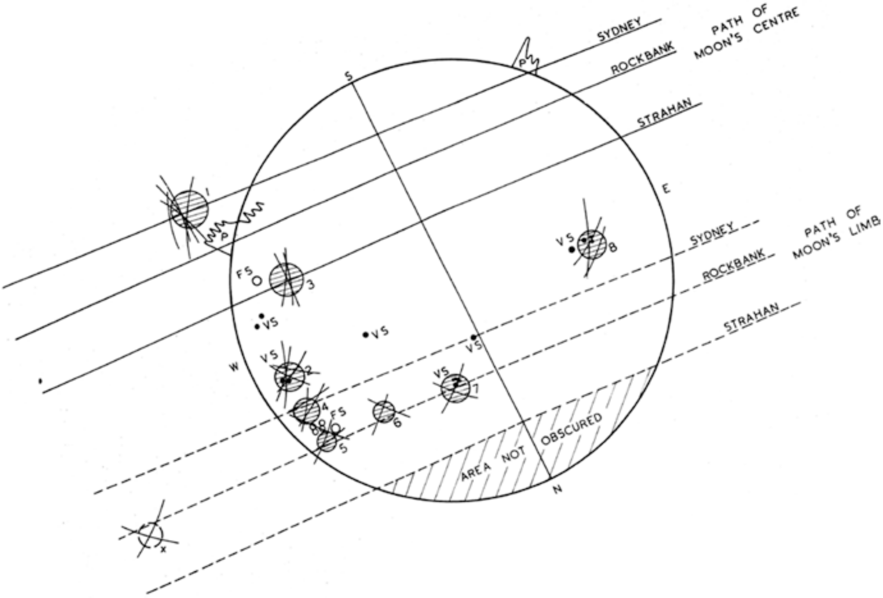


Fig. 5 The location of radio sources on the solar disk. VS = visible sunspot, FS = position of a visible 27 days earlier sunspot, P = solar prominence (after Christiansen et al. 1949a: 513).

Astronomy Committee (Christiansen 1949a). He held this position until October 1951, when Ron Bracewell took over the duties of Secretary.

Following the successful 1948 eclipse observations Christiansen's attentions returned to setting up the 16 × 18-ft aerial control system so that daily observations at 200, 600 and 1,200 MHz could be performed. Yabsley continued to work on the TPS-3 aerials building circularly-polarised feeds for the 1,200 MHz receiver. He also worked on converting the a.c. power supplies to d.c. as sufficient stability could not be achieved with the a.c. supplies (Christiansen 1949a). By June 1949, it was decided to construct polar mounts for the TPS-3 aerials.

The summary paper of the 1948 eclipse results was sent to *Nature* in June 1949 and attention now turned to the next eclipse that was due on 22 October 1949. Given the success of the 1948 observations it was again decided to use the TPS-3 aerials at remote sites and once again this put a hold on Yabsley's limb-brightening observations. A sub-committee was formed to plan the 22 October Eclipse observations comprising Piddington (Chair), Harry Minnett, Don Yabsley and Christiansen.

In July 1949 Yabsley reported that an attempt would be made to obtain a plot of galactic radiation at 200, 600 and 1,200 MHz between 30°N and 30°S using the 16 × 18-ft aerial. This was its first application outside of solar research.

Although observations of the 22 October 1949 eclipse were successfully carried out at Sydney and the remotes sites at Eaglehawk Neck in Tasmania and Bairnsdale in Victoria, no results were ever published (see Wendt et al. 2008a).

Christiansen again returned to his solar monitoring program with the 16 × 18-ft aerial at Potts Hill. This time however, he agreed to give priority to Yabsley's limb-brightening observations using the TPS-3 aerials (Christiansen 1949b). In February 1950 in a letter to Ron Bracewell, Martin Ryle (1950) noted he was very interested to hear of the planned spaced-aerial work at 600 and 1,200 MHz to look for limb-brightening and particularly if a "Fourier analysis" was being used. He noted that H.M. Stanier (1950) performed this experiment at 600 MHz and detected no limb-brightening. It was around this time that the initial idea for the construction of the solar grating array occurred to Christiansen.

Christiansen (1984: 117) has stated that he had been frustrated by waiting for solar eclipse events and that he was seeking a way to perform high resolution observations on a more frequent basis. Clearly the spaced TPS-3 aerials acting as a Michelson interferometer presented such an opportunity, but it was at this time the inspiration for a new aerial configuration occurred to him:

> The idea occurred while reading a description of Bernard Lyot's optical filter in which narrow frequency pass-bands are produced at widely different frequencies. This may seem particularly indirect when the analogy which is more obvious is the optical diffraction grating, but to me as an antenna designer the cos n.cos 2n.cos 4n series of the Lyot filter (see Figure 6) immediately suggested an antenna array and an array of arrays. (Christiansen 1984: 118).

Christiansen had devised an approach that was analogous to a diffraction grating. He realised that by using a number of aerials arranged in a straight line, at a uniform spacing, the combined response of the array would produce multiple beams which would be separated from each other proportionally as the inverse of the spacing between aerials. As such, the array could be configured so that only one of the response beams could be positioned on the Sun at any given time.

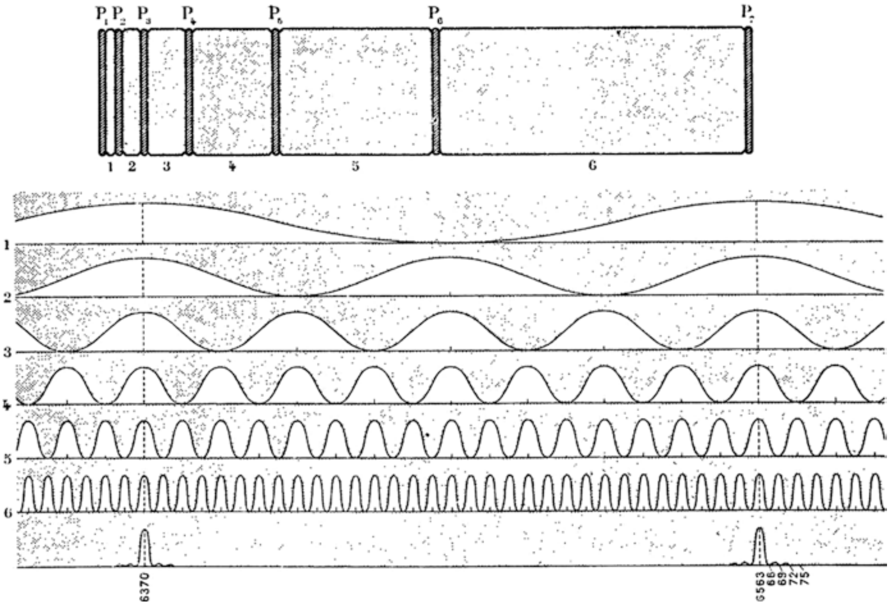


Fig. 6 Diagram illustrating the narrowband response as a result of six optical filters (after Lyot 1944: Figure 1).

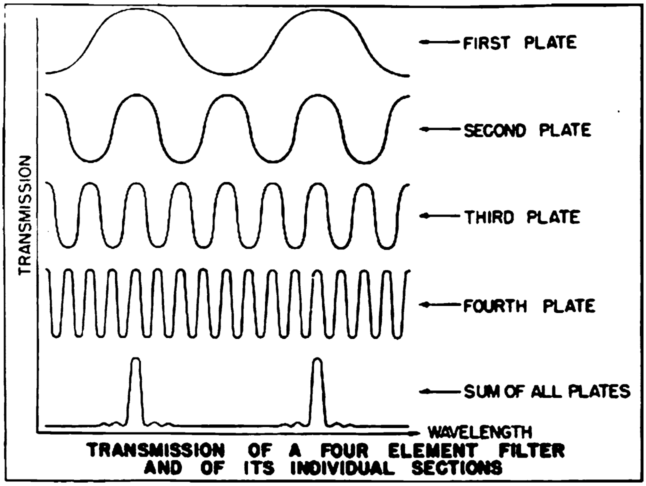


Fig. 7 A slide from Billings' presentation at the 29 December 1946 meeting of the American Astronomical Society (courtesy: National Archives of Australia).

Although not referred to directly by Christiansen in his recollections, it seems likely that he would have been examining Lyot's (1944) paper in the context of a proposal that was first raised by Ruby Payne-Scott (1947) for the acquisition or construction of a spectroheliograph to investigate optical correlations with the solar radio observations. There is a great deal of correspondence on the topic in the Radiophysics archives files during this period. Of particular note is a copy of a paper by Bruce Billings (1946) that had been presented at a meeting of the American Astronomical Society on 29 December 1946. This paper dealt with a tuneable narrowband optical filter and referenced Lyot's earlier paper on the topic. The paper contained a slide (Figure 7) showing the transmission of a four element filter with the resultant narrowband response as illustrated in Lyot's paper and is again analogous to Christiansen grating interferometer.

Christiansen first presented the idea for his 'Multi-Beam Interferometer' to the Radio Astronomy Committee meeting of 4 July 1950 (Christiansen 1950). Shortly after this Yabsley decided to leave the Radio Astronomy Group to work on the development of air navigation technology (Distance Measuring Equipment), and the results of the 600 and 1,200 MHz limb-brightening observations were never published.

In England, Stanier's (1950) use of a two element interferometer to determine the radio brightness distribution over the Sun proved the first practical application of the Fourier imaging technique that had first been suggested by Pawsey, Payne-Scott and McCready in 1946. In doing so, Stanier made the simplifying assumption that the Sun was circularly symmetrical so that the distribution could be calculated from one scanning angle, but this also implied that all the components of the interference pattern were even (cosine) and therefore only the amplitudes and not the phases of the interference fringes needed to be measured. The use of the circular-symmetry assumption, and also the likely presence of localised active regions on the solar disk during observations, meant that Stanier did not detect the limb-brightening effect. It was not until much later that P.A. O'Brien and E. Tandberg-Hassen (1955) used a two-element interferometer at a variety of spacings and observing angles to calculate a two-dimensional brightness distribution based on the amplitude plot of the interference fringes and hence detected limb-brightening.

In July 1950, Jim Hindman joined Christiansen at Potts Hill to take on the systematic recording of solar noise using the 16 × 18-ft aerial and two smaller aerials that had been used in previous eclipse observations. With the design of the solar grating array underway, Christiansen took the opportunity to write up the findings from the long-term solar monitoring program that had been conducted at a variety of frequencies. Drawing on optical data from Mount Stromlo, daily sunspot area records could be used for comparison with the effective temperatures observed at each frequency. This allowed Christiansen and Hindman (1951) to look for correlations and their results were published in *Nature*.

In an earlier analysis, Pawsey and Yabsley (1949) had indicated that the thermal emission associated with the quiet Sun may be subject to longer-term variation in the course of the sunspot cycle. This type of change had been predicted by van de Hulst (1949) based on observations of a decrease in electron density of the corona toward the minimum in the sunspot cycle. The sunspot cycle had peaked in 1947. This change in the cycle provided an ideal opportunity to examine if there were associated changes during the decline in the solar cycle.

During the period 1947–1950 there was almost a 50% decline in sunspot numbers as the cycle moved past its peak. Leading up to 1950, while the average sunspot areas declined, there appeared to be no significant decline in the base level temperature as measured in the scatter plots. There was, however, a significant decline in the slope of the line of best-fit indicating that the rate of temperature changes with sunspot area had significantly declined. This decline in the rate of change of temperature with sunspot area was observed across all frequencies (i.e. 600, 1,200, 3,000 and 9,428 MHz).

At the 1950 USRI Conference, Covington had reported that he had observed a 20% drop in the base level temperature at 600 MHz between 1947 and 1950. This same decline had not been observed in Australia. However, during 1950 a marked drop became apparent at 600, 1,200 and 3,000 MHz. No change was apparent at either 9,428 MHz or at 200 MHz (that was being observed on a daily basis at Mount Stromlo). The decline was most pronounced at 1,200 MHz. Figure 8 is a reconstruction of the observations at 1,200 MHz for three different periods in 1950. This shows the decline in the base level from an average of 2.3×10^5 to 1.4×10^5 K, a decrease of nearly 40%. Christiansen and Hindman noted that these observations were consistent with van de Hulst's predictions.

During this period, Christiansen was also involved as the lead author on a paper that presented the results of multi-frequency analysis of large solar outbursts that occurred on 17, 21 and 22 February 1950 (Christiansen et al. 1951). These observations were supplemented by a range of other data and included measurements of the short-wave radio fadeout in Sydney of the Brisbane radio station VLQ-3 broadcasting at 9.6 MHz, sunspot and solar flare observations from Mount Stromlo, flare observations from the Carter Observatory in Wellington, New Zealand, and

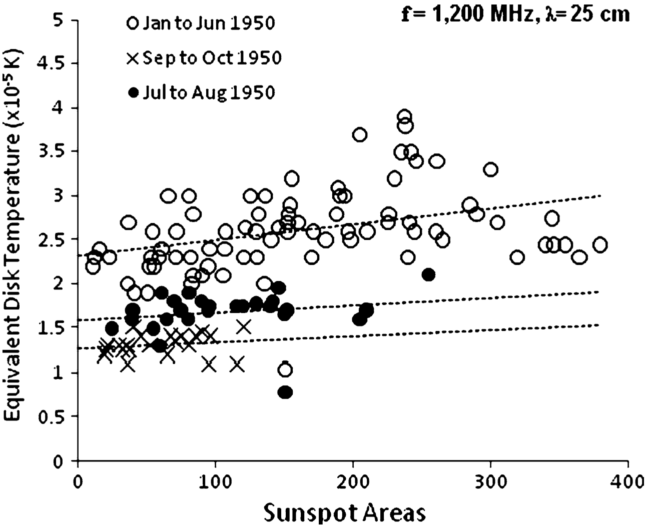


Fig. 8 Plot of 1,200 MHz sunspot area versus apparent temperature showing lines of best fit and base temperature changes for three different periods in 1950.

from Kodaikanal Observatory in India, and magnetograms from the Watheroo Magnetic Observatory in Western Australia. This study demonstrates the increasing cooperative approach being undertaken with other solar astronomy groups both domestic and international.

4.3 The E–W Grating Array

The construction of the E–W Solar Grating Array commenced in July 1950 (Christiansen 1950; Wendt et al. 2008b). The array consisted of 32 aerials evenly spaced at 23-ft intervals along an east–west baseline of 700-ft located on the southern end the northern reservoir at Potts Hill (Figure 9).

Keeping the cost of the design to a minimum level was of prime concern to Christiansen. He was given permission by Bowen and Pawsey to construct the array provided that the material cost for construction could be kept under £500 (Christiansen 1984: 118), although on a different occasion Christiansen recalled that the cost needed to be kept below £180 (Bhathal 1996). The mechanical design of the array was entrusted to Keith McAlister, who proved extremely resourceful in meeting the cost target.

The aerials were constructed in the Radiophysics workshop in the grounds of Sydney University. The array was then assembled at Potts Hill by Radiophysics staff, including two new graduate recruits, Joe Warburton and Rod Davies. These two young scientists used a theodolite to align a series of 32 wooden posts, and Davies (2005: 94) later noted: "At that time we didn't know that Ph.D. meant Post-hole Digger!"

Fig. 9 The 32-element array at Potts Hill (courtesy: ATNF Historic Photographic Archive).

Each aerial consisted of a 66-in. solid parabolic reflector plate. A dipole receiver and reflector were mounted at the prime focus. In this form all of the aerials were horizontally polarised. To observe circularly polarised radiation the aerials could be configured so that alternate aerial dipoles were set horizontally and vertically so that there was a 90º phase shift between pairs. Each aerial was equatorially mounted and could manually be stepped in right ascension via a series of holes in the mounting post and a locking peg to allow tracking of the Sun. During observations the aerial positions were changed approximately every 15 min. This involved someone running down the length of the array and adjusting each of the 32 elements by hand!

The aerials were combined by a branching system of transmission lines. To keep costs down, the transmission lines were a braced open-wire system separated by a ¼λ and supported by polystyrene insulators and spacers (see Figure 10).

To achieve the branching configuration the transmission-lines were stacked vertically in five levels and connected via short vertical connectors. Figure 11 shows a schematic of the transmission-line system.

The use of the open-wire branching system allowed the electrical length of the transmission line to be adjusted so that all of the interference components were added in the correct phase eliminating the subsequent need to measure the phases of the various components as would be necessary in an aperture synthesis technique.

The array produced a series of fan-shaped beams which had a calculated beam width of 2.9′ at 1,410 MHz. The spacing between beams was 1.7º and since the diameter of the radio Sun at this frequency was ~0.5°, this meant that the Sun could

Fig. 10 The array showing the bracing weights for the open-wire transmission lines (courtesy: ATNF Historic Photographic Archive).

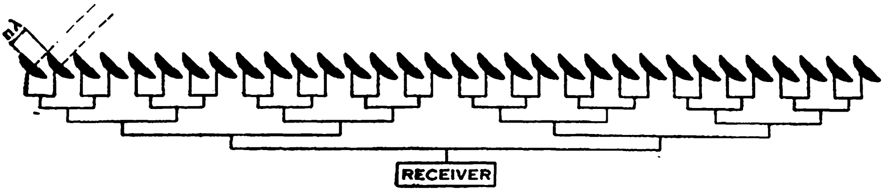


Fig. 11 Schematic diagram of the branching transmission lines on the 32-element solar grating array (after Christiansen and Warburton 1953a: 192).

only be in one of the fan-beams at any one time. Figure 12 shows the beam response produced by the array.

A superheterodyne receiver was connected to the array transmission-line via a radio-frequency switch that contained a rotating condenser which switched the signal at a rate of 25 Hz between the transmission-line and a dummy load. The modulated signal was then passed to a crystal detector which was coupled to a line-tuned heterodyne-oscillator and a 30 MHz amplifier with a 4 MHz bandwidth. After the 30 MHz amplification was a further detector, a 25 Hz amplifier and a phase sensitive detector. This then fed a recording milli-ammeter. A typical output of the recording is show in Figure 13.

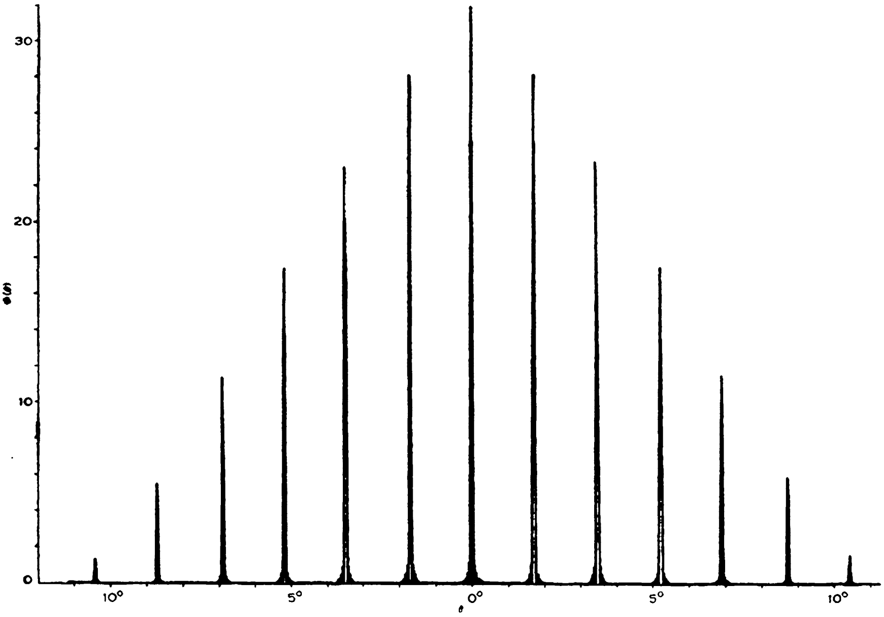


Fig. 12 Beam response diagram for the 32-element array. The power received from the source is shown on the Y-axis and the direction of the source relative to the array beam, on the X-axis (after Christiansen and Warburton 1953a: 192).

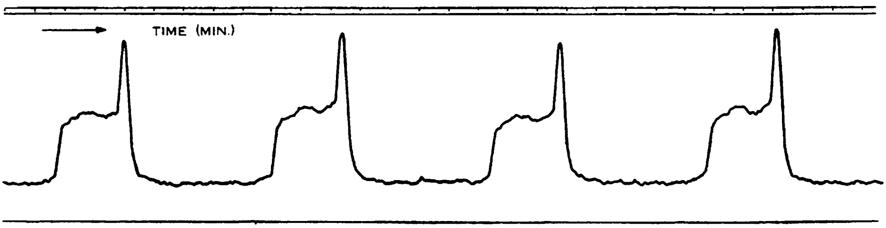


Fig. 13 An example of the output recording showing the passage of the Sun through several beams of the array (after Christiansen and Warburton 1953a: 193). In this example a strong localised source of emission is present near the right-hand limb of the Sun.

When the array was configured to measure polarisation the output recording characteristic would change. For linear or randomly polarised radiation, successive records would be substantially similar in strength as shown in Figure 13. For circularly polarised radiation successive records would show a diminished response depending on the strength of polarisation.

The E–W Solar Grating Array became operational in February 1952 and was used to make daily observations of the Sun. This was generally done by observing over a 2 h period centred on midday. By August 1952, Christiansen reported at the

Radio Astronomy Committee meeting that limb-brightening was clearly evident from the observations and that a base-level and enhanced emission from sunspots was also apparent (Bracewell 1952).

4.4 The H-Line Detection

On 25 March 1951 H.I. Ewen who was working on his Doctoral thesis in the Lyman Laboratory at Harvard University detected the 21-cm emission line of neutral hydrogen (Ewen and Purcell 1951). In a remarkable coincidence, the Dutch radio astronomer, Hendrik van de Hulst, who had postulated the existence of the H-line during WWII, was visiting Harvard at the time and discussed the detection with Ewen and his supervisor E.M. Purcell. Van de Hulst indicated that a Dutch group under Oort and Muller had been attempting to detect the H-line for some time. By Ewen's own account (2003) he was unaware of the Dutch group's work and had dismissed the possibility of the Dutch actively pursuing a detection because he had interpreted van de Hulst's comments in his original paper as indicating that a detection was highly unlikely. In fact, Ewen believed that if any group would undertake a detection attempt it would be from the Soviet Union on the basis of I.S. Shklovsky's independent prediction (1949), with which Ewen was familiar.

Also visiting Harvard University at this time was Frank Kerr from the Radiophysics Laboratory in Sydney (Kerr 1984: 137). Kerr was on a fellowship to Harvard to undertake graduate studies in astronomy at the Harvard College Observatory under Donald Menzel, and on 17 March 1951 he wrote Joe Pawsey in Sydney drawing his attention to the fact that two groups had already made unsuccessful attempts to detect the H-line (Kerr 1951). At that time Ewen had yet to make a detection, and Owren at Cornell University, who was using an 8-ft parabola and a receiver similar to Ewen's but with less sensitivity, had also been unsuccessful. On making the initial discovery on 25 March 1951 Purcell and Ewen shared details of their observations with the Dutch group and were keen to obtain an independent confirmation of the detection. Kerr sent Pawsey an airmail letter on 30 March 1951 alerting him to the discovery and asking if the Sydney group could assist in the confirmation, even though no prior work had been conducted by Sydney (Wendt et al. 2008c). The letter included a hand-drawn sketch of the H-line response on Ewen's receiver (Figure 14). In a letter dated 20 April 1951, Pawsey wrote to Purcell saying that because of the "… great potentialities…" he had assigned two separate Radiophysics groups to attempt the independent detection and they were optimistically hoping to get results "… in a few weeks". He also enquired as to the processes that would be used for publication of the discovery and suggested that they would privately communicate any detection and then publish a confirmation note at the time Ewen and Purcell decided to publish their result.

In his letter to Purcell, Pawsey referred to two independent groups working on attempting a confirmation. A meeting was held on 12 April to coordinate the activities of the Radiophysics Group in attempting a confirmation observation. In attendance

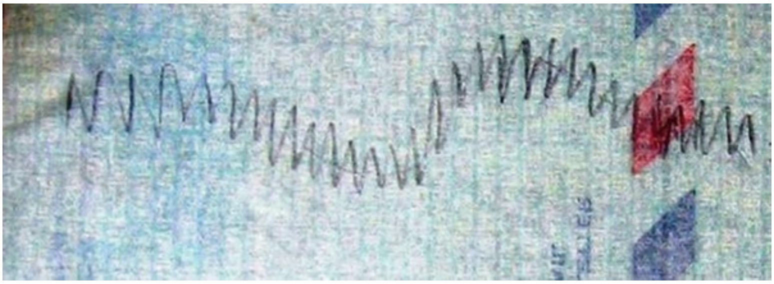


Fig. 14 Hand-drawn sketch by Kerr of the H-line response detected by Ewen, included in a letter to Pawsey dated 30 March 1951 (courtesy: National Archives of Australia – 972420 – C3830 – A1/3/17 Part 1).

at this meeting were Pawsey, Higgs, Piddington, Christiansen, Wild and Bolton. The minutes recorded:

> It was agreed that parallel investigations to check detectability of lines were desirable in order to obtain independent checks but that, in order to avoid cut-throat competition, the groups who were experimenting in the same field, e.g. Piddington, Christiansen and Wild, should consider themselves, at least on the 1,420 Mc/s line, as a single group and possible publication should be joint.
>
> Wild outlined the theoretical results he had obtained (mainly in RPL. 33 and 34). The chief point of interest is the existence of fine-structure lines at 10,905, 3,231 and 1,363 Mc/s with "inherent" line widths of the order of 100 and 20 Mc/s respectively.
>
> It was agreed to recommend Wild to write up this material for publication.
>
> Christiansen and Bolton outlined schemes for attempting to detect the 1,420 Mc/s line with which they were proceeding (also corresponding deuterium line). They hope to have equipment for tests to start in a week or so.
>
> Piddington outlined a different scheme with which he was proceeding. (Pawsey 1951a).

Orchiston and Slee (2005: 139) have stated that Christiansen and Hindman worked independently at the Potts Hill field station before they discovered they had both been tasked by Pawsey to work on the same problem. This is likely a reference to the early parallel work by Piddington and Christiansen. At the time Hindman was working for Piddington. It is unlikely that they did not know about each other's work, but rather this was a deliberate strategy as the minutes of the 12 April meeting reflect. After a short period, Christiansen took the leadership of the group with support from Hindman. It is unclear when Bolton's detection attempts were abandoned. However, in 1953–1954, an unsuccessful attempt was made by Gordon Stanley and R. Price at Dover Heights to detect the postulated deuterium line.

Purcell replied to Pawsey in a letter dated 9 May 1951. He welcomed the efforts of the Sydney group and provided further details of the detection and their receiving equipment. He also indicated that they intended announcing the discovery in *Nature* "… fairly soon …", but would allow time for a reply before proceeding. Pawsey replied in a letter dated 18 May 1951, saying that Christiansen would be, "… attempting the first observations tonight …" and that he would be away for the next fortnight and hence Christiansen would communicate directly if the attempt was successful, although he noted it would likely take several weeks. He also suggested that Ewen may wish to publish a detailed report in the *Australian Journal of Scientific Research*.

Christiansen and Hindman were able to construct a 'makeshift' receiver (1952b: 438) in a very short period through a great deal of improvision. The receiver was in principle similar to that used by Ewen, and by Muller and Oort in Holland. Coupling the receiver to the 16 × 18-ft paraboloid at Potts Hill Christiansen and Hindman were able to confirm the H-line detection. The minutes of the Radio Astronomy Committee of September 1951 record that the confirmation detection was made on 6 July 1951 (Christiansen 1951), only 15 weeks after the original discovery on 25 March 1951.

It is interesting to note Christiansen's (1954) own recollection:

> We knew when we started that our gear was so rotten it mightn't work at all. Without exaggeration it was held together with string and sealing wax; Pawsey said it kept going through sheer will power. To make matters worse sparrows kept nesting in the aerial. We were stuck out at Potts Hill reservoir and it rained like all hell all the time. After observing for 10 days, without any luck we got fed up and went home, leaving the machine switched on. The next morning we found what we were after sitting up on the chart.

Figure 15 shows an example of an H-line observation obtained by Christiansen and Hindman.

Ewen and Purcell's discovery was announced in the 1 September 1951 issue of *Nature* in a letter dated 14 June 1951. It appeared together with a confirmation paper by the Dutch group (Muller and Oort 1951) dated 26 June and a short cabled communication dated 12 July from Australia also confirming the detection of the H-line (Pawsey 1951b).

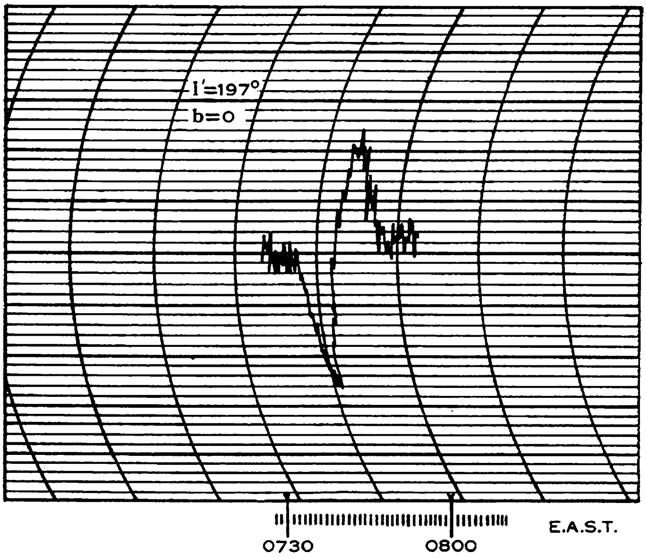


Fig. 15 Example of an H-line observation in the Taurus region (after Christiansen and Hindman 1952b: 444).

Pawsey (1951c) noted in a letter he sent to Bowen on 13 July 1951 advising of the confirmation:

> Christiansen has worked … [day and night] for the last two months. The line is really exceedingly weak and it is necessary to make the right compromises all along the way in order to make the spectrum line evident.

Following the initial confirmation, between June and September 1951 Christiansen and Hindman proceeded to make a preliminary survey of hydrogen emission in the southern sky. The detailed findings of their survey were published in the *Australian Journal of Scientific Research* (Christiansen and Hindman 1952a), and a summary paper also appeared in *The Observatory* (Christiansen and Hindman 1952b).

By taking a series of measurements in progressive steps of right ascension they were able to obtain a series of profiles by declination. Figure 16 shows an example of a series of records taken along the Galactic Equator.

From these individual records, the maximum deflection could be measured and hence a series of brightness intensities could be calculated. Figure 17 shows an example of the profile of peak brightness for declination +10°.

By combining these profiles a contour chart of peak brightness was constructed. A peak brightness corresponding to a brightness temperature of approximately 100 K was observed. Figure 18 shows the final contour map of hydrogen-line emission. From this map it was evident there were marked variations in the peak brightness along the Galactic Equator. Christiansen and Hindman noted that there were two likely causes of these variations. The first was due to line broadening caused by rotation of the Galaxy and the second, and more interesting possibility, was as the result of structural features such as the spiral arms. It is ironic that in the same year that the breakthrough discovery of a radio frequency emission line occurred the first optical evidence for spiral arm structures in our Galaxy was also published (Morgan et al. 1952; see also Sheehan 2008).

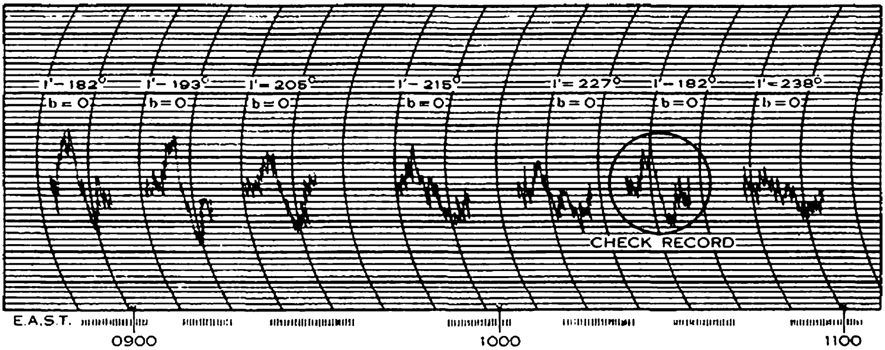


Fig. 16 A series of six records taken along the Galactic Equator. A check record was performed near the end of each observing run to test receiver stability (after Christiansen and Hindman 1952b: 445).

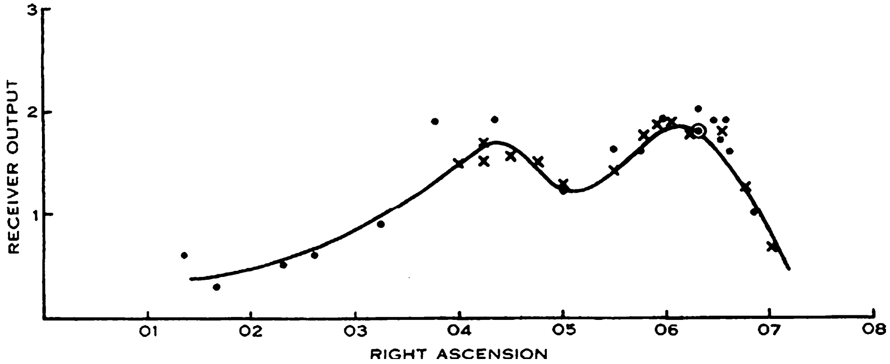


Fig. 17 Example of the peak brightness profile in a strip along declination +10° (after Christiansen and Hindman 1952b: 445).

Following the initial H-line survey, Christiansen returned to his solar observation program. By this stage Kerr had returned from Harvard and, together with Hindman, focused on the construction of a new and more reliable receiver and on the new 36-ft Transit Parabola for use in a dedicated H-line survey of the southern sky.

4.5 Solar Brightness Distributions

With the E–W Solar Grating Array now operational Christiansen's attention returned to the Sun. The distribution of radio emission across the solar radio source was of prime interest as it provided information on the structure, density and temperature of the solar atmosphere. Obtaining high angular resolution in early observations had relied on the use of solar eclipses which were clearly not practical for collecting a large pool of observational data. It was for this reason that Christiansen had decided to build a high-resolution radio telescope that could perform daily monitoring of the Sun. The high-resolution beams of the grating array produced a one-dimensional response scan across the solar disk at 1,410 MHz. Figure 19 shows an example of the output of the Sun passing through the individual aerial beams. Using a succession of daily scans it was possible to determine how the one-dimensional profile changed over a number of days as the Sun rotated. Figure 19 shows the one-dimension brightness distribution on different days in October 1952.

One early finding that greatly simplified the observational analysis task was that the centre of the radio record corresponded with the centre of visual solar disk, and that bright areas near the limb did not materially change the size of the radio disk. By superimposing the individual scans over an extended period a base level for the radiation became clearly evident. This independent method probably provided the final tipping point toward conclusive evidence that a base level in fact existed. Figure 20 shows an example of 20 such superimpositions.

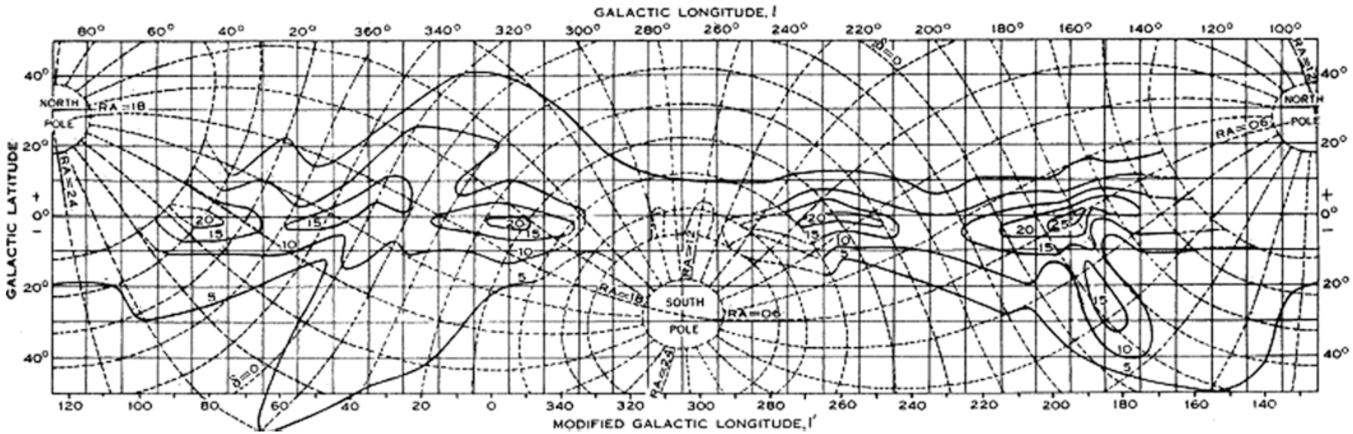


Fig. 18 Full sky contour map of hydrogen-line emission. The peak brightness of 25 units corresponds to a brightness temperature of approximately 100 K (after Christiansen and Hindman 1952b: 446).

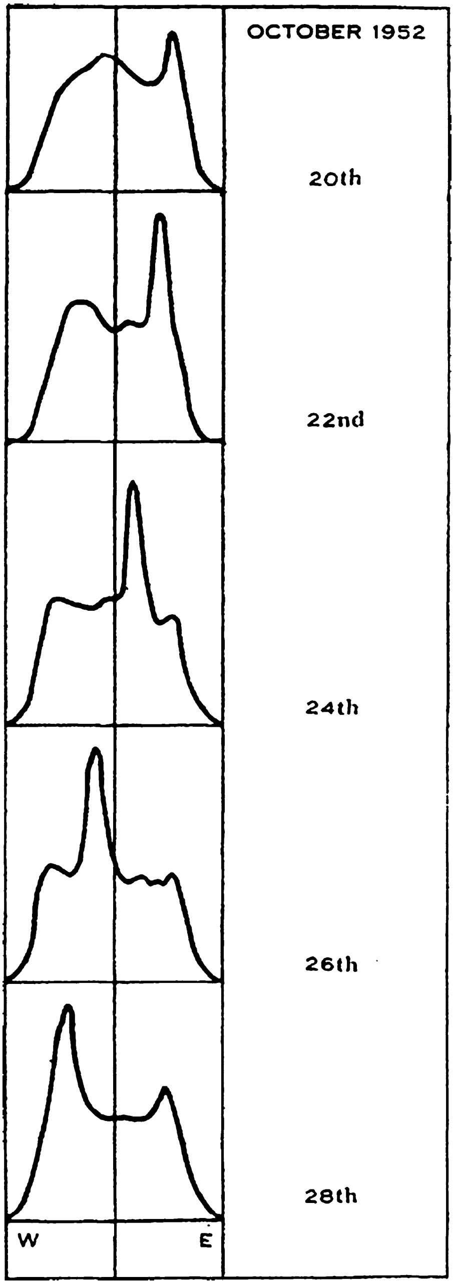


Fig. 19 Daily records of one-dimensional brightness distributions across the solar disk from 20 to 28 October 1952 (after Christiansen and Warburton 1953b: 198).

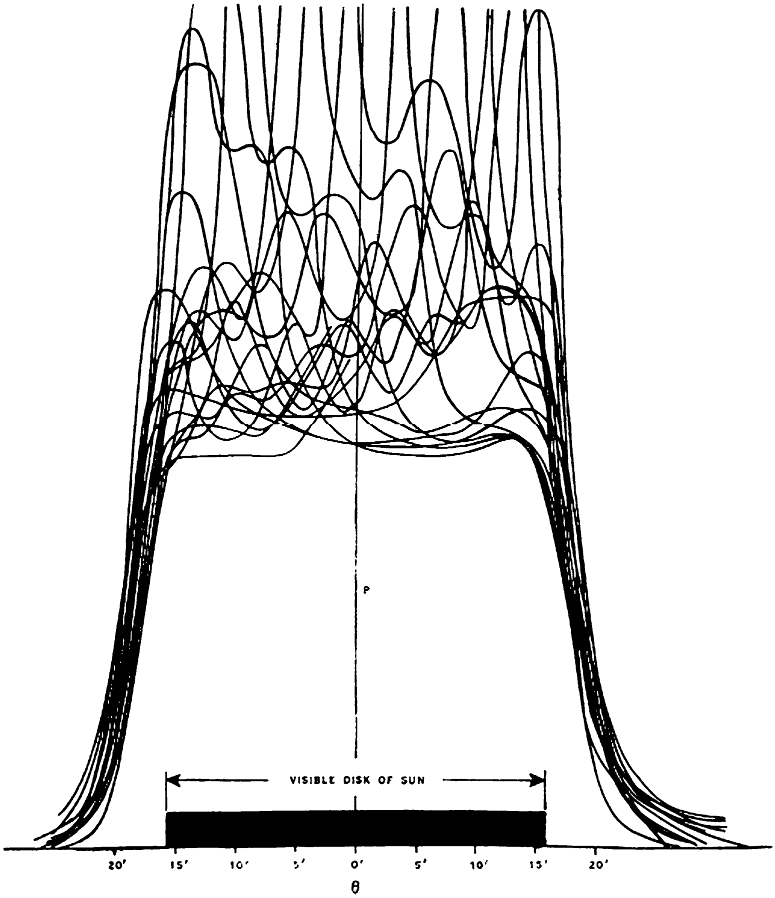


Fig. 20 Twenty daily one-dimensional brightness distribution scans superimposed. The visual solar disk is indicated by the *black bar* on the x-axis (after Christiansen and Warburton 1953a: 200).

Christiansen and Warburton (1953b) used the superimposition technique to determine that the base level temperature of the Sun at 1,420 MHz was 7×10^4 K during the period of observations. Another factor that was clearly evident from the distributions was that the source of the radio emission was larger than the optical solar disk. For simplicity a circular symmetry was assumed for the purposes of the analysis, although there were already indications that the distribution appeared more elliptical (as had already been determined from optical observations). Initially it was thought that the effect of this assumption would be small. However, it was fairly quickly recognised that taking into account the non-circular symmetry would be essential and this was to lead to the construction of the second (north–south) Solar Grating Array so as to allow two-dimensional scans (ibid.).

Even allowing for possible errors in the circular symmetry assumption, it was very clear from the observations that limb-brightening had been detected. Figure 21 shows the initial radial distributions based on the one-dimensional scans.

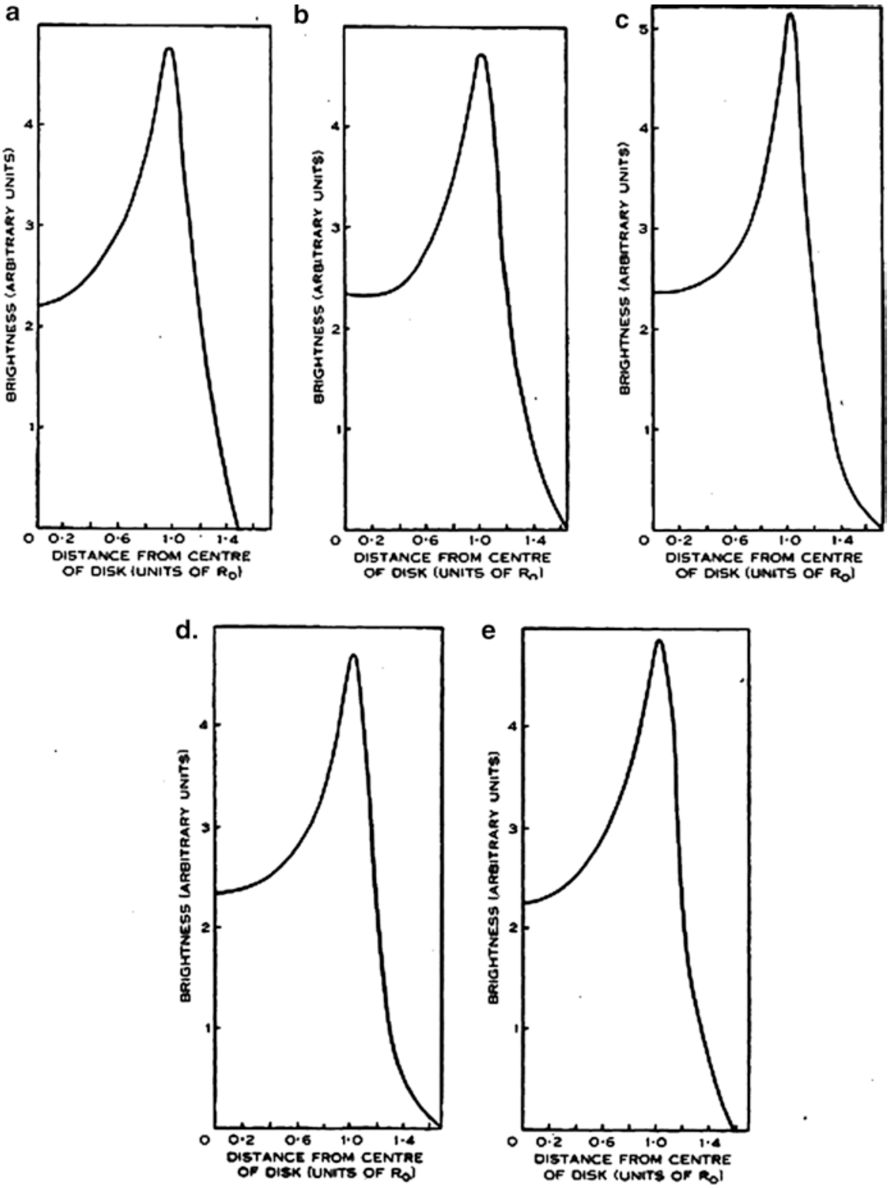


Fig. 21 Radial distributions of brightness across the solar disk based on one-dimensional scan observations (after Christiansen and Warburton 1953a: 268).

These distributions clearly show a limb-brightening effect as predicted in a number of different theoretical models, including one proposed by Radiophysics' Stefan Smerd (1950). Unfortunately, since the distributions were measured at only the one frequency it was not possible to determine exactly which parameters in the models best matched the observations, although they were consistent with Smerd's model for a 10^4 K chromosphere and a $0.3\text{–}3.0 \times 10^6$ K corona.

Christiansen realised that by using a second array arranged in a north–south direction the Sun could be scanned at a variety of angles. The Earth's rotation and orbit presented a very wide variety of angles for observations. By performing a Fourier analysis on the one-dimensional scans taken over a wide variety of angles it was possible to construct a two-dimensional brightness distribution of solar radiation. Although not widely acknowledged, this was the world's first application of Earth-rotational synthesis in astronomy (see Christiansen 1989).

To achieve these objectives, in 1953 a north–south array was constructed on the eastern side of the Potts Hill reservoir where the east-west array was located. The aerial design for this array was quite different. Instead of 32 elements, the N–S Solar Grating Array had 16 elements consisting of open-mesh parabola aerials mounted on much more robust equatorial mounts, as shown in Figure 22.

The array was also somewhat shorter than the E–W array being 760 wavelengths in length as opposed to the 1,028 wavelength of the East–West array. This meant that the aerial produced a slightly wider beam of 4′. The open transmission-line feeds were retained and can also be seen in Figure 22, with the E–W array in the distant background. Figure 23 shows an aerial view of the two arrays. This view is taken from the northeast looking southwest.

Daily observations were made using both arrays from September 1953 to April 1954 (Christiansen and Warburton 1955). By observing over a long period Christiansen and Warburton were able to make use of the seasonable variations of the Sun's orientation with respect to the two arrays. Thus, they were able to achieve

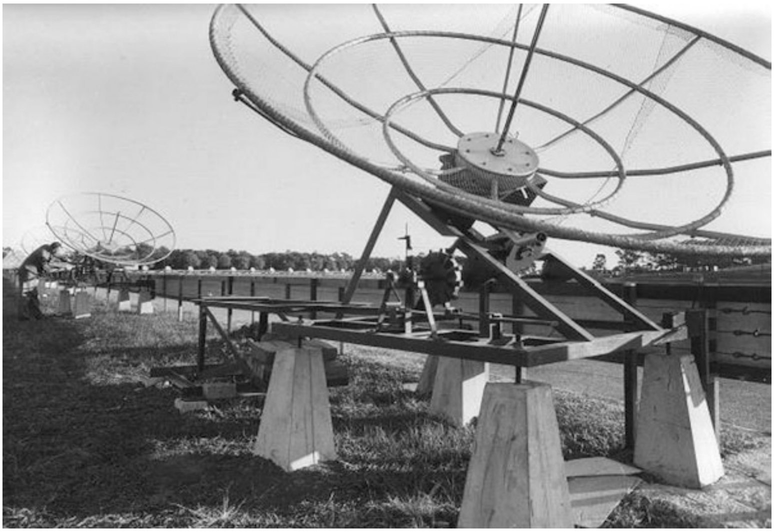


Fig. 22 Part of the North–South Array (courtesy: ATNF Historic Photographic Archive).

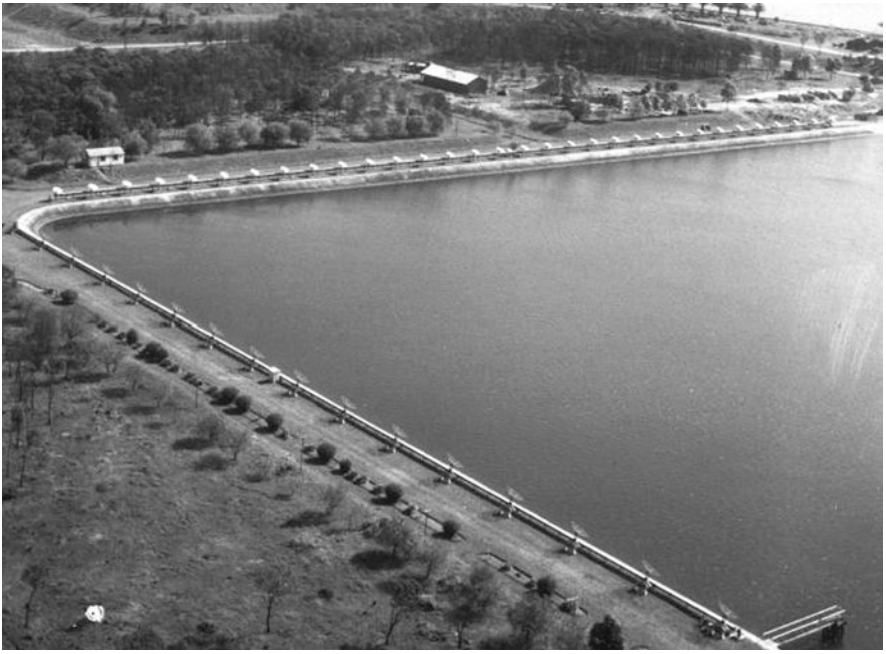


Fig. 23 Aerial view of the 32-element east–west and the 16-element north–south arrays (courtesy: ATNF Historic Photographic Archive: 3474–1).

coverage of 140° out of the 180° range of scanning angles. Figure 24 shows the result of a one-dimension scan taken at different times on a single day and thus achieving scans at different orientations relative to the Sun's axis of rotation.

In order to produce a two dimensional image, a cosine Fourier analysis of the individual one-dimensional distributions for the different scanning angles was performed. The numerical value for each scan was plotted radially corresponding to the direction of the scan and then strip integrated with the strip summations being perpendicular to the scan angle. The cosine Fourier transform of the strip integrals was then taken to give radial cross-sections of the brightness distribution. The final two-dimensional distribution was then constructed by plotting each of the radial cross sections and plotting contour lines joining points of equal intensity. This tedious process took months of calculation and plotting by hand to produce a single two-dimensional image as shown in Figure 25. For comparison, Figure 26 shows a photograph of the Sun taken during the total solar eclipse of 30 June 1954.

The hand calculations were performed by Christiansen and Warburton with assistance from Govind Swarup using electronic calculators (but not computers!). Bracewell has stated (1984) that the graphical method that was used for this reconstruction was adopted from his method of cord construction, although his contribution was not acknowledged in the published paper.

Bracewell had been assigned by Pawsey to work on the issue of fan-beam reconstructions and he shared an office with Christiansen and Minnett during this period.

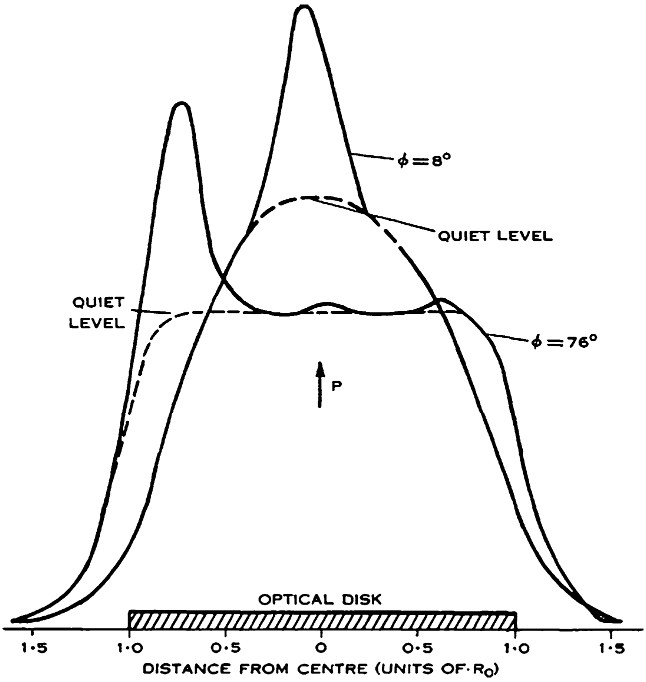


Fig. 24 An example of a one-dimensional scan taken for two different scanning angles by observing at different times on the same day (after Christiansen and Warburton 1955: 478).

In 1956 Bracewell published a paper on strip integration based on this work. The paper included a description of the use of projection-slice theorem which would be used to underpin modern imaging techniques including computerised tomography and medical imaging (see Bracewell 1956; 2005).

Staff at Radiophysics developed Australia's first electronic computer, which was called CSIRAC (CSIR Automatic Computer). This was the fifth (or fourth depending on the definition of 'operational') electronic stored (digital) program computer developed in the world and ran its first program in November 1949 (McCann and Thorne 2000). Figure 27 shows an image of CSIRAC.

CSIRAC was originally called CSIR Mk1 and was used for a variety of applications in the Division, including astronomical table generation. However, the leap of imagination needed to apply this capability to the calculation of Fourier Transforms to produce imaging in radio astronomy was not made while the computer was operated by Radiophysics. Given the close proximity of the work on the computer and the repetitive nature of the manual calculations, it is surprising that this connection was not made. In 1955 it was decided not to pursue the further development of computers in the Division, and CSIRAC was transferred to the University of Melbourne in 1956. Some years later Cambridge made the inevitable connection by applying

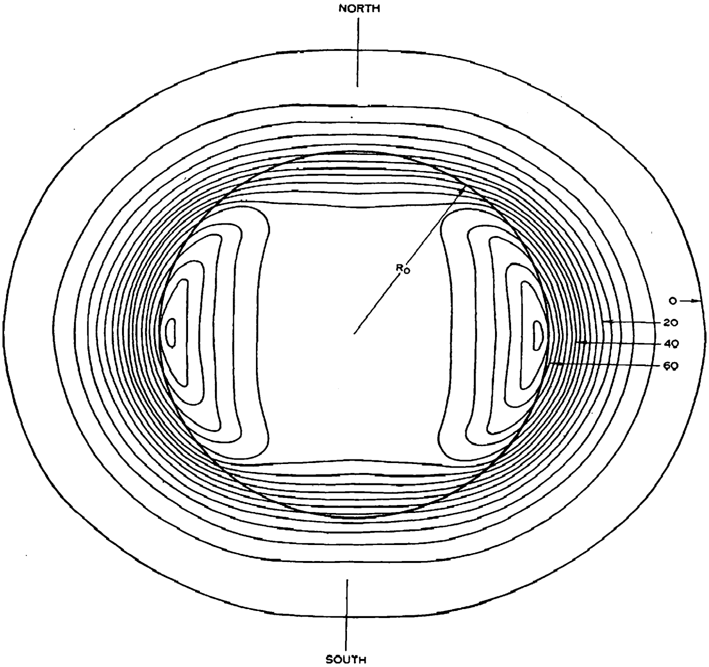
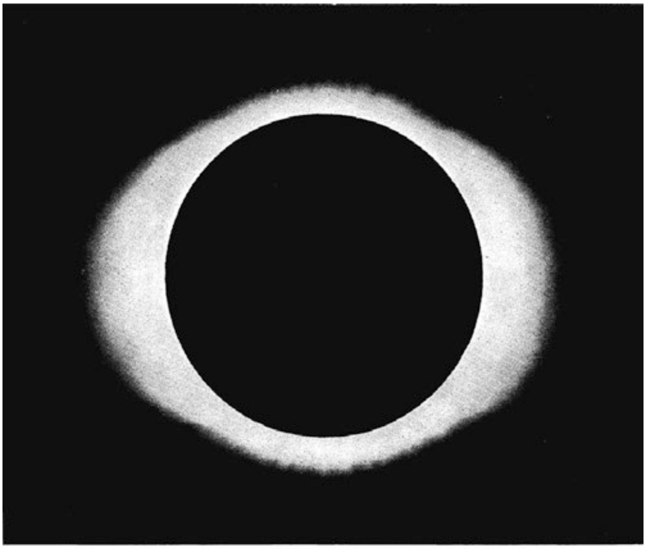


Fig. 25 An example of the derived two-dimensional image of the radio brightness distribution across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K. Contours are spaced at equal intervals of 4×10^3 K (after Christiansen and Warburton 1955: 482).

electronic computers to Fourier Transformations, and this went on to become the mainstay of imaging in radio astronomy. In fact, CSIRAC was eventually used for Fourier analysis after its transfer to the University of Melbourne. However this application of Fourier techniques was by Jim Morrison from the Chemical Physics section of the CSIRO who was measuring ionisation efficiency curves, and was based on his previous experiences in X-ray crystallography. Working with the programming team he implemented the equivalent of a Fast Fourier Transform routine to perform this analysis (see McCann and Thorne 2000: 136).

Figure 25 reveals that the two-dimensional distribution of solar radiation at 1,420 MHz was not circularly symmetrical and showed a strong correlation with the optical form of the corona as seen at times of a total solar eclipse. The elliptical source extended 1.6 times further at the equator than at the poles. The limb-brightening effect was also not evenly distributed, with the strongest brightening at the equator and practically no effect at latitudes above 55°. Christiansen and Warburton noted that this latitude corresponded to the latitude at which structural changes in the corona could be seen optically at times of sunspot minimum. Also, comparing the outline of the 8,000 K contour to the photographic image showed a strong correlation.



Photograph of the Sun at the total eclipse June 30, 1954 (M. Waldmeier).

Fig. 26 Photograph of the Sun during the total solar eclipse of June 30, 1954 (after Christiansen and Warburton 1955: Plate 2).

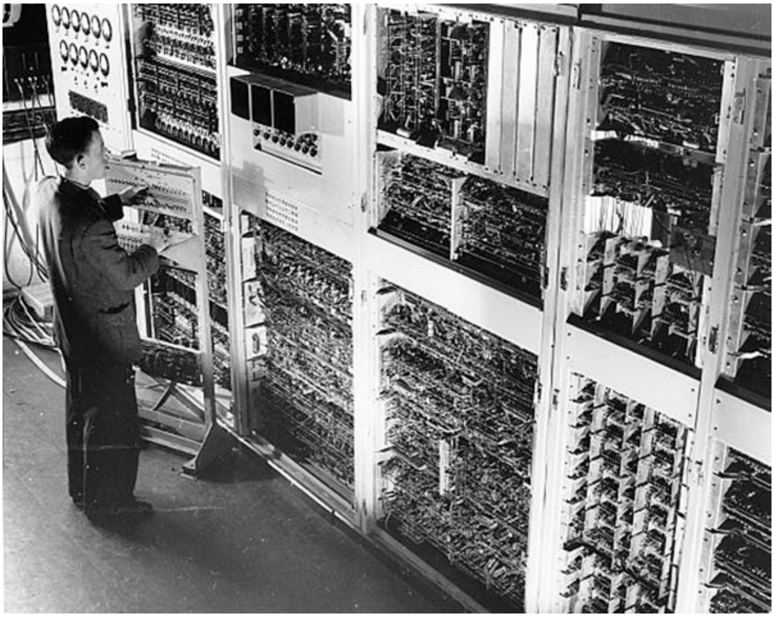


Fig. 27 CSIRAC at the Radiophysics Laboratory in June 1952 (courtesy: ATNF Historic Photographic Archive).

Christiansen and Warburton (1955) concluded that the majority of the radiation at the centre of the image emanated from the chromosphere, while the limb-brightening effect was due to the greater depth of view of the corona with its higher temperature gradient.

Observations made during 1952, 1953 and 1954 showed no change in the shape or level of temperature of the quiet component of solar radiation (ibid.).

In 1957, Christiansen, Warburton and Davies published the fourth and final paper in their solar series based on observations from the Solar Grating Array. This paper examined the slowly-varying component based on the observations made during 1952 and 1953 (Christiansen et al. 1957b). Part of their analysis concluded that the lag effect first suggested by Piddington and Davies (1953b) was not sufficient to provide the sole explanation of the decline in base temperatures. They concluded that it was likely that both the quiet component and the slowly-varying component varied depending on the solar cycle. They also concluded that the original correlation method proposed by Pawsey and Yabsley (1949) gave results that were quantitatively correct. This analysis, although not published at the time, probably influenced Swarup and Parthasarathy to re-introduce the suggestion of a variation in the level of radiation from the quiet Sun.

Christiansen, Warburton and Davies' paper provided an illustration as to why the sunspot area correlation, although strong, was in fact only a partial correlation. The correlation was strongest for areas at maximum intensity. New regions showed a short delay before the radio emission became stronger, hence the moderate correlation, and the old fading sunspots showed continued radio emission and the weakest correlation.

Christiansen, Warburton and Davies reached the conclusion that the radio emission appeared to be associated with plage faculiare rather than with sunspots themselves. The plage faculiare are the areas in the photosphere and chromosphere where sunspot groups grow and decay due to strong localised magnetic fields. Christiansen, Warburton and Davies based this on a comparison of spectroheliograph observations from Mount Stromlo and the Solar Grating Array observations. A similar conclusion had earlier been reached by Dodson (1954) based on a comparison of her optical observations with Covington's radio observations, and this was discussed with Pawsey following an introductory lecture during the August 1955 IAU symposium on Radio Astronomy at Jodrell Bank (Allen 1955: 262).

Using an analysis of the relative rates of rotation of the optical and radio sources, Christiansen, Warburton and Davies concluded that the 1,420 MHz radio emission emanated in a region about 24,000 km above the photosphere. They also found a correlation of $r = 0.85$ between the size of the plages and the sizes of the radio sources and noted that it appeared that the sources behaved like thin disks lying parallel to the photosphere.

4.6 The Genesis of the Chris Cross

During the U.R.S.I. General Assembly in Sydney in 1952 the French radio astronomy representatives invited Christiansen to work with them for a period. So, in

1954 he moved to the Meudon Observatory near Paris on secondment from Radiophysics for 1 year. In Christiansen's absence, Swarup and Parthasarathy (1955a, b) modified the receiving equipment on the East–West Array to carry out solar observations at 500 MHz. From July 1954 to March 1955 they used the East–West Array to measure the one-dimensional distribution of radio brightness of the quiet Sun and to look for limb brightening effects. By tracking the Sun over a period of months they were able to scan the Sun at angle from 90º to 60º with respect to the central meridian.

Christiansen returned from France in 1955. However, during his absence he had determined to build a new array. The seed for this array had been sown in 1953 following a discussion with Mills. As Christiansen (1984: 122) later recalled:

> While visiting Potts Hill one morning in 1953, Mills asked me why we did not couple the two arrays to produce high resolving power in two dimensions. During the ensuing discussion it was agreed that for this to be effective the centres of the two arrays must not be separated (as they were in the Potts Hill antenna), and also that some means had to be devised to multiply the outputs of the array. By the next morning Mills had devised the Cross Antenna consisting of a pair of thin orthogonal antennas with their outputs multiplied to give a single narrow response.

Mills went on to build a Mills Cross prototype aerial at Potts Hill. Christiansen decided to abandon the Earth rotational synthesis technique he had developed,

Fig. 28 On the *left* is a prototype of the larger aerial to be used in the new crossed array at Fleurs being tested at Potts Hill (courtesy: ATNF Historic Photographic Archive).

largely because it was too time-consuming to be useful for observing short-term changes in solar radiation. Instead he returned to the idea of the crossed arrays. Potts Hill did not have sufficient vacant land on which to build an array with a common centre, so Christiansen moved his activities to the field station at Fleurs (Figure 1: Location 6) where a new array was constructed. A prototype of the aerial design that would be used at Fleurs was tested at Potts Hill: Figure 28 shows the larger prototype aerial located next to the original north–south array.

5 Fleurs Field Station

Fleurs field station was established in 1954 in order to accommodate the 85.5 MHz Mills Cross, and was joined 2 years later by the 19.7 MHz Shain Cross. Christiansen's 1,420 MHz crossed-grating interferometer, affectionately dubbed the 'Chris Cross', was erected in 1957 and was the third major cross-type radio telescope to grace the flattish farm paddocks at Fleurs, a former WWII air force base (see Orchiston and Slee 2002, 2005). The relative locations of the three radio telescopes are indicated in Figure 29.

The Chris Cross was the world's first crossed-grating interferometer (Orchiston 2004b), and was designed to receive continuum radiation not H-line emission. It was seen by Christiansen as

> … a novel solution to the problem of obtaining high angular resolution at reasonable cost … it provides, for the first time sufficient discrimination in two dimensions to permit the production of 'radio pictures' of the sun, i.e. detailed maps of the radio-brightness distribution over the solar disk … (Christiansen et al. 1961: 48).

In a paper published in *Nature*, Christiansen et al. (1957a) referred to it as a 'radioheliograph'.

Recently Orchiston and Mathewson (2009: 13) provided a succinct description of this innovative new radio telescope and the way in which it operated:

> The Chris Cross consists of 378 m long N–S and E–W arms, each containing 32 equatorially-mounted parabolic antennas 5.8 m in diameter and spaced at 1.3 m intervals … Antennas in the N–S arm produced a series of E–W fan beams, and antennas in the E–W arm a series of N–S fan beams. Combining the signals from the two arrays in phase and out of phase produced a network of pencil beams at the junction points of the fan beams. Each pencil beam was ~3 arcmin in diameter, and was separated from its neighbours by 1°. Since the Sun has an angular diameter of 30 arcmin, it was only possible for one pencil beam to fall on the Sun at any one time …

Figure 30 presents a schematic drawing of the Chris Cross, and Figure 31 shows a view looking west from the eastern end of the E–W arm.

The rationale for constructing the Chris Cross was to produce daily isophote maps of solar radio emission at 1,420 MHz, and these were derived from a succession of E–W scans of the Sun obtained as the different pencil beams scanned different strips of the Sun (see Figure 32). By introducing a phase-shifting mechanism in the N–S arm, the strip-scanning process was accelerated so that it only took half an hour

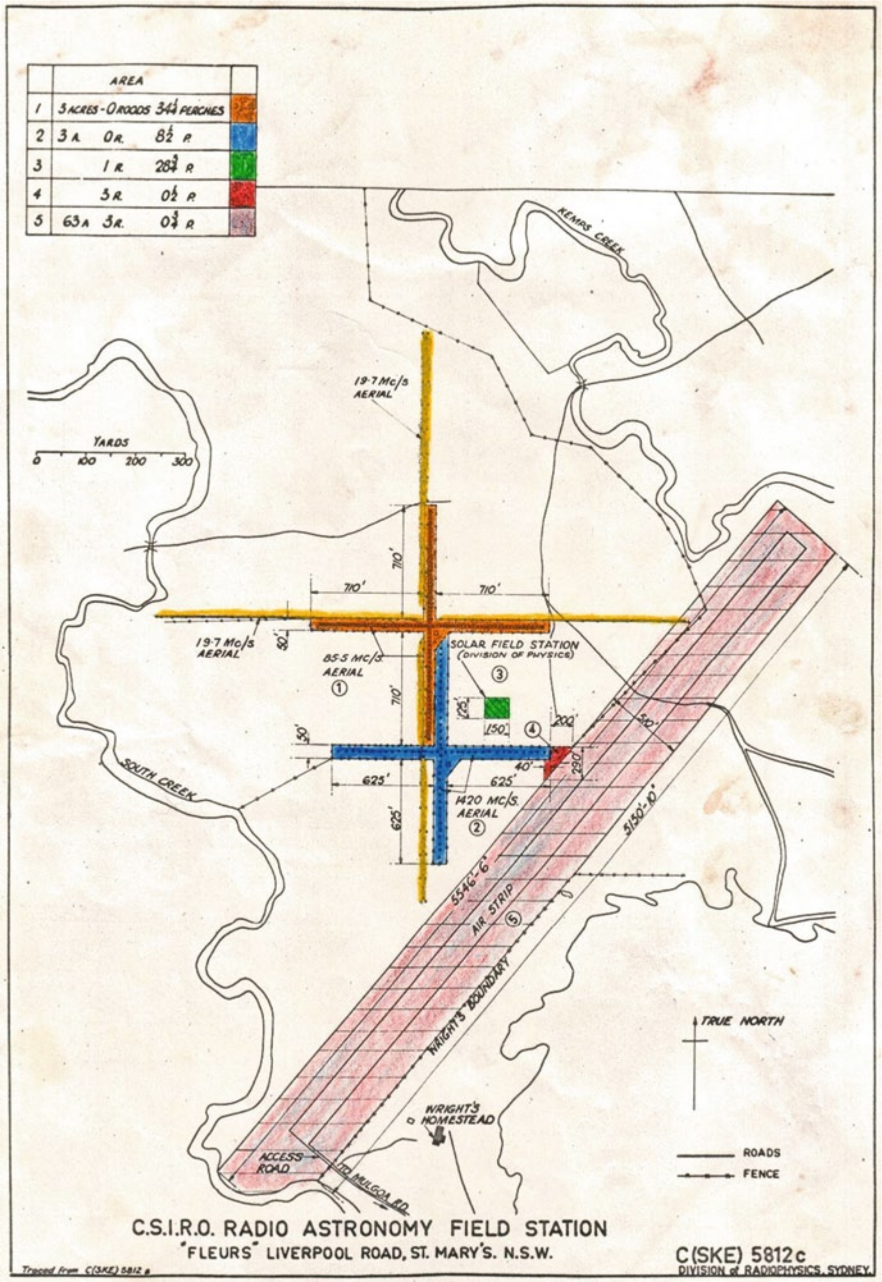


Fig. 29 Fleurs field station showing the disused WWII airstrip (in *pink*), the Mills Cross (*dark brown*), Shain Cross (*pale brown*) and the Chris Cross (*blue*) (courtesy: ATNF Historic Photographic Archive).

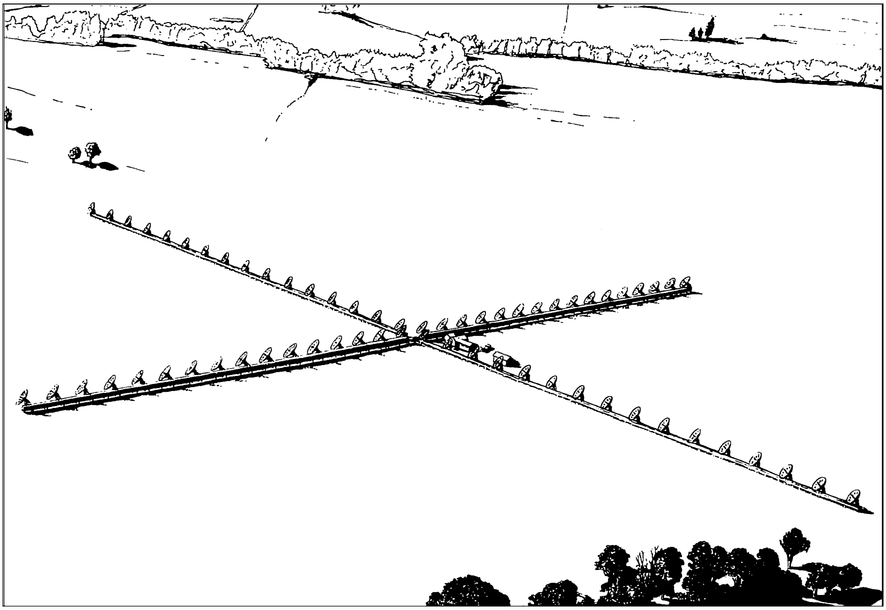


Fig. 30 Schematic aerial view of the Chris Cross, looking north-east (after Christiansen et al. 1961: 49).

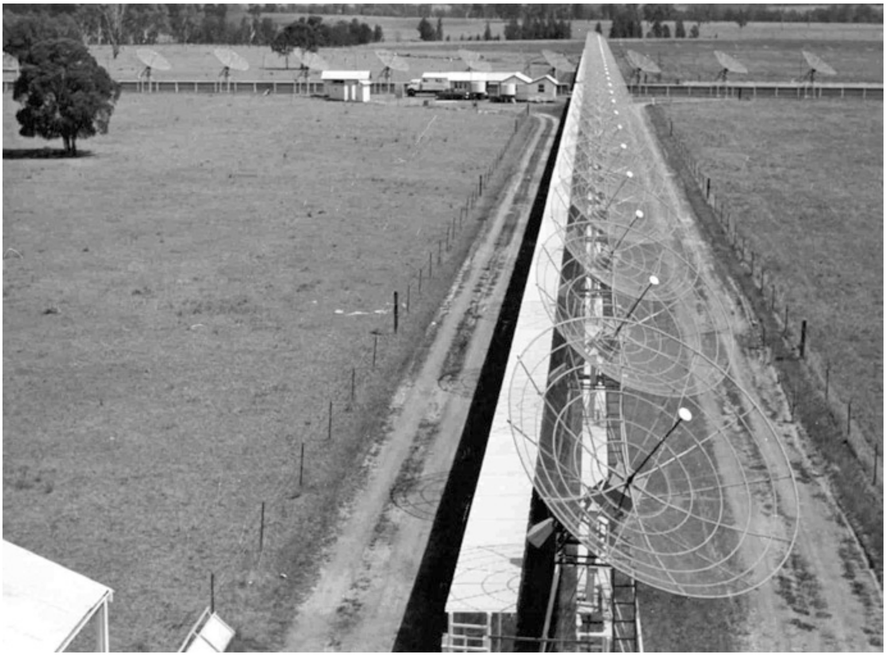


Fig. 31 View from the eastern end of the E–W arm of the Chris Cross, looking west towards the N–S arm and the Receiver Hut (courtesy: ATNF Historic Photographic Archive).

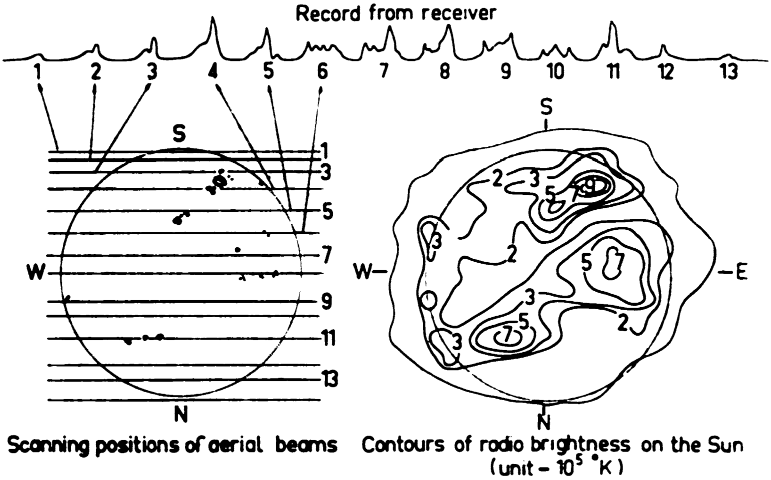


Fig. 32 Diagram showing at the *top* a succession of 13 E–W scans of the Sun obtained on the same day, their corresponding positions on the solar disk (*lower left*) and at the *lower right* the resulting isophote map (after Christiansen and Mullaly 1963: 170).

for the whole Sun to be scanned. The strip scans were then converted into daily isophote maps.

Three different types of solar radio radiation were recorded at 1,420 MHz:

1. Emission from the quiet Sun, which remained relatively constant for long periods but changed in the course of the solar cycle;
2. The 'slowly-varying component', which varied from day to day; and
3. Occasional intense bursts of emission.

Most conspicuous was the slowly-varying component, represented by the so-called 'radio plages', those localised regions of intense emission which rotated with the Sun but varied in form and intensity from day to day (see Figure 33). These, and occasional bursts of emission, were noted soon after the Chris Cross became operational, but research on them was left mainly to three other members of the Division of Radiophysics' Solar Group, T. Krishnan, Norman Labrum and Richard Mullaly (for details and related references see Orchiston and Mathewson 2009).

All this happened at a time of considerable turmoil within the Division as a number of leading researchers with high international profiles competed with varying degrees of success for the limited funding that would support the construction of the next generation of cutting-edge Australian radio telescopes (see Sullivan 2005). Christiansen was one of those who chose to leave the Division and seek support elsewhere, and in 1960 he moved to a Chair in Electrical Engineering at the University of Sydney, thereby bringing to an end his formal association with the CSIRO.

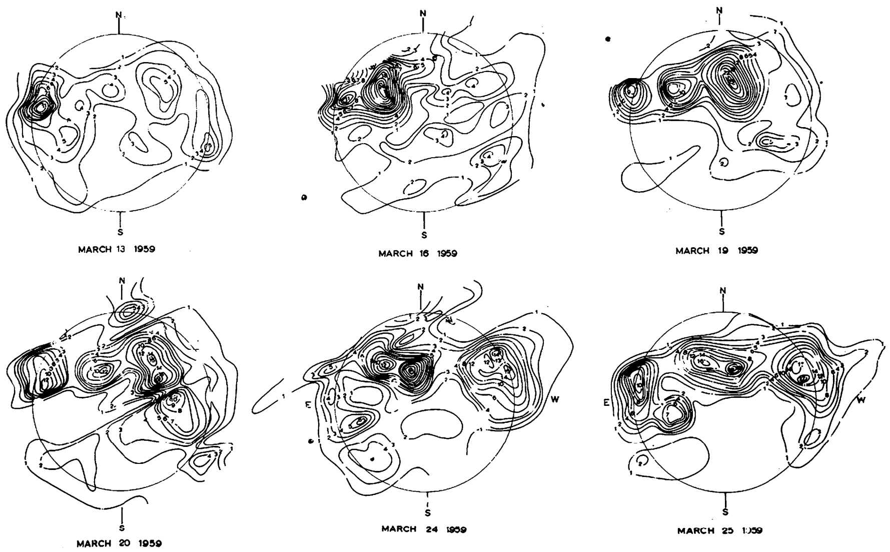


Fig. 33 Six different 1,420 MHz solar isophote maps, for the period 13–25 March 1959. Note the prevalence of radio plages (courtesy: ATNF Historic Photographic Archive).

6 Concluding Remarks

From the time that he joined the CSIRO's Division of Radiophysics in 1948 up until he moved to a Chair in the School of Electrical Engineering at the University of Sydney in 1960, Wilber N. ('Chris') Christiansen made a major contribution to international radio astronomy by inventing innovative new types of radio telescopes and furthering our understanding of the Sun and the Galaxy. He was responsible for developing two different solar grating interferometers at Potts Hill field station, along with the Chris Cross at Fleurs field station, the world's first crossed-grating interferometer. With these instruments he and his collaborators were able to delineate the characteristics of the radio plages, and in a world-first they used Earth rotational synthesis to determine the two-dimensional distribution of radio emission across the face of the Sun and confirm the prediction of theoreticians that there would be limb-brightening at 1,420 MHz. Prior to these achievements, Christiansen was a leading member of the team that used multi-site observations of the 1 November 1948 solar eclipse to pinpoint the positions of 600 MHz emitting regions in the lower solar corona and correlate some of these with optical features.

Christiansen's non-solar contribution was no less impressive. In an almost impossibly-short interval of time in 1951 he and Jim Hindman were able to cobble together a makeshift receiver that could detect the newly-discovered emission line of neutral hydrogen at 1,420 MHz. Using a recycled WWII experimental radar antenna and their new receiver they carried out the first detailed survey of H-line emission in the southern sky and noted anomalies that were later identified with spiral arms in our Galaxy.

As an interesting post-script we should note that Christiansen's departure from the CSIRO's Division of Radiophysics did not sever his ties with the Fleurs field Station. By a strange twist of fate this facility was transferred to the University of Sydney in 1963, and Christiansen, some of his staff and various graduate students, spent the next two decades converting the Chris Cross into the Fleurs Synthesis Telescope (FST). With an ultimate resolving power or 20″ the FST was the most powerful radio telescope in the Southern Hemisphere until surpassed by the Australia Telescope Compact Array (see The Fleurs Synthesis Telescope 1973). During the 1970s and 1980s the FST was used effectively to study large radio galaxies, supernova remnants and emission nebulae, thus allowing Christiansen to return to non-solar targets and build further on his already impressive contribution to international radio astronomy.

During the period when Christiansen was head of the School of Electrical Engineering, a member of his staff and a graduate student also revamped the Shain Cross at Fleurs so it could operate at 29.9 MHz, and then carried out an aperture synthesis survey of discrete sources and of the Galactic Plane (see Finlay and Jones 1972, 1973, 1974; Jones 1973). Christiansen gave this project financial and logistical support, thereby further reinforcing his post-Radiophysics association with the Fleurs field station.

Fig. 34 Professor Christiansen was one of the speakers at the University of Western Sydney's 22 November 1991 ceremony at Fleurs (courtesy: John Leahy).

While Christiansen personally used a number of more conventional radio telescopes and was involved in the development of two totally new types of radio telescopes, it is a sad fact that none of these has survived to the present time. From a heritage perspective arguably the most important of these was the Chris Cross, and in 1990 a decision was made by staff in the Faculty of Engineering at the University of Western Sydney (by this time custodians of the Fleurs site following the closing of the Fleurs Synthesis Telescope in 1988) to retain the 12 centrally-located antennas but remove all of the remaining Chris Cross antennas and associate superstructure from the site. Undergraduate students then cleaned and painted the 12 antennas, and on 22 November 1991 a ceremony was held to mark the refurbishment of these surviving elements of the Chris Cross. It was only appropriate that one of the speakers on this occasion was Professor Christiansen (Figure 34). However, the site became surplus to requirements in 1998 and was closed down, then in 2004 the land-owner, without consulting members of the radio astronomy community, made the unilateral decision to bulldoze the 12 preserved Chris Cross antennas, "… thereby bringing to a sudden and tragic end one of the world's most remarkable solar radio telescopes." (Orchiston and Mathewson 2009: 30).

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A Retrospective View of Australian Solar Radio Astronomy 1945–1960

Ronald Stewart, Harry Wendt, Wayne Orchiston, and Bruce Slee

Abstract The Solar Radio Astronomy Group within the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics established an international reputation for solar research by the early 1960s. This paper examines some of the reasons for this success under four main headings: (1) Serendipity and timing; (2) Innovative design; (3) Support and funding; (4) Early outstanding scientific results. The achievements are compared chronologically with other significant contributions from elsewhere.

1 Introduction

By the early 1960s, the Australian CSIRO Division of Radiophysics had earned a worldwide reputation as a leader in solar radio astronomy research. By this stage the highly-successful Dapto, Dover Heights, Fleurs, Murraybank and Potts Hill field stations had been closed (Orchiston and Slee 2005) with efforts concentrated on the newly-commissioned 64-m Parkes Radio Telescope. W.N. ('Chris') Christiansen, who had led research on the quiet Sun (see Wendt et al. 2008b, 2011; Orchiston and Mathewson 2009), had left to pursue his interests at the University of Sydney. The inspirational leader of the group investigating the active Sun, Paul Wild (see Stewart et al. 2011b), was soon to be the awarded the prestigious Hendryk Arctowski Gold Medal of the US National Academy of Science and the Balthasar van der Pol Gold Medal of the International Union of Radio Science for his metre wavelength studies of solar radio bursts. The Division of Radiophysics had been awarded a large grant by the Ford Foundation (Bowen 1962) for half of the cost of construction of the world's first radioheliograph at Culgoora, in north-western New South Wales.

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Fig. 1 Dr E.G. Bowen, Chief of the Division of Radiophysics from 1946 to 1969 (courtesy: ATNF Historic Photographic Archive).

Woody Sullivan (2005) has discussed the reasons for Australian's early success in radio astronomy attributing this to the imaginative scientists and engineers, innovative equipment and strong sponsorship. In his review he identified four key factors: the strong community of radio physicists that developed in the 1930s with ties to the British ionospheric research community; the British sharing the secrets of radar; a strong local radar research team that remained together after the WWII and the dynamic and skilful leadership of E.G. ('Taffy') Bowen (Figure 1) and Joe Pawsey. Many other factors were also discussed such as the relative size of the group, Australia's isolation, the role of luck and the operation of disparate field stations within the Division.

This paper examines the success of the Division's Solar Radio Astronomy group. Wild (1972) has described the early years of radio astronomy in Australia as naturally falling into three periods. The first, pre-1952, is described as the period of 'little science', with many small groups and rudimentary equipment. This was followed by a middle period when increasingly-sophisticated programs and instruments were developed, culminating in the development of the 64-m Parkes radio telescope which was commissioned in late 1961, and marked the beginning of the third period, of 'big science'.

The first two periods mentioned above are the focus of this paper, which draws on published and manuscript sources and on the personal recollections of three of the authors.[1] While many of the reasons for success are entirely consistent with Sullivan's earlier suggestions, this paper seeks to build on his conclusions and emphasise four key areas that we consider played a crucial role in the solar radio astronomy program. These are:

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[1] Stewart and Orchiston were both members of the Division of Radiophysics' Solar Radio Astronomy Group.

1. Timing and serendipity;
2. Innovative design;
3. Support and funding; and
4. Early outstanding scientific results.

Each of these is discussed individually in the following sections.

2 Timing and Serendipity

In any successful research project there is often a certain amount of chance or *serendipity*. Back on 7 December 1854 Louis Pasteur (1822–1895) stated that "In the fields of observation chance favors only the prepared mind." (see Roberts 1989), therefore one could also argue that success is mainly due to the brilliance and foresight of individuals. This certainly appears to be the case for the early Australian solar researchers as none of them had a background in astronomy.

But it also appears that there was an element of good luck and good timing involved. For example, the initial single-frequency observations by Pawsey et al. (1946) were conducted between 1945 and 1947. These observations were made using modified radar equipment left over at the end of WWII (Sullivan 2005; see Figure 2). Not only was the Solar Group fortunate to have access to a vast store of

Fig. 2 The Dover Heights WWII radar station showing the seaward blockhouse containing a 200 MHz broadside array that was used at 200 MHz for solar radio observations in 1945 and 1946 (courtesy: ATNF Historic Photographic Archive).

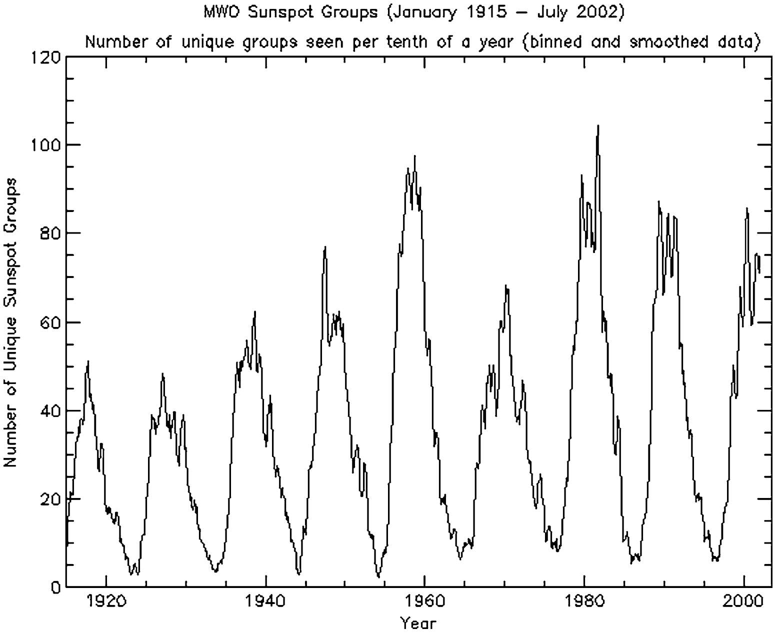

Fig. 3 Sunspot group numbers showing a peak in the solar maximum in 1947 (courtesy: Mt Wilson Observatory).

military surplus equipment, as well as a fully-equipped laboratory with personnel skilled in electronics and radar techniques, but observations were began when the Sun was approaching the maximum in its 11 year cycle (see Figure 3). Had the early solar radio observations coincided with a solar minimum, there would have been few sunspots present and very few episodes of radio burst emission to encourage further investigations. This is precisely what happened to Karl Jansky, who when investigating the source of 'cosmic static' for the Bell Telephone Company in New Jersey, pointed his antenna towards the Sun on 3 days centred on the partial solar eclipse of 31 August 1932 but recorded nothing (Sullivan 1984a). From Figure 3 it can be seen that this was close to solar minimum. Consequently, Jansky missed the opportunity to be the first to detect radio emission from the Sun. However, serendipity helped Jansky in another way, because it meant that the ionosphere *and* the Sun were radio quiet, allowing him to discover radio waves from the Milky Way using a frequency as low as 20.6 MHz.

The initial solar observations by the Radiophysics team led to some early significant successes (outlined in Section 5, below), but these results were not immediately accepted, particularly as none of the members of the Solar Group was an astronomer. As Bowen (1984) later recalled:

> I have a vivid recollection of describing these results, prior to their being published, at a lecture I gave at the Cavendish Laboratory in Cambridge on September 20th 1946. For good measure I also mentioned Martyn's observation of circularly polarized radiation from sunspots,

> similarly unpublished. About thirty or forty members of the post-war Cavendish team were there, including Martin Ryle. At the end of the lecture, Ryle rose quickly to his feet and assured the audience that on two counts I was dead wrong: the solar temperature could not possibly be a million degrees, and there was something very wrong about Martyn's observation of circular polarization.[2] It was some time before they were to change their minds.

In 1947 a landmark paper was published in the prestigious *Proceedings of the Royal Society* (London) where Lindsay McCready, Pawsey and Ruby Payne-Scott showed that by utilising sea-interferometry they could locate a localised source of radio emission on the solar disk and correlate it with the large sunspot group of February 1946. Sullivan (2005: 16) has discussed the good fortune that the appearance of this extremely large sunspot group – the 'sunspot group of the century' (Figure 4) – played

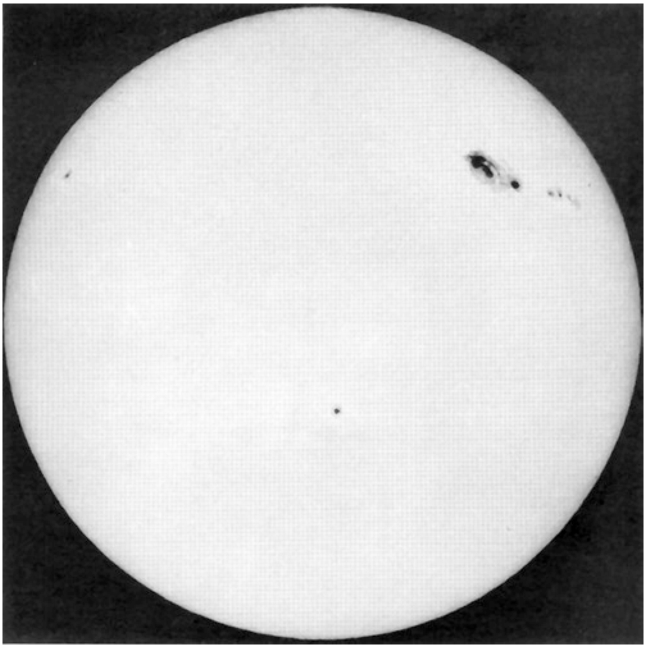

Fig. 4 Photograph of the Sun showing the very large sunspot group of February 1946 (after Stetson 1947: Plate 1).

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[2] In a letter to Pawsey dated 9 October 1946 Bowen wrote:

> Ryle points out that Martyn's observation of change of polarisation from lefthanded to right as the spot crossed the central meridian was either an accident or an error. Actually, the direction of rotation changes at random times, depending on whether the source of noise is predominately on one side of the spot or other.

Fig. 5 (*Left to right*): John Bolton, Gordon Stanley and Joe Pawsey at the Radiophysics Laboratory circa 1947 (courtesy: ATNF Historic Photographic Archive).

in these observations. It was also in this paper that the foundations for the use of Fourier techniques in radio astronomy were introduced. Without the coincidence of Royal Australian Air Force coastal radar stations overlooking the ocean near Sydney, solar sea-interferometry would not have been possible.

Luck and timing again played its hand when right at the peak of the solar cycle in 1947 a very large bipolar sunspot appeared on the limb of the sun. John Bolton and Gordon Stanley (Figure 5) had just finished installing Yagi antennas and receivers at the Division of Radiophysics' Dover Heights field station when the sunspot group appeared (Bolton 1982). Together with McCready and Payne-Scott, they were able to observe an outburst that lasted for some 15 min at 200, 100 and 60 MHz. Although the 200 MHz receiver at Dover Heights was not working at the time of the outburst they were able to obtain a record from a similar receiver which had been installed by Stanley (1994) at Mt. Stromlo Observatory near the nation's capital, Canberra (see Orchiston et al. 2006).

Another example of serendipity was the choice of observing frequencies used by the Sydney radio astronomers. Initially, this was dictated mainly by the availability of receivers and antennae at that time, but the choice could not have been better because, as Wild and his colleagues later showed (see Section 5), metre wavelength radio bursts are generated over a wide range of heights in the solar corona, an area that previously could only be observed optically on the rare occasions of total solar eclipses or with coronagraphs operating at high altitudes to avoid absorption by the Earth's atmosphere. It was well known that coronal spectral emission and absorption lines predominately occur at extreme ultraviolet and soft x-ray wavelengths. These lines could not be observed with ground-based instruments because of atmospheric absorption. The first successful ultraviolet observations of the Sun were made using a converted V2 rocket in October 1946 (Baum et al. 1946) and this was followed by successful X-ray observations in September 1949 (Friedman et al. 1951). However, it was not until the advent of orbiting telescopes in the late 1960s and early 1970s that the solar corona could be studied in detail at these wavelengths.

The restrictions of atmospheric absorption meant that with the exception of those using ground-based coronagraphs, the study of the corona was the realm of the radio astronomers for nearly 20 years. It was during this period that those in the Division of Radiophysics made a number of significant discoveries which enhanced their reputations as members of one of the world's leading solar research group (see Section 5).

3 Innovative Design

During the first few years after WWII, Australia was fortunate to have in the CSIRO Division of Radiophysics a number of highly-creative research scientists and engineers who had worked on the design and installation of wartime radar equipment and radio navigational aids. At first Radiophysics researchers used military surplus radar antennas and receivers to study the Sun, but they soon began designing their own aerials and receivers at frequencies ranging from 18.3 MHz up to as high as 24,000 MHz (see Orchiston et al. 2006). This distinguished Australian group was then responsible for inventing or developing a number of unique instruments.

The first of these was the sea-interferometer (mentioned in the earlier section), which was based on the Lloyd's mirror principle in optics and used a cliff-top location to receive direct signals from the Sun and those reflected off the ocean (see Figure 6). By observing the interference fringes as the Sun rose above the horizon the radiating strips associated with the positions of the sources of radio emission could be established, and the height of the cliff and wavelength imposed an upper limit on the source size (see Bolton and Slee 1953). The sea-interferometry principle was well-known to WWII radar operators, but the Sydney initiatives at the Collaroy and Dover Heights radar stations between October 1945 and March 1946 represented its first application to radio astronomy (Orchiston et al. 2006). Observations with the Dover Heights 200 MHz sea-interferometer showed that solar bursts were associated with sunspots (McCready et al. 1947).

One of the difficulties of the sea-interferometer measurements was that positions could not be obtained for short-duration events. To overcome this limitation, a new type of interferometer was designed, known as the 'Swept-lobe Interferometer'. It was installed and operated at Potts Hill field station from 1948 to 1952 by Payne-Scott and Alec Little (1951) (see Figure 7). This instrument (see Wendt 2008) consisted

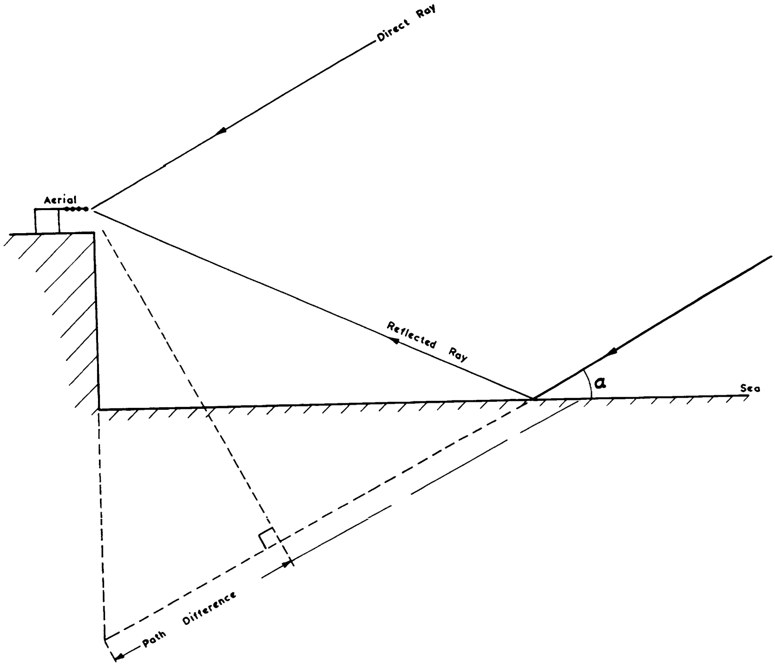


Fig. 6 The sea-interferometry principle. The direct rays and rays reflected off the sea are out of phase when they reach the cliff-top antenna and an interference pattern is formed (courtesy: ATNF Historic Photographic Archive).

Fig. 7 (*Left to right*): Ruby Payne-Scott, Alec Little, George Fairweather, Alan Carter and Joe Pawsey at Potts Hill field station (courtesy: ATNF Historic Photographic Archive).

of three crossed-element 98 MHz Yagi aerials separated by two different spacings between the aerials. In this sense it was similar to the two-element interferometer that was used by Martin Ryle and D.D. Vonberg (1946) at Cambridge to measure the size of a 175 MHz solar burst source in July 1946.

The innovation that was introduced at Potts Hill was to vary the phase of the received signal so that it swept the aerial beam pattern over the source, rather than waiting for the source to move through the aerial beam due to the Earth's rotation, and hence cause an interference pattern. This allowed not only high angular resolution to be achieved, but also allowed very short duration sources to be detected and their positions determined. When fully calibrated the Swept-lobe Interferometer could achieve a resolution of 2′, and could detect a source with a duration as short as 1 s. Additionally, by switching between the vertical and horizontal elements of the Yagi antennas (Figure 8), the polarisation of the source could be determined. Using this instrument Payne-Scott and Little (1951) were able to show the close association of outbursts with solar flares and in one example (see Section 5) to track the apparent movement of the source outwards through the solar corona to a height of 0.6 $R_\odot$ above the solar limb (Payne-Scott and Little 1952).

The use of phase variation to produce a sweeping aerial beam would later be used by a group of Jodrell Bank researchers to develop what they called a 'Rotating-lobe Interferometer' (Hanbury-Brown et al. 1954). This technique would go on to underpin the long-baseline interferometry that Jodrell Bank used to determine the sizes of

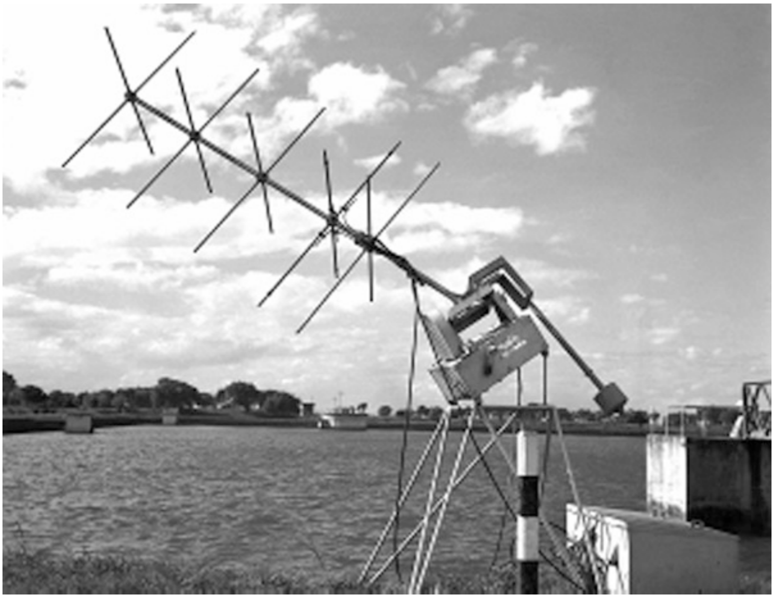


Fig. 8 The western element of the Swept-lobe Interferometer at the Potts Hill field station. Crossed Yagi antennas like this one were used to study the polarisation of solar bursts (courtesy: ATNF Historic Photographic Archive).

discrete source and that would ultimately contribute to the measurements of the angular diameters of quasars.

These single wavelength observations of solar bursts at the Dover Heights and Potts Hill field stations were well and good but they did not reveal the nature of the emission across the wavelength band. In order to achieve this Pawsey (1947a, b) proposed building a spectrograph and this task was assigned to McCready. The Radiophysics Laboratory already had access to some wartime spectrum analysers, but they proved to be too noisy for solar observations and Wild (Figure 9) was given the job of designing a new receiver and a rhombic aerial for the 70–130 MHz band (Stewart 2009). In early 1949 Wild and McCready (1950) installed the world's first radiospectrograph at the Division's newly-established Penrith field station on the western outskirts of Sydney (see Stewart et al. 2010), and it soon produced compelling evidence for the existence of three quite different types of solar burst emission.

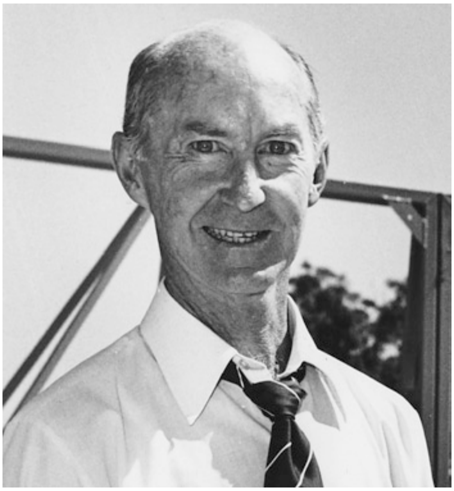
After this initial success, the radiospectrograph was redesigned, extended to operate from 40 to 240 MHz (see Stewart 2009; Stewart et al. 2011a), and relocated to a new radio-quiet field station at Dapto, near the city of Wollongong and ~85 km to the south of Sydney (Figure 10). The great attribute of the Dapto Radiospectrograph was that it swept across a wide range of frequencies twice per second and recorded the information on photographic film. This provided a continuous, high time resolution record of coronal activity for easy viewing. It should be borne in mind that high speed digital recording and computer analysis would not be available for another 20 years or more.

Within a few years of the successful operation of the Dapto Radiospectrograph, Wild and Kevin Sheridan (1958; see Figure 11) went on to design and have built a Swept-frequency Interferometer to measure the heights of the burst emission in

Fig. 9 Head of the Solar Group, J. Paul Wild (*centre*) in 1952, flanked by Frank Kerr (*left*) and Jim Hindman, both of whom conducted research on hydrogen line emission (adapted from an image in the ATNF Historic Photographic Archive).

Fig. 10 The three crossed-rhombic aerials of the 40–240 MHz Radiospectrograph at the Dapto field station (courtesy: ATNF Historic Photographic Archive).

Fig. 11 Kevin Sheridan (adapted from an image in the ATNF Historic Photographic Archive).



the solar corona (for details, see Stewart 2009; Stewart et al. 2011a). This was a variation of the Payne-Scott and Little Swept-lobe Interferometer, using frequency rather than phase to vary the lobe pattern. It had the advantage of being able to measure source positions simultaneously over a range of frequencies from 40 to 70 MHz which was necessary for the study of short duration solar bursts which often exhibited fast frequency drift. An experimental version of this unique interferometer was constructed at Dapto in 1953 for the measurement of radio scintillation patterns from Cygnus A but calibration problems prevented it being used effectively (Jim Roberts, pers. comm., 2007).

In 1951 Christiansen (1984; see Figure 12), after reading a paper by Bernard Lyot on optical filters, was inspired to design a solar grating array (see Christiansen 1953; Wendt et al. 2008b). This consisted of 32 × 66-in. parabolic dishes arranged in an east-west line on one of the banks of the Potts Hill reservoir in suburban Sydney (Figure 13). The array operated at 1,410 MHz and produced a series of fan beams with a resolution of 2.9′. This allowed a one-dimensional profile of the Sun to be produced. The array was later joined by a smaller adjacent north-south array (see Figure 14), and both outputs were used to produce the first two-dimensional radio-frequency isophote map of the quiet Sun.

Christiansen (1989) later claimed that this was the first application of Earth rotational synthesis, although only intensity was included in his original analysis – phase measurements were unnecessary because phased arrays were used. Christiansen (1984: 122) also wrote:

> The fact that the Fourier process had to be done by hand so that the map … took half a year to complete probably deterred further work, but another factor was that those interested in high resolution observations in Sydney were dealing with sources that were variable or else were thought to vary because of ionospheric changes. Hence observations that required a long time to complete were treated with suspicion.

Fig. 12 W.N. ('Chris') Christiansen in 1952 (adapted from an image in the ATNF Historic Photographic Archive).

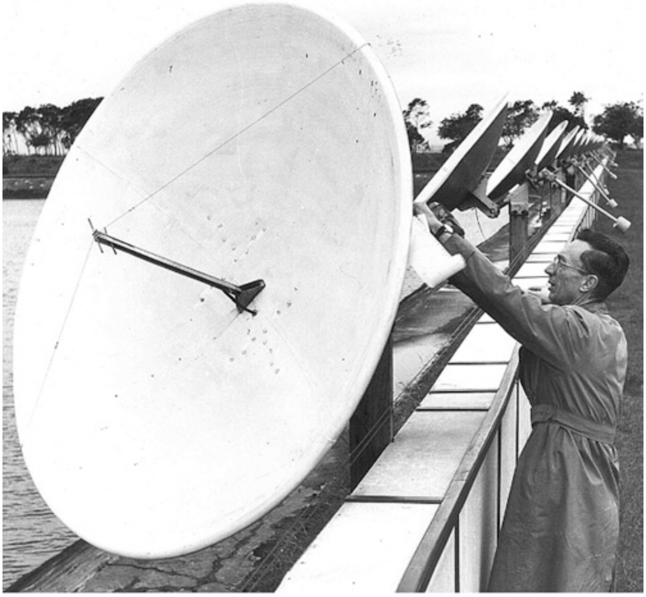


Fig. 13 Joe Pawsey with the East-West Solar Grating Array at Potts Hill field station in 1952 (courtesy: ATNF Historic Photographic Archive).

Fig. 14 Aerial photograph of the northern Potts Hill reservoir looking south-west. Along the eastern bank of the reservoir (*in the foreground*) is the 14-element grating array constructed in 1953 and along the southern bank is the original 32-element grating array constructed in 1951–1952 (courtesy: ATNF Historic Photographic Archive).

In 1953 Bernard Mills and Little constructed the prototype of the Mills Cross at Potts Hill field station (Mills and Little 1953). This instrument combined the low cost of an interferometer with the characteristics of a pencil-beam instrument. It also inspired Christiansen to take the idea of his solar grating array further and combine it with the principle of a cross array to produce the 'Chris-Cross', which was installed at the Radiophysics field station at Fleurs, near Sydney, in 1957 (see Christiansen et al. 1957). This instrument (Figure 15) could scan a pencil beam in a raster fashion across the solar disk to produce a two-dimensional image of the Sun without the need for the laborious Fourier Transforms that had taken 6 months of hand calculation to produce using the Potts Hill solar grating arrays. For a detailed account of the Chris Cross see Orchiston and Mathewson (2009).

All of these examples were innovative in their own way and showed the outstanding inventive skill of their designers. Many of these designs were quickly adopted by other groups internationally.

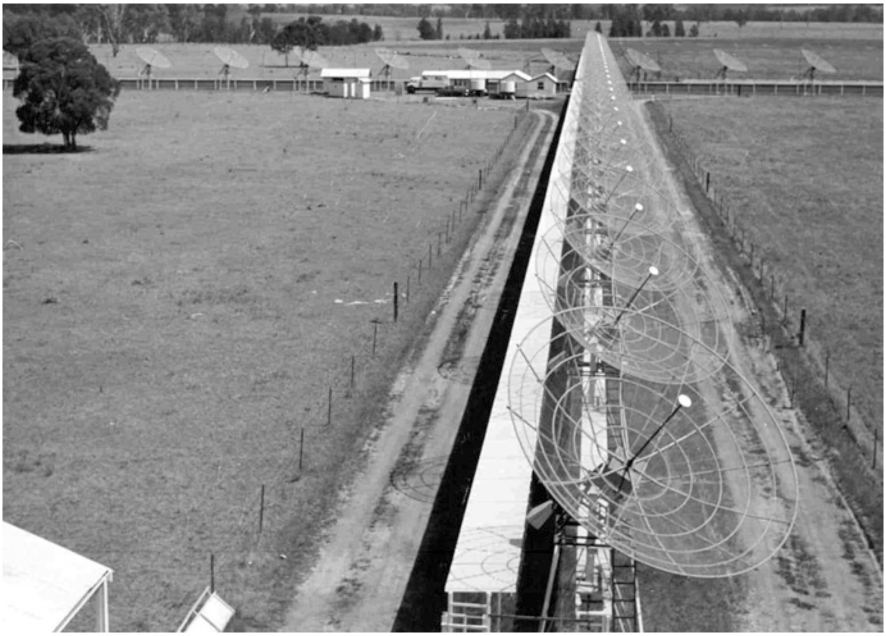


Fig. 15 The Chris Cross at Fleurs field station. This photograph was taken from the eastern end of the EW arm looking west towards the central receiving and other huts and the N-S arm (courtesy: ATNF Historic Photographic Archive).

4 Support and Funding

All of the instruments discussed in this paper were designed and built in-house without outside assistance and were funded solely by the CSIRO which was, and has remained, an Australian Federal Government funded body. This was largely thanks to the tireless persistence and dynamic leadership of 'Taffy' Bowen.

During WWII Bowen had worked in England on the development of radar and had taken the first airborne radar equipment to the USA (see Bowen 1987). Later he used his contacts there to obtain a large grant from the Carnegie Institute for the construction of the 64-m Parkes Radio Telescope (see Robertson 1994).

Bowen, following the example set by Sir David Rivett, the founder of the C.S.I.R.O., believed that the success of a research project depended critically on the team leader and gave his whole-hearted support to his nominated leaders and avoided unnecessary interference. Rumour said that head-office in Canberra held Bowen in awe because he would always get what he wanted when it came to funding requests. Bowen (1984: 109) later wrote:

> We have often been asked how it was that in the years 1946 to 1960 a relatively unsophisticated country like Australia could support studies as new and fundamental as to amount to a revolution in astronomical thinking. Our answer is simple. For every piece of basic science which was done in radio astronomy at the Division, there was an equivalent piece of applied research – in navigation, on computer applications and in weather modification.

It is interesting to contrast Bowen's position with Karl Jansky's in the mid-1930's. Having been asked to investigate the source of noise on long distance radio communications by the Bell Telephone Laboratory and having discovered radio waves from the Galaxy, Jansky was continually shifted to applied projects and never was able to follow up these pioneering investigations (Sullivan 1984b).

Bowen chose Joe Pawsey (see Figure 13) to lead the radio astronomy group. Melbourne-born Pawsey had worked in England during WWII and completed his Ph.D. at Cambridge's Cavendish Laboratory under Ratcliffe. During the early years of radio astronomy he kept in close contact with his Cambridge colleagues despite the fact that the two groups were often in serious competition. He was an expert in radio aerial design and had worked on the development of the first television transmission aerials in the UK (Wild 1963). Pawsey became a mentor and father figure to many of the young research scientists during the 1940s and 1950s. He died prematurely in 1962, but not before assisting Wild to obtain funding from the Ford Foundation for the construction of the revolutionary Culgoora Radioheliograph (see Wild 1967).

Not long before his death Pawsey (1961) wrote about the success of Australian radio astronomy:

> In many cases the equipment is now exceedingly complex but nearly always there has been an organic development. Observations with simple equipment have justified something a little more elaborate. The phenomena then revealed demanded still more elaborate equipment for their elucidation. If the problems involved then appeared of sufficient interest equipment for a third stage was constructed … It should be noted that it can only be followed effectively in a well organized scientific organization in which scientific direction can very quickly make decisions and supply facilities for the really promising developments. In all too many

> cases elsewhere the energies of the scientists are taken up in advertising the potentialities of their prospective investigations in order to obtain any support at all. The result is the neglect of the unspectacular preliminary probing investigations which are often such a vital ingredient in success.

Pawsey (1956) also referred to the lack of interest shown by traditional (optical) astronomers in the emerging field of radio astronomy: "It appears that conservatism can be engendered by specialization in science." According to Jesse Greenstein (1984), the optical astronomers at that time only believed in thermal emission processes and showed no interest in non-thermal particles such as cosmic rays or the energetic electrons associated with solar and cosmic magnetic fields.

The various project leaders at Radiophysics were fortunate to have at their disposal an excellent mechanical and electrical workshop, as well as highly-trained support staff. The Laboratory also maintained its own library to inform its staff about research activities elsewhere, and produced research preprints for circulation to other research centres.

Up to 1960, all of the Division's new radio telescopes were produced in-house and on low budgets by small teams of scientists who were assisted by the Division's technicians and workshop personnel. Keith MacAlister (Figure 16), the Division's resident mechanical engineer, was a 'true Scotsman' and had a magnificent reputation when it came to building cheap antennas. He used the simple 'ball and string' approach – heavy blocks of concrete which hung from steel wires and dropped at a constant rate – to drive the Chris-Cross at Fleurs and the wooden rhombic aerials of the Dapto Radiospectrograph and the Swept-frequency Interferometer.

Fig. 16 Keith McAlister, the Division of Radiophysics' innovative resident mechanical engineer (courtesy: ATNF Historic Photographic Archive).

Wild used to delight in telling a story about an overseas visitor who boasted that he had found a way to keep the paper in his facsimile recorder moving smoothly without crumpling and jamming. He said it had only cost him about $1,000 or so to fix the problem. Wild's response was: "Well, we solved the problem using a piece of string and a lead weight costing a few shillings." This was a true statement because one of the authors (RS) saw the device working at Dapto in 1960 when he was a Division of Radiophysics Summer Student.

Immediately after WWII, the role of Radiophysics had to be revised so as to concentrate on peace-time research, and Bowen prepared a report on possible research topics. One among the many suggested was a "Study of extra-thunderstorm sources of noise (thermal and cosmic)." This was to be the genesis of Australian radio astronomy.

Without the early success of Pawsey and his team, as discussed in Section 2, it is very likely that funding would have quickly been reassigned to the Division's other areas of research such as air navigation, cloud physics,[3] transistor development or electronic computers. But no matter how brilliant the concept and design of the new instruments, success depended upon obtaining new and significant results. In many ways success fed success.

The focus on backing success almost prematurely ended the Radiophysics solar research program in the early 1960s. The successful investigation of galactic and extra-galactic discrete sources by Bolton, Mills, Kerr and their collaborators (e.g. see Bolton 1982; Kellermann et al. 2005; Robertson et al. 2010; Slee 1994; Wendt 2008) meant that the Division's budget needed to be shared by an increasing number of teams investigating different astronomical phenomena. The effect of the transition in the early 1950s from a large number of small projects to a smaller number of large projects has been discussed by Sullivan (2005: 28). In 1953, Bolton left radio astronomy for a period and worked in the Cloud Physics Group when his proposal to build a large interferometer at Dover Heights was turned down in favour of building other instruments such as the Radiospectrograph at Dapto and the Mills Cross at Fleurs (Stanley 1994).

With the very large funding commitment to build the 64-m Parkes Radio Telescope (Figure 17) the Division increasingly needed to consolidate its projects. After much debate a schism clearly emerged among the Division's radio astronomers, even though this has been strongly denied by Bowen (1981: 272). This dissension has been widely discussed (e.g. see Hey 1973; Sullivan 2005). Pawsey, Christiansen and Mills believed more progress could be made with lower-cost instruments built for specific purposes, rather than putting all the Division's 'eggs in one basket' by building a general purpose giant radio telescope. Subsequently, Christiansen and Mills left Radiophysics and successfully pursued their own research objectives at the University of Sydney. Pawsey accepted the Directorship of the newly-formed National Radio Astronomy Observatory in the U.S., but unfortunately

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[3] Despite having a background in radar, Bowen was not a radio astronomer. His primary research field was cloud physics and its application to rain-making.

Fig. 17 The commissioning of the Parkes Radio Telescope towards the end of 1961 effectively marked the death-knell of the Division's scattered field stations in the Sydney-Wollongong region (courtesy: ATNF Historic Photographic Archive).

died of a brain tumour shortly after agreeing to take up the appointment. Meanwhile, back at Radiophysics the continuation of solar research was also under question, and had external funding not been provided by the Ford Foundation it is very likely that the Culgoora Radioheliograph would never have been built.

5 Outstanding Early Scientific Results

The detection by Pawsey (1946) of a one million degree temperature for the solar corona was the first outstanding scientific result of the Division's fledgling solar radio astronomy group, confirming the predictions made that same year by Australia's David Martyn (1946b; see Figure 18) and the Soviet Union's V.L. Ginzburg (1946) – although the Soviet prediction remained unknown to the Australians until 1948 when an abstract was published in *Physics Abstracts* (see Bowen 1984).

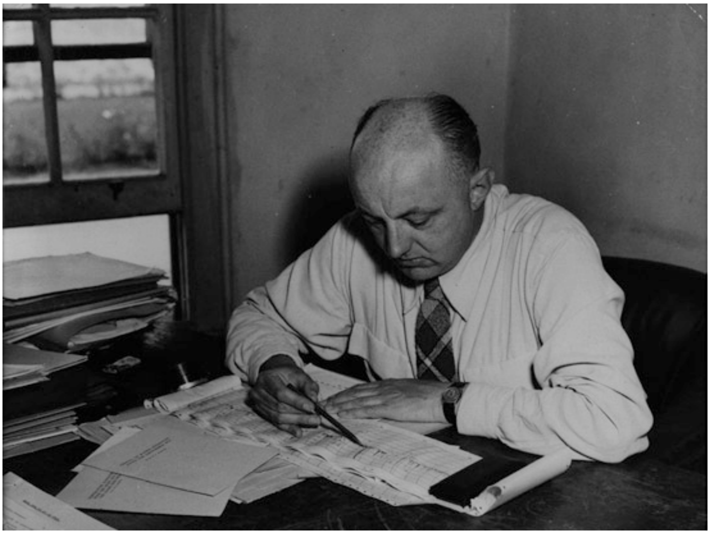

Fig. 18 David F. Martyn was Chief of the Division of Radiophysics early in WWII, but by 1946 was seconded to the Commonwealth Solar Observatory on Mt Stromlo near the nation's capital, Canberra (courtesy: ATNF Historic Photographic Archive).

Also impressive were the observations made by McCready et al. (1947) in February 1946, where they were able to demonstrate conclusively that solar radio bursts were associated with sunspots (see Figure 19). They also used sea-interferometry to set upper limits for the sizes of the radio-emitting regions. Ryle and Vonberg (1946) carried out similar observations with a two-element interferometer at Cambridge several months later (in July 1946), although their results were published before those of McCready et al.[4]

On 8 February 1947 Payne-Scott, Don Yabsley and John Bolton (1947) made simultaneous observations at 60 MHz and 100 MHz of an intense outburst of solar radio emission. Unfortunately their 200 MHz equipment at Dover Heights was not working at the time, but they were able to substitute observations made at this frequency from Mt. Stromlo Observatory. When the three chart recordings were compared (Figure 20) Payne-Scott and her colleagues noticed that the onset time of the burst was different at the three frequencies. They estimated that this indicated the outward passage through the solar corona of a disturbance travelling at ~1,000 km/s, giving a time of travel to the Earth of ~26 h. It is significant that the evening after the outburst was recorded a prominent aurora was observed in Sydney, which was an extremely rare event for a city located at latitude of 34° S. Payne-Scott et al. (1947) reported on this unique solar event in a paper published in *Nature*, where they suggested that perhaps a solar flare triggered a stream of charged particles that was ejected at very

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[4] Both Orchiston (2005a) and Sullivan (2005) have commented on how certain British radio astronomers liked to delay the refereeing of papers submitted by the Australian radio astronomers so that they could quickly conduct similar research themselves and get their own findings into print first.

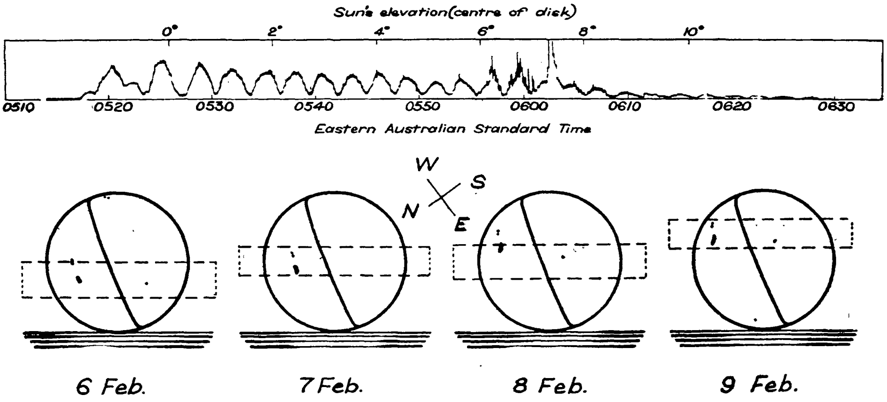


Fig. 19 Sea-interferometer observations made during February 1946 showing on each day the solar emission radiating strip and the positions of major sunspots (after McCready et al. 1947: 369).

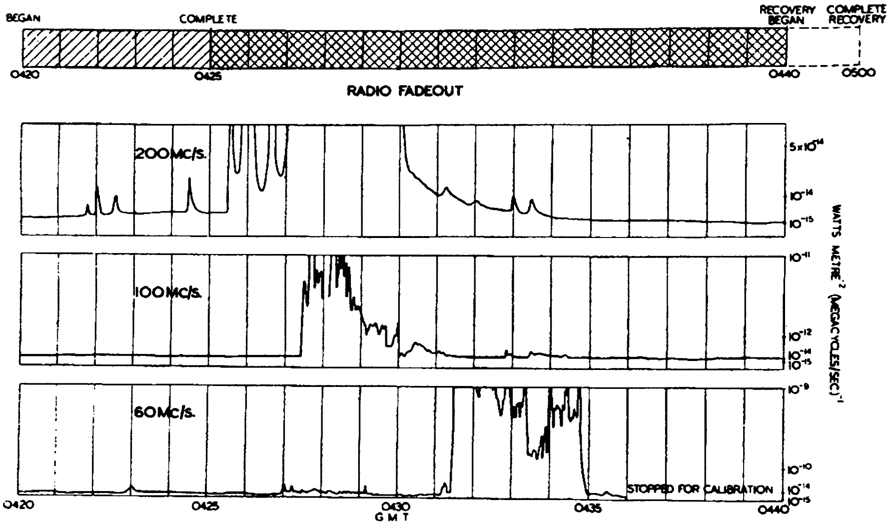


Fig. 20 Delays in the arrival times of an intense solar outburst burst at different frequencies recorded on 8 March 1947 (after Payne-Scott et al. 1947: 257).

high velocities through the solar atmosphere. As the charged particles traversed the corona, radio emission occurred at progressively longer wavelengths, accounting for the delays recorded in Figure 20.

A further breakthrough in solar radio astronomy occurred when three different teams from the Division of Radiophysics recorded the solar emission at 600 MHz from three widely-spaced Australian sites during the partial solar eclipse of 1 November 1949 (see Orchiston et al. 2006). Analysis of the collected data (Christianson et al. 1949) revealed the existence of eight localised sources of radio emission, many of

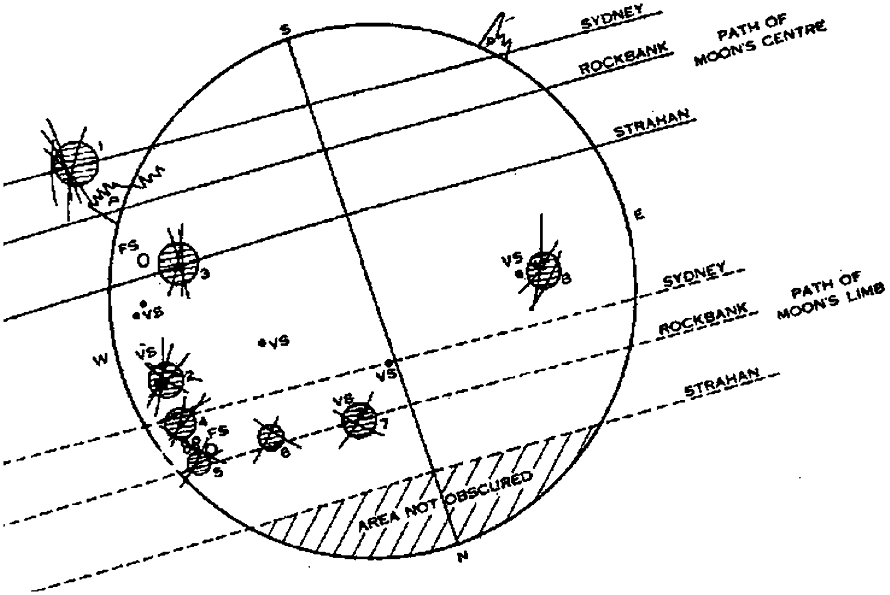


Fig. 21 The eclipse map of 1 November 1949 showing eight active regions (indicated by *hatched circles* or *ellipses*). The localised radio-emitting region above the prominence on the north-western limb is clear evidence that the 600 MHz emission originates in the solar corona (after Christianson et al. 1949: 513).

which were associated with sunspots (see Figure 21). As it happens, this is another example of serendipity relating to the choice of observing frequency. Had the observations been conducted at a lower frequency the variability of the radio emission would have prevented analysis, as observations of another solar eclipse showed in 1949 (see Wendt et al. 2008a).

The complexity of the solar source distribution observed during the November 1948 eclipse convinced Christiansen that simple radiometer or interferometry techniques were insufficient to map the active solar disk and this partly inspired him to design the two 1,420 MHz Potts Hill grating arrays mentioned above, in Section 3. These were used to produce the first two-dimensional radio-frequency isophote map of the quiet Sun. As Figure 22 indicates, this provided definitive evidence of limb-brightening of the quiet Sun at centimetre wavelengths, which had been predicted by Martyn (1947) and was found to be in good agreement with theoretical calculations by Christiansen's Radiophysics' colleague, Stefan Smerd (1950; see Figure 23). Further details of this research are presented in Wendt (2008) and Wendt et al. (2008b).

An important breakthrough in our understanding of the nature of solar burst emission occurred when Wild and McCready analysed observations made with the Penrith Radiospectrograph (Stewart et al. 2010). By 1950 they had sufficient

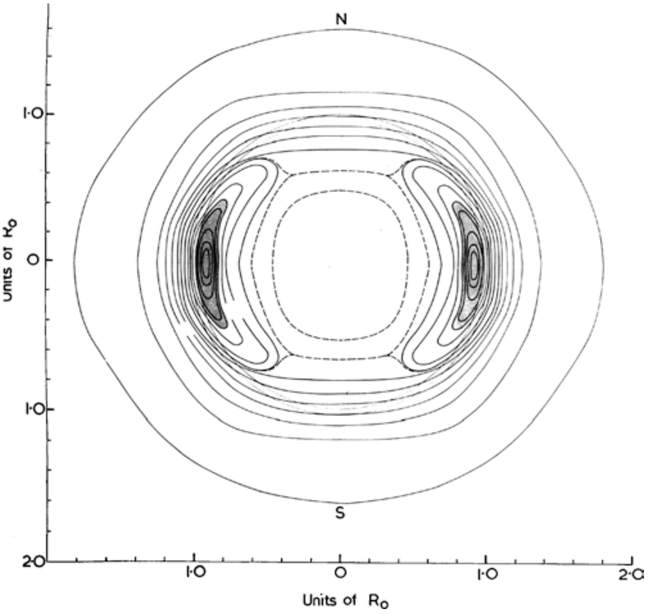


Fig. 22 A two-dimensional map of 1,420 MHz radio emission from the quiet Sun (courtesy: ATNF Historic Photographic Archive).

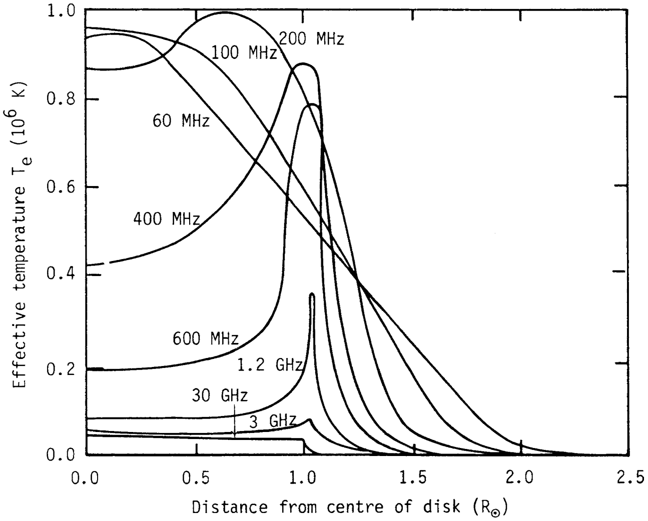


Fig. 23 Theoretical curves for limb brightening of the Sun (after Smerd 1950: 46).

data to present papers on the first spectral classification of solar radio bursts at metre-wavelengths (see Wild 1950a, b; 1951; Wild and McCready 1950). These and later spectral observations helped to remove the confusion that surrounded the earlier single-frequency observations of bursts and outbursts caused by the

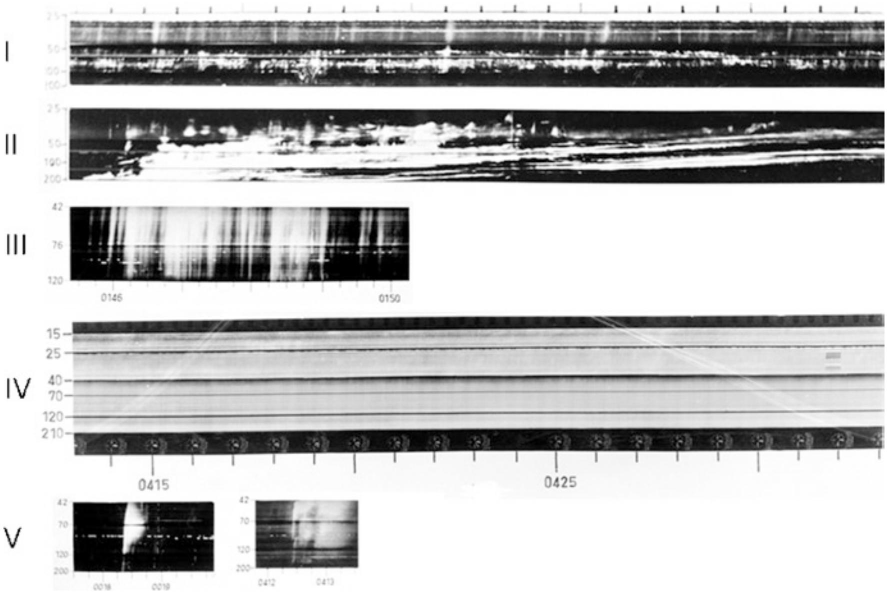


Fig. 24 Examples of the different spectral types of solar bursts first identified by Australian and French radio astronomers (assembled by the authors from examples in the ATNF Historic Photographic Archive).

fact that often as many as five different types of radio emission would occur during a solar flare. Three of these, dubbed Types I, II and III, were first identified at Penrith field station. The Penrith scheme was later extended in order to include bursts of Types IV and V, which were first reported by Andre Boischot (1958) and Wild et al. (1959a) respectively (see Stewart 2009; Stewart et al. 2011a). This spectral classification (Figure 24) remains in use today.

Possibly the two spectral types that most caught the attention of international solar astronomers were Type II and Type III bursts. Both of these showed a drift from high to low frequencies. Wild (1950a, b) pointed out that if the emission occurred at the plasma frequency (as suggested by Martyn in 1947) then the frequency versus time plots or spectral records also represented height versus time plots of the sources moving outwards through the corona. Wild referred to this as the ‘plasma hypothesis’. If Wild was correct, this meant that a dynamic spectrum provided a snapshot of activity every half second from the lower corona out to heights of at least 3 $R_{\odot}$. This would be a monumental result for solar physics.

The discovery of fundamental and second harmonic structure in Type II and III bursts (Wild et al. 1954a), as depicted in Figure 25 for a Type II event, lent support to the plasma hypothesis, and it was finally confirmed when Wild and Sheridan (1958) used the Dapto Swept-frequency Interferometer (Stewart 2009) to measure the heights of burst sources. The positions agreed with the plasma levels of coronal density models, derived from white-light eclipse observations (Figure 26).

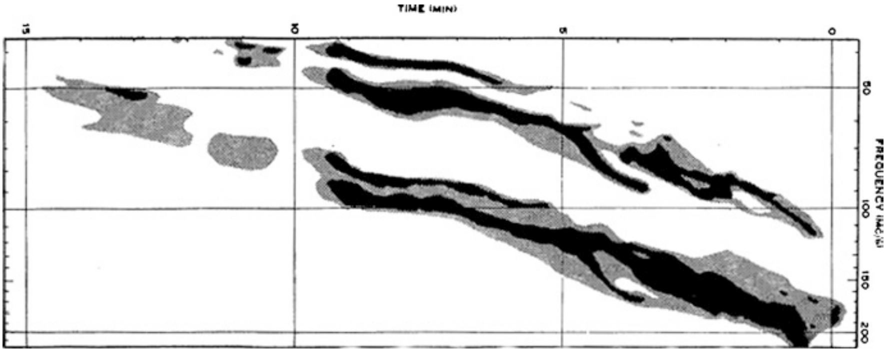


Fig. 25 The first recorded Type II burst showing fundamental and second harmonic (after Wild, Murray and Rowe 1954: 444).

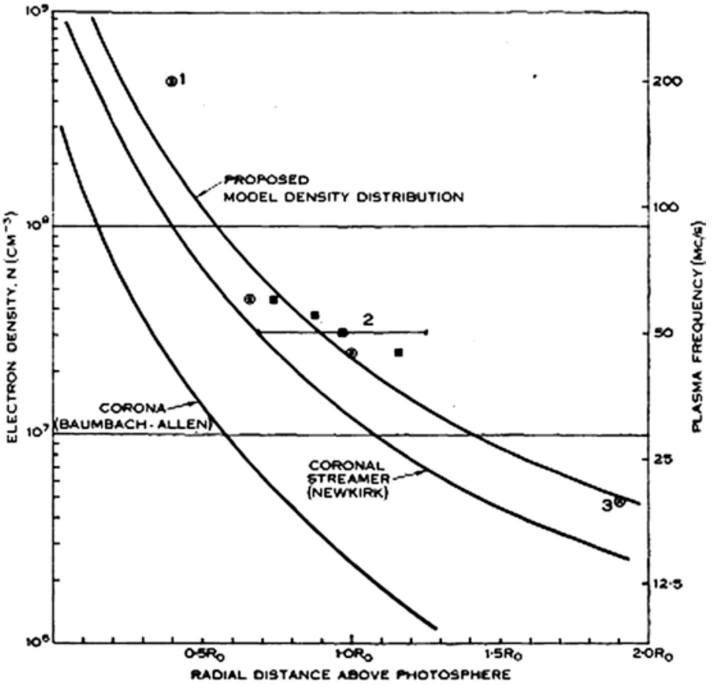


Fig. 26 Comparison of burst heights with coronal density models (after Weiss 1963a: 259).

As discussed in Section 2, the corona was a largely unexplored area of solar research in the 1950s. The drift rates of Type III bursts were found to represent velocities of up to 0.33c (Wild et al. 1954b). This meant that streams of fast particles could be traced outwards from the Sun to heights up to 3 $R_\odot$. Greater heights were excluded because the ionosphere normally absorbs radiation at frequencies below

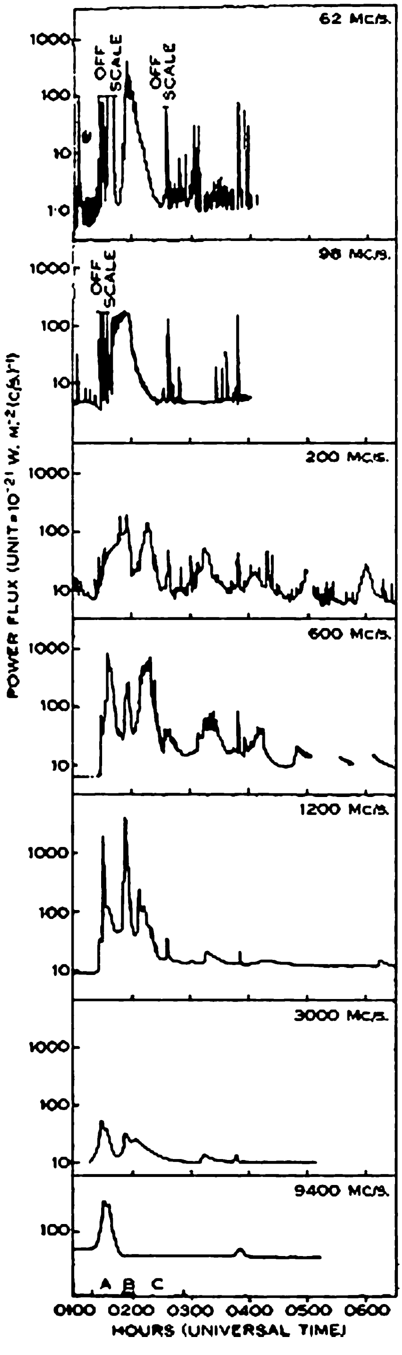
5–10 MHz, depending upon the latitude and longitude of the observing site and the level of the solar activity and hence ionisation.

The drift rate of Type II bursts were found to correspond to outwardly-moving disturbances travelling at velocities of 500–1,000 km/s (ibid.), which is just what was required to explain the 1–2 day delay in the onset of ionospheric disturbances here on Earth following major solar flares. The ionosphere was the subject of intense research during and immediately after WWII because of its importance for long range radio communication. Knowledge of what caused these ionospheric disturbances was of vital interest. As the Cold War developed, the military became very interested and invested a lot of money in solar research to find when ionospheric blackouts were likely to occur in case of a hostile missile attack. Today, despite the end of the Cold War, this is still of great interest because satellite communication can be affected adversely by solar disturbances. In addition to the military, NASA became interested in so-called 'space weather' with the advent of the 'Space Race' and Russia's launch of the first orbiting satellite, Sputnik I, on 4 October 1957. As one of the authors (RS) recalls, during the late 1950s students enrolling in university science courses were encouraged to study physics because of its perceived importance for future research. By 1962, the USA had launched their own satellites and discovered the Van Allen Belts. These regions were considered to be a potential hazard to astronauts, especially after solar flares, if they became filled with energetic particles.

The Type III bursts were considered to be caused by fast particles, but of what type? The constant drift rate indicated no loss of energy for the particle streams as they moved outwards through the corona. If the particles were electrons their energies would be in the KeV range, but if they were protons they would be in the MeV range and much more energetic and therefore dangerous. One of the authors (RS) played a small part in solving this mystery when his first research project after being appointed to Radiophysics in 1965 was to measure the drift rate of Type III bursts to the lowest possible frequency observable on the Dapto spectral records. The results showed that the velocities were constant out to heights of at least 3 $R_\odot$ and suggested that this was due to 20 KeV electrons travelling on open magnetic field lines (Stewart 1965). Soon afterwards, satellite observations (Anderson and Lin 1966) confirmed that Type III bursts were associated with streams of electrons arriving within 30 min at the Earth's orbit. Later satellite observations of Type III bursts at kilometric wavelengths (Fainberg and Stone 1970) traced the radio emission along Archimedes spiral paths in the solar wind.

By 1950 it was evident that the most intense solar flares emitted outbursts over the entire observable radio range, from millimetre to metre wavelengths and later X-ray and γ-ray observations from satellites, especially during the 1980 Solar Maximum Mission, confirmed that highly-energetic electrons also were emitted from the Sun during these times. An early example of a solar radio event recorded at multiple frequencies is shown in Figure 27. For this particular event, Payne-Scott and Little (1952) used the Potts Hill Swept-lobe Interferometer to observe what was probably the first recorded moving Type IV burst (see Figure 28). This was another example of reverse serendipity. The radiospectrograph operations at Penrith had ceased at the end of

Fig. 27 Multi-frequency observations of a large solar outburst on 17 February 1950 (after Christiansen et al. 1951: 53).



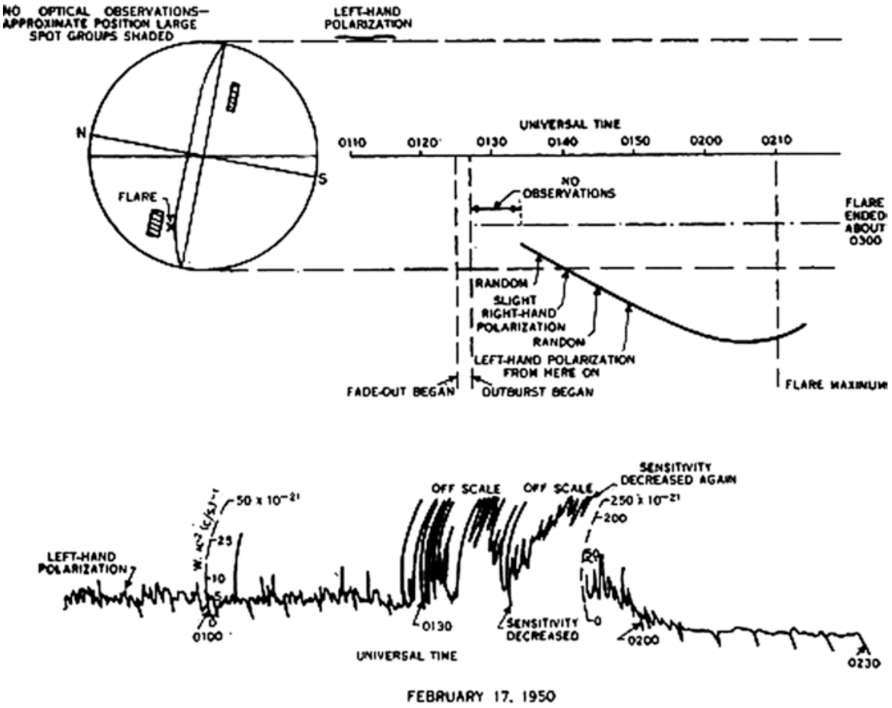


Fig. 28 The 97 MHz interferometer measurements of the outburst on 17 February, 1950 (after Payne-Scott and Little 1952: 34).

1949 and only recommenced in 1951 at Dapto with improved equipment. Consequently Payne-Scott and Little had no spectral observations to help them distinguish between the different types of outbursts such as the Type II and the Type IV. From their polarization and positional measurement (Figure 28) we can now say with the advantage of hindsight that what they observed was a polarized moving Type IV burst (see Wild et al. 1959b). Had they realised this they would have been credited with the discovery of spectral Type IV bursts some 7 years before Boischot.

An account of a moving Type IV burst was first published by Boischot in 1958, based upon his 169 MHz observations with the large interferometer at Nançay (France), and Radiophysics' astronomer, Alan Weiss (1963b), later identified the Type IV stationary component on the basis of observations made with the Dapto swept-frequency interferometer. Its importance became more evident with the advent of orbiting white-light coronagraphs on OSO-7 and Skylab in the 1970s which showed disturbances in the corona where huge amounts of coronal material was ejected at the time of moving Type IV bursts. Studies by Stewart et al. (1974) showed that there was sufficient energy ejected during these coronal transients to account for the interplanetary shock waves which were largely responsible for ionospheric disturbances, but this topic lies outside the scope of the present paper, as does Stewart's (1985) later review of moving Type IV bursts.

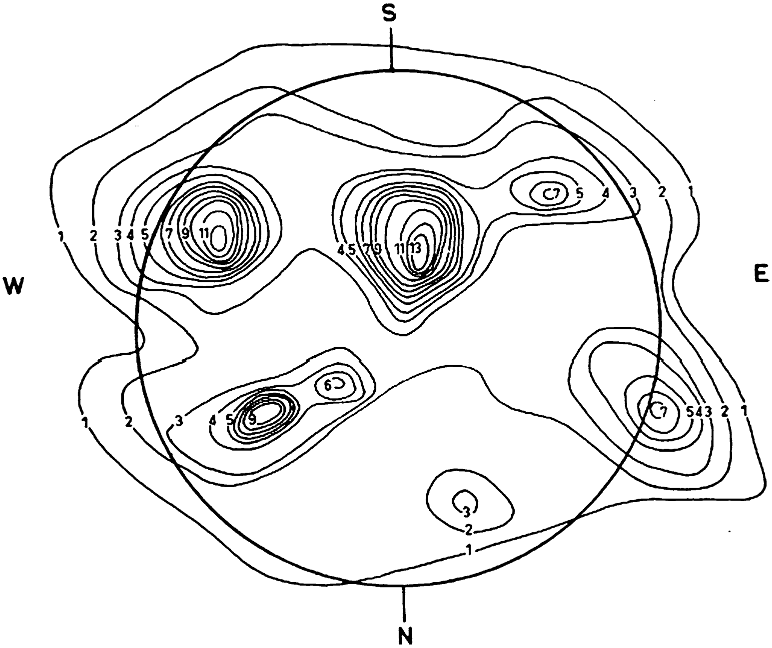


Fig. 29 An isophote map of 1,420 MHZ emission recorded on 3 December 1957 (after Christiansen et al. 1960: 84).

Finally, another important contribution to solar astronomy made by Radiophysics staff during the late 1950s came from the Chris Cross at Fleurs, which was used to generate daily maps of solar radio emission at 1,420 MHz (Christiansen et al. 1957).[5] A conspicuous feature of these isophote maps were localised regions of intense emission, termed radio plages (Figure 29) which were usually associated with chromospheric plage regions above sunspots. By the end of 1962

> … a large amount of data existed on the positions, sizes, temperatures and lifetimes of radio plages. Typically, they were found to be disk-like regions parallel to the photosphere with lateral dimensions of ~25 x 10^4 km and brightness temperatures of ~6×10^5 K (Christiansen and Mathewson 1959: 110, 112). Meanwhile, the height of a radio plage was revealed by its rate of rotation across the solar disk. When this is plotted … the gradient of the line of best fit gives the height of the radio plage in the solar atmosphere. Such plots showed that radio plages are located between 2×10^4 and 10^5 km (with an error of $\pm 10^4$ km) above the photosphere, i.e. in the lower corona. (Orchiston and Mathewson 2009: 18).

These Chris Cross maps and strip scans produced by other radio observatories were published in the *Quarterly Bulletin of Solar Activity* along with the Dapto spectral observations. Collectively, these records provided a more complete picture of activity in the solar corona than was available from any other source at that time.

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[5] During the last couple of years prior to its hand-over by CSIRO's Division of Radiophysics to the University of Sydney's School of Electrical Engineering it was the duty of one of the authors (WO), under the direction of Dr Richard Mullaly, to operate the Chris Cross and produce the daily solar isophote maps.

Following these earlier efforts at Dover Heights, Potts Hill, Penrith, Dapto and Fleurs, in the 1960s the Solar Group's focus shifted to the Culgoora Radioheliograph in north-western New South Wales. This unique radio telescope (Wild 1967) was used to carry out further cutting edge research that helped to maintain Australia's position at the forefront of international solar radio astronomy (e.g. see McLean and Labrum 1985).

6 A Master List of Significant International Contributions to Solar Radio Astronomy, 1942–1960

To put the Radiophysics' research efforts into international and chronological context the following chronological list of significant international contributions to solar radio astronomy is presented.[6] The contributions can be separated into four different groups based upon the observing techniques utilised:

1. Single-frequency flux density and polarization measurements of the total emission.
2. Spectral observations over a continuous frequency range.
3. 1D and 2D mapping of source positions and sizes using interferometers of various types.
4. Eclipse observations using the lunar limb to delineate the positions of the solar radio-emitting regions.

In the following listing, Radiophysics' contributions are given in *italics*.

1942

Solar radio noise was first detected on British radar sets at 35–70 MHz and was found by Hey (1946) to be associated with sunspots.

The temperature of the chromosphere was measured to be 10,000 K at 3,000 MHz and 20,000 K at 1,500 MHz by Southworth (1945).

1943

Reber (1944) detected emission from the quiet Sun at 160 MHz.

1945

Solar emission at 200 MHz was independently detected with New Zealand radar sets and was found by Alexander (1946) to be associated with sunspots (see Orchiston 2005a).

From October, 200 MHz solar radio emission was detected at the Collaroy Radar Station in Sydney and was correlated by Pawsey et al. (1946) with total sunspot area.

Dicke (1946) carried out the first radio observation of a solar eclipse, on 9 July 1945.

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[6] While we believe the following listing to be reasonably complete, it is just possible that we have unintentionally omitted a small number of significant results that were published in languages other than English.

1946

The temperature of the corona was found by Pawsey (1946) to be 10^6 K from 200 MHz observations of the quiet Sun, in agreement with the theoretical predictions of Martyn (1946b) and Ginzburg (1946, 1984).

In February 1946 McCready et al. (1947) used the Dover Heights sea-interferometer to identify 200 MHz emission with a large sunspot group.

Ryle and Vonberg (1946) carried out variable baseline interferometry in July 1946 at 169 MHz to measure the size of the radio source associated with a large sunspot group, and found the emission to be circularly polarized.

Covington (1947) carried out 3,000 MHz observations of the November eclipse in Canada and identified emission associated with a large sunspot group.

Martyn (1946a) found solar noise storms to exhibit circular polarization.

Appleton and Hey (1946) found outbursts at radio wavelengths were associated with solar flares.

1947

A large outburst recorded simultaneously at 60 and 100 MHz from Dover Heights and at 200 MHz from Mt. Stromlo Observatory showed a systematic delay in onset times towards lower frequencies (Payne-Scott et al. 1947), inspiring the development of the Penrith Radiospectrograph.

Khaykin and Chikhachev (1947) observed the April total solar eclipse from Brazil and showed that the radio emission at 200 MHz came from the solar corona, as predicted by Martyn (1946b) and Ginzburg (1946).

Lehany and Yabsley (1948) conducted solar observations at 200, 600 and 1,200 MHz from the Georges Heights field station (see Orchiston 2004).

1948

Piddington and Minnett (1949) conducted solar observations at 24,000 MHz from the Radiophysics Headquarters building in central Sydney.

The 1 November partial solar eclipse was observed at 600 MHz from three widely-spaced locations within Australia. Seven source regions were located above sunspots or former sunspot areas and one source was located beyond the solar limb (Christianson et al. 1949); Sydney-based observations also were conducted at 3,000 MHz by Piddington and Hindman (1949) and at 9,428 MHz by Minnett and Labrum (1950). See, also, Orchiston et al. (2006).

Payne-Scott (1949) conducted solar observations at 18.3, 19.8, 60, 65 and 85 MHz from the Hornsby Valley field station (see Goss and McGee 2009).

Solar monitoring at 75, 140 and 200 MHz by de Voogt (1952) from three sites in The Netherlands was extended in 1951 to a world-wide network for the study of solar effects on the ionosphere (see Strom 2005).

Solar observations at 555 MHz from Meudon (France) by Laffineur and Houtgast (1949) were extended by Laffineur (1954) to 255 MHz in 1949 (see Orchiston et al. 2007).

Lehany and Yabsley (1948) extended their detection of radio outbursts to 1,200 MHz and Schulkin et al. (1948) to 9,500 MHz; this upper limit was later extended by Hagen and Hepburn (in 1952) to 35,000 MHz.

1949

Wild and McCready (1950) commenced observations with the 70–140 MHz Penrith Radiospectrograph, leading to the classification of Type I, Type II and Type III bursts (see Stewart et al. 2010).

Little and Payne-Scott (1951) installed the Swept-lobe Interferometer at Potts Hill, which for the first time measured the source positions and polarization of solar bursts at 98 MHz.

Oda and Takakura (1951) began 3,300 MHz solar monitoring at Osaka University (Japan) and Tanaka (1984) began solar observations at 60, 100 and 200 MHz from Tokyo Astronomical Observatory.

Metre wavelength studies of the Sun by Chikhachev (1950) were conducted by FIAN in the Crimea in Russia (see Salomonovich 1984).

1951

Christiansen (1953) began operating a 1,410 MHz East-West Grating Array at Potts Hill field station, which was later joined by a North-South Grating Array (see Wendt et al. 2008b); these were used to detect limb brightening, in agreement with the theoretical predictions of Smerd (1950).

French observations by Blum et al. (1952) of the 1 September 1951 partial solar eclipse from Makala (Africa) and the 25 February 1952 total eclipse from Dakar (Africa) showed that the corona at 169 MHz had an ellipsoidal shape with maximum extension along the solar equator; limb brightening was also detected at 9,350 MHz (see Orchiston and Steinberg 2007).

Vitkevich (1951) initiated variable baseline interferometric studies of the outer corona using an occultation of the Crab Nebula.

1952

Wild and his colleagues commenced 40–240 MHz Radiospectrograph observations at Dapto field station, leading to the detection of harmonic structure in Type II and Type III bursts (see Wild et al. 1954a; Wild et al. 1954b; Stewart 2009).

Covington and Broten (1954) made 2,800 MHz strip-scans of the Sun from Goth Hill (Canada) using a slotted waveguide array.

1953

Tanaka and Kakinuma (1953) built a 5-element grating interferometer at Toyokawa (Japan) which operated at 4,000 MHz and was used for 1-D solar mapping; this array was extended to 8 elements in 1954, and polarimeters were installed at 1,000, 2,000, 3,750 and 9,400 MHz.

O'Brien (1953) used aperture synthesis to map the quiet Sun at metre wavelengths.

1954

Swarup and Parthasarathy (1955) converted the Potts Hill East-West Grating Array to operate at 500 MHz, and detected limb brightening (see Swarup 2008; Wendt et al. 2008b), in agreement with the theoretical predictions of Smerd (1950).

The Potts Hill East-West Grating Array dishes were donated to India; they were eventually installed at Kalyan and began solar mapping at 610 MHz in 1965 (Swarup 2006).

Fokker et al. (1955) and Seeger (1955) made observations of the quiet Sun at 200, 400, 545, 3,000 and 9,100 MHz from NERA, Kootwijk and the Hague in The Netherlands during the partial solar eclipse on 30 June 1954 (see van Woerden and Strom 2006).

1955

Kundu (1959) set up a two-element variable-baseline interferometer at Nançay (France) which was used for synthesis mapping of solar active regions at 9,350 MHz (see Orchiston et al. 2009).

1956

Maxwell et al. (1958) set up a 100–580 MHz radiospectrograph at Harvard University's Fort Davis field station in Texas and began recording solar bursts; this instrument (Thompson 1961) was extended to 25–580 MHz in 1959 and 2,100–3,900 MHz in 1960 (see Thompson 2010).

Blum et al. (1957) and their Paris Observatory colleagues began observing with the 169 MHz Le Grande Interferometer at Nançay, which consisted of 32 × 5 m antennas on a 1,600 m east-west baseline; a north-south arm was added in 1959 (see Pick et al. 2011).

Covington and Broten (1957) began regular 1-D solar mapping at 3,000 MHz using a compound interferometer at Goth Hill (Canada); in 1959 this was converted to a 4-element array.

1957

The Chris Cross at Fleurs field station comprising east-west and north-south arms each with 32 × 5.8 m antennas (Christiansen et al. 1957) began routine 2-D mapping of the Sun at 1,420 MHz (see Orchiston and Mathewson 2009).

Haddock (1958) began observing solar bursts at the University of Michigan using a 100–580 MHz radiospectrograph.

Pick and Steinberg (1961) began 1-D solar mapping at 9,350 MHz using a 16-element east-west array at Nançay (France) (see Pick et al. 2011).

Firor (1959) began observations at 87 MHz and 340 MHz with an east-west grating array set up by the Department of Terrestrial Magnetism, Carnegie Institute of Washington (Kundu and Firor 1961).

Ikhsanova (1959) and Gelfreich et al. (1959) began 1-D solar mapping at 9,500 MHz with the Big Pulkova Radio Telescope in Russia (see Parijskij 2007).

1958

Wild et al. (1959b) used the 40–70 MHz Swept-frequency Interferometer at Dapto to confirm the 'plasma hypothesis' for the emission of Type II and Type III bursts and Wild et al. (1959a) identified the first Type V burst (see Stewart 2009).

The Dapto Radiospectrograph (see Stewart 2009) was extended from 25 to 210 MHz (Sheridan et al. 1959); 15–210 MHz in 1960 (Sheridan and Trent 1961); 5–210 MHz in 1961 (Sheridan and Attwood 1962) and from 5 to 2,000 MHz in 1963 (Suzuki et al. 1963).

Boischot (1958) identified the first Type IV solar burst using the 169 MHz Le Grande Interferometer at Nançay (France) (see Pick et al. 2011).

Suzuki (1959) set up a 201 MHz four-element multi-phase interferometer at Mitaka (Japan) to measure the positions of the sources of solar bursts.

Observations by Tanaka and Kakinuma (1958) at 2,000, 3,750 and 9,100 MHz from Toyokawa (Japan) and the island of Hachijo-jima (Japan) during the solar eclipse of 19 April 1958 showed that polarized emission occurred directly above bipolar sunspots.

35,000 MHz solar observations began at Puschino in Russia (Salomonovich 1984).

1959

Boischot and Warwick (1959) used a 15–38 MHz radiospectrograph together with two-element interferometers operating at 18 and 38 MHz at the University of Colorado to study low frequency Type I noise storms and Type III bursts.

Young et al. (1961) began using the Convair/Caltech 500–950 MHz radiospectrograph to record solar bursts.

Elgaroy (1961) began using a 190–215 MHz high time-resolution and frequency-resolution spectrograph at the University of Oslo (Norway) to record solar bursts.

Fokker (1960; Cohen and Fokker 1959) used a 254 MHz interferometer and a 200 MHz polarimeter at NERA (The Netherlands) to study noise storms.

1960

Bracewell and Swarup (1961) began using the Stanford University compound interferometer crossed array for solar mapping at 3,260 MHz (see Bracewell 2005).

A considerable number of observatories around the world monitored the Sun at single frequencies during the 1950s and early 1960s and published regularly in the *Quarterly Bulletin of Solar Activity* following the 1957 International Geophysical Year. Some of these observatories have not been acknowledged above but their contributions were nevertheless valuable for statistical studies and for the prediction of geomagnetic disturbances. Simultaneous data recorded at different frequencies and observatories also could be used sometimes to

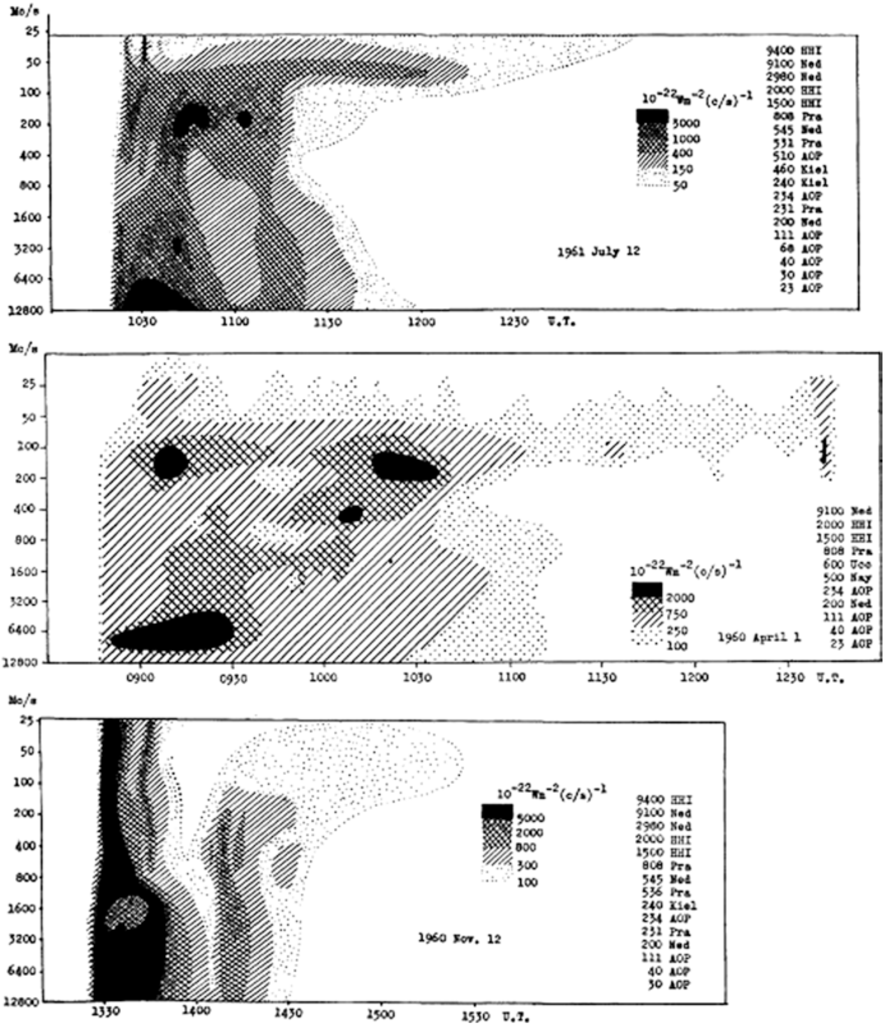

Fig. 30 Synthesized spectra of three major Type IV bursts recorded during 1960–1961 over the frequency range from 30 to 9,200 MHz (after Fokker 1961: 74).

synthesize the spectra of major solar bursts. For example, Fokker (1961) used data from the following observatories to derive a complete picture of the spectra of the major Type IV bursts during 1960–1961 (see Figure 30):

- NERA, the Netherlands (9,200 and 2,900 MHz)
- Heinrich Hertz Institute, Berlin (9,400, 2,000 and 1,500 MHz)
- Ondrejev Astronomical Observatory, Czechoslovakia (808, 551 and 231 MHz)
- Universitats Sternwarte, Kiel (460 and 240 MHz)
- Astrophysical Observatory, Potsdam (510, 234, 111, 60, 40, 30 and 23 MHz)

7 Concluding Remarks

The success of the Division of Radiophysics' solar research program in the late 1940s and throughout the 1950s inspired other groups in America, Japan, France, Holland and elsewhere to build similar instruments for solar radio-frequency investigations. By the early 1960s there was 24-h coverage of solar activity and the reputation of the Radiophysics' Solar Group was well and truly established through its innovative instrument designs and significant research results.

An early recognition of this emerging reputation was that the 1952 URSI Congress was held in Sydney (Robinson 2002). This was the first time the meeting had been held in the Southern Hemisphere, and field trips were made to highlight the solar facilities at the Dapto and Potts Hill field stations (e.g. see Figure 31).

For the Solar Group, a final accolade came when Wild et al. (1963) were invited to write the definitive paper on solar bursts and Christiansen (1963) the review paper on radio telescopes in the first edition of the *Annual Review of Astronomy and Astrophysics*.

While many factors influenced the success of the Division of Radiophysics' initial forays into radio astronomy, this paper has sought to emphasise the importance of four key factors that contributed to the success of the Solar Group.

Fortunately, three of the authors of this paper (RS, WO and BS) were employed by the Division of Radiophysics during part or all of this era and personally knew most of the pioneers of Australian radio astronomy mentioned in this paper.

Fig. 31 The 1952 URSI visit to Potts Hill field station where Sir Edward Appleton (*far right*) discusses the E-W grating array with its designer, Chris Christiansen, who is standing on the *extreme left* beside one of the antennas. *Third from the left* is Sir Frederick White, a former wartime Chief of the Division of Radiophysics and by 1952 Chairman of the CSIRO (adapted from the original in the ATNF Historic Photographic Archive).

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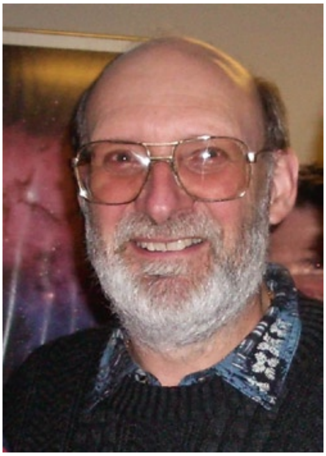
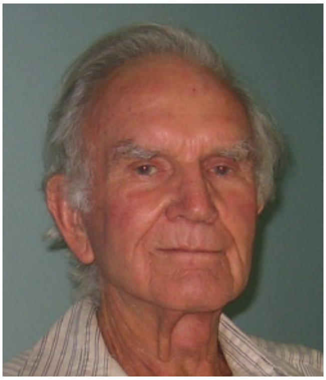


Wayne Orchiston was born in Auckland (New Zealand) in 1943, and has B.A. (Honours) and Ph.D. degrees from the University of Sydney. He is currently an Associate Professor of Astronomy at James Cook University, Townsville, Australia. A former Secretary of IAU Commission 41 (History of Astronomy), he is the founder and former Chair of the IAU Working Group on Historic Radio Astronomy and is also on the Committee of the IAU Working Group on Transits of Venus. In addition to Commission 41, he is a member of IAU Commissions 40 (Radio Astronomy) and 46 (Astronomy Education and Development). He is the founding Editor of the *Journal of Astronomical History and Heritage*. Wayne's research interests lie mainly in astronomical history, astronomical education and meteoritics, and he has more than 200 publications, including the following books: *Nautical Astronomy in New Zealand. The Voyages of James Cook* (1998), *Astronomical Instruments and Archives From the Asia-Pacific Region* (2004, co-edited by Richard Stephenson, Nha Il-Seong and Suzanne Débarbat), *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth* (2005, editor), *Proceedings of the 5th International Conference on Oriental Astronomy* (2006, co-edited by Kwan-Yu Chen, Boonrucksar Soonthornthum and Richard Strom) and *Foundations of Australian Radio Astronomy. A New Picture of the Southern Sky* (2011, co-authored by Woody Sullivan).

John Pearson was born in 1947 in the USA, and has a B.Sc. (Physics) from Redlands University, a Master of Communication and Library Science (California State University) and a Master of Astronomy from the University of Western Sydney (Australia). In 2009 John graduated with a Ph.D. from James Cook University (Townsville, Australia) with a thesis on "The Role of the 40 Foot Schaeberle Camera in the Lick Observatory Investigations of the Solar Corona", supervised by Wayne Orchiston and "Kim" Malville. He is retired, and lives in Rancho Mirage, California (USA). His primary research interests are in the history of solar astronomy and in historic telescopes and other instruments. He is a member of the Antique Telescope Society. In 2008 his paper on "The 40-foot solar eclipse camera of the Lick Observatory" (co-authored by Wayne Orchiston) appeared in the *Journal of Astronomical History and Heritage*.



Bruce Slee is one of the pioneers of radio astronomy. He was born in Adelaide (Australia) in 1924, and received B.Sc. (Honours) and D.Sc. degrees from the University of New South Wales in 1959 and 1971 respectively. He is currently an Honorary Fellow at the CSIRO Division of Astronomy and Space Science in Sydney and an Adjunct Professor in the Centre for Astronomy at James Cook University, Townsville (Australia). He is a member of IAU Commissions 40 (Radio Astronomy) and 41 (History of Astronomy), and the IAU Working Group on Historic Radio Astronomy. He independently detected solar radio emission during WWII, was one of the original discoverers of the first discrete radio sources, participated in the first metre-wave all sky surveys, and along with Bernard Lovell pioneered the investigation of radio emission from stars other than the Sun. His other research interests include scattering in the interplanetary medium, absorption in the interstellar medium, pulsar research, surveys of clusters of galaxies, and radio relics in clusters. He continues to carry out research on active stars, microquasars and clusters of galaxies, and has also published a succession of papers on the history of Australian radio astronomy, mainly in collaboration with Wayne Orchiston and his James Cook University Ph.D. students. [Editors' note: We are pleased to report that all four 2005–2006 issues of the *Journal of Astronomical History and Heritage* were dedicated to Bruce Slee, in recognition of his remarkable 60-year involvement in world radio astronomy.]

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