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Wayne Orchiston
David A. Green
Richard Strom *Editors*

New Insights From Recent Studies in Historical Astronomy: Following in the Footsteps of F. Richard Stephenson

A Meeting to Honor F. Richard Stephenson on His 70th Birthday

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Richard and the late Ellen Stephenson

Wayne Orchiston • David A. Green
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Editors

New Insights From Recent Studies in Historical Astronomy: Following in the Footsteps of F. Richard Stephenson

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Dedicated to the Memory
of Ellen Stephenson (1938–2012)

Foreword

This book is unusual, combining as it does papers on four different aspects of historical astronomy, namely applied historical astronomy, Islamic astronomy, Oriental astronomy and amateur astronomy, yet this mix perfectly reflects the interests of Francis Richard Stephenson. Richard is the acknowledged 'founding father' of applied historical astronomy, which aims to use data extracted from historical records to address present-day issues in astrophysics and geophysics. He also has published prolifically on Islamic and Oriental astronomy, sometimes in collaboration with colleagues who at one time or another were his Ph.D. students at either Durham University (in England) or James Cook University (in Townsville, Australia). The fourth component—the history of amateur astronomy—may seem to be a strange inclusion, for Richard is not widely known to be an active researcher in this field, yet he is an unbridled supporter of amateur astronomy; has been the president of his local Newcastle Astronomical Society continuously since April 1986; frequently lectures on astronomical history to amateur astronomical societies throughout the British Isles; and with a former graduate student, Dr. Stella Cottam, has published on the involvement of US professional *and amateur* astronomers in the 1882 transit of Venus and the 1869 and 1878 total solar eclipses.

And so the idea emerged to conduct an international scientific meeting at Durham University on Richard's 70th birthday, in April 2011, in order to celebrate his lifelong vital contribution to history of astronomy. Richard and his late wife, Ellen (who sadly died in 2012), were excited by the prospect, and when there was support from Arnold Wolfendale, Martin Ward and others from the Physics Department at Durham University, StephensonFest was born. The term 'StephensonFest' was inspired by 'WoodFest' which I previously had organised at the University of Washington in Seattle to celebrate Woody Sullivan's 65th birthday.

The hard work of organising the logistics of the conference fell to the Local Organising Committee (LOC) of Professor Martin Ward (Temple Chevallier Professor of Astronomy, and Chairman of the Committee), Professor Sir Arnold Wolfendale, F.R.S. (the former Astronomer Royal), Dr. Jennifer Gray (Department of Mathematics), Mr. Craig Barclay (Curator of the Oriental Museum at Durham University), Dr. Pete Edwards (the Physics Department's Outreach Officer) and Ms. Lindsay Borrero (the

Astronomy Group Secretary). We thank them for arranging an excellent conference. Meanwhile, the programme was addressed by the Scientific Organising Committee (SOC), which comprised: Associate Professor Wayne Orchiston (Australia; Chairman), Dr. Suzanne Débarbat (France), Dr. David Green (England), Professor Ciyuan Liu (China), Dr. Leslie Morrison (England), Professor Il-Seong Nha (South Korea), Dr. Mitsuru Sôma (Japan), Professor John Steele (USA), Professor Richard Strom (the Netherlands), Dr. David Willis (England) and Professor Sir Arnold Wolfendale (England). All of us had worked closely with Richard in various research, editorial and/or IAU (Commission 41) capacities, over many years.

While the SOC arranged an exciting programme with two and a half days of oral and poster papers, the LOC organised a reception in the Physics Department, a conference dinner at one of the University's colleges and a guided tour of the University's remarkable Oriental Museum. Sir Arnold also kindly arranged to host us at his home one evening. The formal programme is shown on pages xi–xiii.

It now remains for me to thank Durham University and members of the LOC and SOC for making StephensonFest happen; all those who presented papers at the conference or prepared poster papers; Dave Green and Richard Strom for agreeing to co-edit these proceedings and thereby carry some of the editorial burden; Sir Arnold Wolfendale and the late Ellen Stephenson for their unstinted support and encouragement throughout; and finally, my dear friend and 'birthday boy', Richard Stephenson. Richard, we all know that you and Ellen greatly enjoyed StephensonFest, and we now hope that you find equal joy in receiving these proceedings as a final—if rather belated—70th birthday present.

Chiang Mai, Thailand

Wayne Orchiston
Chairman, SOC

Participants

Ahn Sang-Hyeon (Korea)
Craig Barclay (England)
Vitor Bonifácio (Portugal)
Lindsay Borrero (England)
Clifford Cunningham (USA)
Chris Davis (England)
Hilmar Duerbeck (Germany)*
Peter Edwards (England)
David Frew (Australia)*
Mike Frost (England)
Ian Glass (South Africa)*
Jennifer Gray (England)
David Green (England)
Ihsan Hafez (Lebanon)
Lee Ki-Won (Korea)
Lamyong McEwen (Australia)
Isabel Malaquias (Portugal)*
Kim Malville (USA)*
Stephen Marsden (Australia)*
Leslie Morrison (England)
Susan Morrison (England)
Wayne Orchiston (Australia)
Jefferson Sauter (USA)
Irakli Simonia (Georgia)*
Mitsuru Sôma (Japan)
John Steele (USA)
Ellen Stephenson (England)
Richard Stephenson (England)
Richard Strom (The Netherlands)
Kyotaka Tanikawam (Japan)*
Martin Ward (England)

Ian Whittingham (Australia)*
Richard Wielebinski (Germany)*
David Willis (England)
Margaret Willis (England)
Arnold Wolfendale (England)
Kevin Yau (USA)

*Co-authors of papers, who were not able to attend the conference.

StephensonFest Program

These pages (xi–xiii) contains the following introductory text, the Program and the following Notes:

Papers published in these Proceedings are shown in blue print. With co-authored papers the name of the presenting author is underlined.

Day	Time	Program (see Note 1 on page xiii)
Wednesday 13 April 2011	18.00	Welcome Reception and Registration
Thursday 14 April 2011	 09.10 09.30	*Chair: Martin Ward* Welcome and Introduction (Martin Ward and Wayne Orchiston) Arnold Wolfendale: "Richard in Durham – A Brief History"
	10.00	*Morning Tea*
	 10.30 11.30 12.00	*Chair: Arnold Wolfendale* Jefferson Sauter, Irakli Simonia, Richard Stephenson & Wayne Orchiston: "Historical Astronomy of the Caucasus: Sources from Georgia and Armenia" (Keynote Paper) Sang-Hyeon Ahn: "Observer's Location for Central Solar Eclipses in Chinese History" Viewing of Durham University's award-winning 3-D movie, 'Cosmic Origins'
	12.30	*Lunch*
	 14.00 14.30	*Chair: Richard Strom* Leslie Morrison: "The Length of the Day: Richard Stephenson's Contribution" Mitsuru Sôma & Kiyotaka Tanikawa: "Determination of ΔT and Lunar Tidal Acceleration from Ancient Eclipses and Occultations"
	15.00	*Afternoon Tea*
	 15.30 16.00	*Chair: Leslie Morrison* Ihsan Hafez, Richard Stephenson & Wayne Orchiston: "Abdul-Rahmān al-Sūfī and his *Book of the Fixed Stars: A Journey of Rediscovery*" (but see Note 2 on page xii). Richard Stephenson: "Reflections on my Career in Applied Historical Astronomy" (Keynote Paper)
	18.30	Conference Dinner: St Chad's College
Friday 15 April 2011	 09.00 09.30	*Chair: Mitsuru Sôma* Richard Strom: "Some Statistical Aspects of Historical Chinese Astronomy Records" Jefferson Sauter, Irakli Simonia, Richard Stephenson & Wayne Orchiston: "The Legendary Fourth Century Georgian Total Solar Eclipse: Fact or Fantasy?"
	10.00	*Morning Tea*
	 10.30 11.00 11.30	*Chair: David Green* Ki-Won Lee: "Analysis of Mars and Halley's Comet Records from the Joseon Dynasty in Korea" David Frew & Wayne Orchiston: "Nineteenth Century Australian Observations of η Carinae: International Controversy and Astrophysical Implications" Craig Barclay: "The Oriental Museum and its Collections"
	12.00	*Lunch*
	14.15	Tour of the Oriental Museum and viewing of the exterior of the historic Durham Observatory
Saturday 16 April 2011	 09.00	*Chair: John Steele* David Willis & Chris Davis: "Evidence for Recurrent Auroral Activity in the Twelfth and Seventeenth Centuries" (Keynote Paper)
	10.00	*Morning Tea*
	 10.30 11.30	*Chair: David Willis* Clifford Cunningham & Wayne Orchiston: "The Clash Between William Herschel and the Great German 'Amateur' Astronomer Johann Schroeter" Mike Frost: "Henry Beighton's Eclipse Chart"
	12.00	*Lunch*
	 14.00 14.30	*Chair: David Green* Vitor Bonifácio & Isabel Malaquias: "Portuguese Amateur Astronomy (1850-1910)" Wayne Orchiston: "The Amateur -Turned-Professional (ATP) Syndrome: Two Australian Case Studies"
	15.00	*Afternoon Tea*
	 15.30 16.00	*Chair: Wayne Orchiston* Kevin Yau: "The Contribution of Historical Astronomy to Modern Science" End of Conference

Notes:

1. In addition to the above oral presentations, there were two poster papers on display:

Ihsan Hafez, Richard Stephenson & Wayne Orchiston: "Al-Sufi's Investigation of Stars, Star Clusters and Nebulae"

Wayne Orchiston, Hilmar Duerbeck, Ian Glass, Kim Malville, Stephen Marsden, Irakli Simonia, Richard Stephenson, Richard Strom, Ian Whittingham & Richard Wielebinski: "History of Astronomy at James Cook University, Australia"

2. Because this paper was published elsewhere, the following related paper was substituted for publication in these proceedings:

Ihsan Hafez, Richard Stephenson & Wayne Orchiston: *"Abdul-Rahman al-Sufi's 3-step magnitude system"*

These proceedings also include invited papers by SOC members Suzanne Débarbat and Ciyuan Liu, who unfortunately were unable to attend StephensonFest. There is also a paper from Mohammad Mozaffari (Iran) which he was to present, but at the last minute he could not attend StephensonFest.

Conference Photograph

Left to right: Dr. Ki-Won Lee (Korea), Dr. Peter Edwards (England), Mrs Margaret Willis (England), Professor Sir Arnold Wolfendale (England), Mrs Susan Morrison (England), Dr. Leslie Morrison (England), Dr. Kevin Yau (USA), Clifford Cunningham (USA), Dr. Mitsuru Soma (Japan), Professor Richard Stephenson (England), Professor Richard Strom (Netherlands), Associate Professor Wayne Orchiston (Australia), Ms Lindsay Borrero (England), Dr. David Green (England), Dr. Craig Barclay (England), Dr. Sang-Hyeon Ahn (Korea), Dr. Jennifer Gray (England), Dr. David Willis (England), Jefferson Sauter (USA), Professor Martin Ward (England), Dr. Xueshun Liu (Canada) and Dr. Vitor Bonifácio (Portugal). Absent: Dr. Chris Davis (England), Mike Frost (England), Dr. Ihsan Hafez (Lebanon), Ms Lamyong McEwen (Australia), Professor John Steele (USA) and Mrs Ellen Stephenson (England).

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About the Authors

Vitor Bonifácio was born in Lisbon (Portugal) in 1967. He has a 4-year degree from the University of Porto, an M.Sc. from the University of London and a Ph.D. from the University of Aveiro. He is currently an Assistant Professor in the Physics Department at the University of Aveiro and a member of the Research Centre 'Didactics and Technology in Education of Trainers' (CIDTFF). His research interests focus on the history of astronomy and physics, the history of instruments and institutions and science education. Recent publications are 'Portugal and the 1876 South Kensington Instrument Exhibition', *Quaderns d'Història de l'Enginyeria*, XIII, (2012 with I. Malaquias) and 'Early astronomical sequential photography, 1873–1923', *Journal of Astronomical History and Heritage*, 14 (2011). Currently, he is researching the development of astrophysics, late nineteenth-century and early twentieth-century amateur astronomy and early applications of photography and cinema in astronomical research.

Clifford J. Cunningham was born in Canada, and has B.A. and B.Sc. degrees from the University of Waterloo (Canada). He commenced a Ph.D. with Wayne Orchiston, the late Brian Marsden, the late Hilmar Duerbeck and Lutz Schmadel at James Cook University (Townsville, Australia) and is completing this degree at the University of Southern Queensland (Toowoomba). His thesis topic is: 'The First Four Asteroids: A History of Their Impact on English Astronomy in the Early Nineteenth Century'. Asteroid 4276 was named in his honour by the Harvard-Smithsonian Centre for Astrophysics in 1990. He is the author or editor of 12 books, beginning with *Introduction to Asteroids* (1988). He is currently the General Editor of the Collected Correspondence of Baron Franz von Zach and (since 2001) the history of astronomy columnist for *Mercury* magazine, a publication of the Astronomical Society of the Pacific. His papers have appeared in many journals, including *Annals of Science*, *Culture and Cosmos*, *Journal for the History of Astronomy* and the *Journal of Astronomical History and Heritage.*

Chris J. Davis was born in Barton-on-Sea (England) in 1967. He has B.Sc. (Honours) and Ph.D. degrees from the University of Wales (Aberystwyth) and the University of Southampton, respectively. During his Ph.D. he studied the interaction between the Earth's aurora and upper atmosphere. Subsequently he worked at the Rutherford Appleton Laboratory supporting users of the EISCAT radars and running the UK Ionospheric Monitoring Programme. From 2003 to 2012 he worked as the Project Scientist for the Heliospheric Imagers on the NASA STEREO mission, studying the Sun and the solar wind. In 2010 he was appointed as Reader in Space and Atmospheric Physics at the Meteorology Department of the University of Reading. He is currently working on ways to improve space weather forecasting and is studying the influence of the solar wind on the Earth's global electric circuit.

Suzanne Débarbat was born in Montluçon (France) in 1928 and has a Licenciée ès Sciences and a Doctorat d'Etat from Sorbonne University. She spent her entire working life at the Paris Observatory and at the time of her retirement was Director of the research groups Systèmes de Référence Spatio-temporels of the Centre National de la Recherche Scientifique and the Département d'Astronomie fondamentale, which is now named Systèmes de Référence Temps-Espace (SYRTE). Since her retirement she has been attached to this last-mentioned department. Suzanne's primary interest is in French astronomy, and particularly the history of Paris Observatory. She has published extensively, including the following books: *Mapping the Sky* (1988, co-edited by J.A. Eddy and H.K. Eichhorn), *Sur les Traces des Cassini: Astronomes et Observatoires du Sud de la France* (1996, co-edited by Paul Brouzeng), *Optics and Astronomy* (2001, co-edited by Gérard Simon), *Astronomical Instruments and Archives from the Asia-Pacific Region* (2002, co-edited by Wayne Orchiston, Richard Stephenson and Il-Seong Nha) and *Pierre-Simon de Laplace (1749–1827)—Le Parcours d'un Savant* (2012, co-authored by Jean Dhombres and Serge Sochon). She also contributed to the book *L'Observatoire de Paris—350 Ans de Sciences* (2012). Suzanne was the President of IAU Commission 41 (History of Astronomy) in 1991–1994 and of the Bureau des Longitudes in 2004–2005. She is a member of the International Academy of Science.

Mike Frost has an M.A. in mathematics from Cambridge University, an M.Sc. in astronomy from Sussex University and an M.Sc. in control engineering from Coventry University. He is a Member of the Institute of Engineering and Technology and the Institute of Mathematics and Its Applications, a Fellow of the Royal Astronomical Society and a Chartered Engineer. His day job is as a systems engineer for General Electric, commissioning computer control schemes in steel mills around the world. However he has also maintained a lifetime interest in the history of astronomy; he is a founder member of the Society for the History of Astronomy and is the Director of the British Astronomical Association's Historical Section. His research interests in astronomical history include a circle of astronomers based around Samuel Foster, Gresham Professor of Astronomy in London during the mid-seventeenth century and a correspondent of Jeremiah Horrocks; Sir Norman Lockyer, the Victorian solar astronomer who discovered helium; Revd. Doctor William Pearson, the co-founder of the Royal Astronomical Society, and Henry Beighton, an eighteenth century polymath. The principal connection between these people is that all lived at some time within 15 miles of Mike's home in Rugby, Warwickshire. A serendipitous secondary connection is that most, like Mike, had an interest in solar eclipses, of which Mike has seen 8 total and 2 annular.

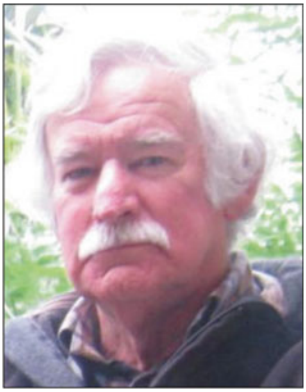
David A. Green was born in Kingston-upon-Hull (England) in 1959. He has B.A. and Ph.D. degrees from the University of Cambridge. He is currently a Senior Lecturer in the Cavendish Laboratory, the Physics Department of the University of Cambridge. His Ph.D. studies started with a measurement of the distance to 3C58, the remnant of the 'historical' galactic supernova of AD 1181. He has continued to study supernova remnants, including the production (since 1984) of a widely used catalogue of galactic supernova remnants, and the identification of the youngest known galactic remnant, G1.9+0.3, which is at most only 150 years old. His research interests also cover a wide range of other radio astronomical topics, and in recent years he has used the Giant Metrewave Radio Telescope (GMRT) in India to produce deep, wide-field low-frequency radio surveys. He has collaborated with Richard Stephenson on studies of the 'historical' supernovae seen in our Galaxy and their remnants, and their co-authored book, *Historical Supernovae and their Remnants*, was published by Oxford University Press in 2002.

Ihsan Hafez was born in Beirut (Lebanon) in 1968. He has B.Sc. and M.Sc. degrees from the American University in Beirut and Boston University respectively, a Master of Astronomy from the University of Western Sydney in Australia and a Ph.D. from James Cook University (Townsville, Australia). He works as a manager in the refrigeration industry in Beirut. Ihsan founded the Middle East's only science and astronomical magazine, *Ilm Wa Alam*, and also the observatory at the Beirut Arab University, where he teaches undergraduate astronomy part-time. His research interests lie primarily in Arabic astronomy. His Ph.D. thesis was on "Abdul-Rahman Al-Ṣūfī and *The Book of the Fixed Stars*: *A Journey of Rediscovery*", supervised by Richard Stephenson and Wayne Orchiston, and currently he is preparing this for publication as a book.

Ciyuan Liu was born in Chengdu (China) in 1948 and has a Ph.D. from Shaanxi Observatory (now the National Time Service Center), Chinese Academy of Sciences. He joined the Observatory as an observer and data analyst at the transit instrument in 1973 and became a research professor in 1993. After a career in astrometry his interests turned to history of astronomy, and he put all his energy into studying ancient Chinese astronomical records. His research includes the investigation of historical variation in the Earth's rotation using lunar and planetary records, the historic chronology of early China and a statistical analysis and collation of all historical Chinese astronomical records. Ciyuan has more than 100 publications, including the following books: *From the Double Dawn to King Wu's Conquest—Astronomical Chronology of the Western Zhou* (2006), *Chinese Historical Canon of Solar Eclipses* (2006) and *A Collation of Astronomical Records in the Histories* (in press).

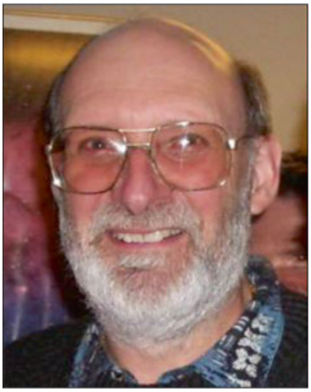
Xueshun Liu was born in Anyang (China) in 1965. He has a Ph.D. degree from the University of British Columbia. He is currently a Chinese Lecturer in the Department of Asian Studies at the University of British Columbia. His research interests include early Chinese astronomy and calendars, and his Ph.D. dissertation, titled "The First Known Chinese Calendar: A Reconstruction by the Synchronic Evidential Approach", was completed in 2005. Some relevant publications are: 'Examination of early Chinese records of solar eclipses', *Journal of Astronomical History and Heritage*, 6, 53–63 (2003, with Ciyuan Liu and Liping Ma); 'Non-linear development of early Chinese calendars', in *Time and Ritual in Early China* (edited by Xiaobing Wang-Riese and Thomas Höllmann), 115–124, (2009); and 'Yin Calendar: the earliest existent prescriptive Chinese calendar', *Yindu Journal*, 2, 24–28 (2009).

Isabel Malaquias was born in Coimbra (Portugal). She is currently an Associate Professor in the Physics Department at the University of Aveiro and belongs to CIDTFF. Her research interests relate mainly to the history of the physical sciences, the history of instruments and institutions and science education. Some recent publications are 'Searching for modernization—instruments in the development of earth sciences in Portugal (18th century)', *Centaurus*, 53, 116–134 (2011; with M.S. Pinto); 'The first astronomical hypothesis based upon cinematographical observations: Costa Lobo's 1912 evidence for polar flattening of the Moon', *Journal of Astronomical History and Heritage*, 13, 159–168 (2010; with V. Bonifácio and J. Fernandes). Her Ph.D. thesis was on 'J. H. de Magellan's Work in the Context of Eighteenth Century Science' (in Portuguese), and currently she is preparing Magellan's correspondence for publication as a book with Rod W. Home and M.F. Thomaz.

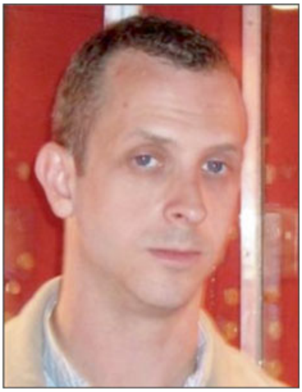


Leslie Morrison was born in Aberdeen (Scotland) in 1939. He studied at Aberdeen University (M.A., D.Sc.) and Sussex University (M.Sc.). He worked at the Royal Greenwich Observatory from 1960 to 1998, specialising in astrometry, the stellar reference frame and the derivation and analyses of historical fluctuations in the Earth's rotation. He collaborated with Richard Stephenson over a period of 20 years and wrote many papers jointly with him on the subject of long-term fluctuations in the Earth's rotation derived from historical observations in the period 700 BC to the present. He was awarded the Tompion Gold Medal of the Worshipful Company of Clockmakers, London, jointly with Richard Stephenson, for their work on the Earth's rotation.

S. Mohammad Mozaffari was born in Lāhijān (Iran) in 1979. He has M.Sc. and Ph.D. degrees in history of astronomy in medieval Islam from the University of Tehran and the Institute for Humanities and Cultural Studies, respectively. He is currently an Assistant Professor in the Research Institute for Astronomy and Astrophysics of Maragha (RIAAM). His research interests include the analysis of planetary parameters in ancient and medieval astronomy, the theory of eclipses, observational instrumentation and astronomy in a social context. One of his recent publications is "Bīrūnī's four-point method for determining the eccentricity and direction of the apsidal lines of the superior planets", which appeared in *Journal for the History of Astronomy*, 44, 207–210 (2013).



Wayne Orchiston was born in Auckland (New Zealand) in 1943 and has B.A. (Honours) and Ph.D. degrees from the University of Sydney. Formerly an Associate Professor of Astronomy at James Cook University, Townsville, Australia, he is currently a researcher at the National Astronomical Research Institute of Thailand and an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowoomba (where he supervises a number of off-campus part-time Ph.D. history of astronomy students). A former Secretary of IAU Commission 41 (History of Astronomy), Wayne is the founder and former Chair of the IAU Working Group on Historic Radio Astronomy and founder and current Chair 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 300 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), *Highlighting the History of Astronomy in the Asia-Pacific Region. Proceedings of the ICOA-6 Conference* (2011, co-edited by Tsuko Nakamura and Richard Strom) and *Mapping the Oriental Sky. Proceedings of the Seventh International Conference on Oriental Astronomy (ICOA-7)* (2011, co-edited by Tsuko Nakamura, Mitsuru Sôma and Richard Strom).



Jefferson Sauter was born in Albany, New York (USA), in 1974. He has B.A. and B.S. degrees from The American University in Washington, DC; an M.A. in Semitics and an M.A. in Medieval and Byzantine Studies from The Catholic University of America in Washington, DC; and a Master of Astronomy from James Cook University in Australia. He works as an actuary in Washington, DC, and is a junior member of the American Astronomical Society. His research interests cover topics in ancient and medieval intellectual history, including astronomy, mathematics, and weather forecasting. Under the supervision of Richard Stephenson and Wayne Orchiston, and with expert input from Irakli Simonia, he is completing a Ph.D. at the University of Southern Queensland in Toowoomba on pre-modern astronomy in the Caucasus.

Irakli Simonia was born in Tbilisi (Georgia) in 1961 and has a Ph.D. from the Abastumani Astrophysical Observatory (where he was employed at the time). Currently he is an Associate Professor in the School of Engineering at Ilia State University, Georgia, and formerly was an Adjunct Associate Professor in the Centre for Astronomy at James Cook University (Australia). His scientific interests are in cometary physics; the physics and chemistry of interstellar and circumstellar matter; cosmochemistry; and the history of astronomy (including archaeoastronomy). Irakli is a member of IAU Commissions 15 (Physical Studies of Comets & Minor Planets), 34 (Interstellar Matter) and 41 (History of Astronomy), and a member of the American Astronomical Society. He has published 56 papers in astrophysics, cosmochemistry and archaeoastronomy, and is the author of an invention in the field of technical physics.

Mitsuru Sôma was born in Kuroiso (Tochigi Prefecture, Japan) in 1954 and has M.Sc. and Ph.D. degrees in astronomy from the University of Tokyo. He is currently an Assistant Professor at the National Astronomical Observatory of Japan. Mitsuru is an Organising Committee member of IAU Commission 41 (History of Astronomy). He is also a member of IAU Commissions 4 (Ephem-erides), 6 (Astronomical Telegrams), 8 (Astrometry) and 20 (Positions and Motions of Minor Planets, Comets & Satellites). In addition he is also a Vice President for Grazing Occultation Services of the International Occultation Timing Association. His research interests include linkage of stellar reference frames with dynamical reference frames using observations of lunar occultations and changes in the Earth's rotation during ancient times using ancient records of eclipses and occultations. His many publications in history of astronomy include the book *Mapping the Oriental Sky. Proceedings of the Seventh International Conference on Oriental Astronomy (ICOA-7)* (2011, co-edited by Tsuko Nakamura, Wayne Orchiston and Richard Strom).

John M. Steele was born in Newcastle (England) and has B.Sc. and Ph.D. degrees from the University of Durham. He is currently Professor of the Exact Sciences in Antiquity in the Department of Egyptology and Ancient Western Asian Studies at Brown University (USA). He serves on the Editorial Boards of the *Journal for the History of Astronomy*, *Isis* and the book series *Time, Astronomy and Calendars: Texts and Studies* and *Wilbour Studies in Egypt and Ancient Western Asia*. John's main research focus is into the history of Babylonian astronomy. He is the author of more than 50 research papers and author or editor of several books including: *Observations and Predictions of Eclipse Times by Early Astronomers* (2000), *Under One Sky: Astronomy and Mathematics in the Ancient Near East* (2002, co-edited by Annette Imhausen), *A Brief Introduction to Astronomy in the Middle East* (2008), *Living the Lunar Calendar* (2012, co-edited by Jonathan Ben-Dov and Wayne Horowitz) and *Ancient Astronomical Observations and the Study of the Moon's Motion (1691–1757)* (2012).

F. Richard Stephenson was born in Newcastle upon Tyne (England) in 1941 and has a B.Sc. (Honours) degree from the University of Durham and M.Sc., Ph.D. and D.Sc. degrees from the University of Newcastle upon Tyne. He is currently an Emeritus Professor in the Department of Physics at the University of Durham and for some years also was an Adjunct Professor in the Centre for Astronomy at James Cook University, Townsville (Australia). Upon his retirement from Durham University he was awarded a Leverhulme Emeritus Fellowship in order to continue his research. A former President of IAU Commission 41 (History of Astronomy), Richard is also a member of Commission 19 (Earth Rotation), and he is on the Editorial Boards of both the *Journal for the History of Astronomy* and the *Journal of Astronomical History and Heritage*. He is widely recognised as the founder of the specialist field of Applied Historical Astronomy, and uses ancient records from Babylon, China, Japan, Korea, the Arabic world and Europe to investigate historical variations in the Earth's rotation, historical supernovae, the past orbit of Halley's Comet, solar variability and historical aurorae. He has also carried out considerable research on ancient Asian astronomical texts and star maps. For his work in historical astronomy he was awarded the Jackson-Gwilt Medal by the Royal Astronomical Society and the Tompion Gold Medal by the Worshipful Company of Clockmakers (London), and minor planet 10979 has been named Fristephenson. Richard has more than 200 publications, including the following books: *The Historical Supernovae* (1977, co-authored by David Clark); *Application of Early Astronomical Records* (1978, co-authored by David Clark); *Atlas of Historical Eclipse Maps: East Asia, 1500 BC – AD 1900* (1986, co-authored by M.A. Houlden), *Secular Solar and Geomagnetic Variations Over the Last 10,000 Years* (1988, co-edited by Arnold Wolfendale), *Oriental Astronomy from Guo Shoujing to King Sejong* (1997, co-edited by Nha Il-Seong); *Historical Eclipses and Earth's Rotation* (1997), *Historical Supernovae and their Remnants* (2002, co-authored by David Green) and *Astronomical Instruments and Archives From the Asia-Pacific Region* (2004, co-edited by Wayne Orchiston, Nha Il-Seong and Suzanne Débarbat).

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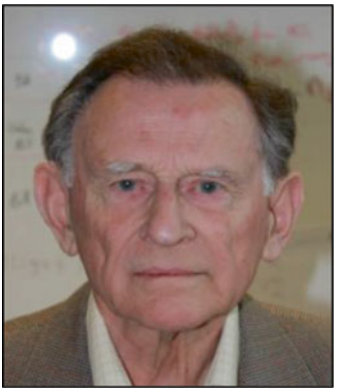
Kiyotaka Tanikawa was born in Gamago-ori (Japan) in 1944 and has M.Sc. and Ph.D. degrees in astronomy from the University of Tokyo. He is now a Special Visiting Scientist at the National Astronomical Observatory of Japan (NAOJ) following his retirement. He began his career in late 1960s as an astronomer by making and analysing colour-magnitude diagrams of globular clusters. He then had a post as an astrolabe observer at the International Latitude Observatory of Mizusawa (ILOM) in 1978 and stayed there until 1990. In 1988, there was a reorganisation of Japanese astronomical institutes and the ILOM and Tokyo Astronomical Observatory of the University of Tokyo united to become the National Astronomical Observatory of Japan. His interests then moved to more theoretical and dynamical aspects of astronomy such as the restricted three-body problem, Solar System dynamics and chaotic dynamics in two-dimensional maps. In 1995 he added the general three-body problem to his research, and introduced numerical symbolic dynamics into this field. In 2001, he turned to history of astronomy when he began investigating historical changes in ΔT. Now he enthusiastically promotes the scientific study of ancient east Asia using the astronomical data that accumulated there.



David M. Willis was born in London (England) in 1936 and has a B.Sc. (Honours) degree from the University of Exeter and a Ph.D. degree from the University of London. He currently holds Honorary Appointments at the Rutherford Appleton Laboratory (Science and Technology Facilities Council) and at the Centre for Fusion, Space and Astrophysics at the University of Warwick. Before retiring in 1996, David was the UK Project Scientist with responsibility for British involvement in the research programmes of the European Incoherent Scatter (EISCAT) Scientific Association. He was a member of the team that produced the design specification for the EISCAT radar facility on the archipelago of Svalbard. He is a former Director of the World Data Centre-C1 for Solar-Terrestrial Physics. He has served on various committees, advisory panels, science teams, and study groups for the UK Research Councils and The Royal Society. He was a member of the Editorial Board of *Geophysical Journal International* for more than 30 years. His research interests include various aspects of geomagnetism, magnetospheric physics, solar physics and space weather, including historical observations of aurorae and sunspots. He has numerous publications on these topics in a range of scientific journals.

Part I
Applied Historical Astronomy

The Length of the Day: Richard Stephenson's Contribution

Leslie Morrison

Abstract Richard Stephenson has transformed the subject of changes in the Earth's rotation over the historical period from one of obfuscation to clarity. His careful amassing and analyses of historical observations of eclipses in the period 700 BC to AD 1600 has led to an accurate determination of the behaviour of the Earth's rotation in that period. The length of the day has increased at an average rate of 1.8 milliseconds per century and on a time-scale of millenia shows fluctuations of about 4 milliseconds about that trend.

1 The Elusive Accelerations

Under the action of tidal friction, angular momentum is transferred from the rotation of the Earth to the orbit of the Moon. As a consequence, the Earth's rate of rotation decreases and the Moon's orbit expands, exhibiting an angular deceleration in its position. Much effort has been expended in trying to measure, what I shall term, these accelerations. In the seventeenth century Halley (1695), and later in the eighteenth century Dunthorne (1749) and Mayer (1753), used observations of ancient and medieval eclipses to show that the Moon had an angular acceleration which could not be accounted for by celestial mechanics. Their numerical results were partly vitiated by the assumption that the Earth's rate of rotation, or, equivalently, the length of the day (lod), is constant. At the beginning of the twentieth century, Cowell (1905), Fotheringham (1920) and de Sitter (1927) analysed reports of ancient eclipses for secular accelerations, both in the Moon's motion and the Earth's rotation. However, correlations between these parameters in their limited data-sets made their separation unreliable.

Meanwhile, in the late nineteenth and early twentieth century, Newcomb (1909) had shown from telescopic observations made during the period AD 1630–1909 that there were inexplicable fluctuations in the Moon's position, and he noted that

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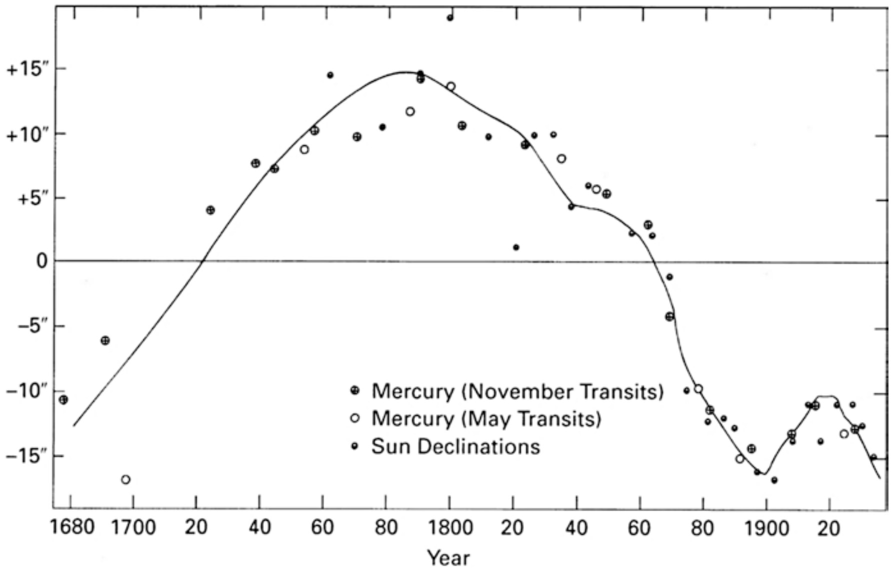

Fig. 1 The fluctuations in positions of the Sun, Moon and Mercury plotted as the inverse ratio of their mean motions to that of the Moon (After Spencer Jones 1939)

these were similar in character to those seen in the position of Mercury (from timings of transits over the Sun) and the first satellite of Jupiter. With prescience, Newcomb hypothesised that these fluctuations might be due to changes in the time-scale against which they were measured—the Earth's rotation. However, it was still suspected that at least some of the fluctuations in the Moon's position were due to deficiencies in the gravitational theory of its motion. In his monumental theory Brown (1919) showed that this was not so, and this re-opened the question of variations in the Earth's rate of rotation. In this regard, inconclusive results were obtained by Glauert (1915), Innes (1925) and de Sitter (1927). These eventually led to the conclusive demonstration by Spencer Jones (1939) (see Fig. 1) that observations of the Sun, Moon and inner planets showed fluctuations in inverse proportion to their mean motions which could only be explained by variations in the Earth's rate of rotation. Also, from Spencer Jones' results, the tidal acceleration of the Moon was found to be −22 arcseconds/century/century. This was the position of the subject in 1939, two years before Richard was born.

2 Richard Enters the Scene

At the behest of Keith Runcorn (sometime Professor of Physics at Newcastle University), Richard began researching into the measurement of the secular accelerations in the rotation of the Earth and the motion of the Moon.

To begin with Richard followed in the footsteps of Fotheringham, using his method to try to separate these two accelerations from historical eclipses. This proved to be unsatisfactory because of the old problem of the correlation in the data between the two parameters. Richard, his collaborator at the time, Paul Muller (see Muller and Stephenson 1975), and independently, R.R. Newton (1970), produced results for the acceleration of the Moon at variance with those from other methods such as the transits of Mercury (see Morrison and Ward 1975). The two accelerations, L' and L with respect to the Earth's rotational time-scale (UT), are shown in Fotheringham's diagram in Fig. 2. Note that Richard's solution (labelled Stephenson) is off-set from the correct solution in the shaded area. There is no shame in this—no-one had the correct value at the time!

The Gordian knot of this problem was cut by using timings of the transits of Mercury over the disk of the Sun from the period AD 1677–1973 to correct for variations in UT, and thus establish a uniform time-scale known as Ephemeris Time (ET). The tidal acceleration of the Moon was then measured with respect to ET from the timings in UT of occultations of stars over the same period, corrected for the difference ET-UT. By this method Morrison and Ward (loc.cit.) derived a

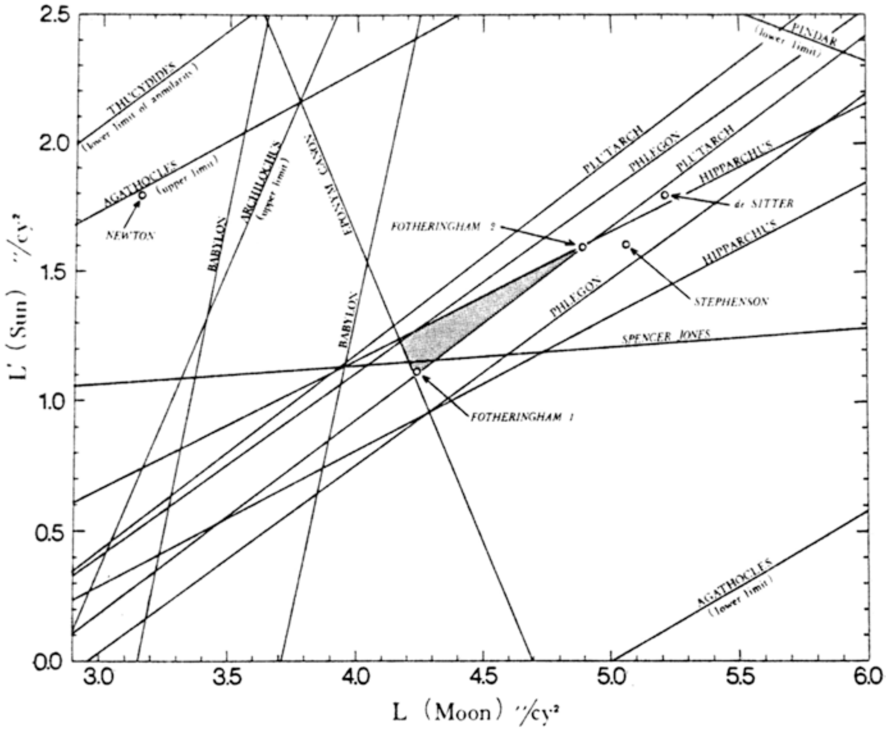

Fig. 2 The 'Fotheringham' solution space for the accelerations of the Sun (the Earth's reflected motion) and the Moon. Richard Stephenson's and R.R. Newton's solutions obtained in the 1970s are shown. We now know that the correct solution is near the centroid of the *shaded area* which Fotheringham (1920) regarded as the most likely solution

value of −26 arcseconds/century/century for the tidal acceleration of the Moon. This value was closely confirmed later from tidal perturbations on low satellite orbits (Christodoulidis et al. 1988), and by laser-ranging to the retro-reflectors on the Moon (Dickey et al. 1994). At about this time, Richard and I decided to collaborate more closely. I took the value of −26 for the lunar tidal acceleration to the problem of the ‘accelerations’ and Richard eked out more pre-telescopic eclipse data, both solar and lunar, with which to derive the remaining unknown in the problem—the acceleration and other variations in the Earth’s rotation prior to AD 1600. The fluctuations after AD 1600 were already known, mainly from timings of lunar occultations of stars.

3 Changes in the Length of Day Before AD 1600

Richard’s endeavours are set out comprehensively in his book *Historical Eclipses and Earth’s Rotation* (Stephenson 1997). The success of this work is dependent on his assiduous compilation of historical data from many sources, and their careful examination for their usefulness in determining variations in the Earth’s rate of rotation. Many of you here at this conference in his honour can attest to this through your collaborations with him. By the early 1980s Richard had assembled over one hundred reliable observations of solar and lunar eclipses. In our analysis of these in the early 1980s (Stephenson and Morrison 1984) we came to the conclusion that one acceleration would not fit all the observations in the pre-telescopic period, and the average acceleration was significantly less than that predicted by tidal friction.

Later in the 1980s Richard continued to amass more observations and by 1995 we were able to carry out a more detailed analysis (Stephenson and Morrison 1995). We had enough observations to split them into two data-sets—untimed and timed—our rationale being that if these two independent subsets gave the same result for the Earth’s rotation, our conclusions would be strengthened. Untimed observations rely on the fact that the belt of totality of solar eclipses is narrow compared to its offset on the Earth’s surface caused by changes in the Earth’s rate of rotation. This is illustrated in Fig. 3 which shows the line of totality for the eclipse of 136 BC, computed on the assumption that the Earth’s rate of rotation, or equivalently, the length of the day (lod), is constant and equal to the value around the present time. From two graphic accounts preserved on dated Babylonian clay tablets, this eclipse was undoubtedly total at Babylon. The rotational displacement of the Earth is 48.8 degrees, which is equivalent to 3.25 hours in time. This is the correction to UT at the epoch 136 BC due to the cumulative changes in the lod between then and the present. This correction is usually designated by ΔT.

Also, large partial solar eclipses and eclipses which were seen to occur at rising or setting on the horizon, provide an upper or lower boundary on ΔT. All the untimed observations are plotted in Fig. 4. The lengths of the lines show the range of possible values of ΔT for each eclipse (for details see Stephenson and Morrison 1995).

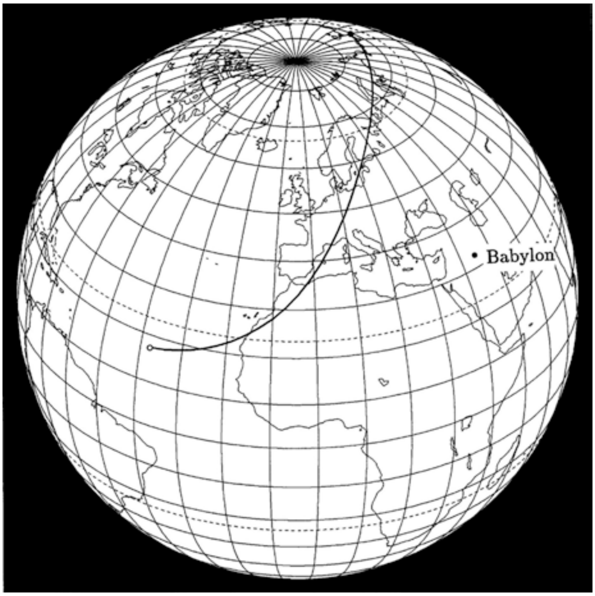

Fig. 3 The computed path of the total solar eclipse of 136 BC calculated on the assumption of a constant rate of rotation for the Earth. It was observed as total at Babylon

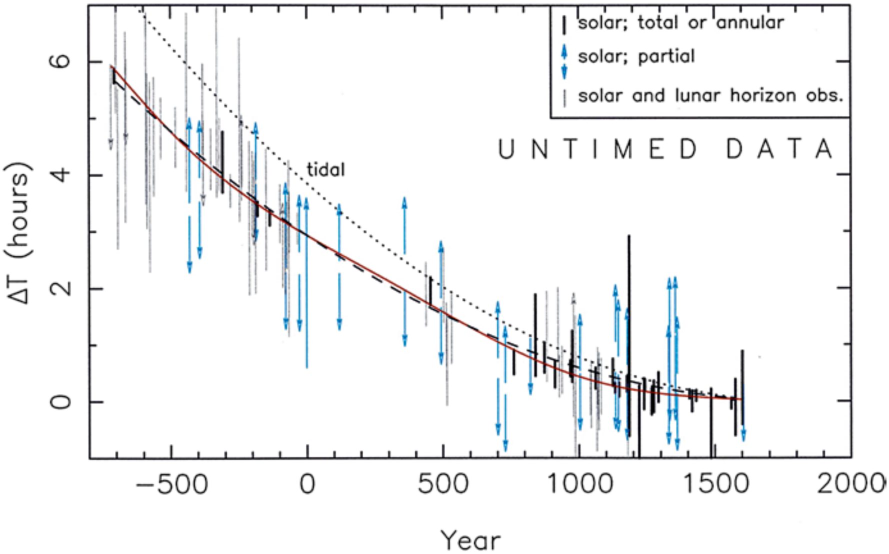

Fig. 4 The results for ΔT derived from untimed eclipses. The *dashed line* is the best-fitting parabola, equivalent to a constant acceleration in the Earth's rotation. The *red line* is the best-fitting curve to all the data in Figs. 4 and 5. The varying slope of this curve denotes changes in rate of rotation on a timescale of millenia. The *dotted* parabola is the predicted change due to tidal friction

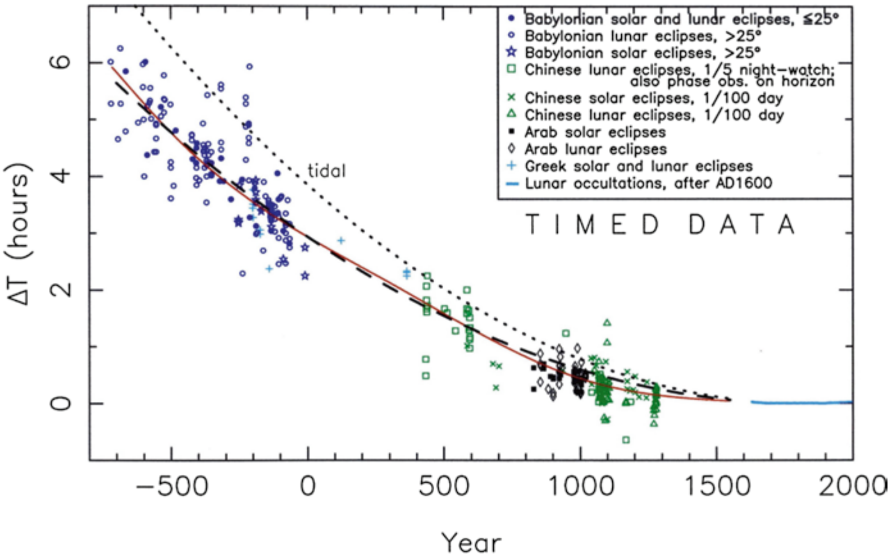

Fig. 5 Plot of the timed data. The curves are the same as those shown in Fig. 4. The *blue line* after AD 1600 is mainly derived from timings of lunar occultations

The timed data were greatly expanded in the late 1980s mainly due to the availability of translations of the Babylonian clay tablets which record a remarkable series of timings of lunar eclipses with respect to the time elapsed from sunset or sunrise. These and the other timed data from Chinese, Arab and Greek sources are plotted in Fig. 5. A detailed discussion of the curve-fitting in Figs. 4 and 5 is given in Stephenson and Morrison (1995).

A parabolic fit to the values of ΔT indicates an acceleration of the Earth's rotation. Both the timed and untimed data agree that the observed acceleration of the Earth is offset from the tidal prediction, and that there are fluctuations on a timescale of millenia. This is seen more clearly in the first derivative along the ΔT curves, which measures the rate of change of the Earth's rotation, or equivalently, the change in the lod. This is plotted in Fig. 6. The non-tidal component of acceleration of −0.5 milliseconds/century is probably due to the rate of change of the oblateness of the Earth caused by viscous rebound from the decrease in load following the last deglaciation. This is consistent with the present-day rate of change of the Earth's zonal harmonic J2 measured by the near-Earth satellite Starlette (Cheng et al. 1989) which implies a rate of change of -0.44 ± 0.05 milliseconds/century in the lod.

4 Conclusion

Richard's contribution to elucidating the changes in the length of day over the past 2,500 years has been considerable. When he entered this subject, it was known that the rotation of the Earth was decelerating under tidal friction, but it was not known

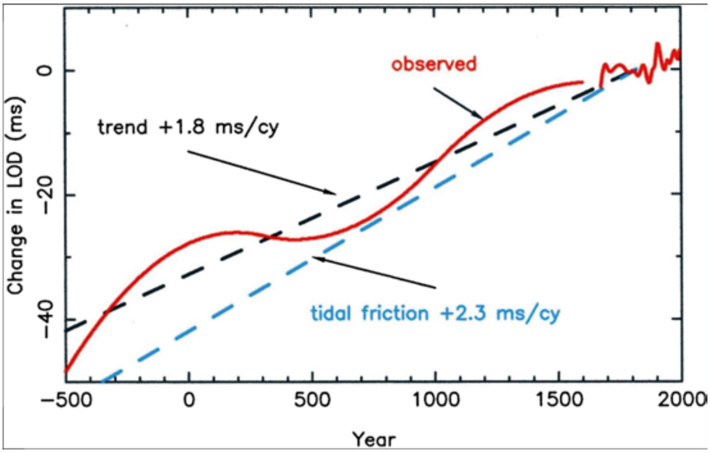

Fig. 6 The change in the length of the day (lod) in milliseconds. The details of the fluctuations after AD 1600 are taken from Morrison and Stephenson (1981)

by how much and there were no details of how the Earth actually varied in its rate of rotation, apart from the decade changes in the lod measured in the telescopic period after about AD 1800. We now have a firm measurement of the actual rate of increase in the lod of +1.8 milliseconds/century, and an estimate of 4 milliseconds for the fluctuations on a timescale of millenia. From a rather confused situation in 1970, a clear picture has emerged, and Richard undoubtedly has been the major contributor to the progress in this subject over the past forty years.

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Determination of ΔT and Lunar Tidal Acceleration from Ancient Eclipses and Occultations

Mitsuru Sôma and Kiyotaka Tanikawa

Abstract In order to investigate the variation of the Earth's rotation speed we have been using ancient solar eclipses and lunar occultations. We are also studying whether or not the Moon's tidal acceleration has been constant from ancient times.

In this paper we show that the records of solar eclipses between 198 and 181 BC in China and in Rome give a value for the lunar tidal acceleration that is consistent with the current one. We also show that the records of lunar occultations of Venus and Saturn in AD 503 and 513 in China are useful for our studies of the Earth's rotation.

1 Introduction

Stephenson (1997) published his monumental work on the investigation of changes in the Earth's rotation using pre-telescopic observations of eclipses between 763 BC and AD 1772. He determined the Earth's clock error, ΔT, for each of the eclipses. ΔT denotes the time difference TT − UT, where TT is Terrestrial Time, which is a uniform measure of time, and UT is Universal Time, which is determined by the rotation of the Earth. We have been trying to determine more precise values of ΔT using contemporaneous solar eclipses. In addition we have been trying to investigate whether or not the Moon's tidal acceleration has been constant since ancient times. In this paper we explain how we are conducting our research. Note that the dates of ancient events given in this paper are indicated using the Julian Calendar.

2 Tidal Acceleration in the Moon's Motion

For the calculation of the Moon's position the quadratic term in the Moon's longitude plays a very important role. Its gravitational component due to planetary perturbations and the Earth's figure perturbations is well established, and according to Chapront

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et al. (2002) based on the analytical theory ELP2000-96 (Chapront and Chapront-Touzé 1997) it is $6''.0590\,T^2$, where T is the time in centuries. It should be noted that the term just mentioned refers to the sidereal motion of the Moon and when we speak of the longitude of the Moon referred to the mean equinox of date, the precessional term should be added. According to Capitaine et al. (2003), the precessional quadratic term is $1''.1054\,T^2$. Therefore, the quadratic term for the above-mentioned Moon's longitude referred to the mean equinox of date is $7''.1644\,T^2$. It should be noted that Brown obtained a comparable value, $7''.14\,T^2$, back in 1919.

There is another component of the quadratic term in the Moon's longitude. This is the tidal component due to the reaction on the lunar motion of the tides raised by the Moon on the Earth, which has to be determined from observations. When we speak of acceleration, the coefficient of the quadratic term in longitude has to be multiplied by 2, and we now denote the lunar tidal acceleration by $\acute{n}$. Table 1 lists values of $\acute{n}$ obtained from past observations.

It should be noted that the large negative values for the lunar tidal acceleration obtained by Van Flandern (1970) and Morrison (1973) were largely due to deficiencies in the planetary terms in Brown's theory of the motion of the Moon (Sôma 1985). The large negative values obtained by Oesterwinter and Cohen (1972) and Van Flandern (1975) may be due to either the short duration of the observations or deficiencies in

Table 1 Principal values of lunar tidal acceleration obtained so far

Author(s)	Year	Tidal acceleration ($''$cy^2)[a]
Spencer Jones	1939	–22.44
Van Flandern	1970	–56.0
Oesterwinter and Cohen	1972	–38
Morrison	1973	–42.0
Van Flandern	1975	–65.0
Morrison and Ward	1975	–26.0
Muller	1976	–30
Calame and Mulholland	1978	–24.6
Williams et al.	1978	–23.8
Ferrari et al.	1980	–23.8
Dickey et al.	1982	–23.8
Dickey and Williams	1982	–25.12
Newhall et al.	1988	–24.90
Dickey et al.	1994	–25.88
Chapront and Chapront-Touzé	1997	–25.64
Chapront et al.	1999	–25.78
Chapront et al.	2000	–25.836
Chapront et al.	2002	–25.858

[a]Note that these values are twice the coefficient of the T^2 tidal term. The value listed for Spencer Jones (1939) was actually derived by Clemence (1948), and based on Spencer Jones' results

the lunar motion models, or both of these. The values obtained from the lunar laser ranging observations since the 1970s converge well at about −25″.9 cy^{-2}.

The ephemeris of the Sun, Moon and planets that we used for our analyses in this paper was the JPL ephemeris DE406. DE406 covers the interval 3000 BC to AD 3000, and it is consistent with DE405 (Standish 1998), which is the ephemeris used for *The Astronomical Almanac* for 2003 through 2014 and covers the interval AD 1600 to 2200. According to Chapront et al. (2002), the lunar tidal acceleration intrinsic to DE405 and DE406 is −25″.826 cy^{-2}, which agrees well with the recently-derived ones discussed above. The value −26″ cy^2 derived by Morrison and Ward (1975) was obtained from comparison of lunar occultations and transits of Mercury since 1677, and the fact that this value is consistent with the recently-determined lunar tidal accelerations derived from the lunar laser ranging observations indicates that the Moon's tidal acceleration has been almost constant since the seventeenth century, but this is no guarantee that the lunar tidal acceleration has been constant since ancient times. Therefore it is important to investigate ancient records of astronomical phenomena and determine whether this value has been constant from ancient times. In the following two sections we will show how we can use data derived from ancient eclipses and occultations to derive values for the lunar tidal acceleration and ΔT.

3 Solar Eclipses Between 198 BC and 181 BC

We have developed a method whereby the ΔT values and the lunar tidal acceleration $\acute{n}$ are simultaneously determined using records of contemporaneous solar eclipses and lunar occultations. The method is briefly described in Sôma et al. (2004), Tanikawa and Sôma (2004) and Sôma and Tanikawa (2005). Here we give an example of the method using ancient Chinese records of solar eclipses dating between 198 and 181 BC.

The great Roman historian Titus Livius (59 BC-AD 17), who is known as Livy in English, wrote about the solar eclipse on 17 July 188 BC as follows: "… darkness had fallen between roughly the third and fourth hours of daylight …" (Yardley 2000: 392). From this we can assume that the eclipse was total in Rome. The same eclipse was also recorded as "… almost total …" (幾既) in the *Hanshu* (漢書), which is the official history book of the Former Han (前漢, 西漢) Dynasty (202 BC-AD 8) of China. We can assume that the records in the *Hanshu* were based on events observed in Chang'an (長安), the capital of the Han Dynasty. Figure 1 shows the area on the Earth where the eclipse was seen, and the area where the total eclipse was visible is indicated by the narrow band crossing Rome. It was drawn using $\Delta T = 12,600$ s and adopting the current value for the lunar tidal acceleration. By changing the value of ΔT we can move the band either in an eastwards or a westwards direction. From this figure we can readily see that astronomers in Rome and Chang'an could not have witnessed the total eclipse simultaneously if we adopt the current value for the lunar tidal acceleration.

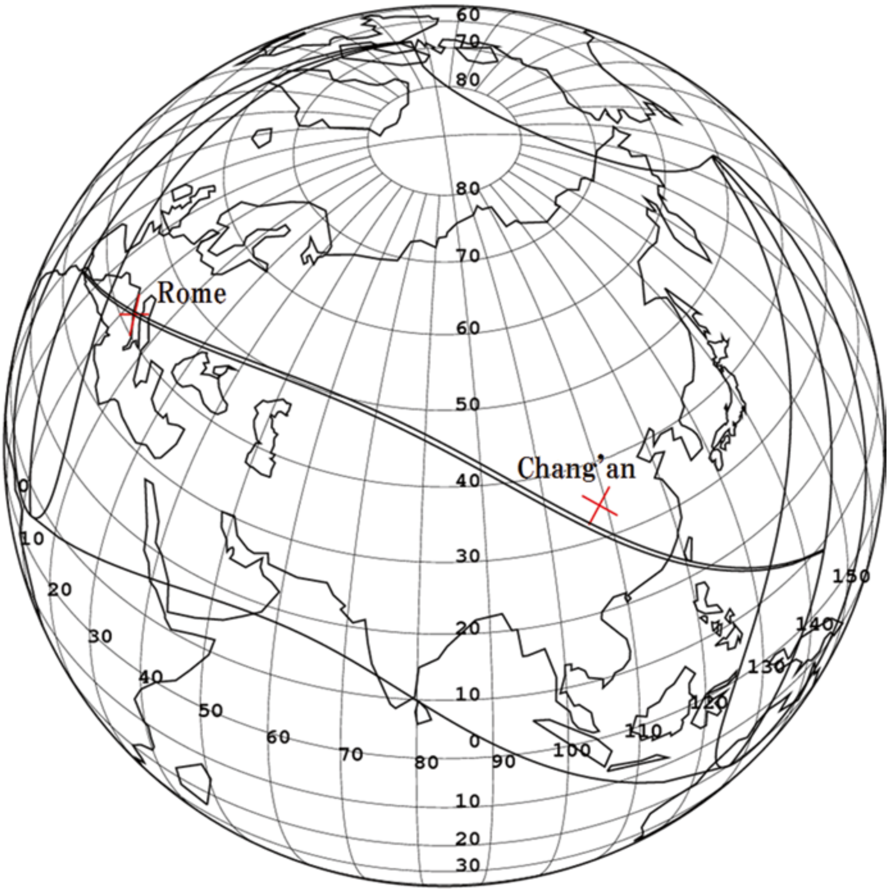

Fig. 1 Solar eclipse on 17 July 188 BC. This gives the area on the Earth where the eclipse was seen, and the area where the total eclipse was seen is indicated by the *narrow band* crossing Rome. It was drawn using $\Delta T = 12{,}600$ s and adopting the current lunar tidal acceleration

Two other solar eclipses within 10 years before and after the 188 BC solar eclipse were recorded in the *Hanshu*. One is the solar eclipse on 7 August 198 BC and the other is the solar eclipse on 4 March 181 BC. They are both recorded as "ji" (既). The ji character usually means a total solar eclipse, but it was also used for an annular eclipse. Modern calculations show that the 198 BC eclipse was annular and the 181 BC eclipse was total, and therefore from these records we can assume that the 198 BC eclipse was annular in Chang'an and the 181 BC eclipse was total, also in Chang'an.

In Fig. 2 we take as the abscissa the correction to the coefficient of the time-square term in the lunar longitude (arcsec century^{-2}) or, in short, the correction to

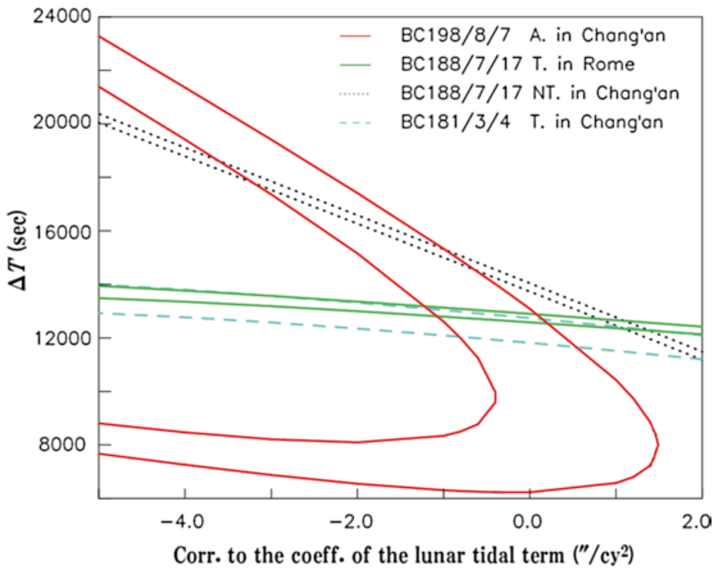

Fig. 2 Diagram showing the possible area of the two parameter values from the solar eclipses between 198 and 181 BC

the lunar tidal term, and take as the ordinate the value of ΔT. We plot on this plane curves of the boundaries of possible values of the two parameters for events observed at known sites. As noted in Sect. 2, the correction to the lunar tidal acceleration is twice that of the coefficient of the time-square term in lunar longitude. The zero in the abscissa corresponds to the current lunar tidal acceleration $-25''.826\,\mathrm{cy}^{-2}$ intrinsic to the JPL ephemeris DE406. In this diagram the possible ranges of the correction to the lunar tidal term and the ΔT value are obtained as the intersections of the plural bands. This figure indicates that the correction, $\Delta\acute{n}$, to the lunar tidal acceleration obtained from all of the eclipse records given above is

$$-2''.42\mathrm{cy}^{-2} < \Delta\acute{n} < 0''.34\mathrm{cy}^{-2},$$

which means that all of the eclipse records given above are consistently explained with the current lunar acceleration. If we adopt the current lunar tidal acceleration, we obtain ΔT values of 12,577 s $< \Delta T <$ 12,896 s from the 188 BC eclipse in Rome, and 11,761 s $< \Delta T <$ 12,688 s from the 181 BC eclipse in Chang'an, and hence as a common range we obtain

$$12{,}577\ \mathrm{s} < \Delta T < 12{,}688\ \mathrm{s},$$

for the epoch around 188 BC.

This method of simultaneously determining the ΔT and $\acute{n}$ values is based on the fact that the ΔT and $\acute{n}$ values can be regarded as almost constant during a short period of time. It should be noted that the $\acute{n}$ value obtained above from the eclipses of around the year 188 BC is not the lunar tidal acceleration value at the times of the eclipses, but it is the mean lunar acceleration value from that period up to the present. The fact that the lunar tidal acceleration obtained above matches the current one does not necessarily mean that the lunar tidal acceleration has been constant during that period. Therefore, we need to investigate further the lunar tidal acceleration from ancient records of other periods.

4 Lunar Occultations and Solar Eclipses Between AD 503 and 522

Lunar occultations of planets and bright stars were often observed and recorded in ancient China, but visible areas of lunar occultations are usually wide, and therefore they rarely can be used to determine ΔT values and lunar tidal acceleration. However, there are some occultation records which can play an important role for our studies. The lunar occultations of Venus on 5 August 503 and of Saturn on 22 August 513 recorded in the *Weishu* (魏書), which is the official history book of the Wei (魏) Dynasty (398–534) of China, are such examples because the former was observed just after the Moon rose in the east and the latter just before the Moon set in the west. Therefore, the combination of these can set limits to the Earth's rotation parameter. It should be noted that these two occultations were seen near the horizon and it is sometimes difficult to observe astronomical phenomena near the horizon because the brightness of stars is diminished by the Earth's atmosphere, but under favorable condition Venus and Saturn are bright enough to be observed near the horizon.

Figures 3 and 4 show the areas where the lunar occultation of Venus on 5 August 503 and that of Saturn on 22 August 513 were seen. As shown in Fig. 3, Luoyang (洛陽), the capital of the Wei Dynasty at the time, was near the western edge of the area where the occultation was seen, so the record gives an upper limit to the ΔT value. On the other hand, Fig. 4 shows that Luoyang was near the eastern edge of the area where the occultation was seen, so this record gives a lower limit to the ΔT value. By combining these two events we can determine limits to the ΔT value.

In the same period there were two solar eclipses recorded in China. One was on 18 April 516 and was recorded in a volume titled Liang Benji (梁本紀) in the official history book *Nanshi* (南史), and the other was on 10 June 522 and was recorded in a volume called Wudi Zhong (武帝中) in an official history book *Liangshu* (梁書). Both were recorded as "ji" (既) in the descriptions of the Liang (梁) Dynasty (502–557). Modern calculations show that the eclipse in 516 was annular while the eclipse in 522 was total. Therefore we can assume that the annular solar eclipse in 516 and the total solar eclipse in 522 were both observed in Jiankang (建康), the capital of the Liang Dynasty at that time. For the areas of visibility for these eclipses see Figs. 5 and 6.

Fig. 3 Lunar occultation of Venus on 5 August 503. This shows the area where the occultation was seen. The area between the *solid lines* saw the occultation at night while the area between the *broken lines* saw it in the day-time. The area within the *dotted lines* saw either the disappearance or the reappearance at night. The cross indicates the location of the capital, Luoyang, of Wei at the time when the observations were assumed to have been made. The figure was drawn assuming $\Delta T = 4{,}500$ sec and the current lunar tidal acceleration

During the 20 years spanning the above-mentioned events the variation in ΔT should be small and we can assume almost the same ΔT value for all four events. Therefore we also can investigate whether those events can be explained with the current lunar tidal acceleration.

Figure 7 shows the possible areas of the parameter values of ΔT and the coefficient of lunar tidal term for the events discussed above. As shown in this figure, the possible common area of the parameter values for the two eclipses in 516 and 522 is included in the possible common area for the occultations in 503 and 513. Therefore we can confirm that the records of these two eclipses are highly reliable.

Fig. 4 Lunar occultation of Saturn on 22 August 513. The explanation for Fig. 3 also applies to this figure

Assuming the current value for the lunar tidal acceleration, we obtain ΔT values of $3{,}573\ \text{s} < \Delta T < 5{,}195\ \text{s}$ from the 516 eclipse in Jiankang, and $3{,}469\ \text{s} < \Delta T < 5{,}093\ \text{s}$ from the 522 eclipse also in Jiankang, and hence as a common range we obtain

$$3{,}573\,\text{s} < \Delta T < 5{,}093\,\text{s}$$

for the epoch around the year 520. On the other hand Stephenson (1997) gave $\Delta T = 5{,}500\ \text{s}$ for the epoch around the year 520. However, this value was mainly determined by the results obtained from three eclipses: the total solar eclipse on 10 August 454 in Jiankang (Stephenson 1997: 242–243; the resulting ΔT range was $6{,}130\ \text{s} < \Delta T < 7{,}900\ \text{s}$); the rising eclipsed Moon on 24 May 514 in Luoyang

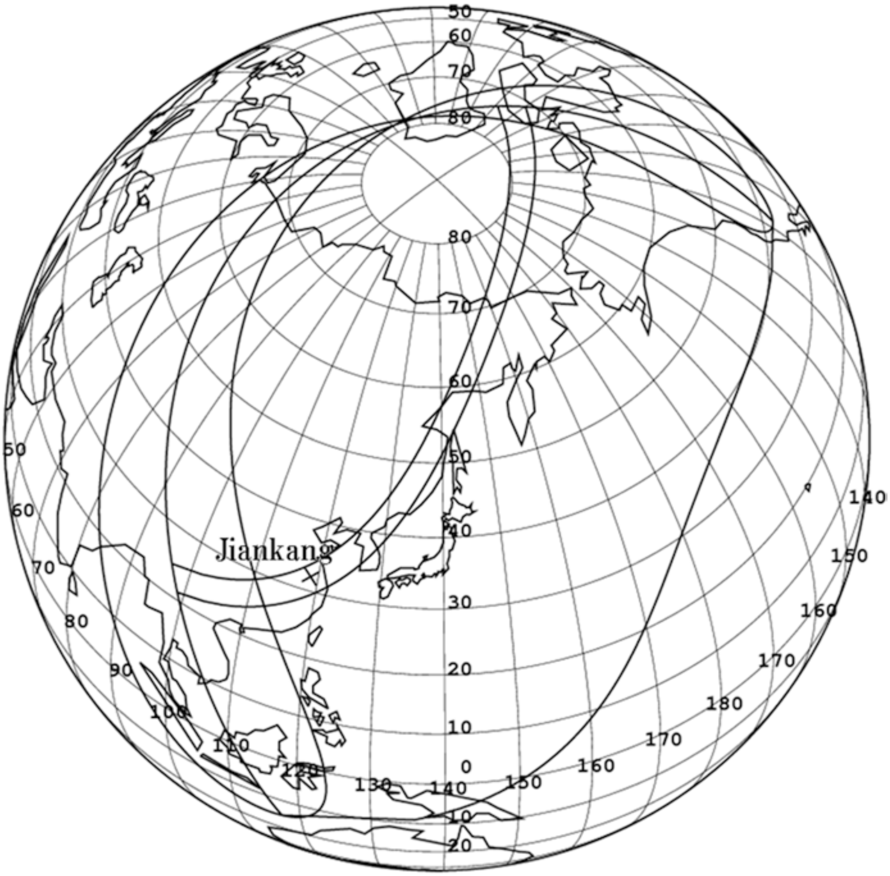

Fig. 5 Annular solar eclipse on 18 April 516. Those within the *narrow band* saw the annular solar eclipse. The *cross* indicates the location of the capital, Jiankang, of Liang at the time when the observations were assumed to have been made. The figure was drawn assuming $\Delta T = 4{,}500$ sec and the current lunar tidal acceleration

(Stephenson 1997: 320–321; the resulting ΔT range was $-250\ \text{s} < \Delta T < 5{,}500\ \text{s}$)); and the total solar eclipse on 5 August 761 in Chang'an (Stephenson 1997: 247–248; the resulting ΔT range was $1{,}720\ \text{s} < \Delta T < 3{,}290\ \text{s}$). A part of Stephenson's Fig. 14.4 is reproduced here in Fig. 8 and our result is plotted on it. The solid line is the cubic spline curve adopted by Stephenson to represent ΔT. From the figure we can see that although our result misses the ΔT curve he drew, it does not contradict any of the records used by him. In fact if we assume that ΔT decreased a little more rapidly between the years 454 and 516, we can draw a line for ΔT which satisfies all the data used by Stephenson and our new result.

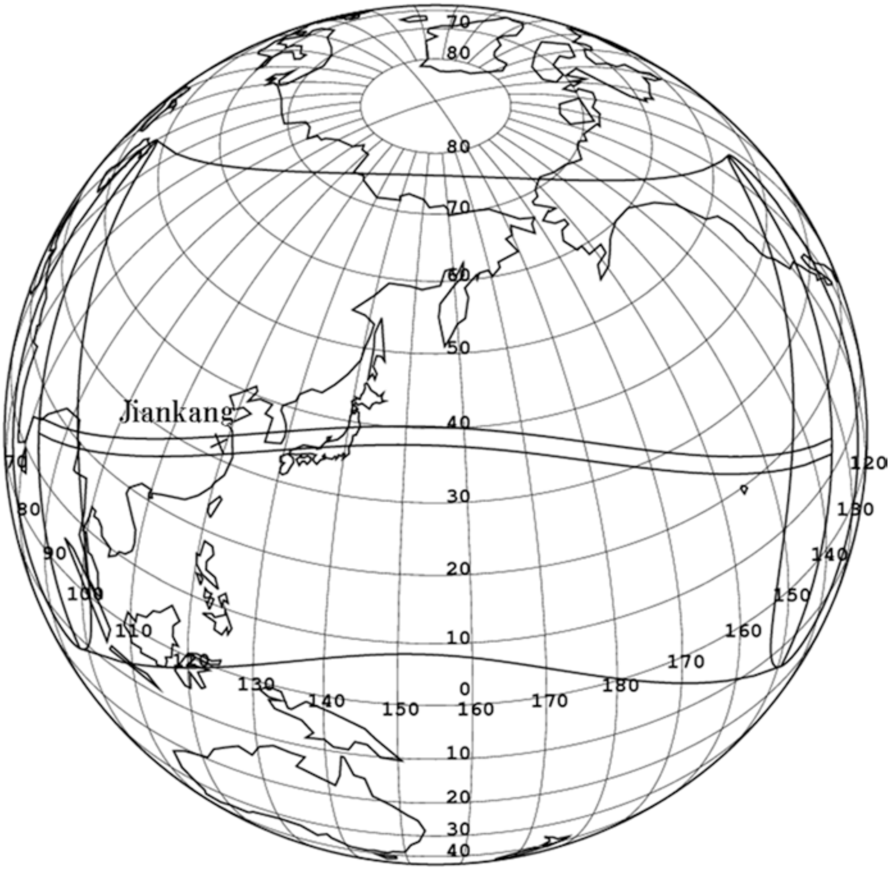

Fig. 6 Total solar eclipse on 10 June 522. Those within the *narrow band* saw the total solar eclipse. For the cross, the ΔT value and the lunar tidal acceleration the same explanation applies as in Fig. 5

5 Conclusion

We have been investigating ΔT and lunar tidal acceleration by depicting possible areas of them on a diagram using contemporaneous plural eclipses and occultations. We have shown that the records of solar eclipses between 198 and 181 BC and of solar eclipses and lunar occultations between AD 503 and 522 give a value for the lunar tidal acceleration that is consistent with the current one. We also obtained reliable ranges of ΔT from these records.

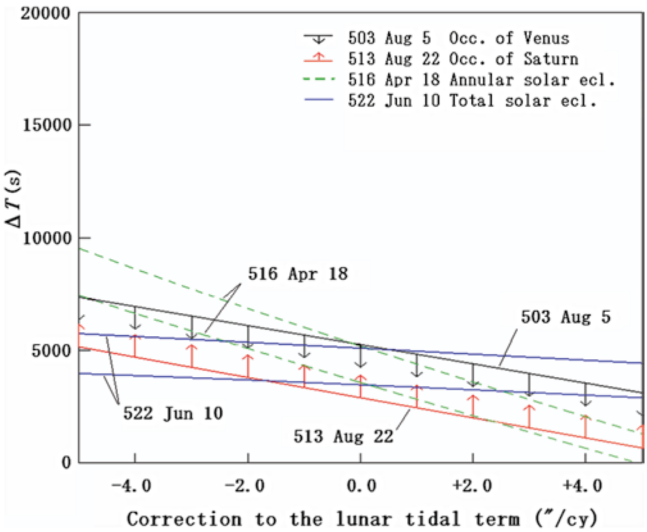

Fig. 7 Diagram showing the possible area of the parameter values from the Chinese events between the years 503 and 522

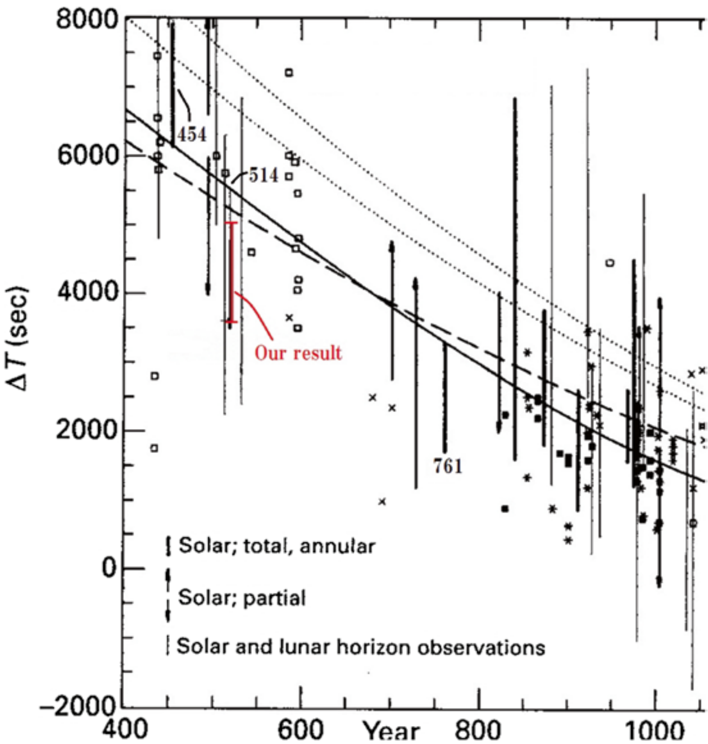

Fig. 8 Reproduction of a part of Fig. 14.4 by Stephenson (1997), with the addition of our result

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The Legendary Fourth-Century Total Solar Eclipse in Georgia: Fact or Fantasy?

Jefferson Sauter, Irakli Simonia, F. Richard Stephenson, and Wayne Orchiston

Abstract In the early fourth century AD, a sudden return of daylight after a darkening of the sky purportedly swayed King Mirian of Georgia to convert to Christianity. Medieval written sources and modern geophysical models suggest that Mirian, whilst on a mountain top near the city of Mtskheta, may have observed a total solar eclipse (TSE). Adjusting for both visibility corrections and constraints on the accumulated clock error known as ΔT, we examine the local circumstances of the TSE of AD 6 May 319, which Gigolashvili et al. (*Astronomical and Astrophysical Transactions 26*, 199–201, 2007; *Transdisciplinarity in Science and Religion 6*, 217–221, 2009) recently proposed as the most likely natural explanation. If the basis for the legendary accounts of Mirian's conversion is this TSE—but we make no judgment upon this question—then the value of ΔT inferred from written sources agrees well with generally-accepted values, such as those derived by Morrison and Stephenson (*Journal for the History of Astronomy 35*, 327–336, 2004), namely, $\Delta T \approx 7{,}450 \pm 180$ s. We also show the extent to which this TSE would have seemed remarkable to observers at Mirian's presumed location and less so to those nearby at lower elevations.

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1 Introduction

Local tradition holds that in the late third and fourth centuries AD, King Mirian reigned over eastern Georgia (Kartli). One day whilst on a hunting expedition during his reign, Mirian was beset by the onset of intense darkness. Forsaking his local deities, Mirian implored the Christian God to save him. Immediately daylight was restored, and the King converted to Christianity. For decades, scholars have debated whether the basis of this story is a total solar eclipse in large part because of two written sources, the late fourth century *Ecclesiastical Histories* by Rufinus of Aquileia and a later Medieval version of a Georgian work known as *The Life of Nino*. It has been suggested (e.g. Gigolashvili et al 2007, 2009) that the total solar eclipse (TSE) of AD 6 May 319 is the most likely natural explanation for the darkness and return of daylight that King Mirian witnessed. A so-called 'eclipse hypothesis' is not new. In 1925, one of the fathers of Georgian historiography, Ivane Javakhishvili, called upon scholars to ascertain whether a solar eclipse was visible in eastern Georgia during the first half of the fourth century AD. As early as 1944, the TSE of AD 6 May 319 was discussed as one possibility (Biusi 1944). In general, scholars have dismissed such explanations in favor of literary fiction or less impressive weather phenomena (e.g. see Akhvlediani 1987, 2002; Schove and Fletcher 1987; Siradze 1985). Such skepticism is not without merit. These and other written accounts omit key details of what Mirian saw. Some versions of the story leave out the hunting expedition altogether, and all are embedded with religious overtones. Moreover, the sources are typically vague about how long the darkness lasted and do not necessarily imply that the darkness which overcame Mirian and, in some versions, his entire entourage, was as brief as one might expect during a TSE. Besides lacking a 'timed' observation of the events Mirian may or may not have seen, surviving accounts are, on the whole, inconsistent and, with the exception of Rufinus' *Ecclesiastical Histories*, were likely written down long after the events themselves.

There are, nonetheless, reasons to suspect a TSE as a plausible explanation. Improvements in geophysical modeling of the Earth's rotation have refined models of visibility conditions of TSEs in the historical past (Stephenson 1997). As Fig. 1 illustrates and as Gigolashvili et al. (2007) point out, these refinements suggest that the local circumstances of the TSE of AD 6 May 319 coincide with elements from the written accounts. Specifically, the Earth's accumulated clock error known as 'Delta T' (ΔT)—the measure in seconds of the cumulative effect of variations in the Earth's rate of rotation from the standard reference epoch of AD 1820—agrees with a natural explanation for the abrupt restoration of daylight that Mirian supposedly witnessed. What makes the TSE of AD 6 May 319 a particularly interesting candidate is that full totality may have been visible only to those at high elevations where Mirian and his companions purportedly were at the time of his conversion, but not necessarily to others at lower altitudes nearby. So, before addressing in Sect. 3 the extent to which the astronomy of the TSE of AD 6 May 319 coincides with the written record, it is appropriate to examine what the sources have to say about this return of daylight.

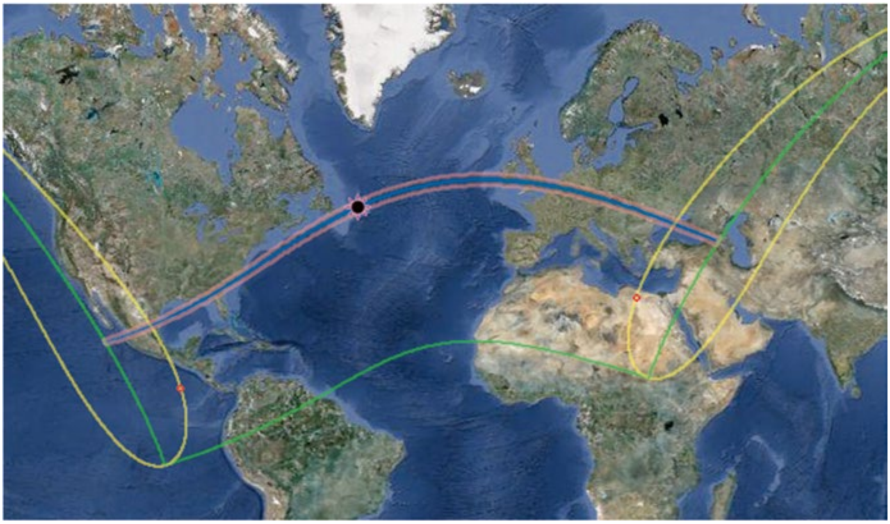

Fig. 1 Map showing the global path of totality of the TSE of AD 6 May 319 with $\Delta T \approx 7{,}450$ s. The path ends near Tbilisi, the capital city of the Republic of Georgia (Image created using Jubier 2007)

2 The Written Sources

The earliest written source describing the conversion to Christianity of the Royal Family of Kartli, now eastern Georgia, is in Latin and dates from the late fourth century AD. In Book 10 of *The Ecclesiastical Histories*, the Roman church-historian Rufinus of Aquileia, who died in AD 410, explains how the Georgian king came to renounce the local religion and adopt Christianity. Rufinus tell us that he himself learned of the account second-hand from a certain local named Bakurius, possibly a high-ranking borderland official (Stephen Rapp, 2011, personal communicaton) or a soldier at the Battle of Adrionople in AD 378 (Braund 1994). According to Bakurius, after a Christian slave-girl's prayers cured Mirian's wife, Queen Nana, of an illness, Mirian prepared to shower the slave with lavish gifts. But the Queen responded:

> "This alone may we give her as a gift, if we worship as God the Christ who cured me when she called upon him." But the king was not then inclined to do so and put it off for the time, although his wife urged him often, until it happened one day when he was hunting in the woods with his companions that a thick darkness fell upon the day, and with the light removed there was no longer any way for his blind steps through the grim and awful night. Each of his companions wandered off in a different way, while he, left alone in the thick darkness which surrounded him, did not know what to do or where to turn, when suddenly there arose in his heart, which was near to losing hope of being saved, the thought that if the Christ preached to his wife by this woman captive were really God, he might now free him from this darkness so that he could from then on abandon all the others and worship him. No sooner had he vowed to do so, not even verbally but only mentally, than the daylight returned to the world and guided the king safely to the city. He explained directly to the

> queen what had happened. He required that the woman captive be summoned at once and hand on to him her manner of worship, insisting that from then on he would venerate no god but Christ. (Translated by P. Amidon in Rufinus of Aquileia 1997: 21–22)

A number of details with respect to the emergence of daylight are worth noting. Perhaps most obvious is that we cannot say exactly how long the darkness lasted nor what time of day it occurred. It is arguable that Rufinus is implying that those not on the mountain, but still nearby, did not witness the darkness and illumination because the King "… explained directly [protinus] to the queen what had happened." On the other hand, Mirian may simply have sought to convey to the Queen his epiphany. Rufinus also tells us that after "… a thick darkness fell upon the day, and with the light removed there was no longer any way for [the King's] blind steps through the grim and awful night …" the hunting party "… wandered off in a different way, while [the King], left alone in the thick darkness which surrounded him…" It is therefore conceivable that it was not just the King but also his companions who witnessed the darkness. There is less doubt, however, that sunlight reappeared all of a sudden, after he had renounced all other gods but before he could verbalize his thoughts because "No sooner had he vowed to do so, not even verbally but only mentally, than the daylight returned to the world and guided the king safely to the city." The fact that daylight "returned to the world" does suggest that the darkness which overcame the King was widespread. A second source, written in Georgian after Rufinus' account, offers other clues to what the King and his companions may have encountered during the hunting episode.

Amongst the sources written in Georgian recounting the conversion of King Mirian is *The Life of Nino,* a text within a larger work called "The Conversion of Kartli", itself a section of the literary monument known as *The Life of Kartli.* A separate text within the collection, also entitled *The Conversion of Kartli*, includes a much shorter, and distinct, description of Nino's life without Mirian's hunting expedition (Rapp 2003). One of the versions of *The Life of Nino* is now known as the Chelishi variant, being named after the village in which the manuscript was discovered. This version recounts, with significant embellishment compared to Rufinus' account, Mirian's hunting expedition and adoption of Christianity. The actual manuscript in which this variant is found, designated H-600, may have been copied in Jerusalem as early as the middle of the thirteenth century from an eleventh-century copy (Lerner 2004), although others, including Rapp and Crego (2006), have suggested that the manuscript was produced later, during the fourteenth or fifteenth centuries. Unfortunately, we cannot be certain when *The Life of Nino* was composed, except to say that it was likely between the eleventh and fifteenth centuries. Here, and in later Georgian versions, the captive woman has a name: Nino. According to the Chelishi variant, a woman named Sidonia "… saw and wrote down the conversion by miracle of King Mirian and his submission to Nino." The Chelishi account also includes a number of details that are absent from Rufinus' record:

> It happened one summer's day, on 20 July, a Saturday, that the king went out to hunt in the vicinity of Muxnari. That secret enemy, the devil, approached and infused his heart with love for idols and fire. He decided to serve them totally and to kill with the sword all the Christians … The king crossed the whole district of Muxnari, and went up the high mountain of T'xot'i in order to look towards Kasp and Up'lis-C'ixe. He reached the summit of

Fig. 2 According to Sidonia's account in the *Life of Nino*, King Mirian and his companions travelled "up the high mountain" of Tkhoti in order to look towards Kaspi and Uplistsikhe. The *blue line* shows the king's journey through the Mukhrani district. (From http://wikimapia.org/. Accessed 30 November 2010)

> the mountain, when at mid-day the sun grew dark over the mountain and it became like the dark night (of) eternity. The gloom covered the region in all directions, and they were scattered from each other in distress and anxiety. The king remained alone; he wandered through mountains and forests, terrified and shaking in fear. He stood at a certain spot and abandoned hope for salvation. But when he recovered his sense, he reasoned thus in his heart. "Behold, I have called on my gods, yet I found no relief. Now could I not be rescued from this distress through hope in the cross and crucified one which Nino preaches and through which she works cures? For I am alive in hell, and I do not know if this perdition has occurred for the whole land or if it was only for me. Now if this ordeal is merely for me, O God of Nino, turn this darkness into light for me and show me my dwelling. Then I shall confess your name and shall set up the wood of the cross and worship it. I shall also build a house for my prayers and become obedient to the religion of the Romans."
>
> Once he had said this, the sun shone out brilliantly … Queen Nana and all the people went out to meet the king, for they had first heard that he had perished and then that he was safely returning. They met him at K'injara and Ğart'a. Now the blessed Nino was at evening prayer in the bramble, at the hour that was her custom; and we were with her, fifty persons. When the king arrived, the city was in turmoil …
>
> The next day King Mirian sent envoys to Greek territory, to Constantine king of the Greeks, and also a letter of Nino's for Queen Helena. They informed them of all the wonders (performed) by Christ which had happened to King Mirian in Mc'xet'a, and they urgently requested priests for the sake of baptism. (Thomson 1996: 118–22)

Unlike Rufinus' version of events, Sidonia gives enough local information to work out a journey Mirian could have taken had he started from his home in the city of Mtsketa. Figures 2 and 3 map out how King Mirian and his companions could have journeyed "… up the high mountain of T'xot'i to look towards Kasp and Uplis-C'ixe." The blue line in Fig. 2 shows the journey through the "Muxnari" (today known in Georgian as the Mukhrani) district with Mirian's presumed location northeast of the modern city of Kaspi. Such a trip would take just a few miles. Sidonia's account adds another striking detail that our analysis in Sect. 3 ultimately discards, namely, that Mirian's expedition was on the 20th day of July and that the day of the week was Saturday. (In fact, another manuscript variant puts the expedition instead on the 20th day of June.) And, just as Rufinus depicts the sky as though "… a thick darkness fell upon the day, and with the light removed there was no longer any way for his blind steps through the grim and awful night …", so Sidonia describes how the sky "… became like a dark night (of) eternity." In Sidonia's

Fig. 3 Terrain map at the assumed location of Mirian's hunting expedition. We have chosen the location marked by the cross ('+') for geophysical models (as the written accounts do not specify where precisely on Mount Tkhoti Mirian witnessed the returning daylight). The mountain at this location reaches an elevation of approximately 1,000 meters above sea level (From http://wikimapia.org. Accessed 30 November 2010)

version, the onset of darkness engenders fear within the entire expedition, not just the King: "The gloom covered the region in all directions, and they were scattered from each other in distress and anxiety." Whereas Rufinus does not say when daylight was obscured, Sidonia is more specific and says that darkness happened at mid-day. Here, too, one must proceed with caution because a phrase such as "… at mid-day the sun grew dark …" harkens back to Chapter 8:9 of the Book of Amos in the Old Testament where God says: "I will cause the Sun to go down at noon, and I will darken the Earth in the clear day …" (King James Version). Still, neither the Latin version nor the Chelishi variant of the Georgian account of Mirian's expedition seems to imply that the Sun supernaturally set. Rather, the Georgian version, and possibly the Latin as well, suggest that the darkness and return of light were visible to everyone on the mountain though not necessarily to the townspeople below.

Besides a purported date, place and time of day, the Chelishi variant includes other detail not in Rufinus' account. Mirian first prays to his own gods before begging the Christian God for help; near mid-day, the Sun shines brightly after the darkness; and the expedition was near Mtskheta at or after sunset because it was at that time when Nino would have been in evening prayer. As Sidonia tell us, after darkness overwhelms the King, he turns first to his traditional gods before imploring Nino's God. After Mirian asks whether the darkness was "… for the whole land …" or solely for himself, daylight abruptly reappears and "… the sun shone out brilliantly …" He goes back to his subjects and Queen Nana, who did not know whether he had perished or was safely traveling home. Near sunset, they meet near Kindzara and Gharta, northwest of Mtskheta. Sidonia does not state the precise time of Mirian's arrival, only that he encountered the Queen and townspeople when Nino was in evening prayer "… at the hour that was her custom …" Now if by evening prayer Sidonia was referring to a Vesper service, Nino would have presumably started her prayers at sunset. It is difficult to know for exactly how long Nino prayed. And, unfortunately, the location of Kindzara in the fourth century AD is not known to us with certainty. According to Wardrop (1903), "Kindzara is a few miles north of Mtskheta, on the river Naretsvavi, near its junction with the Aragva. Gharta is in the same district." Today, the villages of Old Kanda and Little Kanda are about halfway from Kaspi to Mtskheta, south of Mukhrani. (The village now known as

Gharta, however, is relatively far to the west of Kaspi, seemingly in the opposite direction of Mtskheta.) Inconsistencies notwithstanding, the descriptions in these Latin and Georgian sources corroborate that there was an onset of darkness during the day and a sudden reappearance of light, and that these events produced a striking reaction in the King and, perhaps, his companions as well. But how successful is a TSE at explaining these events?

3 Astronomical Considerations

Rufinus of Aquileia's Latin and Sidonia's Georgian depictions of intense darkness in the daytime, the restoration of light, and the King's noteworthy reaction might indicate not a TSE, but instead less impressive meteorological phenomena such as haze or fog. As we mentioned above, other variants of *The Life of Nino* do not include the same level of detail of the hunting trip that we find in the Chelishi version, whereas some Georgian versions omit entirely the episode (Rapp and Crego 2006; Thelamon 1981). One such account is the so-called Shatberdi variant, named after the monastery in what is now northeastern Turkey where the manuscript was rediscovered. This manuscript has been dated to the tenth century. A third version of the *Life of Nino* is in the Anaseuli which includes portions of the story of Mirian's hunting expedition; it is in this version where we have the variant date of 20 June. And, unlike the Annaseuli and Chelishi variants, a later Arabic account states explicitly that only Mirian witnessed the darkening of the sky: "As to his fellow-hunters, they saw the sunlight commonly, only the king was bound by the shackles of blindness." (Walbiner and Nanobashvili 2008). To confuse matters further, Armenian versions of Sidonia's account seem to attribute the darkness solely to haze (e.g. see Thomson 1996). These variants do not support the hypothesis that a TSE is the ultimate basis for the story. A further problem in testing any 'eclipse theory' stems from our uncertainty of the year of Mirian's conversion.

When might Mirian have converted to Christianity according to internal and external evidence, and does a date of 20 July (or June) and day of the week as a Saturday elucidate matters? Let us set aside for the moment the question of the day of the month and week. Estimates by historians for the year of the conversion of the Royal Family of eastern Georgia have ranged over much of Mirian's (suspiciously) long reign, which lasted from AD 284–361. For example, Gogitidze (1997: 28–29) lists the following dates together with the scholars who proposed them: AD 312 (D. Bagrationi); AD 317 (V. Mtkitsebi, S. Baratashvili, D. Bakradze and I. Gvaramadze); AD 318 (P. Ioseliani, G. Sabinini and R. Tsamtsievi); AD 320 (V. Bagrationi); AD 323 (M. Janashvili and S. Gorgadze); AD 323–325 (T. Zhordania); AD 326 (A. Natroshvili); AD 327 (Ts. Baronius); AD 328 (M.-F. Brosset, who earlier advocated AD 323); AD 330 (L. Sanikidze, who earlier proposed AD 335); AD 331 (T. Bagrationi); AD 332 (A. Khakhanashvili also known as A. Khakhanov); AD 332–333 (E. Taqaishvili); AD 334 (B. Gigineishvili); AD 335 (K. Tsinstadze); AD 336 (S. Kakabadze, who earlier favoured AD 331); and AD 337 (I. Javakhishvili and L. Janashia). A widely-accepted date has been AD 337, although many scholars nowadays favour AD 326, which coincides with the year traditionally held by the

Georgian church (Gogitidze 1997; Pataridze 2000). Gogitidze theorises that Nino came to Mtskheta in June AD 318; Mirian's hunting expedition was on 20 June AD 324, which was in fact a Saturday; and the Royal Family was formally baptised in AD 326. In the year AD 319, however, 20 July was a Monday; 20 June was a Saturday; and 6 May, the date of the TSE under investigation, was a Wednesday. In other words, Gogitidze's theoretical timeline could be compatible with the eclipse hypothesis if we move Mirian's hunting expedition from June 324 to May 319. Indeed, could it have been another TSE, or might another meteorological or weather event just as well explain Mirian's reaction?

The TSE of AD 319 was not the only eclipse visible in this part of Georgia during the Middle Ages, but it is the most likely candidate if we aim to adhere as closely as possible to the accepted years of Mirian's reign and to Gogitidze's chronology. In a paper titled "Visibility Conditions for Solar Eclipses in Georgia in the First Half of the Fourth Century AD", the astronomer E. Biusi (1944) lists several possible eclipses on which Sidonia's account could be based, the most likely being the only two TSEs visible in eastern Georgia during Mirian's assumed reign. These occurred on Wednesday, AD 6 May 319, and Friday, AD 6 June 346. Without modern values of ΔT, however, the band of totality of the AD 319 TSE was deemed not to reach as far east as Mtskheta. Whereas the AD 319 TSE did reach eastern Georgia, the AD 346 TSE would be late in Mirian's reign but also very early in the morning at about 7 AM local time in Mtskheta (Espenak and Meeus 2007). On the other hand, scholars have inferred from Rufinus' *Ecclesiastical Histories* and other contemporaneous accounts a 'non-eclipse' in about AD 331:

> A Byzantine record describes what was almost certainly merely a meteorological darkness due to a cold front. Darkness in Iberia (north-east of Armenia) is mentioned somewhere around AD 331 in the ecclesiastical historians Socrates Scholasticus (born about 379) and Sozomen (born about 400) … There was no striking eclipse in Iberia around the year in question (cf. however AD 346). (Schove and Fletcher 1987)

Although meteorological phenomena such as fog or haze can account for the apparent disappearance and reemergence of sunshine, they hardly explain the reaction of King Mirian who, as a result, immediately renounced his faith in favour of Christianity. Moreover, Mirian's emotional response to the darkening of the sky and to the subsequent onset of daylight evokes the lure and awe experienced by eclipse observers even today:

> A total solar eclipse is one of the most dazzling events a person can experience. Those who have never seen one don't understand what all the fuss is about. Those who have are converted into pilgrims on the eclipse path. Every eclipse is different. Every eclipse is a surprise. Every eclipse has suspense. Every eclipse has more things taking place in a short time than you can possibly observe. (Krupp 2009).

Among many other things, during an eclipse hues and shadows become strange, the temperature drops noticeably and the Sun quickly changes into a blackish-blue sphere surrounded by the otherwise invisible corona (Levy 2010). To the unexpecting witness, these phenomena would be particularly striking. At Georgia's latitude of 40° N, a TSE generally occurs about every 330 years or so at a given location, making them rare events (Meeus 1997; Stephenson 1997: 54). Indeed, the TSE of AD 319 was the first such eclipse visible at Mtskheta and Kaspi in over two centuries.

Table 1 Possible clues for a TSE on AD 6 May 319 from the Chelishi variant of *The Life of Nino*. Not all these clues, such as the day of the week and month, agree with the circumstances of the AD 6 May 319 TSE

Type	Clue
Location	41.99344° N; 44.55746° E
Altitude	1,000 m
Date	20 July (a Saturday)
Time of Day	Mid-day or sunset
Event	Darkness witnessed in all directions
Observers	King Miriam and his retinue
Azimuth	West (towards (Kaspi and Uplistsikhe)
Year	AD 284–361 (especially AD 300–340)
Duration	At least several minutes
Topography	Summit of Mt. Tkhoti (mountains & valleys)

If we assume, for the sake of argument, that the TSE of AD 6 May 319 plausibly explains how Mirian ultimately came to convert to Christianity, then, as Table 1 shows, at least some clues inferred from the written sources should align with the circumstances of that particular TSE. A few points should be kept in mind about the Georgian sources which offer these so-called clues. Firstly, unlike other sources useful to the up-and-coming field of Applied Historical Astronomy, much evidence for a TSE observed in Georgia in AD 319 comes not from a contemporaneous historical chronicle, but from accounts of a Saint's life that were probably revised numerous times and many years after the events themselves. Furthermore, Nino was not just any saint; she was the 'Enlightener of Georgia,' who brought Christianity to a small kingdom at the politically-volatile crossroads of the Byzantine and Sassanian worlds. Therefore, it is not surprising that the story of her life incorporates much literary, cultural and biblical symbolism. Also, Nino reputedly performed numerous miracles, such a curing King Mirian's wife (Queen Nana) and harnessing natural forces through the Holy Spirit to smash pagan idols (Paul Crego, 2009, personal communication). In addition, as David Braund explains, it is of prime significance that Mirian was hunting at the time of his religious conversion on Tkhoti: "In the ideology of the contemporary Sassanian world, hunting was a supreme act of kingliness. For that reason the Sassanian king is often portrayed as a hunter in both literature and art … Yet a human king, however great, is subject to God." Thus, Nino's "… miraculous cures show God's power over life and death: the hunting incident shows God's power over kingship. The king is easily isolated and thrown into despair while at his most kingly, hunting." (Braund 1994: 253). Moreover, no exact time of day, nor a description of the Sun while obscured, appears in the Chelishi variant of *The Life of Nino*. And with regard to a precise time of day, all we can say is that darkness overcame Mirian "… at mid-day …", but even this could be a literary embellishment based on religious symbolism. Furthermore, the supposed date, month, and day of the week of Mirian's expedition, Saturday 20 July, is suspect, not only because the TSE of AD 319 occurred on a Wednesday in the month of May. The day, 20 July, also happens to mark the feast day of the Prophet Elijah whose cloak is mentioned in *The Life of Nino* shortly before Sidonia's account. And, the Anaseuli redaction of Sidonia's account gives the month as June (in Georgian 'ivnissa') instead of July ('ivlissa'), the difference being just one letter. This could be a scribal error or even perhaps a subsequent change to the story that reflects a later historical eclipse such as the one on AD 20 June 540.

Other elements of the story may also have been tailored for biblical symbolism. For example, associating the occurrence of brilliant light with 20 July may have been aimed to link Mirian's conversion to the Transfiguration of Christ, in which the Prophet Elijah figures prominently. On the other hand, even if Rufinus and the author of *The Life of Nino* had in mind a TSE, it could purely be literary fiction. Works by John of Damascus, widely read in Georgia, Byzantium and the Latin West during the Middle Ages, deemed eclipses useful as a means for converting those pagans whose beliefs included veneration of the Sun. These are just a few of the reasons for hesitating to conclude definitively that Mirian converted to Christianity in AD 319, and as a result of witnessing a TSE. Yet there are so few useful eclipse records available to investigate the accumulated clock error for the fourth century AD that even highly-problematic accounts such as ours deserve some examination.

Would current geophysical models of the Earth's accumulated clock error of ΔT need to be refined for Sidonia's account to be based on the TSE of AD 6 May 319? Extant records of reliable eclipses generally fall within two periods: 700 BC–50 BC and AD 800–1600. However, for the period

> … between 50 BC and AD 800 there is a significant lacuna in the available data. This deficiency is particularly serious between 50 BC and AD 300—during which period scarcely any eclipse observations of real value in the study of Earth's past rotation are preserved. The subsequent interval of 500 years is more productive, but even over this period no more than about 50 useful records are extant. Hence in order to study the behaviour of ΔT between AD 300 and 800 it is necessary to investigate each available observation with special care." (Stephenson 2007)

Even within this gap, the fourth century AD is meager with respect to timed and untimed historical eclipses. Timed eclipses can yield estimates of ΔT whereas untimed eclipses can set upper and lower limits for a given date. Timings of solar eclipses from Theon of Alexandria's commentary on *The Almagest* yield ΔTs for AD 364 of 8,100 s, 8,300 s, and 8,400 s based on the local time of first contact, mid-eclipse, and last contact, respectively. For untimed eclipses, a partial solar eclipse from AD 360 gives a $\Delta T < 7{,}120$ and $> 9{,}400$ s. Another record for an eclipse on AD 27 July 306 produces ΔT within the range of 6,550 s and 7,890 s (Stephenson 1997). As Fig. 4 illustrates, such records show the variability of ΔT for a period when so few records exist. If the conventional value of $\Delta T \approx 7{,}450$ s for AD 319 is assumed, then at Tkhoti the TSE of AD 319 was a sunset eclipse. Table 2 describes the local circumstances for Mirian's presumed location at 41.94966° N, 44.45755° E. First contact of the eclipse (C1), which is the time the disk of the Sun begins to be obscured by the Moon, was at 14 h 59 m Universal Time (UT). At C1, the Sun was close to the horizon at an altitude of 10° (zenith angle = 80°). Second contact, marking the onset of totality when the solar disk is completely covered by the Moon (C2), occurred at almost 18 h 51 m local time. (Obscuration was 100 % with a magnitude of 1.01768. Umbral depth, that is, relative proximity to the central path, was 97.6 %.) At maximum eclipse (ME), the solar altitude was barely above the horizon, although the Sun could have appeared higher by several degrees due to refraction and the dip in the horizon from a mountain elevation. For example, the visibility conditions on

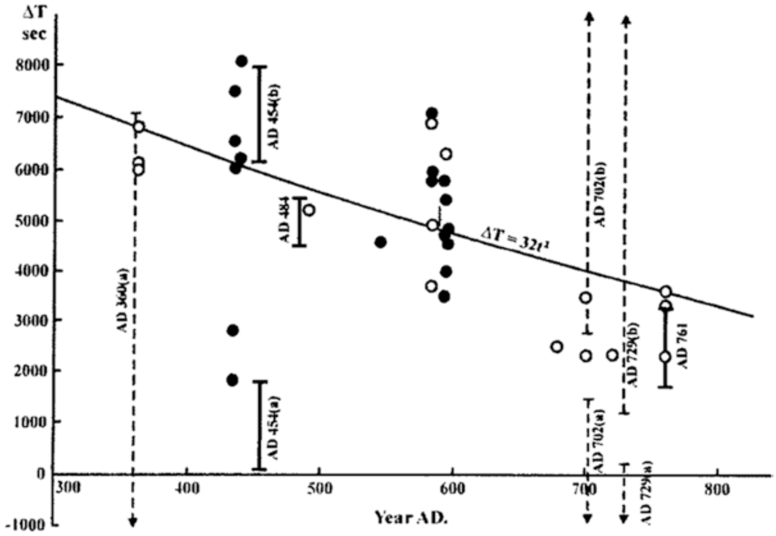

Fig. 4 ΔT and limits to ΔT derived from solar and lunar eclipse observations between AD 300 and 800 (After Stephenson 2007)

Table 2 Local circumstances of the TSE of AD 319 at Tkhoti, Georgia, with ΔT≈7,450 s, as derived by Morrison and Stephenson 2004 (Data extracted from Jubier 2007)

	Hour of day		Degrees of solar altitude		
Phase of eclipse	Universal time	Local time	No refraction	Refraction	Degrees of Azimuth
First contact	14 h 59 m 02.7 s	17 h 56 m 52.5 s	10.4	10.5	282.9
Second contact	15 h 52 m 55.7 s	18 h 50 m 45.5 s	0.9	1.3	291.6
Maximum eclipse	15 h 53 m 52.2 s	18 h 51 m 42.0 s	0.7	1.1	291.8
Third contact	15 h 54 m 48.4 s	18 h 52 m 38.2 s	0.6	1.0	291.9
Fourth contact	16 h 45 m 01.0 s	19 h 42 m 50.8 s	–7.7	–7.8	300.6

Tkhoti could have been similar to the 15 July 2010 TSE as seen at sunset from the mountainous terrain of Patagonia in South America (Jay Pasachoff, personal communication, January 2011). Be that as it may, at ME, the solar azimuth was about 292° and the Sun was in the western part of the sky. From the vantage point of Tkhoti, this coincides with the general direction of the Sun being towards Kaspi and Uplistsikhe, from Sidonia's account in the Chelishi variant. Totality ended at third contact (C3) which at Tkhoti occurred just before 18 h 53 m. The Sun was completely obscured for about two minutes. By the time the Moon passed completely over the disk of the Sun at fourth contact (C4), at about 19 h 43 m, the Sun had set about 45 minutes earlier. It is, therefore, unlikely, but not impossible, that Mirian could have noticed the very end of the eclipse because at that time the Sun was about 7.7° below the horizon. Even correcting for mean refraction by up to 1°, the

Sun may nevertheless have seemed to hover only about 1° at the horizon just before and after totality.

Before we show what this brief analysis has the potential to tell us about ΔT, how might the local topography have affected the appearance of the AD 6 May 319 TSE to Mirian and his entourage at Tkhoti? Georgia is a mountainous country, so it is appropriate to examine the true and apparent horizon for our 'sunset eclipse', that is, the effect of the so-called 'dip' in the horizon. If Mirian looked west towards Kaspi, Uplistsikhe and the setting Sun, would any gain in visibility be achieved with respect to the depressed horizon? According to Gigolashvili et al. (2007), the answer is no:

> Sunset began 5.6 min after the third contact. Taking into account the mountainous character of the district, it is necessary to assume that possibly Mirian could not see the Sun at the moment of the second (and especially the third) contact and saw only the sudden approach of darkness and its end.

This statement is plausible, but whether Mirian could actually observe totality, assuming favourable viewing conditions, depended on his perspective. From the direction of Kaspi, when the setting Sun was due west, Mirian would have had a more impressive view of the eclipse than where the view was obscured by nearby mountain ridges which virtually surround the city of Mtskheta. With the Sun at an azimuth angle of about 292°, Mirian's field of vision may have been directed towards the valley before being further hindered by another mountain range. Be that as it may, we can approximate the correction for altitude by adding arc-minutes to the solar altitude equal to about 1.07 times the square of the elevation in feet (ignoring refraction) (Kelley and Milone 2011: 63). At about 1,000 feet above sea-level the Sun might have appeared in the sky as much as 30 arc-minutes higher; while at 500 feet above the valley below the Sun would have appeared 24 arc-minutes higher than at lower elevations. Since we do not know where Mirian was at totality, back-of-the-envelope calculations such as these are tenuous at best, but a small increase in altitude can affect visibility conditions in a valley or on a mountain top at twilight. At Tkhoti the Sun was very close to the horizon at totality during the TSE. This means that any correction for refraction will "… depend primarily on atmospheric structure *below* the observer and varies so much (tens of minutes, or even several degrees) that only very crude predictions can be made." (Young 2004). But as Gigolashvili et al. (2007) rightly point out, we cannot be absolutely sure what may have shielded Mirian's view because the written accounts do not specify exactly where Mirian was. We can nevertheless make a few valuable points about ΔT based on the clues we can extract from the written sources, and suggest why this eclipse, the central path of which is illustrated in Fig. 8, would have been so striking to King Mirian.

Table 3 shows the extent to which the accumulated clock error of ΔT impacts on visibility of the eclipse of AD 6 May 319, as observed from near Tkhoti (41.94966° N, 44.45755° E). At this location, full totality takes effect for 7,100 s $\leq \Delta T \leq$ 8,000 s but not outside this range. As the limits of this range are approached, the band of totality shifts away, so that the eclipse becomes a partial rather than a total eclipse. The maps of the visibility limits show the circumstances of the TSE for ΔT = 7,200 s (Fig. 5) and ΔT = 7,700 s (Fig. 7). At 7,500 s, which is close to current models of

Table 3 Changes in assumed values of accumulated clock error of ΔT affect the visibility conditions of the eclipse of AD 6 May 319 at Mirian's presumed location at Tkhoti. Specifically, the solar eclipse is total only for 7,100 s $\leq \Delta T \leq$ 8,000 s but is otherwise a partial eclipse. *C1* means 'First Contact', *ME* Maximum Eclipse', *C4* 'Fourth Contact' (Data generated using Jubier 2007)

ΔT (seconds)	Eclipse type	C1 (°)	C1 with refraction (°)	ME (°)	ME with refraction (°)	C4 (°)
7,000	P	9.0	9.1	–0.4	–0.4	–8.8
7,100	T	9.3	9.4	–0.2	0.3	–8.6
7,200	T	9.6	9.7	0.0	0.5	–8.4
7,300	T	9.9	10.0	0.3	0.7	–8.1
7,400	T	10.2	10.3	0.5	0.9	–7.9
7,500	T	10.5	10.6	0.8	1.2	–7.7
7,600	T	10.8	10.9	1.1	1.4	–7.4
7,700	T	11.1	11.2	1.3	1.7	–7.2
7,800	T	11.4	11.5	1.6	1.9	–7.0
7,900	T	11.8	11.9	1.9	2.2	–6.7
8,000	T	12.1	12.2	2.1	2.4	–6.5
8,100	T	12.4	12.5	2.4	2.7	–6.2
8,200	P	12.7	12.8	2.7	2.9	–6.0
8,300	P	13.0	13.1	3.0	3.2	–5.8
8,400	P	13.3	13.4	3.2	3.5	–5.5
8,500	P	13.6	13.7	3.5	3.7	–5.3

Fig. 5 Map of the visibility limits showing the circumstances of the TSE of AD 6 May 319 for ΔT = 7,200 s, in eastern Georgia. Current geophysical models yield $\Delta T \approx$ 7,450 s. If a TSE is described in the written sources, it would have been a sunset eclipse and a spectacular sight at Tkhoti but less so at lower elevations with obstructed views such as at Mtskheta (Image generated using Jubier 2007)

Fig. 6 Map of the visibility limits showing the circumstances of the TSE of AD 6 May 319 for $\Delta T = 7{,}500$ s in eastern Georgia (Image generated using Jubier 2007)

Fig. 7 Map of the visibility limits showing the circumstances of the TSE of AD 6 May 319 for and $\Delta T = 7{,}700$ s, in eastern Georgia. (Image generated using Jubier 2007)

$\Delta T \approx 7{,}450$ s ± 180 s, the central line passes near the presumed location of Mirian's hunting expedition, as Figs. 6 and 8 portray. In this way, Mirian's emotional reaction to the restored daylight is suggestive of a TSE where C2 and C3 were observable at Tkhoti, although C4 would be visible to Mirian only for $\Delta T \approx 10{,}500$ s, which is not likely in light of other historical eclipse records (Stephenson 1997). In fact, no value of ΔT appreciably extends solar irradiance beyond C3 while at the same time allowing for the TSE of AD 319 to be visible. Even correcting additionally for dip in the horizon due to the terrain (which can allow us to add perhaps 0.5° to the values in Table 3) is unlikely to change this result substantively. So if Mirian was witness to the TSE of AD 319, then no change to current values of the accumulated clock error of ΔT would be necessary for Mirian to have observed totality. In other words, we have relatively concrete upper and lower boundaries to ΔT if we admit to the possibility that the TSE of AD 319 was the basis of the written accounts.

An additional question remains for us: Mirian explained "directly" (Rufinus) to Queen Nana, and, in Sidonia's account, the towns people, presumably what happened on the mountain. Did only Mirian and his companions observe a fantastical event? Or, is there a factual explanation?

The written sources tell how the King and his companions were on the mountain and the Queen and townsfolk were in the surrounding valleys when darkness enveloped the region. Shortly after, the Sun quickly shone forth for Mirian, who then explained to Nana what happened to him. Figures 9, 10, and 11 show how the TSE

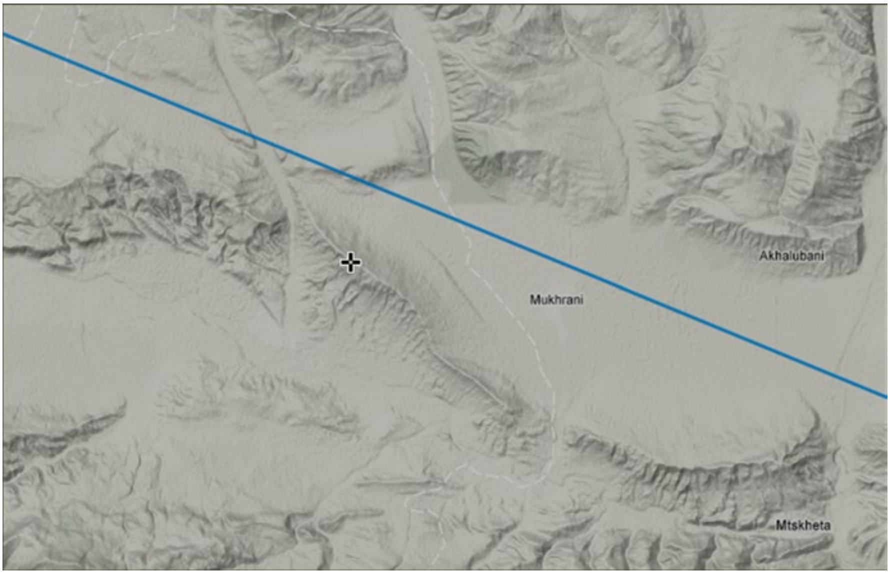

Fig. 8 Central path of the TSE of 6 May 319 ($\Delta T \approx 7{,}450$ s). The cross (+) marks Mirian's presumed location near Tkhoti (41.94966° N, 44.45755° E) (Image generated using Jubier 2007)

Fig. 9 The sky as seen from an elevation of 200 meters above sea level and 10 minutes before totality on AD 6 May 319. $\Delta T = 7{,}500$ s and the solar azimuth is about 290°. Figures 9, 10, and 11 aim to portray the view from Mirian's vantage point on the mountain, looking towards Kaspi. (Image generated using Starry Night Software 2009)

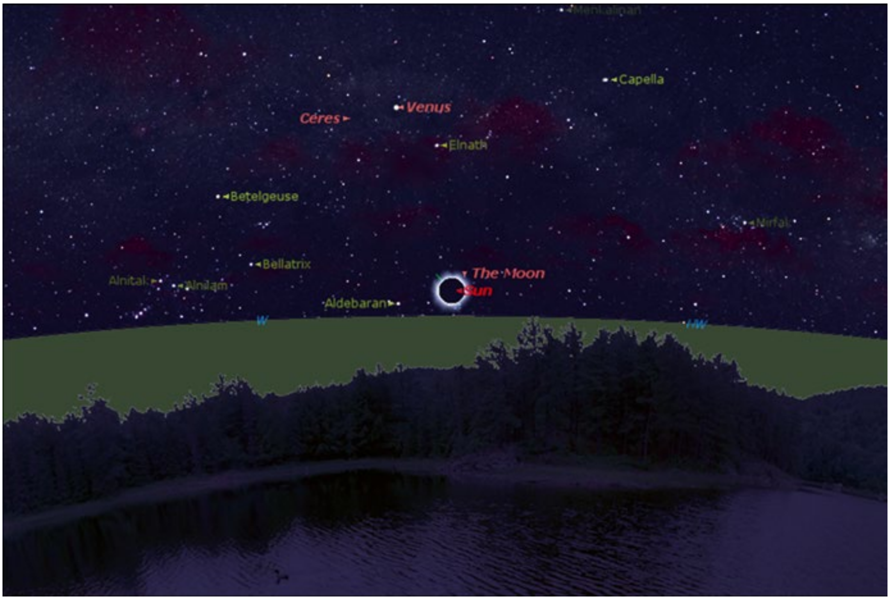

Fig. 10 The sky as seen from an elevation of 200 meters above sea level and at totality on AD 6 May 319. Note that Venus appears near the eclipsed Sun (Image generated using Starry Night Software 2009)

Fig. 11 The sky as seen from an elevation of 200 meters above sea level and 10 minutes after totality on AD 6 May 319. Note that Venus appears near the eclipsed Sun (Image generated using Starry Night Software 2009)

may have appeared on the mountain 10 minutes before totality, at totality, and 10 minutes after, respectively, for $\Delta T = 7{,}500$ s, close to the conventional value of ΔT. Here, we assume only a 200-meter elevation above sea-level (see Fig. 3). A possible view by the townspeople is achieved by changing the elevation from 200 meters to sea-level, as Figs. 12, 13, and 14 similarly depict. A dramatic difference in the effect of totality occurs when the Sun is above the horizon and not obstructed: Mirian would have witnessed totality, whereas the townspeople would not. For higher-elevation observers with unobstructed views to the west, the Sun indeed could have "… shone out brilliantly …" just minutes after totality. At lower elevations, such as the location in Fig. 14, the sky would have become a little brighter and then nightfall would have followed, without the stunning effect of totality, that is, the Sun would no longer appear visible in the sky before the eclipse ended. Current geophysical models for ΔT in AD 319 do not contradict the remarkable possibility that Mirian and his fellow hunters, but not the townspeople nearby, witnessed totality during the TSE on AD 6 May 319—and that this offers a natural explanation for descriptions in the written sources of how daylight was restored after a period of intense darkness.

Fig. 12 The sky as seen from sea level and 10 minutes before totality on AD 6 May 319. $\Delta T = 7{,}500$ s and the solar azimuth is about 290°. Figures 12, 13, and 14 aim to portray the view from Mtskheta, where townspeople and the Queen might have been during the TSE according to the Life of Nino (Image generated using Starry Night Software 2009)

Fig. 13 The sky as seen from sea level and at totality on AD 6 May 319. $\Delta T = 7{,}500$ s and the solar azimuth is about 290° (Image generated using Starry Night Software 2009)

Fig. 14 The sky as seen from sea level and 10 minutes after totality on AD 6 May 319. $\Delta T = 7{,}500$ s and the solar azimuth is about 290°. Although appreciably brighter after totality, the Sun does not reappear that day (Image generated using Starry Night Software 2009)

4 Conclusions

Contemporaneous and later medieval written sources recount how, whilst on a hunting expedition in the mountains of eastern Georgia, King Mirian witnessed an unexpected and inexplicable sudden darkening of the sky, which caused him to disavowed his traditional religion and adopt Christianity, whereupon daylight immediately returned. A total solar eclipse (TSE) is one possible natural explanation for these events, which are documented in the *Ecclesiastical Histories* of Rufinus of Aquileia and the Chelishi variant of *The Life of Nino*. For Mirian's presumed location, near the city of Mtskheta, local circumstances of the TSE of AD 6 May 319 explain some, but not all, of the clues contained in these written sources, although other sources contradict the 'eclipse hypothesis'. The mountainous terrain in eastern Georgia could have hindered observing totality, which would have been visible just before sunset, but it also leads to an intriguing possibility. During the eclipse of AD 6 May 319, observers at lower elevations near Mtskheta, with obstructed views perhaps similar to Fig. 15, would have seen the sky grow prematurely dark and then slightly brighter, without the Sun reappearing over the horizon. At higher elevations nearby such as where Mirian and his hunting party might have been, totality of a sunset eclipse may indeed have been a remarkable sight. Although current geophysical models for AD 319 for $\Delta T \approx 7{,}450 \pm 180$ s, as derived from Morrison and Stephenson (2004), do not contradict this scenario, it remains an open

Fig. 15 View at dusk from the courtyard of the Svetitskhoveli Cathedral, Mtskheta, Georgia, on 26 October 2009 (Image courtesy J. Sauter)

question whether the ancient and Medieval written accounts of Mirian's conversion to Christianity are ultimately based on fact … or fantasy.

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The Eclipse of Theon and Earth's Rotation

John M. Steele

Abstract The solar eclipse of AD 364 June 16 described by Theon of Alexandria in his commentary on Ptolemy's *Almagest* has been used to study the secular acceleration of the Moon and the long-term changes in the rate of rotation of the Earth since the first investigations of these topics. All previous studies of this eclipse have been based (directly or indirectly) upon the 1538 Basel edition of the Greek text of Theon. In this paper I discuss the implication for studies of the Earth's rotation of a correction proposed by A. Rome in 1950 to the text of the passage describing this eclipse in the Basel edition.

1 Introduction

Ever since Edmond Halley's discovery of the secular acceleration of the Moon in the last decade of the seventeenth century, historical eclipse observations have provided the primary data source for analysing the long-term changes in the Moon's mean motion. Independent methods of determining the lunar acceleration using observations of the transits of Mercury and, more recently, lunar laser ranging have resulted in the switching of attention away from the secular acceleration of the Moon to the long-term variability of the Earth's rate of rotation. The cumulative effect of small changes in the length of the day caused by this variability in the Earth's rotation is to produce a 'clock error' of several hours for calculations made for dates in antiquity. The Earth's rotational clock error, commonly referred to as ΔT, is the difference between Terrestrial Time and Universal Time.

For the past 30 years, F.R. Stephenson and L.V. Morrison have been at the forefront of long-baseline studies of ΔT and its geophysical implications (see especially Stephenson and Morrison 1995; Stephenson 1997). Through their work the empirical foundation for our knowledge of ΔT has been substantially expanded by their careful use of historical eclipse records from Babylonia and China in addition to the

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eclipse records from ancient and medieval Europe and the medieval Islamic world that had been used by previous investigators. Because of Stephenson and Morrison's work, the value of ΔT is known back to the mid-first millennium BC with far greater accuracy than previously. What follows may be regarded as a small footnote to their pioneering work.

2 The Eclipse of Theon and Its Use in the Investigation of ΔT

A general dearth of preserved eclipse records from the first to the fifth centuries AD from both China and the West means that the solar eclipse observed by Theon of Alexandria is of greater importance for the investigation of ΔT than would otherwise be the case. In his commentary to Book Six of Ptolemy's *Almagest*, Theon reported his observation of the solar eclipse which took place on AD 364 June 16 (Jones 2012). In the same chapter, Theon presented his calculation of the circumstances of the same eclipse using the tables from the *Almagest* and the *Handy Tables*. Theon's purpose was to compare these two sets of calculations with observation to demonstrate the accuracy of the different sets of tables.

The only published edition of Theon's commentary to Book Six of the *Almagest* is the Basel edition of AD 1538. A summary of the eclipse (almost certainly derived from the Basel edition) was included in the lists of historical observations included in Giovanni Battista Riccioli's *Almagestum Novum* (1651) and Albertus Curtius' *Historia Coelestis* (1666), although both authors incorrectly gave the year of the eclipse as AD 365 and did not reproduce complete accounts of the observed times. As a result, anyone who has worked with Theon's eclipse has had to use the Basel edition.

From the eighteenth century onwards, Theon's eclipse has been used extensively in investigations of the Moon's secular acceleration and of ΔT. Richard Dunthorne, who published the first detailed study of the Moon's secular acceleration in the *Philosophical Transactions* for 1749, summarized the eclipse observation, citing the page number from the Basel edition and giving the correct year. Other early investigators of the Moon's secular acceleration either used the Basel edition or relied upon Dunthorne's summary of the eclipse (Steele 2012). To my knowledge, the first English translation of Theon's account of his observation of the eclipse was given by J.K. Fotheringham in his 1920 paper 'A solution of ancient eclipses of the Sun'. Citing the Basel edition as his source, Fotheringham (1920: 114) translated the account as follows:

> … the time reckoned by civil days and equinoctial hours of the exact ecliptic conjunction which we have discussed, and which took place according to the Egyptian calendar in the 1112th year from the reign of Nabonassar 2 5/6 equinoctial hours after midday on the 24th of Thoth, and according to the Alexandrine calendar reckoned by simple civil days in the 1112 year of the same reign 2 5/6 equal or equinoctial hours after midday on the 22nd of Payni … And moreover we observed with the greatest certainty the time of the beginning of contact, reckoned by civil and apparent time as 2 5/6 equinoctial hours after midday, and the time of the middle of the eclipse as 3 4/5, and the time of complete restoration as 4 1/2 hours approximately after the said midday of the 22nd of Payni.

Fotheringham correctly gave the date of the eclipse as AD 364 June 16. In his translation, Fotheringham simplified the Greek fractions into their more familiar modern forms (e.g. rendering 1/2 (+) 1/3 as 5/6).

From his analysis of the eclipse, Fotheringham (1920: 124) concluded that:

> Theon's time was 37, 32, and 38 minutes slow at the three observed phases of the eclipse. He would appear to have observed the intervals with some approach to precision, but to have made a large initial error in the time.

Subsequent investigations of Theon's eclipse have usually cited Fotheringham's translation for the report of the observation (in part this is probably because until its recent digitization the 1538 Basel edition—the only printed Greek text of the observation—was difficult to access for most scholars). Newton (1970: 152 and 154) quoted the times of the eclipse phases from Fotheringham, and argued that "When the acceleration parameter D″ is allowed to vary in the way that I have found from using both ancient and medieval data, the measurements of Theon seem to be rather accurate." (Newton 1979: 218–219). Newton's value for the acceleration, however, now finds little support among scholars working in this field. Stephenson (1997: 364–365) derived values for ΔT of between 8,100 and 8,400 seconds from the observation, again working from Fotheringham's translation. Finally, in Steele (2000: 103–104), I also quoted Fotheringham's translation and concluded that Theon's times of the eclipse phases were all early by about half an hour compared to calculations made using Stephenson and Morrison's (1995) spline fit for ΔT.

Stephenson and Morrison's spline fit, determined from a large number of timed and untimed eclipse observations from a variety of different cultures, gives a value for ΔT of about 7,000 seconds for AD 364, with a standard deviation of about 160 seconds (Stephenson and Morrison 1995; Morrison and Stephenson 2004). However, the ΔT values derived by Stephenson from Theon's observation are in the range 8,100–8,400 seconds, considerably greater than the value from the spline fit. What is the reason for this discrepancy? The obvious answer, and the one to which I have previously subscribed, is simply that a badly calibrated water clock or whatever other device Theon used to time the eclipse caused a systematic error in his timings. In fact, however, the discrepancy is caused by a problem with the report of the eclipse as it is known from the 1538 Basel edition of the text. Rome (1950) has convincingly demonstrated that the Basel edition contains an error in the timing of the eclipse: the word 'equinoctial' that is given alongside the time of first contact is an error (see also Jones 2012). It is not in the oldest manuscript of Theon, and, as Rome showed, Theon's discussion of the calculation of this eclipse only makes sense if we assume that the observed times are given in seasonal not equinoctial hours. Thus the times of the eclipse phases are 2 5/6, 3 4/5 and 2 1/2 *seasonal* hours after noon. Interestingly, in his 1749 paper on the Moon's secular acceleration, Dunthorne stated without comment that these times were in seasonal hours, presumably on the basis of a similar study of Theon's calculation as undertaken by Rome (Steele 2012).

If we accept Rome's correction to the 1538 Basel edition and assume that the times of the eclipse phases given by Theon are in seasonal hours, we will find values of ΔT that are somewhat smaller than are found on the assumption of equinoctial hours. At Alexandria (latitude: 31° 13′ N, longitude: 29° 55′ E), sunrise took place

Table 1 ΔT values derived from Theon's timings of the phases of the eclipse of AD 364 June 16 on the assumptions they are timed using equinoctial and seasonal hours. Stephenson and Morrison's spline fit for ΔT in this year gives a value of 7,000 seconds

	Equinoctial hours		Seasonal hours	
Contact	LT (h)	ΔT (s)	LT (h)	ΔT (s)
Beginning	14.83	8,300	15.35	6,800
"Middle"	15.80	8,100	16.49	6,100
End	16.50	8,400	17.32	6,100

at 4.90 hours after midnight on AD 364 June 16 (here and elsewhere times are given in hours and decimals). Thus one seasonal hour of day was equal to 1.18 equinoctial hours. The observed local apparent times of the beginning, middle and end of the eclipse were therefore 15.35, 16.49 and 17.32 hours after midnight. Using computer programs for the calculation of the circumstances of solar eclipses written by F.R. Stephenson and generously made available to me, I have determined the values of ΔT derived from these times using the procedure described in Stephenson (1997: 71–74). I have assumed that Theon's "middle" of the eclipse corresponds to the moment of maximum eclipse, which may differ by several minutes from the time of mid-eclipse; Theon's time for the "middle" of the eclipse is about 9 minutes later than the midpoint of his beginning and ending times, in agreement with this assumption.

The ΔT values derived from Theon's timings of this eclipse are shown in Table 1. For comparison I give the ΔT values derived on the two assumptions of seasonal and equinoctial hours. For convenience, I have rounded my results to the nearest 100 seconds, which is a little more precise than is justified by the precision of Theon's recorded times. Recall that Stephenson and Morrison's spline fit gives the value of ΔT for this year as 7,000 seconds. The derived ΔT values are all significantly closer to the spline fit on the assumption of seasonal rather than equinoctial hours, which can be taken both as confirmation of the correctness of this assumption and of the accuracy of the spline fit. The value derived from the moment of first contact is very close to the spline fit. Theon says that he observed this moment "… with the greatest certainty …", whereas the time of last contact, which gives a rather lower value for ΔT, is qualified as "… approximate …" (but see the comments on the meaning of this term in Jones 2012, note 7).

3 Conclusion

Rome's correction of the error in the text of the report of the eclipse of AD 364 June 16 found in the 1538 Basel edition of Theon's commentary on the *Almagest* resolves a problem with the ΔT values determined from this observation. Previously, the ΔT values had appeared anomalously high, suggesting a systematic error in his timings, but knowing now that Theon's times are given in seasonal rather than equinoctial hours, we find values that are in good agreement with Stephenson and Morrison's spline fit for ΔT. This has the mutually pleasing result of both vindicating Theon's observation from suspicion of being poorly observed (which is important given the relatively small number of observations known from this period), and of confirming the general reliability of Stephenson and Morrison's spline fit for ΔT.

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Homage to Richard Stephenson: French Observations of the Sun at the Time of the 'Sun King'

Suzanne Débarbat

Abstract After the creation by King Louis XIV (the 'Sun King') of the Royal Academy of Sciences (1666) and of the Paris Observatory (1667), astronomers had quadrants equipped with micrometers which they could use to obtain positions and diameters of celestial objects. They also could observe the physical aspects of these objects with long-focus refractors. One of their favourite targets was the Sun, and they were particularly interested in its position, as well as its diameter, sunspots and eclipses. Richard Stephenson has successfully employed old solar eclipses records, mainly from Chinese chronicles, to study long-term variations in the rotation rate of the Earth.

1 Solar Observations

Throughout human history, solar and lunar eclipses have been among the celestial phenomena that have most impressed astronomers and the general public. During a lunar eclipse the Moon can take on a red, pink, orange or golden hue and look extremely attractive. In the case of a total solar eclipse, the Moon actually occults the Sun so the Sun disappears totally from view, but during the short interval of totality prominences can often be seen around the limb of the Sun along with the reddish chromosphere, and above them the faint white outer atmosphere of the Sun, the corona, is visible. It is not surprising, therefore, that total, and even partial, solar eclipses are often mentioned in historical records, always as impressive visual spectacles, but sometimes as terrifying phenomena (Proctor 1896). While the succession of day and night was accepted as a fact of life early in human history (although the ways in which this was explained varied greatly form civilisation to civilisation and culture to culture; e.g. see Selin and Sun 2000; Walker 1996), the sudden disappearance—within an interval of only a few minutes—of a bright object like the Sun, was regarded as remarkable. At times when there was no eclipse, if the sky was cloudy or hazy, and especially when the Sun was near the horizon, careful observers were

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able to see large sunspots with the unaided eye (e.g. see Clark and Stephenson 1977; Eddy et al. 1989). However, with the advent of the Galilean telescope (*lunette de Galilée*, in French) and its regular use for solar observations, the Sun would soon be seen in a totally different light.

In 1667, one year after the creation of the Royal Academy des Sciences, King Louis XIV (1638–1715) decided to establish a 'Royal Observatory' in Paris, and this would soon be known as the Paris Observatory (see Fig. 1; Bobis and Lequeux 2012). Meanwhile, by this time some French and European astronomers had already equipped their quadrants with refractors. In addition, in 1666 Adrien Auzout (1622–1691) and Jean Picard (1620–1682) were able to install micrometers on their quadrants which, with a fixed wire and the mobile one, allowed them to measure the diameters of celestial objects. Then in 1669 Picard installed two

Fig. 1 This painting shows King Louis XIV visiting the Royal Garden. Note that Paris Observatory was under construction at the time and is visible through the window (After Perrault 1676: frontispiece)

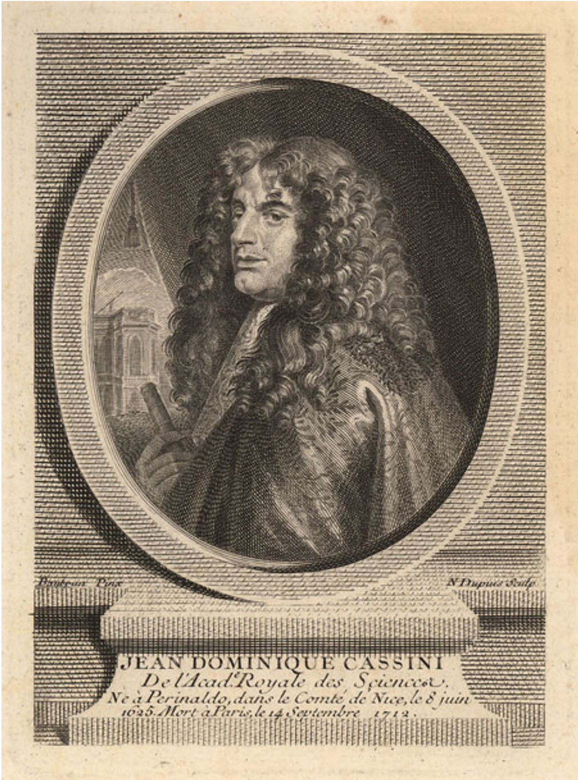

Fig. 2 Portrait of Jean Dominique Cassini holding a small refractor in his right hand, and to his left is the West Tower of the Paris Observatory with a long focal length refractor visible on the roof (© Académie des Sciences-Institut de France)

refractors on his quadrant, a fixed one and a moveable one, so that he could start to make observations that combined astronomy and geodesy (Anonymous 1982). In doing so, he was able to extend the Paris Observatory meridian line—represented by the symmetry axis of the Observatory (nowadays the building named the Bâtiment Perrault, after one of its architects)—from Amiens (north of Paris) to La Ferté-Allais (to the south of Paris).[1]

The astronomers of the Academy soon were able to perform new types of observations, such as measuring changes in the solar diameter in relation to variations in the Earth-Sun distance throughout the year. Meanwhile, their solar right ascension and declination observations, together with those of the then-known planets, allowed them to increase the accuracy of their tables depicting the motions of these planets around the Sun. Simultaneously, Jean Dominique Cassini (1625–1712; Fig. 2)[2]

[1] In 1982 a colloquium was organised in Paris to mark the tercentennial of the death of Picard. Among the papers presented was one about Picard as an astronomical observer (Grillot 1987) and another that utilised his measurements of the diameter of the Sun over a 6-year period to gauge the quality of his astronomical observations (Débarbat 1987). Subsequently, Toulmonde (1995) included a critical review of Débarbat's findings in a thesis he wrote on measurements of the solar diameter.

[2] When Cassini moved from Italy to France, he also changed his name from Giovanni Domenico Cassini to Jean Dominique Cassini, and I have opted to use the latter version in this paper.

Fig. 3 A woodcut showing observers in the foreground, in front of the Paris Observatory, using two of the very long focal length refractors. Their objectives were attached to the Observatory building itself (in the case of the left-hand pair of observers) and to the Marly Tower (in the case of the right-hand observer). The eyepieces of these telescopes were held by the observers. The lines apparently joining the objectives and the eyepieces in this woodcut are there to indicate the incoming light rays, not tubes, as these telescopes lacked tubes (indeed these were referred to as 'telescopes without tubes' by Cassini). Meanwhile, the much shorter focal length telescope in the background, on the terrace and attached to the mast, does have a tube (After Wolf 1902)

who arrived in Paris, in 1669, to join his French colleagues both at the Academy and at the Paris Observatory, brought from Italy long focus lens to be employed as telescope objectives. They were very powerful, and when silvered on their surface or coated with lamp-black allowed Cassini to make solar observations; however, these observations endangered his eyes, and a few years before his death he became blind (Débarbat et al. 1990).

From that time, the astronomers expanded their range of solar observations, with their portable or mural quadrants installed along any meridian, or with their long focal length telescopes equipped with eyepieces that magnified up to 600× (ibid.). In the latter case they installed the objectives on the tops of buildings, or on the Marly Tower, which previously was used to bring water to Versailles but then was transferred to Paris Observatory and erected in the garden on the southern side of the building (see Fig. 3). For accurate time-keeping, the astronomers used clocks that Christiaan Huygens (1629–1695) had improved by the mid-1650s fifties as a result of introducing Galileo Galilee's pendulum, and converting them into regulators. Through the writings of Joannes Kepler (1571–1630), it was known that planets followed elliptical orbits around the Sun, even if—for a while—Cassini proposed

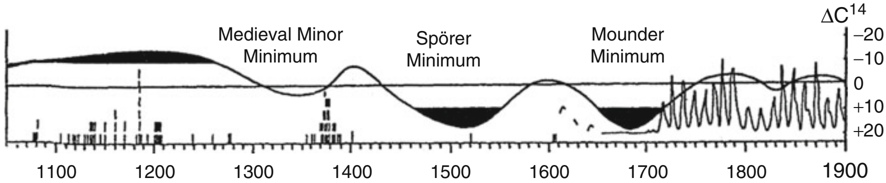

Fig. 4 Variations in sunspots over the past 850 years (After Clark and Stephenson 1978: 408)

Fig. 5 A map showing the path of totality of the solar eclipse of 22 May 1724 (Courtesy: http://xjubier.free.fr/en/site_pages/solar_eclipses/Solar_Eclipses_France_pg01.html)

an oval for which the product of distances to the focus was constant instead of the sum. Meanwhile, measurements of altitudes of the Sun allowed Cassini to improve the tables of refraction.

The French astronomers attentively observed sunspots, and remarked on the latitudinal zones where they were found, and on their shapes and their motions. By the end of the seventeenth century, they noticed that sunspots were not so frequent, and indeed sometimes no sunspots were visible. Later, this period, during the reign of King Louis XIV, was named 'The Little Ice Age' or the 'Maunder Minimum' (Fig. 4; see Eddy 1976), and it brought famine to Europe. On 22 May 1724, nearly nine years after Louis XIV's death, a total eclipse was visible from Paris, and a broadsheet containing a map showing the path of totality was published in Germany (Fig. 5). This rare map is discussed in a short paper I wrote for *l'Astronomie* (Débarbat 1999). Meanwhile, the eclipse was a great spectacle, and it so impressed the general population that later it supposedly was featured in a painting that is now at the Paris Observatory, but in reality this painting actually depicts the partial solar eclipse of 3 May 1715 which also was seen from Paris (see Débarbat 2000 for details).

2 Richard Stephenson and Old Solar Eclipse Observations

Given their impressive appearance, it is understandable that accounts of total solar eclipses can be found in old, even very old, documents. Such eclipses can provide valuable information about variations in the rotation rate of the Earth, in that each historic eclipse would only have been visible from along a geographically-restricted path of totality. Richard Stephenson has made a deep study of this topic, drawing mainly on data in old Chinese chronicles.

In the mid-1970s, Richard's attention was drawn to old astronomical phenomena, and he and David Clark published a book about historical supernovae (Clark and Stephenson 1977).[3] The following year he and Clark published *Applications of Early Astronomical Records* (Stephenson and Clark 1978), which discussed the records of novae and supernovae, solar eclipses, and sunspots and associated polar aurorae derived from historical European, Middle Eastern and Oriental sources.

Richard's other well-known book, *Historical Eclipses and Earth's Rotation*, was published in 1997 by Cambridge University Press, and runs to more than five hundred pages. This tome is based on studies carried out with a number of collaborators, including Leslie Morrison, and presents an exhaustive study of total solar eclipses recorded in historical Oriental, Middle Eastern and European records. Their occurrence times and the terrestrial locations where they should have been visible can be computed and then compared with the actual historical observations. If the results are not coherent, then variations in the rotation rate of the Earth (ΔT) and thus in the length of the day are considered responsible. After recalling the historical facts related to variations in the rotation of the Earth, Richard then provides twelve chapters where he examines in detail all of the eclipses for which he was able to collect data. In the final chapter he summarises the overall results derived from the various analysis, and documents the way in which ΔT varied in the course of the last 2,700 years (see Fig. 6, which covers the period 700 BCE to AD 2000). Such results are of special interest not only for the study of the Earth's rotation but also for the long-term evolution of the Earth-Moon System. Such a study—over a very long time interval—of the variation in ΔT, is also very useful concerning the present discussions related to the universal coordinate time which is employed in our everyday lives.

[3] Twenty-five years later a substantially-revised and expanded version of this book was published, authored on this occasion by Richard Stephenson and David A. Green (2002).

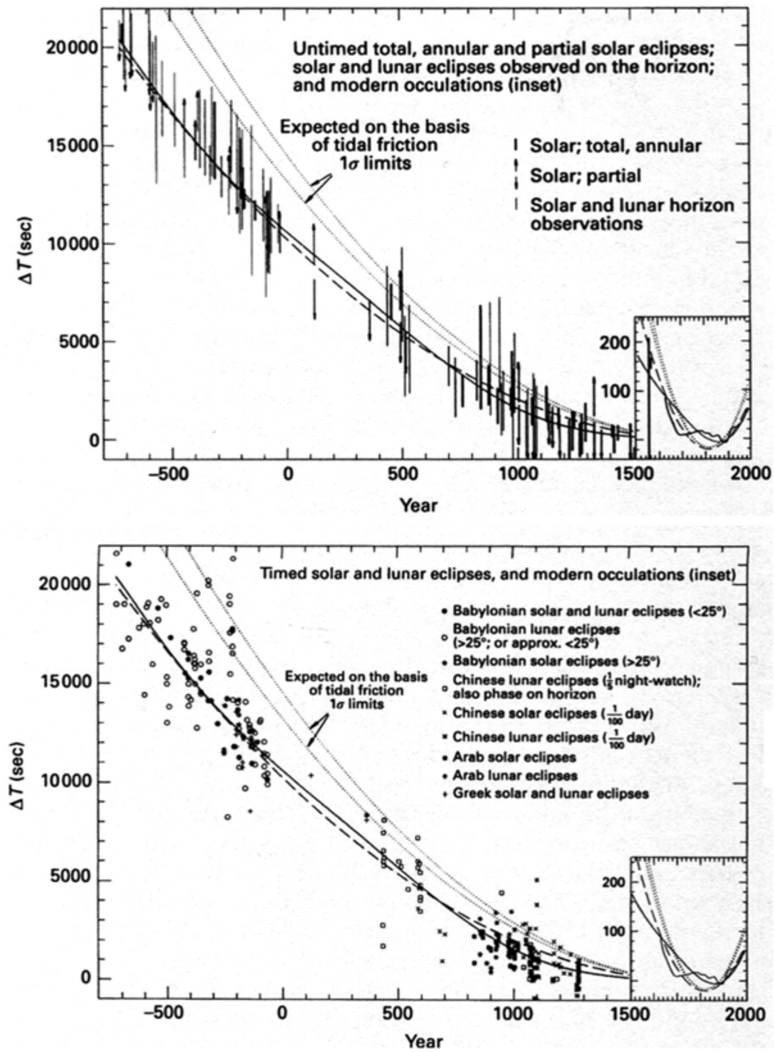

Fig. 6 Variations in *ΔT* derived from ancient solar eclipse untimed (*top*) and timed (*bottom*) observations (After Stephenson 1997: 504)

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Evidence for Recurrent Auroral Activity in the Twelfth and Seventeenth Centuries

David M. Willis and Chris J. Davis

Abstract The existing evidence for recurrent auroral activity during the third decade of the twelfth century is reviewed and new evidence for recurrent auroral activity during the third decade of the seventeenth century is presented. The earliest known drawing of sunspots appears in *The Chronicle of John of Worcester*, which was compiled in the first half of the twelfth century. In this medieval chronicle, the Latin text describing the sunspots is accompanied by a colourful but idealised drawing, which shows the apparent sizes and positions of two sunspots on the solar disk. The date of this observation of sunspots from Worcester, England, is firmly established as 8 December 1128. About 5 days later, on the night of 13 December 1128, a red auroral display was observed from Songdo, Korea (the modern city of Kaesong). This auroral observation was recorded in the *Goryeosa*, the official Korean chronicle of the period. In addition, five Chinese and five Korean descriptions of auroral displays were recorded in various East Asian histories between the middle of 1127 and the middle of 1129. These ten Oriental auroral records correspond to six distinct auroral events, which provide evidence for recurrent, though possibly intermittent, auroral activity on a timescale almost exactly equal to the synodic-solar-rotation period (approximately 27 days). The existing catalogues of East Asian auroral observations, together with new auroral observations gleaned from two additional Korean histories, namely the *Seungjeongwon Ilgi* and the *Jeungbo Munheon Bigo*, are used to investigate auroral activity in the interval 1624–1627.

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Strong evidence is found for recurrent auroral activity between about the middle of 1625 and the middle of 1626. There is also some evidence for prolonged auroral activity at this time, sometimes extending over several consecutive nights. It is shown that these patterns of auroral activity are most unlikely to have occurred by chance. Further extensive searches of the *Seungjeongwon Ilgi* are required to consider the patterns of auroral activity during the long interval 1623–1894. Such searches should help to elucidate the nature of geomagnetic storms during past centuries.

1 Introduction

This paper is an expanded version of part of a talk presented at the conference, held at Durham University, England, on 13–16 April 2011, to celebrate Professor F. Richard Stephenson's 70th birthday and mark his important contributions to 'Applied Historical Astronomy'. The oral presentation was intended to be a wide-ranging review of the importance of historical observations in solar-terrestrial physics. The purpose of this paper, however, is to present detailed evidence for recurrent auroral activity during parts of the twelfth and seventeenth centuries. In particular, the existing evidence for recurrent auroral activity in the restricted intervals AD 1127–1129 and AD 1624–1627 is discussed and examined critically. The evidence for recurrent auroral activity in the interval 1127–1129 has been investigated in detail previously (Willis and Stephenson 2001) and therefore only the main results are reviewed in this study. However, the evidence for recurrent auroral activity in the interval 1624–1627 is based on East Asian auroral observations from all known sources, including some observations recorded in histories that have only been investigated recently.

This paper forms a fitting tribute to Richard Stephenson in the sense that none of the results presented in the following sections could have been achieved without his outstanding expertise and scholarship. His extensive knowledge of Classical Chinese and East Asian history, together with his meticulous attention to detail and insistence on complete objectivity, have been of paramount importance in many studies of the physics of the Sun-Earth environment, which relate to a time interval spanning more than two-and-a-half millennia.

2 Observations of Sunsots on 8 December 1128

Stephenson and Willis (1999) have discussed the earliest known drawing of sunspots, which appears in *The Chronicle of John of Worcester*. This medieval chronicle, which was compiled during the first half of the twelfth century (Darlington et al. 1995; McGurk 1998), contains records of various celestial phenomena and objects, including eclipses of the Sun and Moon, comets, meteor showers and aurorae. A remarkable description of two sunspots that were seen on 8 December in the year

Fig. 1 The earliest known drawing of sunspots, which appeared in *The Chronicle of John of Worcester* (Corpus Christi College, Oxford). This drawing shows the apparent positions and sizes of two sunspots that were observed on 8 December 1128 from Worcester, England. Part of the surrounding Latin text describes the two sunspots and also presents historical information that enables this medieval sunspot observation to be dated precisely. A translation of the relevant part of the Latin text is presented on the following page

AD 1128 from Worcester, England (52.2° N, 2.2° W) is of particular relevance to the study of the Sun-Earth environment during historical times. In the solitary manuscript (probably contemporary) containing this account, which is in the archives of Corpus Christi College, Oxford (Ms No. 157), the Latin text is accompanied by a colourful drawing that shows the apparent positions and sizes of the two sunspots on the solar disk. The drawing and the surrounding Latin text are reproduced in Fig. 1. Although the drawing is embellished and idealised, it appears to be the earliest known illustration of sunspots on the solar disk, despite the fact that unaided-eye observations of sunspots had been recorded in Chinese dynastic histories for more than 1,000 years prior to AD 1128.

For the period from 1128 to 1140, *The Chronicle of John of Worcester* contains much unique information and is possibly written in the hand of John of Worcester himself (Darlington et al. 1995: xxi, xxix–xxxv; McGurk 1998: xix). The entry describing the observation of two sunspots (or two dense sunspot groups) on 8 December 1128 in England, as translated by McGurk (1998: 183), is as follows:

> [1128] In the third year of Lothar, emperor of the Romans, in the twenty-eighth year of King Henry of the English, in the second year of the 470th Olympiad, seventh indiction, twenty-fifth moon, on Saturday, 8 December, there appeared from the morning right up to the evening two black spheres against the Sun (*quasi due nigre pile infra solis orbitam*). The first was in the upper part and large, the second in the lower and small, and each was directly opposite the other as this diagram shows. (Corpus Christi College Ms No. 157, folio 380, lower half).

As noted by Stephenson and Willis (1999), the date of this observation of sunspots is firmly established as 8 December 1128. The reference to the third (full) year of Lothar, King of Germany, and the twenty-eighth (full) year of Henry (I), King of England, is consistent with the year AD 1128, as is the reference to the seventh indiction (a 15-year fiscal period). However, John of Worcester has miscalculated by 26 years when giving the date in terms of the Olympiads (a secondary year count). Despite this miscalculation, a date in 1128 is confirmed by the fact that 8 December was indeed a Saturday in that particular year. John of Worcester has also made a mistake in giving the day of the lunar month: 8 December was the 15th rather than the 25th day. This latter discrepancy could be the result of a scribal error or, alternatively, simply a lack of the necessary astronomical knowledge, which was not uncommon among medieval European chroniclers. McGurk (1998) mentions (in a footnote) that the sunspots observed at Worcester were not recorded elsewhere. In fact, there is no known record of any other sunspot observation in either Occidental or Oriental histories (Stephenson and Al-Dargazelli 1998; Wittmann and Xu 1987; Yau and Stephenson 1988) from essentially the beginning of 1122 (Oriental sunspot sighting on 10 January) until the spring of 1129 (Oriental sunspot sighting on 22 March).

Nevertheless, it may well be highly significant that observations of a single sunspot from both China and North China on 22 March 1129 (Yau and Stephenson 1988) occurred approximately four synodic-solar-rotation periods after the sighting of two sunspots from Worcester, England, on 8 December 1128. The relevant East Asian historical records originate from two separate empires, one of which may be termed China proper (the territory ruled by the native Chinese Sung Dynasty) and one in northern China (the territory conquered by the invading Chin Dynasty). Presumably, the Chinese and North Chinese observations of a sunspot on 22 March 1129 were independent. Around this time, the Jurchen tribes from Manchuria, who had established the Chin Dynasty in 1115, overran the northern half of the Sung Empire. They captured its capital Pien (modern name Kaifeng) in January of 1127 and the emperor was taken into exile. The Sung court fled south and the Dynasty never regained its lost territory. A new Sung emperor was enthroned at Ying-t'ien (close to the modern city of Shangqiu) in June of that year.

The two sunspot records (*Sung-shih*, 25, 52) from China proper (capital: Hangchou, later named Lin-an, the modern city of Hangzhou) and the single record (*Chin-shih*, 20) from North China (principal capital: Shang-ching in Inner Mongolia, the modern city of Acheng) state that "… there was a black spot within the Sun …" on 22 March 1129. The relevant Chinese histories are presented in italics (e.g. *Sung-shih*), together with the corresponding chapter number (e.g. 25). Both the 'Annals'

(*Sung-shih*, 25) and the 'Astronomical Treatise' (*Sung-shih*, 52) from China proper state further that "… the black spot within the Sun died away …" on 14 April 1129. However, there is no explicit mention in these Chinese histories of sunspot sightings on any other day in the interval between 22 March and 14 April. Since the same sunspot cannot have been seen continually for 24 days, these particular Chinese records imply that more than one large sunspot (or dense sunspot group) was observed during the interval 22 March–14 April.

Therefore, it is quite likely that the level of solar activity was pronounced throughout this interval, although the seasonal variation of suitable atmospheric viewing conditions in East Asia tends to favour the detection of sunspots during the spring (Willis et al. 1980, 1988). It is also possible that one of the two sunspots observed on 8 December 1128 from Worcester in England survived for a further 104 days to be observed again on 22 March 1129 from both Hang-chou in China and Shang-ching in North China. This latter possibility follows from the fact that a large sunspot would certainly be visible with the unaided eye (in the absence of obscuring cloud cover) up to about 6 days before or after its central meridian passage. Therefore, since the meteorological conditions during the first quarter of 1129 are essentially unknown, a time separation of 104 days is compatible with the same sunspot being observed again after four synodic-solar-rotation periods (about 108 days). Unfortunately, none of the East Asian records gives any indication of the position on the solar disk of either the single sunspot seen on 22 March 1129 or the different single sunspot seen on 14 April 1129. However, in recent times, large sunspot groups have been known to persist for several solar rotations.

Despite the fact that the sketch shown in Fig. 1 is clearly idealised, there appears to have been a quite deliberate attempt, almost nine centuries ago, to depict two sunspots of different sizes, which are distinctly off-centre in the northern and southern solar hemispheres. Approximate quantitative estimates of the total areas (umbral plus penumbral) and heliographic latitudes of the sunspots depicted in Fig. 1 have been discussed in the literature (Stephenson and Willis 1999; Willis and Stephenson 2001) but these estimates are not germane to the central theme of this discussion.

Although it is indeed remarkable that there exists a drawing and accompanying description of sunspots observed on 8 December 1128 from Worcester in England, it is perhaps even more remarkable that the aurora borealis was observed 5 days later in Korea (Willis and Stephenson 2001).

3 Observation of the Aurora Borealis on 13 December 1128

The Korean observation of the aurora borealis on 13 December 1128 is taken directly from the catalogue of auroral observations from China, Korea and Japan (193 BC–AD 1770) published by Yau et al. (1995), which is based on the work of both Keimatsu (1970–1976) and Dai and Chen (1980). However, an independent search of East Asian histories was undertaken in the process of compiling this later catalogue. (The subsequent inclusion of yet further auroral observations, recorded in previously unexamined Korean histories, is discussed in Sect. 5.) Willis and

Stephenson (2000) have considered in detail the background information required for a proper interpretation of the East Asian auroral observations. For completeness, those facts that are strictly relevant to this investigation are summarised briefly, immediately after the presentation of the Korean auroral record for 13 December 1128. However, some of these facts are more relevant to the discussion of the nine additional East Asian records between the middle of 1127 and the middle of 1129, which are presented in Sect. 4.

The entry describing the observation of the aurora borealis from a site in Korea on 13 December 1128 may be translated as follows:

> 1128 December 13 [Korea, Songdo] King Injong … 6th year … 11th month, day *keng-tzu* (37). “From the NW to SW, a red vapour soared and filled the sky.” (*Koryo-sa*, 53) [NB. Although not stated in the text, this was the 20th day of the lunar month.]

The Korean book title is presented in italics (*Koryo-sa*, *Goryeosa* in pinyin), together with the appropriate chapter number (53). The text, along with several other auroral entries in the early years of King Injong, is illustrated in Fig. 2: the Chinese

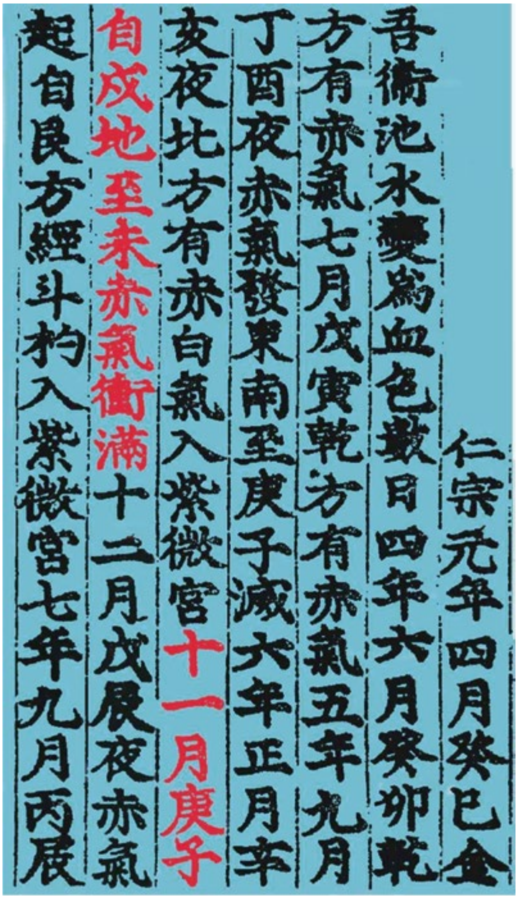
仁宗元年四月癸巳金
吾衛池水變爲血色數日四年六月癸卯乾
方有赤氣七月戊寅乾方有赤氣五年九月
丁酉夜赤氣發東南至庚子滅六年正月辛
亥夜北方有赤白氣入紫微宮十一月庚子
自戌地至未赤氣衝滿十二月戊辰夜赤氣
起自艮方經斗杓入紫微宮七年九月丙辰

Fig. 2 Description of an observation of the aurora borealis on the night of 13 December 1128 from Songdo (Kaesong), Korea, as recorded in the *Goryeosa* (the official Korean chronicle of the period). The Chinese characters coloured *red* in the fifth and sixth columns from the right describe a *red* vapour that “soared and filled the sky” from the north-west to the south-west and also present calendrical information that enables this medieval auroral observation to be dated precisely (Yau et al. 1995). A translation of the relevant part of the Chinese text is presented above. Several other auroral observations in the years 1126, 1127, 1128 and 1129 are also described on this page from the *Goryeosa* (see also Table 1) characters coloured red in the fifth and sixth columns from the right provide the greater part of the preceding English translation (beginning with the month).

Following Willis and Stephenson (2000), it is assumed that the actual location at which a Chinese or Korean auroral observation was made is in the vicinity of the imperial or royal capital, unless there is evidence to the contrary. For example, it is assumed that the Korean auroral observation on 13 December 1128 was made at Songdo (the modern city of Kaesong), the Korean capital for almost the entire period from AD 936 until 1392. The location Songdo (38.0° N, 126.6° E) is added within square brackets after the country name in the quoted record (i.e. [Korea, Songdo]). As already noted, the political situation in China around this period was extremely complex. Presumably, the Sung auroral observations during September in 1127 (see Table 1) were made at Ying-t'ien, the modern city of Shangqiu (34.4° N, 115.6° E) but at this turbulent period there can be no certainty about the exact location.

Table 1 Chronological list of auroral observations recorded in East Asian histories from the middle of 1127 to the middle of 1129 (From Yau et al. 1995). An asterisk* after the (Julian) date signifies that the appropriate text is included in Fig. 2

1. Autumn 1127 (10 August-5 November)
[China, Chia-hsing] Chien-yen reign-period, 1st year, autumn. "There was a violet vapour between (the lunar lodges) *(Nan-) Tou* (Southern Dipper) and *Niu* (Ox)." (*Chia-hsing Hsien-chih*, 1)
2. 20 September 1127
[China, Ying-t'ien] Chien-yen reign-period, 1st year, 8th month, day *keng-wu* (7). "In the NE direction, there was a red vapour." (*Sung-shih*, 64)
3. 22 September 1127
[China, Ying-t'ien] Chien-yen reign-period, 1st year, 8th month, day *jen-shen* (9). "This evening, in the NE, there was a red vapour." (*Sung-shih*, 24)
[China, Ying-t'ien] Chien-yen reign-period, 1st year, 8th month, day *jen-shen* (9). "In the NE, there was a red vapour." (*Sung-shih*, 60)
[China, Ying-t'ien] Chien-yen reign-period, 1st year, 8th month, day *jen-shen* (9). "In the NE direction, there was a red vapour." (*Wen-hsien T'ung-kao*, 294)
4. 17 to 20 October 1127*
[Korea, Songdo] King Injong, 5th year, 9th month, day *ting-yu* (34). "At night, a red vapour appeared in the SE. On day *keng-tzu* (37) —— 20 October —— it was finally extinguished." (*Koryo-sa*, 53)
5. 28 February 1128*
[Korea, Songdo] King Injong, 6th year, 1st month, day *hsin-hai* (48). "At night, in the N direction, there was a red-white vapour entering *Tzu-wei-kung* (Purple Subtlety Palace)." (*Koryo-sa*, 53)
6. 20 October 1128
[Korea, Songdo] King Injong, 6th year, 9th month, day *ping-wu* (43). "A red vapour from the NW passed *Tzu-wei* (Purple Subtlety) and entered the NE. Also, dark vapours were running into it from the S and N." (*Chungbo Munhon Pigo*, 8)
7. 13 December 1128*
[Korea, Songdo] King Injong, 6th year, 11th month, day *keng-tzu* (37). "From the NW to the SW, a red vapour soared and filled the sky." (*Koryo-sa*, 53)
8. 10 January 1129*
[Korea, Songdo] King Injong, 6th year, 12th month, day *wu-ch'en* (5). "At night, a red vapour rose from the NE direction. It passed through *Tou-shao* (handle of the Northern Dipper) and entered *Tzu-wei-kung* (Purple Subtlety Palace)." (*Koryo-sa*, 47, 53)

The Chinese calendar, which was luni-solar, was adopted with little change in Korea. However, in both China and Korea, years were numbered relative to the reign of the appropriate ruler. In both countries, most years contained twelve lunar months, each of length 29 or 30 days. Every three years or so, an intercalary month was inserted in order to keep the calendar in step with the seasons. Intercalation was not always implemented simultaneously in China and Korea, but differences were usually slight. Days were sometimes counted from the start of each lunar month. However, a 60-day (sexagenary) cycle was also adopted. This cycle, which covered a little over two lunar months, was independent of any astronomical parameter. Its regular use facilitates the conversion of dates to the Julian or Gregorian calendar. A computer program has been devised to expedite such date conversions.

Only one of the East Asian auroral records presented in Sect. 4 mentions a specific time of night, namely the evening of 22 September 1127 (see Table 1). Azimuthal directions were usually very approximate, no more than N, NE, E, SE, S, SW, W and NW. Some East Asian records mention the star group(s) in which an auroral display was visible. These are identified in this paper by italicised names beginning with a capital letter (see Table 1); for example, *Niu* (Ox), *(Nan-) Tou* (Southern Dipper), *Tou-Shao* (handle of the Northern Dipper), *Tzu-wei* (Purple Subtlety) and *Tzu-wei-kung* (Purple Subtlety Palace). Traditional East Asian star groupings differ considerably from Occidental constellations, both in size and in the constituent stars. Of the quoted star groups, *Niu* was part of Capricorn and *Nan-Tou* was part of Sagittarius, while *Tou-shao* was part of Ursa Major. *Tzu-wei* (also equivalent to *Tzu-wei-kung*) was very extensive and embraced the northern constellations Cepheus, Draco, Ursa Major and Camelopardus. Willis and Stephenson (2000) have provided further background information on all of these general matters.

Another important physical variable is the phase of the Moon at the time of a particular auroral display. In general, faint aurorae are more likely to be detected near new Moon, as will be illustrated in Sect. 5. The phases and elongations of the Moon presented in this and the following Section have been calculated using a specially-designed computer program. The phase and elongation of the Moon at 16:00 UT (which corresponds approximately to midnight in East Asia) on the night of 13 December 1128 were 0.79 and 125° W respectively. However, the Moon would not have risen until about 4 h after sunset (i.e. at about 20:45 LT) on this particular night. Therefore, unless the auroral observations were made early in the evening (before the Moon had risen), the auroral light must have been visible in the presence of strong moonlight. The latter possibility is consistent with the conclusion that the auroral observations on the night of 13 December 1128 were associated with an intense geomagnetic storm (Willis and Stephenson 2001).

There is clearly a delay of about 5 days between the observation in England on 8 December of two sunspots on the solar disk and the night-time observation in Korea on 13 December of a red auroral display. This time delay is typical of the average delay between central meridian passage of an active solar region (or a halo mass ejection) and the onset of a geomagnetic storm at the Earth. Some authors have derived typical delay times in the approximate range 3.0–5.5 days (e.g. Brueckner et al. 1998; Wang et al. 2002; Webb et al. 2000). These delay times are measured from the onset of an energetic solar event to the peak of the main phase of the geomagnetic storm (as measured by either the K_p index or the D_{st} index). Other authors have derived typical delay times in the approximate range 1.0–5.0 days (e.g. Cane et al. 2000; González-Esparza et al. 2003; Gopalswamy et al. 2000; Richardson and Cane 2010). However, these latter delay times are measured from the onset of the solar event to the arrival of ejected solar plasma at the orbit of the Earth and hence the occurrence of a storm-sudden-commencement (SSC). The time delay between the occurrence of the SSC and the peak of the main phase can easily be half a day, perhaps slightly longer (Gopalswamy 2008; Park et al. 2002; Taylor et al. 1994). Therefore, a time delay of about 5 days in December in 1128, between the observation of sunspots in England and the observation of a red aurora in Korea, is consistent with modern measurements of this time delay.

4 Evidence of Recurrent Auroral Activity in the Twelfth Century

All the East Asian auroral records between the middle of 1127 and the middle of 1129, as included in either the catalogue published (in English) by Yau et al. (1995) or the catalogue published (in Chinese) by the Beijing Observatory (1988), are presented in Table 1, which is reproduced with minor changes and simplifications from the paper by Willis and Stephenson (2001). The catalogue published by Yau et al. includes Chinese, Japanese and Korean auroral records, whereas the catalogue published by the Beijing Observatory contains only Chinese auroral records. The two-year time interval between the middle of 1127 and the middle of 1129 has been chosen because there is clear evidence for a 27-day recurrence tendency in auroral activity at both the beginning and end of this interval (see Table 2). The format used in Table 1 is essentially the same as that adopted by Yau et al. (1995), apart from the introduction of new reference numbers (appropriate to the limited time interval) and the inclusion of relevant place names. The modern names for Chia-hsing, Ying-t'ien and Songdo, respectively, are Jiaxing, Shangqiu and Kaesong. For each record, the title of the relevant East Asian history (in italics) and the appropriate chapter number are given in parentheses [e.g. (*Sung-shih*, 64)].

The auroral record for 13 December 1128, which has already been presented and discussed in Sect. 3, is repeated in Table 1 in order to emphasise the recurrent nature of auroral activity within the specified two-year interval. The first record in Table 1 is retained, even though the date is imprecise (namely Autumn; defined as the 7th, 8th and 9th lunar months, equivalent to the interval 10 August–5 November in 1127). This first record (from a local history, rather than an official court compilation) mentions the appearance of a violet aurora near two southern star groups [*(Nan-) Tou* in Sagittarius and *Niu* in Capricorn]. These star groups were in the declination range −15° to −30°, corresponding to meridian altitudes between 30° and 45°. Hence this particular auroral display was observed to be closer to the southern horizon than the zenith.

Table 2 The difference in days between the dates of consecutive *distinct* auroral events, as extracted from the East Asian records presented in Table 1 (see the text for further details). Also shown are the phase and elongation of the Moon at the times of these auroral events. The asterisk (*) signifies that the numerical values for the phase and elongation of the Moon apply to the first date (night) in the quoted interval

Date of auroral event (or range of dates)	Difference in days between dates	Moon phase (0–1)	Moon elongation (° E or ° W)
20–22 September 1127		0.97*	160° E*
	27		
17–20 October 1127		0.82*	131° E*
	134		
28 February 1128		0.13	42° W
	235		
20 October 1128		0.27	63° W
	54		
13 December 1128		0.79	125° W
	28		
10 January 1129		0.91	145° W

It should be noted that the earlier sightings in Table 1 are all from China, whereas the later ones are all from Korea. As discussed in Sect. 2, the political situation in China was very unstable at this period. Although Korea enjoyed relative peace, unfavourable weather conditions may have prevented observations in either or both countries. However, it should be emphasised that Medieval astronomical records from both China and Korea are by no means complete. Chinese and Korean astronomical and other records of this period are no more than summaries of the original material, possibly with the loss of much important information.

Table 2 presents the dates of the *distinct* auroral 'events' listed in Table 1. It is assumed that the records for 20 and 22 September 1127 refer to the same auroral 'event' or, more specifically, the same geomagnetic storm. This simplification is consistent with the grouping of the four consecutive auroral records for 17 to 20 October 1127 in Dai and Chen (1980) into a single entry (see Table 1) in Yau et al. (1995). The absence of an East Asian auroral record for 21 September 1127 may not be significant in the context of solar-terrestrial physics. For example, extensive cloud cover might have precluded auroral observations on that date or, alternatively, the original records might have been lost. Therefore, the date of the first auroral sighting in a set of consecutive or contiguous sightings is necessarily regarded as the 'time of onset' of that particular auroral 'event'.

On this basis, Table 2 gives the difference in days between the times of onset of consecutive auroral events recorded in the catalogue of Yau et al. (1995): the catalogue published by the Beijing Observatory (1988) does not yield any additional auroral events in the specified two-year interval. It is assumed that each of these six *distinct* mid-latitude auroral events signifies the concurrent existence of a geomagnetic storm, which was sufficiently intense to produce mid-latitude auroral displays in East Asia. Clearly, no incontrovertible information exists on geomagnetic storms that might have occurred at times when ancient East Asian auroral observations were precluded by extensive cloud cover. Consequently, with the present assumption, the concomitant list of geomagnetic storms is probably incomplete. Nevertheless, all the time differences presented in Table 2 are almost exact multiples of the 27-day synodic-solar-rotation period (e.g. 134 = 5 × 27–1), apart from the long interval (235 days) between the auroral sightings on 28 February and 20 October in 1128. However, even this long interval of 235 days could conceivably be explained if a four-sector structure, or a two-sector structure, of the interplanetary magnetic field prevailed at this time (e.g. 235 = 8 × 27 + 3 × 7–2, or 235 = 8 × 28 + 14–3).

It is now assumed tentatively that the results presented in Table 2 actually imply *continual* ('uninterrupted recurrent') geomagnetic activity every 27 days between 20 September 1127 and 28 February 1128, and again between 20 October 1128 and 10 January 1129. With this further assumption, there would have been seven geomagnetic storms in the first 'uninterrupted' series of recurrent storms (i.e. 20 September, 17 October, 13 November and 10 December in 1127, and 6 January, 2 February and 29 February in 1128, on the basis of an exact 27-day recurrence interval). Likewise, there would have been four geomagnetic storms in the second 'uninterrupted' series of recurrent storms (i.e. 20 October, 16 November and 13 December in 1128, and 9 January in 1129, again on the basis of an exact 27-day recurrence interval). However, it should be remembered that corroborative solar evidence exists for just one of the geomagnetic storms (13 December 1128) in the second series of recurrent storms, namely the English sunspot sighting on 8 December. Indeed, no occurrences of intense geomagnetic storms were identified during this interval (1127–1129) in a subsequent investigation by Willis et al. (2005), which involved a search for 'approximate coincidences' between sunspot and auroral observations recorded in East Asian histories. The lack of any Oriental sunspot records (see Sect. 2), associated with the Oriental auroral records presented in Table 1, suggests that Oriental sunspot observations may have been precluded at this time (1127–1129) by the lack of suitable atmospheric viewing conditions in East Asia (Willis et al. 1988, 1980). It is clear from various historical records that sunspots were often sighted when the brightness of the Sun was much reduced (e.g. when the Sun was low in the sky, namely just after sunrise or just before sunset, or when fog, haze, mist or smoke prevailed). However, the generally very low frequency of East Asian sunspot sightings, on average only about one per decade, indicates a very incomplete record of these events (Eddy et al. 1989; Strom 2015).

The auroral records presented in Table 1, and hence the results presented in Table 2, refer to the two-year interval between the middle of 1127 and the middle of 1129. As mentioned previously, this time interval has been selected primarily because there is clear evidence for a 27-day recurrence tendency in auroral activity at both the beginning and end of the interval (although the phase changes sometime between 28 February and 20 October in 1128). However, this two-year time interval is slightly arbitrary in the sense that there is some tentative evidence for recurrent auroral activity before the middle of 1127. For example, the date of the (Chinese) auroral observation in the catalogue of Yau et al. (1995) that immediately precedes the first precise date in Table 1 (i.e. the second entry) is 5 April 1127. The time difference between 5 April and 20 September is 168 days (=6×28 days). Before 5 April, the situation is more problematic, with (Chinese) auroral observations on 13 and 21 February, although these last two dates may imply that a four-sector structure of the interplanetary magnetic field existed at this time. Therefore, it is just conceivable that the first series of recurrent geomagnetic storms extended over a time interval as long as approximately 12 synodic-solar-rotation periods. Similarly, the date of the (Korean) auroral observation that immediately follows the last entry in Table 1 is 25 October 1129. The time difference between 10 January and 25 October is 288 days (=10×29 – 2 days or, possibly, = 10×28+8; the later possibility implying a four-sector structure of the interplanetary magnetic field). Although a period of 29 days is significantly different from a period of 27 days, it is still possible that the second series of recurrent geomagnetic storms extended over a time interval appreciably longer than three synodic-solar-rotation periods.

Any attempt to distinguish reliably between a synodic-solar-rotation period of 27 days and one of 28 days (and possibly even one of 29 days) on the basis of such ancient auroral data is likely to prove very difficult. Only one of the ten records included in Table 1 quotes a specific time of night (evening) for the auroral observation. The times of the observations described in the other nine records are uncertain by at least about 6 h. This simple estimate is based on the assumption that each uncertainty is approximately equal to half the corresponding number of hours of darkness. Moreover, the period of synodic solar rotation varies with heliographic latitude. The synodic rotation period, based on observations of sunspots, varies from about 27 days at the solar equator to about 29.5 degrees at heliographic latitude 40° (Balthasar et al. 1986; Phillips 1992). These rotation rates, and many others quoted in the literature, have been derived from analyses of the *Greenwich Photoheliographic Results, 1874–1976*; further background information on these tabulated sunspot observations can be found in the paper by Willis et al. (1996). Unfortunately, however, the tabulated Greenwich data after the end of 1915 contains information only on sunspot groups, not individual sunspots (Willis et al. 2013). Therefore, the solar rotation rates derived from these data may not be entirely representative of individual sunspots (Howard 1984, 1996), although the rotation rate of active regions is probably the important quantity in determining the time interval between successive recurrent geomagnetic storms.

Table 2 also gives the phase and elongation of the Moon at 16:00 UT for the six *distinct* auroral events within the specified two-year interval. Where a range of dates is given, the phase and elongation apply to the first date (night) in the interval, as indicated by an asterisk. For example, during the first auroral event, the phase and elongation changed from 0.97 and 160° E on 20 September to 1.00 and 176° W on 22 September. Likewise, during the second auroral event, the phase and elongation changed from 0.82 and 131° E on 17 October to 0.98 and 164° E on 20 October. Thus the first of the six auroral events spanned full Moon, while the second auroral event occurred near full Moon. Moreover, it is clear from the values of phase and elongation presented in Table 2 that two of the remaining four auroral events occurred during one of the gibbous phases of the Moon (i.e. between half and full Moon).

The unaided-eye detection of four of the six auroral events in the presence of strong moonlight corroborates the conclusion that all of these mid-latitude auroral events were associated with two series of intense recurrent geomagnetic storms.

5 Catalogues of East Asian Auroral Observations

All of the preceding results on recurrent auroral activity in the third decade of the twelfth century have been published in the literature (Willis and Stephenson 2001). These results are reproduced here, however, to emphasise the important fact that valuable scientific information on the state of the Sun-Earth environment during past centuries can be gleaned from historical records. Indeed, the evidence for an intense geomagnetic storm on 13 December 1128 is based on historical records from two entirely different cultures; one Occidental, the other Oriental. Moreover, the systematic recording of astronomical observations in the histories of East Asia has resulted in the additional scientific conclusion that recurrent auroral activity, and hence also recurrent geomagnetic activity, existed throughout much of the interval between the middle of 1127 and the middle of 1129. These remarkable results have prompted a search of East Asian histories for further evidence of intervals of recurrent auroral activity. Perusal of the catalogues of East Asian auroral observations has resulted in fragmentary evidence for recurrent auroral activity at many other times, particularly during the sixteenth and seventeenth centuries. Obviously, recurrent auroral activity is most likely to be detected at times when auroral observations are relatively frequent. Accordingly, the following study is restricted to the short interval AD 1624–1627. In order to explain the reasons for selecting this particular interval, it is first necessary to discuss the relevant catalogues and listings of East Asian auroral observations.

As noted in Sects. 3 and 4, the investigation of recurrent auroral activity during the third decade of the twelfth century was based essentially on the catalogue of auroral observations from China, Korea and Japan (from 193 BC to AD 1770) published by Yau et al. (1995). In subsequent studies of possible historical occurrences of intense geomagnetic storms, using combined sunspot and auroral observations from East Asia (Willis et al. 2005, 2006, 2009), this catalogue was supplemented with additional auroral data from three further sources. These additional sources were: (1) Chinese auroral records included in the catalogue published (in Chinese) by the Beijing Observatory (1988), which extends the Chinese auroral observations back to 210 BC and up to AD 1911; (2) the list of Japanese auroral records since AD 1600 included in the catalogue published (in Japanese) by Osaki (1994); and (3) a research paper by Matsushita (1956) on ancient aurorae seen in Japan.

In East Asian history, aurorae are sometimes described in vivid detail, with specific reference to forms such as columns, rays, streamers, etc. (Yau et al. 1995). However, as well as these readily-identifiable auroral features, numerous brief accounts of one or more seemingly featureless red glows occurring in specific directions of the sky after dark are preserved in the history of Korea over several centuries

(Stephenson and Willis 2008), especially during the last dynasty (the Joseon: 1392–1910). No similar phenomenon has ever been recorded in daylight. The nocturnal sky glows that are most frequently reported in Korean history are typically described as "vapours like fire light" (pinyin transliteration: *qi xiang huo guang*). Occasionally, the record affirms that the colour was definitely red (*hong*) but this is rare. Surprisingly, there are no known parallels in the histories of other East Asian countries. However, it should be emphasised that the chronicles of the Joseon (or Yi) Dynasty are much more extensive than their Chinese or Japanese counterparts.

The most well-known Korean chronicle covering the Joseon Dynasty is the *Joseon Wangjo Sillok* (*Veritable Records of the Joseon Dynasty*). This extensive chronicle is written using Classical Chinese characters (*Hanmun*); the Korean characters (*Hangul*), although devised in the fifteenth century, did not find favour among Korean scholars until the twentieth century. The complete *Joseon Wangjo Sillok* (conveniently abbreviated to '*Sillok*') is a complete compilation of the 'Veritable Records' of the first 25 kings of the Joseon Dynasty and thus extends from the start of the Dynasty in 1392 up to 1863. Photographic copies of the entire text are now accessible in several major libraries worldwide. A typical set of the *Sillok* comprises 48 volumes, each containing about 750 double pages (approximately 50 M Chinese characters). The complete *Joseon Wangjo Sillok* has been made available on-line and on CD-ROM, thus facilitating a search of the text for particular phenomena. The *Sillok* was the main source of Korean observations in the auroral catalogue published (in Chinese) by Dai and Chen (1980) and the auroral catalogue published (in English) by Yau et al. (1995).

A much more comprehensive Korean chronicle than the *Sillok* exists for the interval 1623–1894. This great chronicle, which is titled *Seungjeongwon Ilgi* (*Daily Records of the Royal Secretariat*), is also written in *Hanmun* (Classical Chinese). Although the *Seungjeongwon Ilgi* (conveniently abbreviated to '*Ilgi*')——like the *Sillok*——was begun in 1392, all the records down to 1592 were destroyed by Japanese invaders in the latter year. Still more of the 'Daily Records', from 1593 to 1622, were lost during a rebellion. Photographic copies of the remaining *Ilgi* in more than 100 volumes, each containing about 1,000 double pages, are available in major libraries. This huge compilation (some 150 M Chinese characters) is now also accessible on-line. Further information on the *Seungjeongwon Ilgi* as a major source of Korean astronomical records can be found in a paper by Stephenson (2011). In the context of auroral studies, it should be mentioned that the *Ilgi* almost always gives the time of night when a "vapour like fire light" was seen, whereas this information is rare in the *Sillok*.

Stephenson and Willis (2008) noted that a complete investigation of the astronomical records in the *Seungjeongwon Ilgi* appeared (at the time of publication) to be a huge task, which would occupy a team of scholars for many years. Thus their study was deliberately restricted to the very first volume of the chronicle, which covers the interval from the first year of King Injo (1623) to the middle of his sixth year (1628). Unfortunately, the data from the whole of 1624 are missing. Therefore, attention was focussed on the relatively continuous entries over the three-and-a-half year interval commencing at the beginning of 1625. Study of the celestial records even in this short interval involved first scanning by eye some 1.5 M Chinese characters and then translating the many astronomical records. In this context, it should be noted that official scribes were each given the task of writing up the entries in the *Ilgi* for a period of about two weeks (typically about 20 double pages of text). Often the style of writing varied considerably from one scribe to the next, ranging from neat handwriting to a cursive script that is sometimes difficult to read. However, the fact that the *Seungjeongwon Ilgi* is now available (and searchable) on-line in a standard character set eliminates all problems resulting from different calligraphic styles and also greatly facilitates the search of this Korean history for specific astronomical phenomena.

Even during the short period from the start of 1625 to the middle of 1628, several lacunae in the astronomical observations reported in the *Ilgi* have been noted; for example a gap of one-and-a-half lunar months in 1626 and a larger gap covering the first four lunar months of 1628. Nevertheless, it is clear that the *Ilgi* is the prime source of East Asian astronomical records from the early seventeenth century to the late nineteenth century. Furthermore, as a result of a careful study of the astronomical records in both the *Ilgi* and the *Sillok* over the interval 1625–1628, it proved possible to compile a list of as many as 96 references to “vapours like fire light” (Stephenson and Willis 2008). Of these, 69 are cited in the *Ilgi*, 54 in the *Sillok,* but only 27 are common to both sources. As already noted, there are significant gaps in the *Ilgi* record at this early period. Despite the existence of lacunae in the *Ilgi*, however, the superiority of the *Ilgi* to the *Sillok* is evident. In particular, no luminous vapours are cited in the *Sillok* between March 1627 and February 1628, whereas the *Ilgi* chronicles as many as 21 separate events. In addition to these 96 references to “vapours like fire light”, a single report of a similar observation (on 4 April 1628) was included from a separate work titled *Jeungbo Munheon Bigo* (*Enlarged Official Encyclopaedia*): the corresponding title *Chungbo Munhon Pigo* (Wade-Giles) is used in Sect. 3 for consistency with the cited publications. Table 1 in the paper by Stephenson and Willis (2008) lists the dates of all these 97 references to “vapours like fire light”, together with the historical source (or sources), the day of the lunar month, the night watch (or watches), and the compass direction (or directions) of the featureless red vapours in the night sky.

Figure 3 shows the variation in the frequency of occurrence of the “vapours like fire light” listed in Table 1 of the paper by Stephenson and Willis (2008) as a function of lunar age (arbitrarily divided into steps of 3 days). It should be noted that lunar months can contain either 29 or 30 days but this should not significantly affect the form of the histogram. It is apparent from Fig. 3 that fewer sightings were recorded around full Moon, which occurred on the 14th, 15th or 16th day of the lunar month. This result suggests that at least some of the “vapours like fire light” were fairly faint. In addition, Fig. 3 also illustrates graphically the fact that 69 observations are cited in the *Ilgi*, 54 in the *Sillok*, but only 27 are common to both histories.

By analogy with the discussion of recurrent auroral activity in the twelfth century (1127–1129) in Sect. 4, recurrent auroral activity in the interval 1624–1627 is considered in the following Section. The choice of this particular interval is a minor compromise based on the number of distinct auroral events currently available

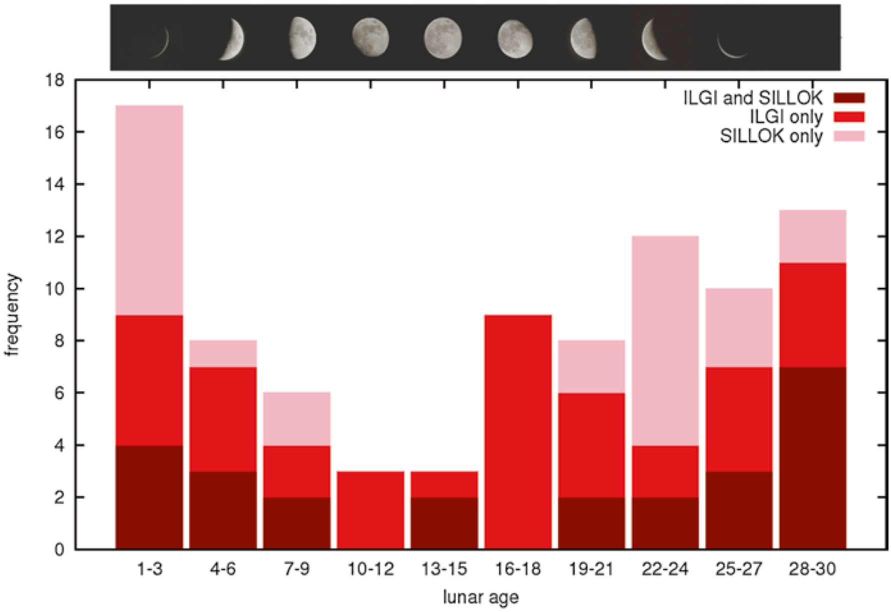

Fig. 3 Variation in the frequency with lunar age of sightings of "vapours like fire light" recorded in the Korean chronicles *Seungjeongwon Ilgi* (*Daily Records of the Royal Secretariat*) and *Joseon Wangjo Sillok* (*Veritable Records of the Joseon Dynasty*) between the beginning of 1625 and the middle of 1628. Note that the pattern in this figure is skewed, partly as a result of the excess of observations made in the early hours of the night

from both the *Ilgi* and the *Sillok* in the slightly longer interval 1624–1628. There are seven *distinct* auroral events recorded in the *Sillok* in the year 1624 (Yau et al. 1995), whereas there are at most four *distinct* auroral events in the *Ilgi* and one in the *Jeungbo Munheon Bigo* (conveniently abbreviated to '*Bigo*') in the first half of 1628 (Stephenson and Willis 2008). Moreover, further searches of the *Bigo* have revealed three additional auroral observations in the interval 1624–1627 but no more in the first half of 1628 (Stephenson 2010). The dates of these additional observations, which are included in the analysis presented in the following Section, are: 4 March 1624, 15 January 1626 and 27 August 1626. Therefore, until the search for featureless "vapours light fire light" in the *Seungjeongwon Ilgi* is extended beyond the middle of 1628, the four-year interval 1624–1627 is perhaps the one that is most complete, at least in terms of including observations from all known historical sources. The *Ilgi* also needs to be searched systematically for red auroral observations with structure (i.e. features), as well as auroral displays exhibiting colours other than red. Nevertheless, the list of auroral observations used in this study is largely similar to, but not exactly identical to, the list of auroral observations in the same four-year interval presented in the paper by Lee et al. (2004, see their Table II).

6 Evidence for Recurrent Auroral Activity in the Seventeenth Century

A new visual method of illustrating recurrent auroral activity in the interval 1624–1627 is presented in this Section. Figure 4 shows time, starting on 1 January 1624, divided into consecutive 28-day intervals, which are presented as successive rows of a table

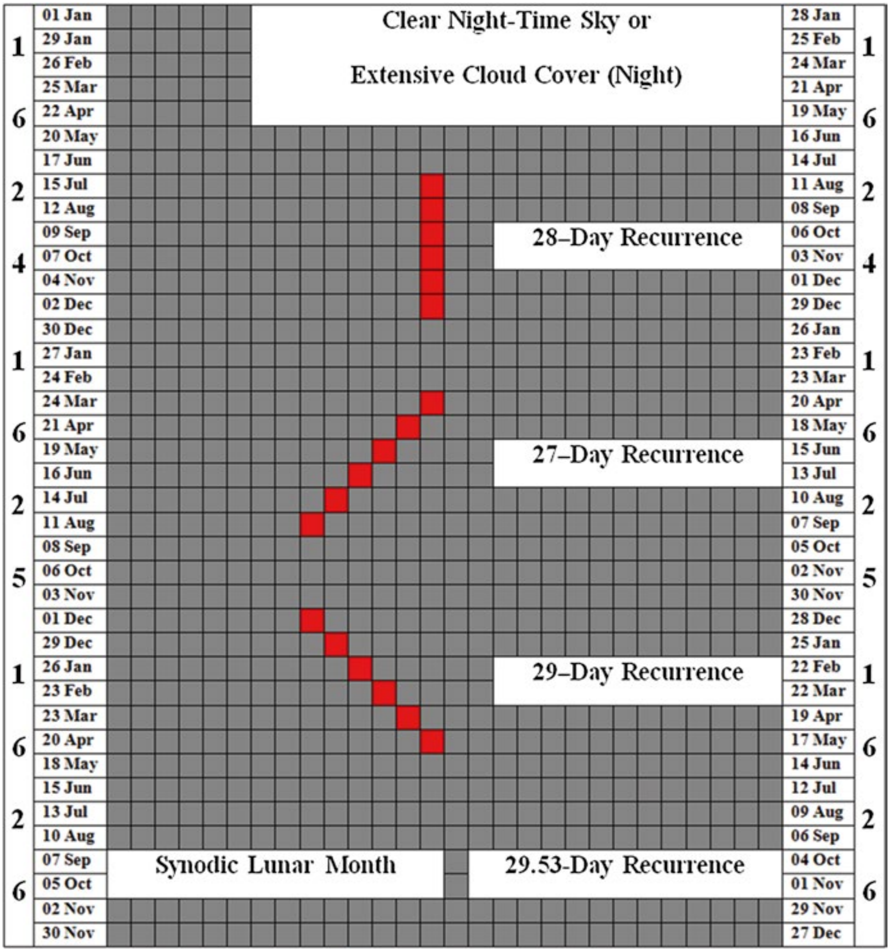

Fig. 4 A schematic illustration of recurrent auroral activity. For illustrative purposes, time is divided into consecutive 28-day intervals, starting on 1 January 1624 and finishing on 27 December 1626. Each small square represents a 24-hour period. A small square is coloured *grey* if there is no known auroral observation during the corresponding night, whereas it is coloured *red* if there is a known auroral observation (of any colour) during the corresponding night. Auroral observations separated by exactly 28 days appear as a vertical column of contiguous small *red squares*. Similarly, auroral observations separated by 27 days or 29 days appear as *diagonal lines* of small *red squares* sloping downwards to the *left* or *right*, respectively. It should be noted that the length of the synodic lunar month is 29.53 days

containing 28 columns. Since Fig. 4 is only intended to be schematic, it shows just the 39 rows covering the shorter time interval 1 January 1624 to 27 December 1626, rather than the 52 rows covering the essentially four-year interval 1 January 1624 to 26 December 1627 (see Fig. 5). Each of the small squares in Fig. 4 represents a day (i.e. a 24-h period). A small square is coloured grey if there is no known auroral observation during the corresponding night; such a situation could arise from either a clear sky or extensive cloud cover throughout the night. Conversely, a small square is coloured red if there is a known auroral observation (of any colour) during the corresponding night. With this form of presentation, auroral observations separated by exactly 28 days appear as a vertical column of contiguous small red squares. Similarly, auroral observations separated by 27 days appear as a diagonal line of small red squares sloping downwards to the left and auroral observations separated by 29 days appear as a line of small red squares sloping downwards to the right. It must be remembered, however, that the synodic lunar month is 29.53 days. The fact that the synodic rotation periods of the Sun and Moon are very similar is important because Fig. 3 illustrates the fact that the "vapours like fire light" are seen more frequently near new Moon.

Following the style adopted in Fig. 4, which illustrates recurrence patterns for 27, 28 and 29 days, Fig. 5 presents all the auroral observations in the interval 1 January 1624–26 December 1627, derived from the catalogues and lists discussed in Sect. 5. However, as a refinement of the previous figure, Fig. 5 gives the correct colour, or colours, of the auroral observations in this four-year interval, as recorded in the appropriate East Asian history. In those cases for which compound colours are quoted in the original records, for example "green-white" and "blue-red", both colours are included separately by dividing the appropriate small squares into two halves. In addition, certain symbols are occasionally inserted in the small squares in order to clarify the historical source: in particular, the superimposed letter 'B' signifies that the corresponding Korean auroral observation was recorded in the *Jeungbo Munheon Bigo* and the superimposed letter 'J' signifies that the corresponding Japanese auroral observation was found in the catalogue published (in Japanese) by Osaki (1994). The auroral observation on the evening of 4 March 1624 is described in the *Bigo* as being "dark", and this description is provisionally represented in Fig. 5 by the colour "dark red". The Japanese auroral observations in the interval 1624–1627 are all from the section of Osaki's catalogue entitled "Banner Clouds". As the titles of the other three sections in this catalogue are "Red Clouds", "White Vapours" and "Red Vapours", it is assumed provisionally that "Banner Clouds" are "white" (although this tentative assignment of colour is always qualified by superimposing the letter 'J'). Finally, solid dots (●) signify the days on which sunspots were observed in East Asia (Stephenson and Al-Dargazelli 1998; Yau and Stephenson 1988). It should be noted that the inclusion of sunspot observations in Fig. 5 conflates daytime and night-time observations and hence it should be emphasised that the background colour of each small square refers solely to the night-time conditions.

The inclusion of sunspot observations in Fig. 5 provides a clear graphical representation (for the interval 1624–1627) of a procedure developed previously to

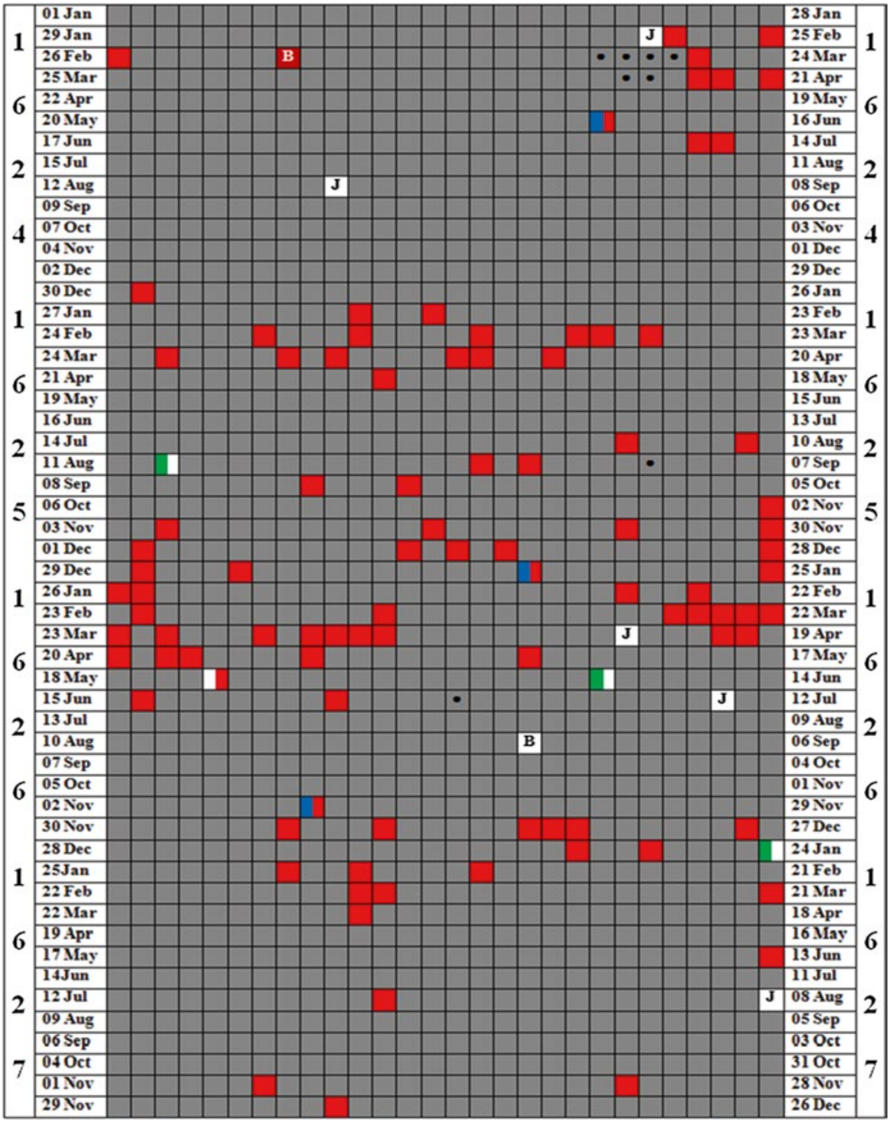

Fig. 5 Similar to Fig. 4 but with all known auroral observations in the interval 1 January 1624–26 December 1627 included. This figure shows the correct colour(s) of the auroral observations, as recorded in the appropriate East Asian history. If compound colours are quoted, both colours are shown. The letter 'B' signifies that the corresponding Korean auroral observation was recorded in the *Jeungbo Munheon Bigo*: the observation on the evening of 4 March 1624, which is described as being "*dark*", is provisionally represented by the colour "*dark red*". The letter 'J' signifies that the corresponding Japanese auroral observation was found in the catalogue published by Osaki (1994): the colour of these Japanese observations is tentatively assumed to be "*white*". *Solid dots* (●) signify the days on which sunspots were observed in East Asia (although the background colour of each small square refers solely to night-time conditions)

identify historical occurrences of intense magnetic storms, using combined sunspot and auroral observations from East Asia (Willis et al. 2005). In the earlier study, it was assumed that a magnetic storm occurred if the time interval, T (measured in days), between the observation of a sunspot and the associated auroral display satisfies the condition $-8 \leq T \leq +15$. This condition was based on three simplifying assumptions: (i) a sunspot could have been seen continually (in the absence of cloud cover) by the East Asian observers if it was within ± 5 days of the central solar meridian; (ii) the energetic solar event (e.g. a coronal mass ejection) producing the storm occurred when the associated sunspot was within ± 4 days of the central meridian; and (iii) the time delay between the energetic solar event and the onset of the ensuing geomagnetic storm was in the range 1–6 days. The upper limit of the condition corresponds to the situation in which a sunspot was first seen on day − 5 (the presumed first possible day of detection with the unaided eye), the energetic event occurred 4 days after central meridian passage of the sunspot (the presumed last possible day), and the time delay between the energetic solar event and the onset of the magnetic storm was 6 days (the presumed maximum delay). The lower limit of the condition corresponds to the situation in which the sunspot was first seen on day + 5 (the presumed last possible day of detection with the unaided eye), the energetic solar event occurred 4 days before central meridian passage of the sunspot (the presumed first possible day), and the time delay between the energetic solar event and the onset of the magnetic storm was 1 day (the presumed minimum delay).

In this context, Fig. 5 shows the auroral observation on 21 March 1624, which immediately follows the sunspot observations in the interval 17–20 March (Willis et al. 2005; see Ref. No. 16 in their Table 1). Similarly, this same figure shows the auroral observations on 18, 19 and 21 April 1624, which follow almost immediately after the sunspot observations on 15 and 16 April (see Ref. Nos. 17–19 in Table 1 of Willis et al. 2005). Likewise, Fig. 5 illustrates the ambiguity that arises for the auroral observations on 28 August and 16 September 1625, in the sense that either auroral observation could apparently be associated with the sunspot observation on 2 September, according to the condition $-8 \leq T \leq +15$ (see Ref. Nos. 20 and 21 in Table 1 of Willis et al. 2005). Finally, this same figure also illustrates the ambiguity that arises for the auroral observations on 24 June and 10 July 1626, in the sense that either could apparently be associated with the sunspot observation on 29 June (see Ref. Nos. 22 and 23 in Table 1 of Willis et al. 2005). These ambiguities arise both from the fact that the East Asian records rarely specify the position of a sunspot on the solar disk (which partly accounts for the wide 'acceptance interval' $-8 \leq T \leq +15$) and also from the fact that European telescopic sunspot observations indicate that some large sunspots were not seen with the unaided eye in East Asia at these particular times (Willis et al. 2005), presumably because of unfavourable local atmospheric viewing conditions.

Visual inspection of Fig. 5 reveals two examples of a sequence of four auroral observations separated by exactly 28 days. The dates of the first sequence are 2 November, 30 November and 28 December in 1625, and 25 January in 1626; the dates of the second sequence are 2 December and 30 December in 1625, and 27

January and 24 February in 1626. Comparison with Fig. 4 indicates that these two sequences of auroral observations provide evidence for recurrent auroral activity in the third decade of the seventeenth century. Of course, it is clear from Fig. 5 that the true physical situation is rather more complicated than two separate sequences of four auroral observations separated by exactly 28 days. A disadvantage of the form of presentation adopted in Fig. 5 is that it can exaggerate, at least visually, the separation between two sequences of recurrent auroral observations, since there is an abrupt spatial separation of consecutive days every 28 days. In reality, the two sequences of recurrent auroral observations shown in Fig. 5 are never separated by more than two nights without aurora over four synodic-solar-rotation periods. The situation is further complicated by the fact that the apparent absence of an auroral observation may indicate the existence of extensive cloud cover throughout the night, rather than the true absence of any auroral display. Further visual inspection of Fig. 5 reveals one example of auroral observations on 6 (strictly) consecutive nights (18–23 March 1626) and one example of auroral observations on 4 (strictly) consecutive nights (31 March–3 April 1626). If allowance is again made for the possible existence of extensive cloud cover throughout the night, these auroral observations could possibly have extended over 8 and 6 consecutive nights, respectively, or even longer intervals.

However, the nightly meteorological conditions in East Asia are essentially unknown in the interval 1624–1628. Therefore, it is assumed in the subsequent discussion that the auroral observations presented in Fig. 5 represent the true 'physical' situation, if only in terms of the absence or existence of auroral records. Hence the small squares coloured grey in Fig. 5 represent nights for which no auroral record exists, whereas all the other coloured squares represent nights for which an auroral record does exist. In order to perform a meaningful initial statistical analysis, no distinction is now made between the different colours of the auroral displays, as recorded in the historical records. Accordingly, Fig. 6 shows the dates on which an auroral observation of any type was recorded in East Asia (small red squares) during the interval 1624–1627. However, the letter 'F' is included to distinguish between an apparently featureless (F) red glow, which is described in the historical records as a "vapour like fire light", and auroral displays exhibiting either structure or colours other than red. The latter categories are now *all* coloured red but are not qualified by any letter. Moreover, the East Asian sunspot observations (●) are omitted from Fig. 6, in order to focus attention solely on the occurrence of auroral displays. The probability of obtaining the distribution of auroral occurrences shown in Fig. 6 purely by chance can be considered using the appropriate theory in combinatorial chance (David and Barton 1962, Chapter 6). The presentation adopted in Fig. 6 is merely a convenient visual aid in the search for recurrent auroral activity in the interval 1624–1627, as illustrated schematically in Fig. 4. The actual combinatorial problem can be defined rather more accurately in terms of the distribution theory of runs, namely the runs of grey and red squares in Fig. 6, which is then conceptualised in a simple rectilinear format (ibid.). However, a somewhat simpler approach is employed in the following Section.

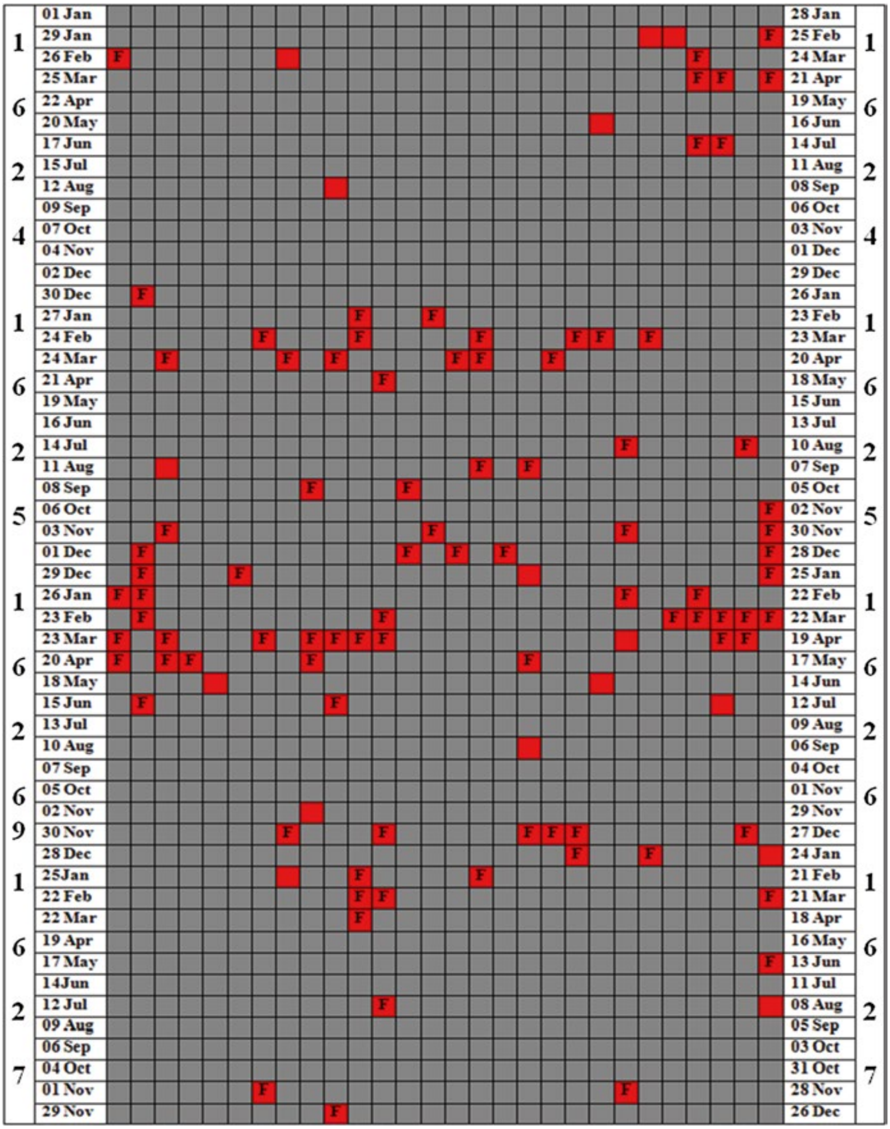

Fig. 6 The same as Fig. 5 but with all known auroral observations now coloured red, irrespective of the colour(s) quoted in the historical records. The letter 'F' is included to distinguish between an apparently featureless (F) *red* glow, which is described in the historical records as a "vapour like fire light", and an auroral display exhibiting either structure or a colour other than *red*. All other qualifying letters (i.e. B and J) are omitted, as are the sunspot observations (●). Visual inspection of Fig. 6, or Fig. 5, reveals two examples of a (vertical) sequence of four auroral observations separated by exactly 28 days. Further visual inspection of either figure reveals one example of auroral observations on six consecutive nights and one example of auroral observations on four consecutive nights. The statistical significance of the pattern of auroral events shown in Fig. 6 is discussed in Sect. 7

7 Statistical Significance of Recurrent Auroral Activity in the Seventeenth Century

Suppose that the 105 auroral events in the interval 1624–1627, which are depicted in Fig. 6 as small red squares (some of which are qualified by the letter 'F' to signify that the historical record merely describes a featureless red glow), are now repeatedly distributed randomly within a tabular array comprising 52 rows and 28 columns (i.e. a 52×28 array). These randomly-generated tabular arrays are similar to the one shown in Fig. 6, with the small squares defining auroral events again coloured red and all remaining small squares coloured grey. The 105 auroral events are distributed randomly by a process that is analogous to shuffling a pack of cards. The procedure adopted is to generate a 52×28 array of zeros (0) and then set the first 105 values to one (1); this is the initial (non-random) event array. A similar array is populated with random numbers between 0 and 1 (using the **rand** function in MATLAB). These 1,456 random numbers are then arranged in order of increasing numerical magnitude and the new location of each is stored in an index array. By using the positional transformation between the random-number array and the index array, the initial event array (containing 105 ones followed by 1,351 zeros) is transformed to a random-event array. A typical example of the distribution resulting from this method of randomly distributing 105 auroral events in a 52×28 array is shown in Fig. 7.

In practice, 1,000 such randomly-generated event arrays are constructed and the number of times, N, that a sequence of n ($2\leq n\leq6$) contiguous events occurs in either a row or column is counted. In the case of contiguous events in a row, proper allowance is made for the fact that (contiguous) events at the end of a particular row in the 52×28 array may be followed immediately by (contiguous) events at the start of the next row (i.e. for identifying contiguous events in rows, the elements of the array are essentially considered to be in a line). The percentage probability of obtaining n contiguous events in a row or column is then given by $N/10$. This process is repeated 100 times in order to determine the uncertainty in each probability. The results of these calculations are presented in Table 3. If the entire procedure is repeated, the percentage probabilities vary very slightly but within the quoted uncertainties.

It is immediately clear from the entries in Table 3 that for $n=2$ the percentage probabilities increase as N increases ($1\leq N\leq6$) for both columns and rows. Conversely, for $n\geq3$ the percentage probabilities decrease as N increases ($1\leq N\leq6$). The different result in the case $n=2$ can be explained as follows. If 105 auroral events are distributed randomly within a 52×28 array, the existence of two contiguous auroral events in either a column or a row ($n=2$) occurs relatively frequently. Hence the chance of obtaining just one example ($N=1$), or even a few examples ($N\leq3$), of two contiguous events ($n=2$) is smaller than the chance of obtaining several examples ($4\leq N\leq6$). Indeed, in the case $n=2$, the percentage probabilities only begin to decrease when $N>7$. However, the existence of three or more contiguous auroral events in a column or a row ($n\geq3$) occurs relatively infrequently and thus the corresponding percentage probabilities decrease monotonically as N increases.

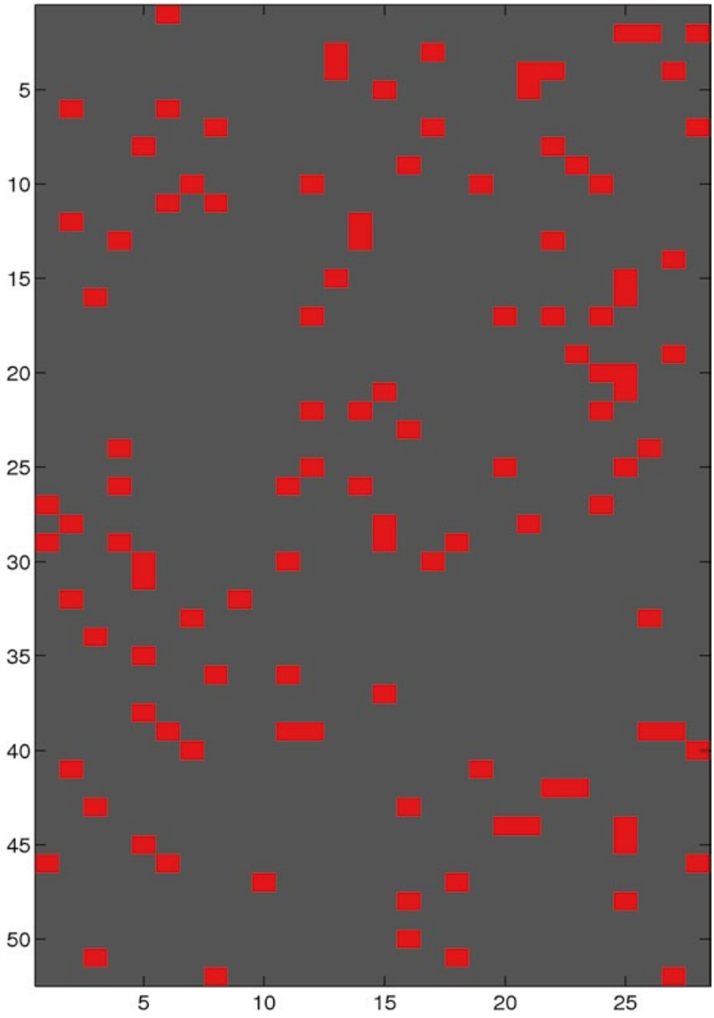

Fig. 7 A typical example of the distribution that arises if the 105 auroral events shown in Figs. 5 and 6 are distributed randomly within an array comprising 52 rows and 28 columns. As discussed in Sect. 7, 1,000 examples of such random arrays are generated to determine the percentage probabilities presented in Table 3. The entire process is then repeated 100 times to determine the uncertainties in these probabilities, which are also given in Table 3

The percentage probabilities presented in Table 3 indicate that the chance of obtaining two examples ($N=2$) of 4 contiguous auroral events ($n=4$) in a column (cf. Fig. 6), if 105 auroral events are distributed randomly in a 52×28 array, is 0.24 ± 0.02 %. Similarly, the chance of obtaining a single example ($N=1$) of 6 contiguous auroral events ($n=6$) in a row (cf. Fig. 6) is as small as 0.02 ± 0.00 %, which is virtually zero. Even the chance of obtaining a single example ($N=1$) of 4 contiguous auroral events ($n=4$) in a row (cf. Fig. 6) is only 3.07 ± 0.06 %. Therefore, it is highly improbable that the actual distribution of auroral events shown in Fig. 6

Table 3 Percentage probabilities (*N*/10) and corresponding uncertainties of obtaining *N* examples of *n* contiguous auroral events in either a column or a row if the 105 auroral events occurring in the interval 1624–1627 (cf. Fig. 6) are located randomly within an array containing 52 rows and 28 columns (cf. Fig. 7). The probabilities are determined by distributing the 105 events randomly within the array 1,000 times and the uncertainties are determined by repeating this procedure 100 times

Number (n) of contiguous auroral events in a column or row ($2 \le n \le 6$)		Percentage probability (N/10) and corresponding uncertainty of obtaining N examples of n contiguous auroral events in a column or row in the case of 1000 randomly-generated (52 × 28) arrays, each containing 105 auroral events (cf. Fig. 7)					
		N					
n	Column or row	1	2	3	4	5	6
2	Column	0.31 ± 0.02	1.28 ± 0.04	3.55 ± 0.06	7.13 ± 0.08	11.27 ± 0.09	14.74 ± 0.10
2	Row	0.26 ± 0.01	1.16 ± 0.03	3.19 ± 0.05	6.72 ± 0.08	10.74 ± 0.11	13.96 ± 0.11
3	Column	28.46 ± 0.14	8.00 ± 0.08	1.83 ± 0.04	0.28 ± 0.02	0.05 ± 0.01	0.01 ± 0.00
3	Row	29.15 ± 0.13	8.34 ± 0.08	1.85 ± 0.04	0.37 ± 0.02	0.05 ± 0.01	0.01 ± 0.00
4	Column	3.08 ± 0.05	0.24 ± 0.02	0.03 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
4	Row	3.07 ± 0.06	0.26 ± 0.02	0.03 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
5	Column	0.21 ± 0.01	0.01 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
5	Row	0.25 ± 0.01	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
6	Column	0.01 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
6	Row	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

occurred purely by chance. In particular, it is most unlikely for two examples of four contiguous auroral events in a column to occur by chance. Moreover, the dates of three elements of each sequence of four contiguous auroral events are separated by just 2 days (i.e. 30 November and 2 December in 1625; 28 and 30 December in 1625; 25 and 27 January in 1626). Therefore Fig. 6 and Table 3 provide statistically-significant evidence for recurrent auroral activity in the third decade of the seventeenth century. Furthermore, it is even more unlikely for a single example of six strictly consecutive auroral events to occur purely by chance. Nevertheless, Fig. 6 provides clear evidence for auroral activity on six strictly consecutive nights, in a time period that closely follows the period of recurrent auroral activity. Finally, it should be noted that both of these statistically-significant results apply to the featureless (F) red glows described in the *Joseon Wangjo Sillok* and the *Seungjeongwon Ilgi* as "vapours like fire light".

8 Discussion and Concluding Remarks

It has been shown in Sect. 4 that there is evidence for recurrent auroral activity during a time interval extending from 20 September 1127 to 10 January 1129. This evidence is summarised succinctly in Table 2. Although there were no auroral observations for almost eight months near the middle of the quoted interval (28 February–20

October 1128), there is clear evidence for a 27-day, or 28-day, recurrence tendency in auroral activity at both the beginning and end of the interval. The relevant auroral records, which have been extracted from official Chinese and Korean histories, are listed in Table 1. The precisely-dated records (day, month and year all known exactly) in this table refer to the observation of a "red vapour" in certain regions of the sky, although not all of the records state explicitly that the observation was made during the night.

Similarly, it has been shown in Sect. 6 that there is evidence for recurrent auroral activity during a time interval extending from 1 January 1624 to 26 December 1627. This evidence is illustrated in Figs. 5 and 6. It is clear from these figures that recurrent auroral activity, with a periodicity of about 28 days, is most pronounced between about the middle of 1625 and the middle of 1626. Moreover, it follows from Fig. 6 that this pronounced recurrent auroral activity results mainly from the featureless (F) red glows that are recorded in the Korean histories titled *Joseon Wangjo Sillok* and *Seungjeongwon Ilgi*, and are described therein as "vapours like fire light". As noted in Sect. 5, the interval from 1 January 1624 to 26 December 1627 was deliberately selected because a detailed manual search had already been made of the *Seungjeongwon Ilgi* for references to "vapours like fire light" in the short interval extending from the beginning of 1625 to the middle of 1628 (Stephenson and Willis 2008).

Perusal of the various auroral catalogues discussed in Sect. 5 reveals other intervals of recurrent auroral activity, particularly during the sixteenth century. Nevertheless, perhaps the most important requirement for further understanding of recurrent auroral activity is a search for references to "vapours like fire light" in the *Seungjeongwon Ilgi* throughout the entire time interval covered by this Korean history (1623–1894). This seemingly formidable task is now manageable because an automatically searchable version of the *Seungjeongwon Ilgi* has been developed by the Kyujanggak Institute for Korean Studies at Seoul National University.

It remains to be seen, however, if the number of Korean auroral observations recorded in the *Seungjeongwon Ilgi* during the nineteenth century is sufficient for meaningful comparisons to be made with the Catalogues of Geomagnetic Storms (Great Storms: 1840–1954 and Small Storms: 1874–1954) published by the Royal Greenwich Observatory (1955). A similar reservation applies to comparisons between Korean auroral observations recorded in the *Seungjeongwon Ilgi* and the magnitude of the available geomagnetic indices: *Ak* (1844–1868) and *aa* (1864 onwards). The *Ak* (Helsinki) geomagnetic index was introduced by Nevanlinna and Kataja (1993) and discussed further by Nevanlinna (2004): the *aa* geomagnetic index is defined in the book by Mayaud (1980). In this context, it should be noted that Willis et al. (2007) investigated in detail all of the accessible auroral observations recorded in Chinese and Japanese histories during the interval 1840–1911. It was found that 5 of the great geomagnetic storms ($aa > 150$ or $Ak > 50$) during either the second half of the nineteenth century or the first decade of the twentieth century were clearly identified by extensive auroral displays observed in China or Japan. Indeed, two of these great geomagnetic storms (2 September 1859 and 4 February 1872) produced auroral displays seen in both countries on the same night. Conversely, however, at least 27 (64 %) of the 42 Chinese and Japanese auroral observations occurred at times of weak-to-moderate geomagnetic activity (*aa* or $Ak \leq 50$), in agreement with the examples of sporadic aurorae observed in the United States during the interval 1880–1940 (Silverman 2003). Further research is required to explain how aurorae can occur at relatively low magnetic latitudes in East Asia (and the United States) at times that apparently correspond to weak-to-moderate levels of geomagnetic activity.

Another matter requiring further investigation is the extent to which the distribution of auroral events in the interval 1 January 1624 to 26 December 1627, as depicted in Figs. 5 and 6, provides potential information on the time-varying structure of the interplanetary magnetic field during this four-year interval. It is known from modern measurements that some weak-to-moderate geomagnetic storms are associated with high-speed solar-wind streams and co-rotating interaction regions (CIRs), rather than coronal mass ejections (CMEs), and this topic has been discussed by Borovsky and Denton (2006), Gopalswamy (2008) and Tsurutani et al. (2006). Hence it is at least conceivable that the pattern of auroral events shown in Figs. 5 and 6 provides information on the different types of geomagnetic storms that occurred during part of the third decade of the seventeenth century. Moreover, this possibility provides added motivation for searching the entire *Seungjeongwon Ilgi* (1623–1894) for further auroral events.

In conclusion, it is appropriate to emphasise——especially in this collection of papers celebrating Professor F. Richard Stephenson's invaluable contributions to 'Applied Historical Astronomy'——that historical auroral and sunspot observations provide important information on the state of the Sun-Earth environment during past centuries. This information enhances our understanding of both space climate and space weather, which are becoming increasingly important scientific disciplines because of the widespread adoption of advanced technological infrastructures over the past 40 years (Hapgood 2011). It is a great honour and privilege to record this tribute to Richard Stephenson's outstanding expertise and scholarship, which underpins all of the scientific results presented in this paper and also the scientific results given in numerous other published papers on the use of historical observations in solar-terrestrial physics, many of which are cited in the text and included in the accompanying list of references.

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Historical Supernova Explosions in Our Galaxy and Their Remnants

David A. Green

Abstract Supernova explosions mark the end points of stellar evolution, releasing large amounts of material and energy into the interstellar medium. In our Galaxy the expected rate of supernovae is about one in every fifty years or so, although it is only the relatively nearby ones that are expected to be visible optically, due to obscuration. Over the last two thousand years or so there are historical records of nine Galactic supernovae. The majority of these records are from East Asia (i.e. China, Japan and Korea), although the most recent historical supernovae have European records, and there are a variety of Arabic records also available for some events. Here I review these records of the historical supernovae, and the modern observations of the supernova remnants that they have produced.

1 Introduction

The end-point of the evolution of some stars is a 'supernova' (SN), which is an incredibly violent explosion that destroys the progenitor star. Supernovae are of astrophysical interest for a variety of reasons, in particular for cosmological research in recent years. The interaction of the energy and mass released by supernovae with their surroundings create extended 'supernova remnants' (SNRs). There are historical records of apparently new stars in our Galaxy, some of which were supernova, from the last two millennia or so. Most of these supernova records are from China, but there are also records from Korea, Japan, and in some cases various Arabic and European sources. Here I review some of the observations of these historical supernovae, and their remnants. More details discussions of these are given in Stephenson and Green (2002).

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2 Background

Supernovae were first recognised as extremely violent explosions of stars in the 1920s, when it became clear that some optical nebulae were not within our Galaxy, but are in fact distant galaxies. Some transient stars—'novae' from the Latin for 'new'—in such galaxies are intrinsically very much more luminous than the much closer novae seen in our own Galaxy, hence the term 'supernovae' (e.g. Baade and Zwicky 1934). Subsequently, supernovae have been of astrophysical interest for a variety of reasons, but in particular they are used as 'standard candles' in cosmology, and also they are important for the injection of heavy elements into their surrounding interstellar medium. As of early April 2011, over 5500 SNe have been identified in external galaxies, with about 300 more identified each year.

Supernovae are divided into various types, with the basic distinction—which dates back to Minkowski (1941)—being between 'Type I' and 'Type II' SNe not having or having hydrogen lines in their optical spectra respectively. This is consistent with 'Type II' SNe being from more massive stars, as is the fact that 'Type I' SNe are observed in both spiral and elliptical galaxies, whereas 'Type II' SNe are only seen in spiral galaxies. Spiral galaxies, unlike ellipticals, have appreciable ongoing star formation, so have short-lived, high-mass stars. In recent decades 'Type I' SNe have been further sub-divided into the classic low-mass 'Type Ia's (which are those used as 'standard candles' in cosmology), and 'Type Ib's and 'Type Ic's, are from massive stars which have lost their outer, hydrogen-rich layers, so lack H in their optical spectra (but unlike 'Type Ia', they do have Si in their optical spectra). Theoretical/numerical models of supernovae imply that 'Type Ia's will not leave behind a compact remnant, whereas the others may (as is discussed below, these are sometimes seen as a 'pulsar', which is a rapidly-rotating neutron star). Supernovae release a large amount of energy ($\sim 10^{44}$ J) and mass (of order of a solar mass or more) into the surrounding interstellar medium (ISM), at speeds of the order of 10^4 km s^{-1}. The interaction of the energy and mass released produces an extended *supernova remnant* (SNR).

Currently there are 274 SNRs identified in our Galaxy (Green 2009), along with many more possible and probable remnants that required further observations to clarify their nature. Almost all the catalogued SNRs have been detected at radio wavelengths, but only ≈ 35 % are detected in X-rays, and ≈ 25 % in the optical, due to absorption along the line-of-sight in our Galaxy. SNRs are generally classified into three types: ~70 % are 'shell' type SNRs showing more or less complete limb-brightened rings of emission at radio wavelengths; ~5 % are 'filled-centre' (or 'plerions')—like the Crab Nebula, see Sect. 3.4—showing centrally brightened emission, with a growing fraction having central pulsars identified; and ~20 % are 'composite' types, showing some properties of both 'shell' and 'filled-centre' remnants at radio wavelengths. (The remaining ~5 % consist of objects conventionally considered as SNRs, although they do not easily fit into the three categories above, e.g. CTB 80 (=G69·0+2·7), see Angerhofer et al. 1981; Strom et al. 1984). SNe and SNRs are the major source of energy input into the interstellar medium (causing turbulence, shocks in molecular clouds, triggering star formation). SNR shocks are thought to be

Table 1 Historical supernovae in our Galaxy

European and oriental records		
AD 1604	12 months	Kepler's SNR
AD 1572	18 months	Tycho's SNR
Oriental and Arabic records		
AD 1181	6 months	3C58
AD 1054	21 months	Crab Nebula
AD 1006	3 years	G327·6+14·5
Less certain Chinese records		
AD 393	8 months	
AD 385?	3 months	G11·2–0·3?
AD 369?	5 months	
AD 185	8 or 20 months	G315·4–2·5?

the sites of acceleration of very energetic particles (cosmic rays), at least up to energies of about 10^{15} eV.

From the supernova rate in external galaxies, it is expected that there is about one SN every fifty years in our own Galaxy, although only some of these would be expected to be seen, as distant ones would be too faint due to galactic obscuration. Although no galactic supernova has been seen in the telescopic era, there are historical records of several SNe over the last two thousand years or so, which are summarised in Table 1. These are discussed in detail in Stephenson and Green (2002), and Stephenson and Green (2005, 2009) discuss other possible historical SNe that have been proposed.

The most recent two historical SNe, from AD 1604 and 1572, have extensive European records available, in addition to records from East Asia (China, Korea and Japan). But older historical SNe are known almost exclusively from East Asia—predominantly China—or Arabic records, with only a few European records of the very bright SN of AD 1006. This is because Chinese Royal courts employed astronomers/astrologers who recorded a wide range of astronomical phenomena, and printed records of these have been preserved, albeit often only as summary copies of the older records.

Below I review the five most recent known historical supernovae, which are well chronicled. The older SNe, or possible SNe, have limited information available for them, with each having only one Chinese record. Hence the nature of some of them is not certain, and their positions are not well defined, so that identification of their remnants is also not clear (see Stephenson and Green 2002 for more discussion).

3 Historical SNe and Their Remnants

3.1 The SN of AD 1604: Kepler's SN

This supernova was first reported in Europe on 9 October 1604, but was not seen on 8 October, as observers recorded a nearby conjunction of Mars and Jupiter on that date, with no mention of the new star. This SN was studied in detail by Johannes

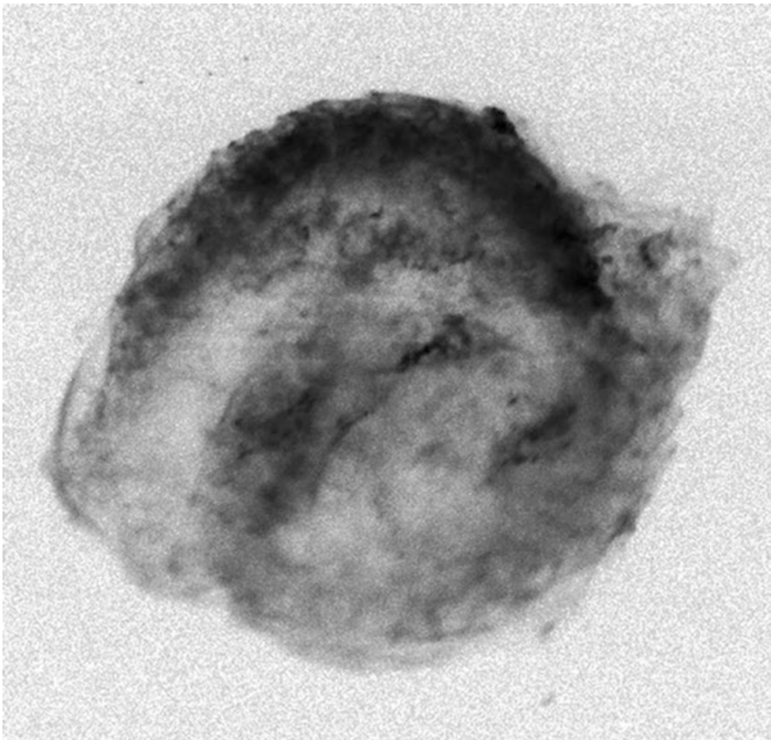

Fig. 1 X-ray emission from Kepler's supernova remnant (Chandra public archive)

Kepler from Prague. It also was observed in China, first on 10 October 1604, and in Korea from 13 October. It reached optical maximum about three weeks after detection, with an apparent magnitude of approximately −2 or −3. Its position is defined to better than 1 arcmin by Kepler's observations, and the remnant of this supernova was first identified as a faint optical nebulosity by Baade (1943). The remnant, =G4 · 5 + 6 · 8, first identified in the radio in the 1950s, is a smooth 'limb-brightened' radio shell $\approx$ 3 arcmin in diameter, with a similar structure shown in X-rays (DeLaney et al. 2002; Reynolds et al. 2007)—see Fig. 1.

3.2 The SN of AD 1572: 'Tycho's SN'

This was first reported in Europe on 6 November 1572, in China two days later, and was reported in Korea also. At its peak its apparent magnitude was about –4. This SN was studied in detail by Tycho Brahe, who did not first see it until 11 November, due to bad weather. Tycho studied the supernova until March 1574, and subsequently wrote a treatise *Progymnasmata* on this 'new star'. This discusses the new star

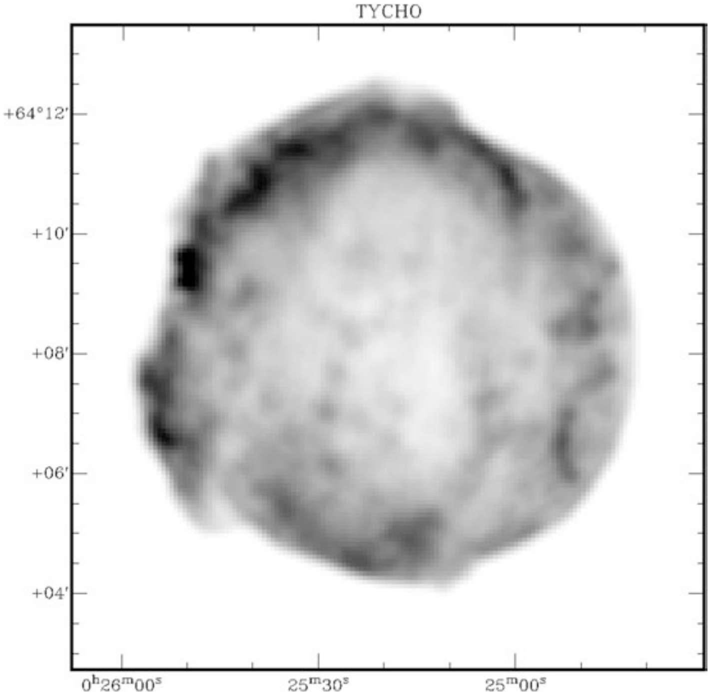

Fig. 2 Radio image of the Tycho's supernova remnant, from VLA observations at 1.5 GHz, with a resolution of ≈ 13 arcsec (NRAO/VLA Archive Survey, © 2005–2007 AUI/NRAO)

in the context of the then-conventional view, dating back to Aristotle, of multiple spheres, with the 'fixed' stars in the most distant, eighth sphere. The planets, Moon and atmospheric phenomenon—which move—were associated with the inner spheres. From his observations, Tycho concluded that the new star had not shown any proper motion, so that it was so distant as to be associated with the 'fixed' stars, yet had changed in magnitude, and so had contravened the widely-accepted view that change could only occur in regions closer than the Moon.

The position of the SN was defined to a few arcmin by Tycho's observations, and the remnant was first identified as a bright radio source (3C10, =G120 · 1 + 1 · 4) in 1952. This is a smooth 'limb-brightened' radio shell ≈ 8 arcmin in diameter, see Fig. 2 (e.g. see Katz-Stone et al. 2000). This remnant has a few faint optical filaments associated with it, and also shows a shell of X-ray emission (e.g. see Ghavamian et al. 2001; Warren et al. 2005). The measurement of expansion of the remnant, and its known age, allow the dynamics of the remnant to be studied (see Tan and Gull 1985; Reynoso et al. 1997).

For various reasons, studies of the remnant have implied that Tycho's SNe was a 'Type Ia'. Recently, this has been confirmed *directly* using light echoes, i.e. light from the SN reflect off clouds in the interstellar medium that has travelled a further ≈ 434 light years than the direct light observed in AD 1572, so it was observed

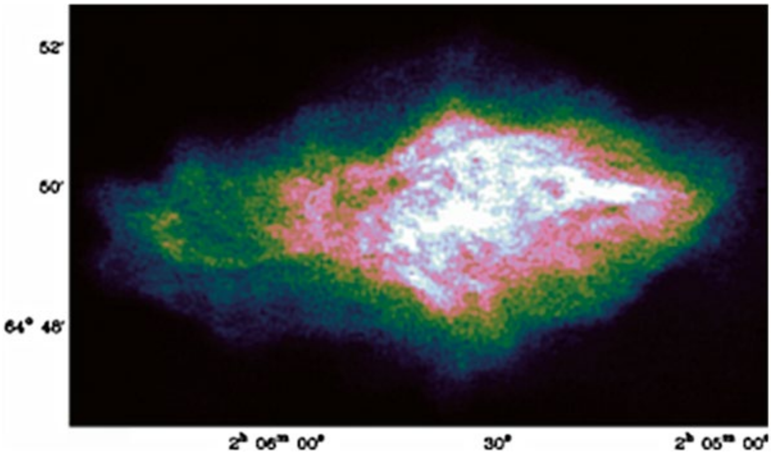

Fig. 3 Radio observations of 3C58, the remnant of the supernova of AD 1181, at 2.7 GHz using the Ryle telescope (see Green 1986)

in 2006, and its optical spectrum taken. Krause et al. (2008) show that the spectrum of the light echo from Tycho's SNe, after correction for obscuration along the line of sight and scattering, is consistent with that of a 'Type Ia'.

3.3 The SN of AD 1181

This supernova was reported in both the northern and the southern Chinese empires, but with limited detail. The 'guest star' reported was visible for six months, but its position is not precisely defined. There are also several Japanese reports of this new star. A bright radio source (3C58, =G130·7+3·1) was first identified as the remnant of this supernova by Stephenson (1971). This is a centrally brightened (or 'filled-centre') radio source $\approx 5 \times 10$ arcmin^2 in extent (see Fig. 3). This remnant also shows centrally-brightened X-ray emission (e.g. see Slane et al. 2004), and also has faint optical filaments (e.g. see van den Bergh 1978). The central brightened emission seen in the radio and in X-rays implies that this remnant contains a central, compact remnant left behind after the supernova explosion, which is injecting energy into the SNR. For many decades the existence of the compact central source had to be assumed, but searches for it were unsuccessful. However, Murray et al. (2002) were successful in identifying the central pulsar in 3C58.

3.4 The SN of AD 1054

This supernova was reported extensively over near two years in China—from 4 July 1054—with a few records also available from Japan. The following Chinese record reports the end of the visibility of the guest star.

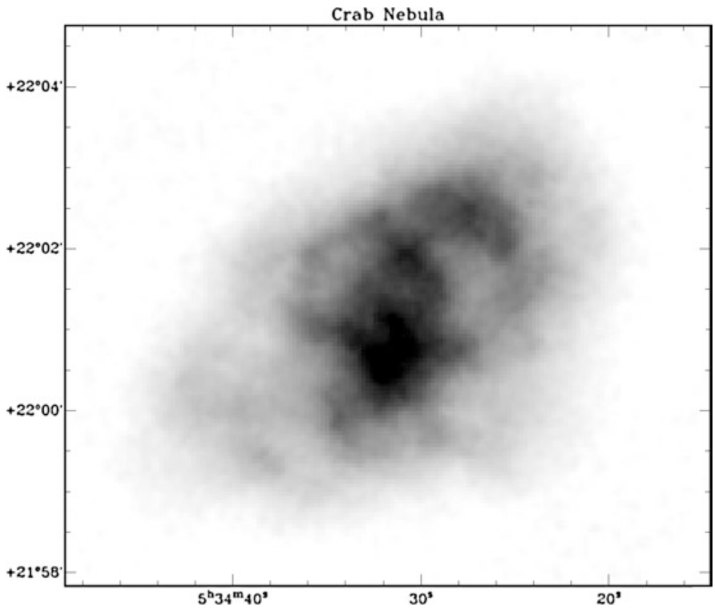

Fig. 4 Image of the Crab Nebula, the remnant of the supernova of AD 1054 at 850 μm (see Green et al. 2004)

> Jiayou reign period, first year, third lunar month, (day) *xinwei* [8] [=6 April 1056]. The Director of the Astronomical Bureau reported that since the first year of the Zhihe reign period, fifth lunar month, a guest star had appeared (*chu*) at daybreak (*chen*) at the east, guarding (*shou*) *Tianguan*. Now it has vanished (*mo*). (Stephenson and Green 2002: 123).

Although there have been some claims of European reports of this SN, none of the proposed records is completely convincing (see Stephenson and Green 2003).

The 'Crab Nebula' (=Messier 1), a unusual optical nebulosity, was first proposed as the remnant of this SN in the 1920s, and has generally been accepted to be the remnant of this SN since the 1940s. In the optical the Crab Nebula consists of both thermal filaments and polarised synchrotron emission. The Crab Nebula is one of the brightest radio sources in the sky (Taurus A, =3C144, =G184·6−5·8) first identified in the remnant in Bolton and Stanley (1949) and Bolton, Stanley and Slee (1949)—see Orchiston and Slee (2006). This is a 'filled-centre' radio source (see Fig. 4), containing a pulsar which was first identified by Staelin and Reifenstein (1968). It is also the brightest X-ray and γ-ray sources in the sky, with centrally-brightened emission, and pulsed emission from the pulsar (e.g. see Seward et al. 2006; Weisskopf et al. 2000).

3.5 *The Bright SN of AD 1006*

The SN of AD 1006 was the brightest of the historical supernovae, perhaps as bright as apparent magnitude −7 (Stephenson and Green 2002), which was visible in daylight, and seen for several years. There are extensive records of the SN from China, Japan, various Arabic lands, and a few records from Europe. The position of the SN is constrained within a few degrees in a variety of ways: (i) an RA range from Chinese observations, (ii) an ecliptic longitude range from Arabic records, and (iii) a lower declination limit from European records (from the St Gallen Monastery in Switzerland, where the new star was, just, visible). The remnant of this SN was first recorded during the 85.5 MHz Mills Cross survey at Fleurs, but its identification as a SNR was made later by Gardner and Milne (1965)—see Milne and Whiteoak (2005) and Orchiston and Slee (2006) for details. This SNR is a large (about ½ degree diameter) limb-brightened shell of radio emission (PKS 1,459 − 41, =G327 · 6 + 14 · 5), which has some faint optical filaments, and also a limb-brightened shell in X-ray (e.g. see Cassam-Chenaï et al. 2008).

4 Conclusions

Although there are over 270 known SNRs in our Galaxy, quantitative studies of almost all of these are limited by the fact that we do not have accurate ages for them. Ages can be estimated from their physical sizes, but not precisely, and in any case it is difficult to derive accurate distances for SNRs also. However, in the case of the remnants of the historical supernovae discussed above, precise ages for the remnants *are* available, which allow more quantitative astrophysical studies of the remnants.

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Part II
Islamic and Oriental Astronomy

Historical Astronomy of the Caucasus: Sources from Georgia and Armenia

Jefferson Sauter, Irakli Simonia, F. Richard Stephenson, and Wayne Orchiston

Abstract We present preliminary findings of a study of astronomical phenomena observed and extant in written sources from Georgia and Armenia. By way of background, we discuss prior research by Georgian and, to a lesser extent, Armenian scholars on the practice of astronomy in medieval Georgia and Armenia. To date, we have assembled numerous regional accounts of naked eye observations of comets, meteor showers, solar and lunar eclipses, and other Solar System phenomena. We show how the primary accounts prove useful to Applied Historical Astronomy—a field to which one of the authors (FRS) has made many contributions over the past four decades.

1 Introduction

Georgia and Armenia lie in the Caucasus region (see Fig. 1). To the north is Russia; to the east, modern-day Azerbaijan; to the south, Turkey; and to the west, the Black Sea. In ancient times, western Georgia was known as Colchis—this is where Jason and the Argonauts are reputed to have sailed to retrieve the Golden Fleece—and eastern Georgia was Iberia, or Kartli. Armenia has historically occupied lands in

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Fig. 1 A map showing Georgia, Armenia and adjacent countries

eastern Asia Minor as well as the modern-day boundary of the Republic of Armenia. The predominant religion of Georgia and Armenia has been Christianity since the fourth century AD. Culturally and politically, both nations have been bound to Greek, Roman, Byzantine, Persian, Arab, and, later, Russian spheres of influence. Yet few foreigners have shown a scholarly interest in these cultures, particularly with regard to astronomical pursuits.

Until recently, scientific literature on the study of astronomy in Georgia and Armenia has been published mostly in Georgian, Armenian, and, to a lesser extent, Russian, making this research obscure for most scholars in the West. With respect to written sources from the ninth through nineteenth centuries, however, many manuscripts still exist that are important to historians of cultural astronomy,[1] and some may have information that is pertinent to Applied Historical Astronomy.[2] Most data that are useful to modern astronomy come from historical chronicles and annals. Many more sources are extant in Armenian than in Georgian, but because earlier

[1] That is, archaeoastronomy and ethnoastronomy. According to Ruggles (2005:19) 'archaeoastronomy' is "…best defined as the study of beliefs and practices concerning the sky in the past, and especially in prehistory, and the uses to which people's knowledge of the skies were put." 'Ethnoastronomy' is "The study of beliefs and practices concerning the sky among modern peoples, and particularly among indigenous communities, and the uses to which people's knowledge of the skies are put … There is no clear dividing line between archaeoastronomy and ethnoastronomy, and many would prefer simply to combine the two fields under one heading, such as cultural astronomy." (ibid: 152). See, also, Ruggles and Saunders (1993).

[2] Applied Historical Astronomy is the application of primarily pre-telescopic (i.e. pre-AD 1609) astronomical records, mostly written, to fields of modern science (see Stephenson 1996).

studies, such as those by Tumanian (1964) and Eynatian (2008), have described the Armenian sources in detail, our initial focus will be on previous scholarship on Georgian sources. We then expand our view to Armenian sources, and we show how these can be applied to modern problems in astronomy.

2 Astronomy in Georgia

The first widely-accessible survey of the history of ancient and Medieval astronomy in Georgia was co-authored by astronomers E. Kharadze and T. Kochlashvili. This brief study appeared in the then-Soviet journal *Historical-Astronomical Investigations* in 1958 (but also see Melikset-Bek 1930; Kharadze 1960). Earlier, D. Tskhakaia had described several Georgian calendrical, mathematical and astronomical texts in a series of papers later assembled into a book and translated from Georgian into Russian (1959), and I. Ingoroqva had examined Georgian ‘pagan’ calendars in detail (1929, 1931). From the 1960s until the early 2000s, the historian of astronomy G. Giorgobiani authored studies on, among other things, astrolabes, angle-measuring devices, and evidence from literary sources for observatories and comets in medieval Georgia (1965, 1971, 1980, 1986; Giorgobiani and Ramishvili 2002). In the 1980s, seminal papers explored the life and astronomical works of a thirteenth century Muslim astronomer from Georgia who worked later at Maragha in Iran (Japaridze 1984), and the famous Georgian Christian astronomer Abuserisdze Tbeli (Fig. 2) from the same century (Sulava 1998; Simonia 2003). Georgian scholars have also produced studies on the so-called total solar eclipse of Nino which King Mirian may (or may not) have observed (see Sauter et al. 2015). Since the 1990s, a co-author of this paper (IS) has published studies, many in English, on themes ranging from archaeoastronomy and medieval astronomy in Georgia, to the nineteenth century

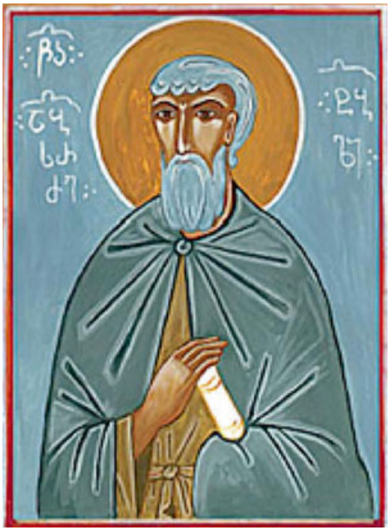

Fig. 2 Icon of St. Abuserisdze Tbeli, a thirteenth century Georgian theologian and astronomer whose work The Complete Timekeeper elevates him to a special place in Georgian astronomy (Simonia 2001)

observatory in Tbilisi, Georgia's capital (e.g. Bronshten and Simonia 2000; Simonia 2001; Simonia et al. 2008, 2009).

Also worthy of mention are studies on topics of cultural astronomy in Georgia (and although we only discuss a few here, many more are listed in the bibliographies of the works cited below). These examine cosmological treatises; astrological texts and celestial divination (Brosset 1868; Sauter and Simonia n.d.; Shanidze et al 2007); astronomical references in theological and philosophical works such as Ioane Petritsi's commentary of Proclus' *Elements of Theology* (Mamatsashvili 1972); the cosmological world-view in literary works such as the *Knight in the Panther's Skin* by Georgia's most famous poet, Shota Rustaveli (e.g. Imedashvili 1950; Khintibidze 2009; Tevzadze 1978, 1984); and religious calendars (e.g. Gippert 1988; Kekelidze 1941). Of particular note is King Vakhtang VI's translation activity, including his translation during the eighteenth century of the astronomical tables (*zijat*) of Ulugh Beg (Abuladze 1985; Dondua 1926; Marr 1926). But with the exception of Simonia's numerous studies—and the occasional reference (e.g. Kulikovsky 1967)—the history of Georgian astronomical pursuits, be they astronomical observations or cultural astronomy, remains largely hidden from those without knowledge of Russian and Georgian.

Generally, though perhaps unsurprisingly, less is known about the lives of the Georgian and Armenian astronomers than about their works. Without question, the most famous name of these is Anania Shirakatsi (Ananias of Shirak), the seventh century Armenian astronomer and mathematician (see Fig. 3). Approximately two dozen of his works are extant. Anania wrote on a variety of astronomical, mathematical, geographical and calendrical topics, and is well known for his work on

Fig. 3 Statue of Anania Shirakatsi, the seventh century Armenian astronomer and mathematician (Source: http://commons.wikimedia.org/)

Armenian chronology. We know of no Georgian equivalent, but written sources in Arabic do suggest that some Muslim astronomers may have been of Georgian extraction or from Georgia, though whether they were Georgian speakers is often difficult to judge. Fakhr al-Din al-Khilati (1197–1282) was "… a doctor, philosopher and mathematician, a worker at the Maragha Observatory, one of the closest assistants of Al-Tusi." (Simonia 2001; see also Buniyatov 1971; Matvievskaia and Rozenfeld 1983). The Maragha Observatory was founded in the late 1250s by Nasir al-Din al-Tusi, after whom the mathematical device now called the 'Tusi couple'—an important contribution to medieval planetary theory—is named (De Young 2008; Saliba 1991; Saliba and Kennedy 1991). It has been suggested that Al-Khilati possibly worked at a fortress in Tbilisi called Nariqala (Giorgobiani 1971; Japaridze 1984; Simonia 2001), and one of the extant works attributed to him is, "The Light of Indication concerning 'Restoration' and 'Completion'" (our English translation), which is in Arabic (Matvievskaia and Rozenfeld 1983). Another Muslim astronomer with ties to Georgia may also have been Abul Fazl Hubaysh Tiflisi, who in the 12/13th centuries wrote two astronomical works in Persian: "Introduction to the Study of the Stars" and "Description of the Stars" (ibid.; Mikhalevich 1976; our English translations). Georgian works dating from the thirteenth century of the theologian and astronomer, Abuserisdze Tbeli, are also extant (Brosset 1868; Sulava 1998). We shall return to Tbeli shortly when we discuss extant works by Georgian astronomers, but let us now turn to the Georgian manuscripts.

The astronomer G. Kevanishvili (1951) estimated that there were about 300 manuscripts with astronomical themes among Georgia's four largest collections of manuscripts (Simonia 2001). Having at our disposal manuscript descriptions more recent than Kevanishvili had, we now estimate that about 200 manuscripts from these collections contain about 300 individual works which, to varying degrees, touch on themes that could be deemed 'astronomical'. Several factors likely explain why so few such works have come down to us. Firstly, many Georgian manuscripts may have been destroyed during wars with and invasions by neighboring peoples—Arabs, Mongols, Persians and Turks. Secondly, technical works in Greek, Arabic and Persian were accessible to Georgians during the Middle Ages. These could presumably have been read in the original languages by Georgians who, by the way, had a significant presence at centres of learning such as Mount Sinai, the Black Mountain and Mount Athos in the Christian world, as well as in Persia. Finally, as far as we know, the total number of Georgian speakers has never been very large, and at times the language and population were almost entirely wiped out. The result is the relative paucity of Georgian manuscripts on astronomical subjects that we see today.

Of the Georgian texts on astronomical topics that have survived, few have attracted the attention of scholars during the past hundred and fifty years. There are, however, notable exceptions. Manuscript A-24, housed at the National Centre of Manuscripts in Tbilisi, was copied in the twelfth century, and it includes a translation of John of Damascus' "On the Orthodox Faith" (our translation), which contains an elementary treatise on the heavens that was widely read throughout the Middle Ages. A second manuscript of note is MS A-38, which dates from AD 974. It includes a detailed account of the Georgian cycles in time-keeping as well as solar days and months, and tables for computing solar and lunar days (see Tskhakaia 1959). Another manuscript, A-65, was apparently copied in AD 1188–1210 and contains descriptions of lunar phases, time-reckoning techniques and ornate illustrations in gold and other colors (Alibegashvili 1951; Shanidze et al 2007). Yet another is MS A-85, one of the better-known works by the Georgian astronomer and theologian Abuserisdze Tbeli, whom we mentioned earlier (see Fig. 2). Tbeli's work, "The Complete Timekeeper" (our translation), is "… the first astronomical work of [a] theoretical nature produced in Georgia, and this elevates Abuseridze Tbeli to a special place in Georgian astronomy." (Simonia 2001; cf. Brosset 1868; Sikharulidze 1991; Simonia 2003; Sulava 1998).

Several recent studies shed light on cosmological writings from Georgia. For example, "The Star Book" (our translation) was copied at the turn of the eighteenth century. This text, found in MS Q-867 now in Tbilisi, Georgia, refers to the so-called 'stars' of Venus and Mars (Simonia 2001; cf. Giorgobiani 1980). Meanwhile, the contents of a contemporaneous manuscript (MS A-883), titled "Elementary Cosmography" (our translation), is the subject of a recent paper by I. Simonia (2004). Despite these studies, the history of astronomy in Georgia has yet to be written, whereas monographs on the history of astronomy and calendars in Armenia first appeared nearly fifty years ago (see Tumanian 1964, 1972).

3 Our Project

In Sect. 2, above, we have briefly surveyed some of the scientific literature on early astronomy in Georgia and a few of the manuscripts already studied in some detail, and mentioned that an estimated 300 works written in Georgian on astronomical themes are known to exist in Georgia. In 1930, L. Melikset-Bek wrote in his study "Towards a History of the Exact Sciences in Armenia and Georgia":

> Georgian literature in the course of the entire so-called 'Middle Ages', unlike Armenian, as strange as it may be, preserved almost no monuments on physical-mathematical topics—neither in the original, nor in translation unless one considers Epiphanius of Cyprus's treatise 'On Measures and Weights' …" (our translation).

In light of the manuscripts and scientific literature we have described above, such a statement can be misleading. It is true that we are currently unaware of technical astronomical treatises from the Middle Ages that are not on calendrical themes (cf. Simonia 2001). Still, historical written sources from ancient and later times often include valuable observational data, as well as vast knowledge on cultural topics (see Sect. 2 above). We therefore believe that Georgian manuscripts both from Georgia and elsewhere in the world need to be examined from the perspective of Applied Historical Astronomy (as defined in Note 2 on page XXX). For example, an inscription at a church in western Georgia purportedly refers to a comet seen in the sky in April 1066—no doubt 1P/Halley (Brosset 1849: 116–118; Giorgobiani 1986; Giorgobiani and Ramishvili 2002).

With respect to the Georgian sources, a convenient place to begin an investigation into historical (and cultural) astronomy is the unpublished descriptions by

Kevanishvili (1951). Cited by Kharadze and Kochlashvili (1958) and Simonia (2001), this compilation of manuscripts (not individual works) remains to this day difficult to access and, having been assembled before more detailed descriptions were available, it is incomplete and is now out of date. Still, Kevanishvili (1951) is a useful starting point because his catalogue covers the four largest Georgian-language manuscript collections in Georgia (collections A, H, Q, and S). Based on the variety within Kevanishvili's catalogue, one can assign the texts contained in these manuscripts to five different preliminary categories:

1. '*Astronomy and astrology texts*' might include those that describe cosmology, solar phenomena, lunar phases, the zodiac and astronomy proper. These texts—and those in the next three categories—were almost always included in or added to manuscripts developed primarily for ecclesiastical purposes.
2. '*Divination and prognostication texts*' are not dissimilar to predictions found in a farmer's almanac of today. These were copied in manuscripts containing ecclesiastical texts but are themselves distinct works. The four most common divination and prognostication works in Kevanishvili's catalogue are: lists of lucky and unlucky days; Calendologia, or predictions based on the day of the week of New Years or Christmas; selenodromia (lunaria), or predictions for the days of the month with biblical references; and brontologia, which include prognostications from weather and such phenomena as thunder, earthquakes and eclipses. MS A-620, which we describe below, falls within this category.
3. '*Calendar texts*' include lists of lunar and solar days as well as how to determine the moveable feast of Easter (also known as 'paschaliae'). Like the categories above, calendar texts are almost always copied in a manuscript that includes other ecclesiastical works. These texts, obviously, often overlap with those in the first category of astrological/astronomical texts.
4. '*Liturgical texts*', for lack of a better term, are works used in conjunction with the Eastern Orthodox liturgy and that do not fall within the three categories listed above. The most common texts which Kevanishvili included in his catalogue are horologia ("Books of Hours") and menologia ("Books of Months") (our translations), i.e. services for fixed feasts (not connected to the Easter cycle) arranged chronologically by month. (Kevanishvili did not include every such work that is now known in the four collections he surveyed.) Many of these are not typically thought of as astronomical works.
5. '*Later technical texts*' refer to manuals and treatises on geography, history, philosophy, geometry and arithmetic, physics and geodesy. Generally, these are later works composed or copied in the eighteenth and nineteenth centuries.

It must be emphasized that these categories are imperfect and by no means the last word on the number and types of Georgian astronomical manuscripts. Some manuscripts in Kevanishvili's catalogue include texts that fall into more than one category—for example, at least one manuscript described as a "Book of Hours" is known have appended to it a prognostic text, and there are probably many other similar situations. Also, to include, as Kevanishvili did, strictly liturgical works such as "Books of Hours" and "Books of Months" misrepresents the practice of astronomy in Georgia over time. Nonetheless, our rough-and-ready categories aim for a preliminary (and admittedly blurry) picture of astronomical knowledge in Georgia over time. It is also worth repeating that, except for published descriptions of collection H, detailed descriptions of manuscripts from the four largest collections appeared after 1954 and, therefore, were probably inaccessible to Kevanishvili.

Of the 332 manuscripts in Kevanishvili's catalogue, eight are well-known literary works or have since been removed from collections A, H, Q, or S because they were miscategorized, e.g. because they were not in Georgian. Most of the remaining 324 texts are concerned with church or calendar matters. About two fifths are liturgical texts, and approximately one fifth of the manuscripts in Kevanishvili's catalogue deal with calendar computations. Another fifth concern astronomical themes, divination, and prognostication, and the remaining fifth are later technical works.

How are different kinds of texts distributed over time? When possible, we confirmed the dates of manuscripts from published manuscript descriptions.[3] Of the 295 manuscripts (i.e. ~90 %) whose dates we are confident of, only 47 manuscripts were copied during or before AD 1600. Moreover, no more than nine manuscripts in any single category have been dated to any one century. The distribution of post-1600 texts within the first four 'ecclesiastical' categories, however, does not vary greatly by topic. We hesitate to draw other conclusions about the distribution of early texts over time without further study.

On the other hand, data useful to Applied Historical Astronomy usually come not from so-called astronomical works, but from unrelated texts—we have no evidence that Kevanishvili included any of his manuscripts with this in mind. Let us now turn from the written sources themselves to the benefits of studying Georgian and Armenian texts from the perspectives of cultural and historical astronomy.

4 Applied Historical Astronomy

A written source is generally considered relevant to Applied Historical Astronomy when it contains data that are applicable to modern problems in geophysics and/or astronomy (see Steele 2005). Three areas where observational data are particularly useful are studies of solar eclipses and the Earth's rotation (see Stephenson 1997), historical supernovae (see Stephenson and Green 2002) and comets (see Hasegawa 1980; Jansen 1991). Data often come from historical chronicles and monastic records as well as from colophons of manuscripts that are not necessarily astronomical.

Armenian texts are known to contain observations of comets, meteors, eclipses, and—it has even been argued—the supernova of AD 1054 (Astapovich 1974; see also, e.g. Astapovich and Tumanian 1969, 1971; Barseghian and Epremian 1989; Broutian 1988; Eynatian 2008). Many of these observations are potentially useful to

[3] The dates of the manuscripts included by Kevanishvili were compared with the manuscript descriptions of collections A, H, Q, or S published by the National Centre of Manuscripts. See Garitte (1961).

Applied Historical Astronomy. Indeed, historical references to naked eye sunspots and other phenomena associated with the Sun would be of particular interest as are how these and similar ideas were transmitted and evolved over time. For example, Barseghian (1988) has associated solar activity with two observational records from the late eleventh century. A noteworthy observation is from the Armenian chronicle of Etum Patmich (*Minor Chronicles*, 2: 53), who tells us that "… in the year 1048 AD … in the fifth year of the rule of Pope Levon [Leo IX, whose papacy lasted from 12 February 1049 until his death on 19 April 1054] … in that year on the disk of the Moon appeared a star, when it was New Moon on 13 May, in the first part the night." Here, Astapovich (1974: 6–7) reads 1054 instead of 1048 and 14 May instead of 13 May because "… Patmich is reporting about the connection of the supernova and the Moon, which took place 29 hours after New Moon, i.e., in the evening of 10 May 1054, at the setting of the Moon in Yerevan, accounting for almost 3 hours of its eastern longitude." We hesitate to alter the text to agree with a specific celestial event—especially because Astapovich and Tumanian (1969) previously characterized this observation as being of a "… bright stationary meteor, a Nova, or an active lunar volcano." Another possible explanation is that a lunar meteorite impact was observed and recorded, as Beech and Hughes (2000: 21) point out that "… optical transients resulting from large meteoroid impacts on the Moon's surface are to be expected occasionally …"

Other data from Armenian and Georgian sources are on firmer grounds. Numerous references to astronomical phenomena from the works of Armenian chroniclers including Samuel Anetsi, Stepanos Asogik, and Ananun Sebastetsi are gathered in Semenov (1941). These sources record brief observations of attested comets, meteor showers and bolides, and solar and lunar eclipses. Among these are: about 20 solar eclipses ranging from 966 until 1654; a partial solar eclipse in 1666; and descriptions of the Sun being "… half hidden …" for 10 months in 614 and 618.[4] Many of these records are vivid. Samuel Anetsi describes an annual solar eclipse in 1590 as lasting three hours with the Sun "… blacker than the bottom of a pot." This eclipse would have been visible in Armenia on 31 July 1590. Some records of solar eclipses point to the time of day of the eclipse (e.g. noon, end of day), as well as the year, day of the week and month. Although it was not uncommon for chroniclers to use stock phrases like "… the stars appeared …" and "… day was like night …", many eclipse records collected by Semenov are marred by scribal errors or confusion of the Armenian chronology. Others may have been borrowed from other sources. Among the records from Armenian sources worthy of further study are the solar eclipses of 1133, 1337, 1654 and 1666 (which has a narrow band of totality through Armenia).

Records of comets and meteors tend to contain more detail than Armenian eclipse records. Astronomers S. Vsekhsvyatsky and B. Tumanian (1971) continued Semenov's work by improving on about 50 records of comets, most of which correspond with entries in Hasegawa's 1980 catalogue. The Armenian records seem to document several unattested comets including one from 1094 recorded by Mkhitar

[4] Perhaps also in 560 and 571—it is not yet clear whether these dates are given in the Armenian calendar or in years AD. As the result possibly of volcanic activity, see Arjava (2005).

Ayrivanetsi; another from 1574 by Vardan Bagishetsi; and yet another, said to be visible for 20 days, in 1576, by Andrias Sarkavag Evdoketsi. Some of the records are independent accounts that add new details of well-known comets, e.g. Khachatur Kafaetsi's account of the comet of 1618 or Arakel Davrizhetsi's of the comet of 1664. Others are in agreement with European counterparts, such as Matevos Uraetsi's description of the comet of 1097 which was seen in the month of Areg (September/October) for 15 days. Barseghian and Epremian (1989) confirmed that observations of Comet 1P/Halley were recorded in Armenian sources during the comet's appearances in 989, 1066, 1222 and 1531. They also corrected one of the conclusions of Vsekhsvyatsky and Tumanian (1971) who had asserted that the twelfth century author Matevos Uraetsi witnessed Halley's Comet in the beginning of 1067, at which time the comet would have been too faint to have been seen in Armenia, at a visual magnitude between +8 and +9, an error resulting from misreading 1067 instead of 1066.

In addition, accounts of meteor events describe fireballs and bolides in 1023, 1265, 1358 (in Spain) and 1641 near Yerevan. The fireball from 1641 offers us one of the few ostensibly first-hand Armenian accounts. It is by Zakaria Sarkavag, who was born in 1627 and tells us that:

> I needed to have written down this history earlier, in 1080(90) [i.e., AD 1631(41)],[5] but it is written here with forgetfulness. When I was a boy at our home in Kanaker, on the Day of the Procession of the Cross [12 September], we went with my father to the garden which lies near the village called Karmirberd on the shore of the river Urastan, below the bridge. At sunset, my father made evening prayers. It was not dark yet and there was still daylight. All of a sudden, there was blue ether in the eastern side of the sky and there descended a large and powerful light [bolide]; it was wide and long, and came down until it approached the earth; and its beam illuminated the heavens with light brighter than the Sun's. The beginning part of the light spun (lit. drew) like a wheel moving to the north calmly and peaceably and emitted red and white light and in front of the light, at an elbow's length, was held a star the size [in brightness] of Venus. My father stopped his prayer and, weeping, began to sing the 43rd Sharakan [hymn], "O Light Thou, that with the light of God …" While he was singing six sharakans, the light was visible, but then [the light] went away and became invisible. And we heard that they saw this heavenly and miraculous light as far as Akhaltsikhe. (Cited in Semenov 1941: 145–146; our translation).

The Georgian town of Akhaltsikhe is about 200 kilometres from Yerevan. To sing six sharakans (Armenian hymns) would probably take 10–20 minutes. We know of no other celestial events recorded in Armenian sources that were more or less contemporaneous with this one except for a comet in 1618 and a solar eclipse in 1654. But other sources record a meteorite weighing more than 1 1/3 kilograms having fallen between 1347 and 1362, and a meteor display of the Leonids in 902 (Astapovich and Tumanian 1971). Note that the latter was one of the remarkable Leonid meteor storms (as opposed to the regular Leonid meteor showers) that are known to occur on average every 33 years (see Dick 1998).

Compared to Armenian historical sources, Georgian chronicles and other records that have been edited are fewer in number. But written sources from Georgia have

[5] The uncertainty of the year arises because the year is written alphabetically; here we have 1000, then 80, then 90.

Fig. 4 A Georgian brontologion (MS A620). The text is in the Georgian ecclesiastical script. The opening lines of the brontologion, or "thunder-book", on the *upper left-hand side* of right-hand page are: Signs of the times and months of eclipses of the luminaries, lunar halos and solar halos, lightning and earthquakes and rainbows and thunder

the potential to yield similar results. An enlightening example is the recent study of seven comets observed in Georgia between 1066 and 1811 (Giorgobiani and Ramishvili 2002). A pair of unconventional written sources from Georgia are also worthy of note. The first example comes from a seventeenth century divination text—a brontologion, or 'thunder book', in MS A620 at the National Centre of Manuscripts in Tbilisi, Georgia—arranged as a month-by-month almanac starting with January and containing approximately two hundred omens (see Fig. 4). For each omen, the text gives the (Roman) month, e.g. January; the sign, e.g. "… if it thunders …"; and one or more predictions that may concern the state, agriculture, health, weather, and so forth. For most months, the signs are presented in strict order (see Sauter and Simonia n.d.). For each month, the first four omens relate to solar and lunar eclipses and halos; then to rainbows, thunder and lightning; and lastly to earthquakes during the day and to earthquakes at night—for a total of nine possible signs per month. The copyist of the Georgian brontologion in MS A620 included no solar eclipse omen for the month of July, and has altered the syntax for that month's omen so as to clarify that a solar eclipse in July was not intended to serve as an omen of any sort. But is this omission significant?

The answer possibly concerns the story of St Nino of Cappadocia, one of the most significant saints in the Georgian Orthodox Church. In a version of the life of St. Nino, a miraculous darkening of the sky is said to have swayed the Georgian

King, Mirian, to renounce his pagan beliefs and convert to Christianity. This account implies a more-or-less precise geographical location and includes a description of the onset of darkness and sudden return of daylight. The story vividly describes the psychological reaction of the observers that accords with many first-hand testimonies of observing a total solar eclipse. We recently carried out a detailed analysis of this case (Sauter et al. 2015) and showed that a total solar eclipse which would have been visible in this part of the world on AD 6 May 319 would have been striking from Mirian's presumed location on a mountain but less so at lower elevations. Now if Mirian did indeed witness an eclipse—but we cannot know for sure—then we would be able to derive upper and lower limits for ΔT, the measure of accumulated time-lag between terrestrial dynamical time and ephemeris time. Reliable solar eclipse records from the fourth century AD are few in number, but data derived from the *Life of Nino* would, in fact, yield a rare confirmation of contemporaneous records.

We would hope that the examples in this preliminary study are merely a portent to other equally-illuminating accounts relevant to Applied Historical Astronomy that currently await discovery in Georgian and Armenian astronomical written sources.

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Annular Eclipses and Considerations About Solar and Lunar Angular Diameters in Medieval Astronomy

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Abstract This study deals with considerations on the angular diameters of the Sun and Moon in ancient and medieval astronomy and focuses on their role in predicting the existence of annular eclipses. Historical reports of annular eclipses probably date back to the ancient Greeks. From that period there are some documented theoretical considerations about the angular diameters of the Sun and Moon, implying the possible existence of annular eclipses. Nevertheless, according to the Ptolemaic context, since the minimum angular diameters of the Sun and Moon were considered to be equal, there was no justifiable basis for annular eclipses. During the medieval Islamic period, some observational evidence, including annular eclipses in AD 873 and 1283, and a total solar eclipse in AD 876 in which the Sun was completely covered for an unusually long interval, led to attempts by the astronomers of the time to revise Ptolemaic ideas, and come up with acceptable alternatives. Accordingly, non-Ptolemaic ideas concerning the angular diameters of the Sun and Moon were adopted from Indian astronomy, inserted into the Ptolemaic model, and eventually transferred to European astronomy. Finally, by the late medieval period a 'bright ring eclipse' had become an accepted term for one of the three types of solar eclipses—the others being total and partial. With the progress of astronomy, the discussion of annular eclipses was back on the agenda whenever the idea of homocentric models arose, and were used to reveal their glaring deficiencies.

1 Annular Eclipses in the Ancient and Medieval Periods

In about AD 150 Ptolemy deduced that the apparent angular size of the Moon was equal to or larger than that of the Sun, the latter always being assumed constant. He noted that the angular diameter of the Moon was at a minimum (and equal to that of the Sun) when the Moon was at apogee. Under these circumstances an annular solar eclipse was impossible (*Almagest*, V, 14). Johannes Kepler (AD 1571–1630)

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repeated these same ideas in his *Epitome Astronomiæ Copernicanæ* (IV, 4) (Kepler 1990: 876). Furthermore, the majority of Ptolemy's followers during the medieval period, including Naṣīr al-Dīn al-Ṭūsī (AD 1201–1274) in his *Taṣrīr al-Majisṣī* ("Exposition of the Almagest"; al-Ṭūsī 2: f. 37v) and Regiomontanus (AD 1436–1476) in his *Epitome Almagesti Ptolemæi* (Schmeidler 1972: 143) also favoured these ideas. Thus, at first sight it seems that in the period between Ptolemy and Kepler no-one was interested in changes in the angular sizes of the Sun and the Moon and their relations.

According to Ptolemy, his predecessors, including Hipparchus (ca. 190–120 BC), believed that the angular diameters of the Sun (assumed constant) and Moon were only equal when the Moon was at its mean distance from the Earth, thus rendering an annular eclipse possible (Toomer 1998: 252–253, especially n. 53). A Pseudo-Eudoxan papyrus of around 190 BC (now known as Papyrus, Paris 1, Col. 19.16–17) also tells that solar eclipses can never be total and at most can be annular (see Neugebauer 1975: 686f). It is unknown what astronomical implications at the time when the papyrus was written led to the belief that the diameter of the Moon must always appear smaller than that of the Sun. Neugebauer (1975: 668 and 688) says nothing about this, but he does suggest that this conclusion could be the result of the observation of an annular eclipse by Polemarchus [*sic*], the younger contemporary of Eudoxus. Neugebauer (1975) states that this observation is mentioned in Simplicius' commentary on *De Caelo*, but I could find no sign of it (see Simplicius 1894: 505, lines 20f; see also the translation and critical comments in Bowen 2008: 53 (esp. n.179), 75 and 107).

Nevertheless, it seems that since on the basis of the homocentric models the distances of celestial bodies must always remain constant, if one finds that the angular diameter of the Moon is smaller than that of the Sun, then immediately it can be concluded that in solar eclipses the Moon can never completely cover the Sun. Therefore, it seems strange that after a time interval of around three centuries the situation was completely reversed by Ptolemy.

Although non-scientific reports of annular eclipses probably date back to the ancient Greeks, neither Ptolemy, nor his followers in the medieval period, refer to them. Retrospective computation indicates that the eclipses of 3 August 431 BC and 14 August 394 BC were annular, but since they were described as 'crescent shaped' by Thucydides and Xenophon, respectively, it would seem that only the partial phase was witnessed in each instance (see Stephenson 1997: 346–348 and 366–367).

From the observations recorded by Ptolemy in his *Almagest* (Pedersen 1974: 408–422) we find that he and his contemporaries and his recent predecessors, i.e. Agrippa of Bithynia (located in the west of Asia Minor), Menelaus of Rome and Theon of Smyrna ($\phi = 38°\ 25'$; $L = 27°\ 9'$), were in action between the latter part of the first century AD and the first half of the next one. As indicated by modern computations, the eclipses of AD 49 May 20 and 80 March 10 were annular in Egypt, both in the vicinity of Alexandria. The first was also observable in the east of Asia Minor, but not in either Smyrna or Bithynia. In the first part of the second century AD there was an annular eclipse on AD 121 July 2 that was visible from the south of Egypt. Whether these eclipses were recorded or not in Egyptian chronicles we do not know.

The only annular eclipse which was visible near Alexandria during Ptolemy's career occurred on AD 132 November 25. On this occasion the Sun set in the longitude of Alexandria before the beginning of the annular phase of the eclipse, and hence it was unobservable. The only annular eclipse visible in the Eastern Mediterranean during the second half of the same century occurred on AD 164 September 4, and this does not seem to have been noticed by Ptolemy. In fact, the last astronomical observation recorded in the *Almagest* is of Mercury on AD 141 February 2 (*Almagest*, IX, 7).

As we have seen, during Ptolemy's lifetime there were no appropriate opportunities for him to observe an annular eclipse, nor records available to him of earlier eclipses of this type observed by others. It would seem that these conditions allowed Ptolemy to trust his measurements of the apparent diameters of the Sun and the Moon (*Almagest*, V, 14) and consequently to ignore annular eclipses, as well as to reject his predecessors' considerations of the apparent diameters of the Sun and the Moon.

The first account of an annular eclipse seems to have been given by Sosigenes the Peripatetic (second century AD), and reported by Simplicius in his commentary on Aristotle's *De Caelo* (Simplicius 1894: 505). Simplicius used the fact that "… sometimes … a ring is left appearing during mid-eclipse …" as evidence against the idea of homocentric planetary spheres, but it is not perfectly clear that this account relates to a real observation of an annular eclipse. Neugebauer (1975: 104) has suggested that it was the annular eclipse of AD 164 September 4 that is mentioned by Sosigenes, but Bowen (2008: 89–90) questions this. Besides considering the annular eclipse, Simplicius' text says that in some total solar eclipses there is an appreciable duration of the period of darkness (Simplicius 1894: 505; cf. Bowen 2008: 74), which the majority of medieval astronomers erroneously assumed to have been ignored by Ptolemy (see Sect. 3.2.3, below). It is rather amazing that a philosopher who was an approximate contemporary of Ptolemy provides information on the different types of solar eclipses, yet Ptolemy ignores annular eclipses.[1] All of these details of solar eclipses would be revisited

[1] That is, unless we assume that the account of the conditions of the solar eclipse was made by Simplicius rather than Sosigenes. However, Proclus (1909: 131) also attributes the account of the annular eclipse to Sosigenes (and for discussion on this assumption see Bowen 2008: 89–90). Another assumption, which may seem even cruder, is that Sosigenes may be Sosigenes of Alexandria (first century BC) not Sosigenes the Peripatetic. Note that Simplicius refers to Sosigenes, but does not assign any 'title' to him. It is only Proclus who identifies him as 'The Peripatetic'. We know that Sosigenes was ordered by Julius Caesar (100 BC–44 BC) to modify the new Julian calendar (and for Sosigenes' contributions to astronomy see Pliny 1938–1962, 1: 193 and 5: 325). Of the annular eclipses that occurred during the first century BC, four were observable in the south of Egypt, four in the middle of Europe and the one (i.e. on 5 January 29 BC), on the eastern shore of the Mediterranean Sea and in the north of Egypt. All of these eclipses were partial in Rome ($\phi = 41°$ 54 N and $L = 12° 30'$ E) and Alexandria ($\phi = 31° 13'$ N and $L = 29° 55'$ E). It is worth mentioning that the annular eclipses of 7 March 51 BC, 6 March 78 BC, and 29 June 94 BC all were annular in the north of Italy. If the account of the annular eclipse resulted from a real observation, then Sosigenes of Alexandria had clearly more opportunities than Sosigenes the Peripatetic to observe it.

again during the medieval period (e.g. compare Sosigenes' account, above, with the one provided by Bīrūnī, as discussed in Sect. 3.2.3 below).

During the next two centuries it may be computed that several annular eclipses were visible in the Mediterranean region but in no case is there any mention of the actual ring effect.

Therefore, we do not yet have indisputable records of astronomers actually observing annular eclipses in ancient times or during the early medieval period, and the fact that Ptolemy apparently ignored them in his discussion of solar eclipses would suggest that he was unaware of them.

However, there are at least four clear reports of annular eclipses in the medieval period,[2] and two of these derive from the Islamic world (see Said and Stephenson 1991, 1996, 1997; Stephenson 1997: Chapter 13; and Stephenson and Said 1991). These four eclipses are discussed below.[3]

1. The earliest of these four eclipses was observed by an Iranian astronomer, Abu al-ᶜAbbās Īrānshahrī on Tuesday 29 Ramaḍān 259 H (=AD 873 July 29, JDN 2040130) from Nīshābūr in Khurasan-Iran, ($\phi = 36°\ 12'$ N and $L = 58°\ 48'$ E) (see Goldstein 1979; Said and Stephenson 1997: 45), and is mentioned by Bīrūnī (AD 973–1048) in his *Al-Qānūn al-Masᶜūdī* (Bīrūnī 1954: 632). Bīrūnī used it as evidence for rejecting the homocentric solar model of Abū Jaᶜfar al-Khāzīn (AD 900–971) (see Samsó 1977: 274).
2. The eclipse of AD 1147 October 26 was observed from Brauweiler, Germany (Stephenson 1997: 394). The record of this eclipse, which according to computation was definitely annular, is to be found in the *Annales Brunwilarenses* and states that "… a circle of different colours and spinning rapidly was said to be in the way (of the Sun)."
3. The eclipse reported by another Iranian astronomer, Shams al-Dīn Muḥammad al-Wābkanawī al-Bukhārī (AD 1254–ca. 1320), who appears to have presented the only detailed report of an annular eclipse prior to the Renaissance period. On Saturday 29 Shawwāl 681 H (=AD 1283 January 30, JDN 2189703), he observed an annular eclipse from Mughān, a green plain located in the north of Azerbaijan Province in Iran (at $\phi = 39°\ 00'$ N and $L = 47°\ 00'$ E) (see Mozaffari 2009, 2013a, b).
4. The annular eclipse of AD 1292 January 21 was observed from Beijing, China, and the report contains a clear reference to the ring phase (see Stephenson 1997: 62 and 258–259).

[2] For optical considerations that may make it difficult to distinguish an annular eclipse with the naked eye, see Stephenson (1997: 62–63), and also Sect. "3.1".

[3] Besides these reports, it is possible that the annular eclipse of AD 715 August 4 was observed in the early Islamic Period. In his *Taḥdīd*, Bīrūnī says that in Ghazna (a city in old Khurasan state, now in central Afghanistan, located at $\phi = 33°\ 33'$ N and $L = 68°\ 25'$ E), he found an old *zīj* (written on a parchment) at the end of which was a list of solar eclipses observed between 90 A.H./AD 708 and 100 A.H./AD 719 (Bīrūnī 1962: 249). In the 710 s and 720 s only one annular eclipse, i.e. that of AD 715 August 4, occurred in the region from the eastern coast of the Mediterranean Sea to the far eastern boundaries of the Islamic lands. The eclipse was observable as annular in Central Asia, including the north of Khurasan (now Kazakhstan), and, of course, was partial in other places, including Ghazni.

Shortly before and after Wābkanawī's observation, there were reports of two annular solar eclipses in European chronicles; however, neither was in fact annular. One of these occurred on AD 1263 August 5, during a military campaign by the King of Norway against Scotland, and the other was on AD 1310 January 31 and was observed from Durham Abbey in England (Johnson 1900, 1905; Lynn 1905). The central line of the first eclipse passed over Norway. The report in the Haconar Saga says that the eclipse was observed as annular in the Orkney Isle; however, the calculated maximum magnitude of the eclipse there was ~0.85, so it could not have been observed as an annular eclipse (see also Stephenson 1997: 404). Also, the second eclipse was partial in Durham ($\phi = 54° 46' 34''$ N and $L = 01° 34' 24''$ W), with the magnitude of 0.89. This eclipse was annular in the extreme south-east of England, reaching a magnitude of 0.93.

Probably Guy de la Marche (ca. AD 1257–1315) observed the annular eclipse of AD 1310 January 31 (see below). Another annular eclipse was reported on AD 1433 June 17 in the Pseudo-Regiomontani text, *Refutatio errorum Alpetragii de motibus celestibus*, including comments against the homocentric models constructed by the Muslim astronomer Al-Biṭrūjī (see Shank 1992: 17–19, 26). This eclipse was not annular, and on the basis of Shank's study, this work is substantially based upon an earlier treatise written by Guy de la Marche himself, which included his probable observation of the annular eclipse of AD 1310 January 31. It seems, as with the above-mentioned case of Abū Jaᶜfar al-Khāzin, that the discussion of the occurrence of annular eclipses caused support for the homocentric planetary model to wane in Europe before the advent of Copernicus (see, also, Shank 1998: 162–163; Swerdlow 1999: 5, 22 n.7).

If we put aside the report by Clavius of an annular eclipse visible from Rome on AD 1567 April 9, which in fact was total (see Lynn 1896: 332–333; Stephenson 1997: 410), then the annular eclipse of AD 1601 December 24 viewed from Norway (Stephenson 1997: 411) was the first one reported after the medieval period.

2 Methods of Calculating the Angular Diameters of the Sun and Moon in Medieval Astronomy

2.1 Historical Notes

What has been presented in Sect. 1 is a summary of the annular solar eclipse as an observational phenomenon up to the Renaissance. Now we will discuss this type of eclipse from a theoretical point of view. This is necessary because the observations of two annular eclipses in the medieval Islamic period (numbers (1) and (3) above) do not seem to be purely accidental. From Wābkanawī's detailed report on the eclipse of AD 1283 January 30, we know he had calculated the parameters beforehand, and expected the eclipse to be annular. Moreover, he devoted a whole chapter of his *zīj* to an account of annular eclipses. Thus, in Book III, Section 13, Chapter 22 we read:

> *On knowing the total eclipse in which a ring of light will remain around the circumference of the Sun:*
>
> This will be possible if the [apparent] diameter of the Moon is smaller than the [apparent] diameter of the Sun. Therefore, if, at maximum eclipse, the apparent latitude [i.e., the topocentric latitude] of the Moon is zero, the ring of light, '*ḥalqih az nūr*', will remain around the circumference of the disk of the Sun [and] equal in thickness.
>
> If the Moon has a slight latitude, whose magnitude is less than the subtraction of two diameters [i.e., the apparent diameters of the Moon and the Sun], the ring of light will not be equal in thickness. Thus, if the [apparent] latitude of the Moon is to the south, the thickness of [the ring of] light will be greater in the north direction, and if the [apparent] latitude of the Moon is to the north, it will be greater in the south direction.
>
> If the [apparent] latitude of the Moon is equal with the subtraction of two diameters, the circumference of the circle of the Moon in the one direction will be tangential to the circumference of the circle of the Sun. If the [apparent] latitude of the Moon is to the north, this will be in the north direction and if it is to the south, it will be in the south direction. (Wābkanawī, ff. 126v–127r; my translation).

There is a similar chapter in the *Zīj-i Ashrafī* by Muḥammad b. Abī ᶜAbd-Allāh Sanjar al-Kamālī, a contemporary of Wābkanawī, written ca. A.D. 1300 in Shiraz, Iran (Kamālī, Book V, Sec. 18: ff. 152v-153r; about this *zīj,* see Kennedy 1956a: 124, no. 4; King and Samsó 2001: 44). We also come across a similar phrase in al-Ṭūsī's *Ilkhanid Tables*, Book II, Ch. 9 (al-ūsī, 1: f. 24r):

> It is possible for the whole of the Sun's disk to be eclipsed and a ring of light, "*ḥalqat al-nūr*", remains, if the apparent latitude [of the Moon] is not zero.

However, it is clear that the *Ilkhanid Tables* actually do not refer to an annular eclipse because the principal condition of an annular eclipse (that the Moon's apparent diameter is less than that of the Sun) is not mentioned. Nonetheless, these statements from the late Islamic medieval period contain clear and direct hints of the possible occurrence of annular solar eclipses. Accordingly, we can deduce that the astronomical context in which Wābkanawī and Kamālī were working allowed them to view an annular eclipse as a *justified* phenomenon. In other words, Wābkanawī and his contemporary, Kamālī, believed that changes occur in the angular diameter of the Sun due to variations in the distance from the Earth to the Sun in the course of a year. Not only do they mention that the solar diameter varies (which is a non-Ptolemaic remark), but in their own *zīj*s Wābkanawī (Bk. III, Sec. 11, cap. 2, ff. 112r-113r) and Kamālī (Bk. V, Sec.11, ff. 140v-141r) present some formulae for determining the apparent diameters of the Sun and the Moon.

The first question to ask here is whether those formulae—which we shall discuss shortly—appeared for the first time in the astronomical tables of Wābkanawī and Kamālī, or did they simply 'borrow' them from earlier astronomers?

The answer is that they took them from earlier writers, for we find these formulae in the *Zīj al-ᶜalā'ī* by a certain ᶜAbd al-Karīm al-Fahhād, which was written ca. AD 1176 (see Kennedy 1956: 135, no. 84; King and Samsó 2001: 45; Pingree 1985: 155f), and in Khāzinī's *Zīj al-muᶜtabar al-Sanjarī* (which dates to AD 1115), and also in Khāzinī's *Wajīz* (Khāzinī 2:f. 21r). This work is valuable because it includes marginal notes that mention all of the numerical values that were applied in the formulae found in Khāzinī's *zīj*.[4]

[4] For details of this *Zīj* see Kennedy (1956: 129, no. 27) and King and Samsó (2001: 45), and for its geographical tables, see King (1999: 71f).

Both Wābkanawī and Khāzinī were especially in favour of studying solar and the lunar eclipses. As we can see in his *zīj*, Wābkanawī knew Khāzinī's work well, and he taught Gregory Chioniades about it, and Chioniades then translated it into Greek (Leichter 2004). In the *Zīj al-Sanjarī*, we also find an incidental reference to annular eclipses, although there is no reference to complicated variances in their appearances, as can be found in Wābkanawī's account, or mention of an actual example (Khāzinī 2, f. 28r; Leichter 2004: 129). In this context it is worth noting that between AD 1050 and 1135 no annular or hybrid eclipses were visible from Marw ($\phi = 37°\ 36'$ N and $L = 61°\ 50'$ E) where Khāzinī was based. If we pursue this historical line we end up with al-Battānī's *Zīj al-<.>Sābi* where we find criticism of some of the values derived from observations made by Ptolemy. Al-Battānī (ca. AD 858–929) gives the variation of the apparent diameter of the Sun based on Ptolemy's observations as 31′ 20″ to 33′ 40″, and of the Moon as 29′ 30″ to 35′ 20″, and he also provides a formula for determining the lunar diameter (see Nallino 1899(1): 58; Swerdlow 1973: especially 99–100).

The second, and more important, question is this: from what source(s) and from which astronomical tradition(s) did these formulae originate? As we travel back through history, we finally find the origin of these formulae in Indian astronomical traditions which had a prominent effect on early Islamic astronomy (such as al-Khwārizmī's *zīj*).[5]

From the historical chain of events presented here, we can distinguish the important presence of Indian-originated formulae in medieval astronomy, which was not reduced by the passage of time. Moreover, it is worth mentioning that besides the Islamic *zīj* literature, in his *India* Abū al-Rayḥān al-Bīrūnī (AD 973–1048) presents a detailed critical discussion of the methods the Indians employed in determining the angular diameters of the Sun, the Moon and the Earth's shadow, as well as other aspects of Indian astronomy. His discussion put other medieval Islamic astronomers directly in touch with Indian concepts and their fundamental theoretical basis (e.g. see Bīrūnī 1964: 62–80). However, most medieval astronomers did not blindly follow this Oriental tradition. As we shall see below, instead they incorporated the Indian formulae within the framework of Ptolemaic astronomy. These revised formulae, along with the critical work of al-Battānī, made their way into European astronomy during the late medieval period (see Swerdlow 1973: 98, 105 n. 9).

2.2 *Formulae of Indian Origin Viewed in Medieval Astronomical Context*

First we will commence by expounding the Indian hypotheses on the angular diameters of the Sun and Moon. Then, we will focus on the modifications and improvements that were made, and on the new formulae that evolved during the medieval period.

[5] However, in Al-Khwārizmī's *zīj* the variation in the solar diameter is listed as from 31′ 20″ to 33′ 48″, and the lunar diameter from 29′ 16″ to 34′ 34″ (see Neugebauer 1962: 105–106).

The Indian hypotheses for determining the solar and lunar angular diameters probably originated from the Greeks, and may be summarized as followings:

1. One arc minute in the lunar orbit equals 10 or 15 *Yojana*s (depending on which Indian tradition is adopted—see Pingree 1976: 121; the *Yojana* is an Indian unit of the length of between 4 and 9 miles). Thus, the apparent angular diameters of the Sun and the other planets at their mean distances from the Earth (i.e., when the planets have mean angular velocities, $\bar{\omega}$) are computed by drawing an analogy between the ratio of their sizes and distances from the Earth and the lunar size and distance to the Earth. This is done by multiplying their actual diameters (in *Yojana*s) either by the proportion of the Moon-Earth distance to their distances to the Earth, or by the proportion of the number of their revolutions in a given period (e.g., in *Kalpá*) to the number of the Moon's revolutions in that same period (see below).
2. The angular diameter of a planet is one variable function of its angular velocity and/or its distance from the Earth. When a planet is at apogee, its maximum distance from the Earth, its angular velocity is minimum, and vice versa in the case of perigee.

By applying these hypotheses, as we see in *Súrya Siddhánta*, IV, 1–5 (1861:41), the Indian formulae for calculating the angular diameters of the Sun and Moon are

$$\vartheta_S = \frac{1}{15} D_S \frac{R_S}{R_M} \frac{\omega_S}{\bar{\omega}_S} \tag{1}$$

$$\vartheta_M = \frac{1}{15} D_M \frac{\omega_M}{\bar{\omega}_M} \tag{2}$$

where ϑ_S and ϑ_M are the apparent angular diameters of the Sun and the Moon; D_S and D_M, the diameters of the Sun and the Moon (in *Yojana*$_s$); $\bar{\omega}_S$ and $\bar{\omega}_M$, the mean diurnal velocity of the Sun and of the Moon; and ω_S and ω_M, the true diurnal velocity of the Sun and of the Moon, the *Buht* of the Sun/Moon, which is the Arabized form of the Sanskrit term 'Bhukti'(*Súrya Siddhánta* 1860: 14). Also, in Indian astronomy (e.g. the *Súrya Siddhánta*, III, 45:1861:39) 'Bhukta' is defined as that point on the ecliptic which the Sun has passed and 'Bhugya' is that point on the ecliptic which the Sun has yet to pass; and R_S and R_M are the number of revolutions of the Sun and of the Moon in one *Kalpá*—i.e., 4,320,000,000 years (Pingree 1976: 119).

Substituting the numerical values for $\bar{\omega}_S$, $\bar{\omega}_M$, R_S and R_M (Pingree 1970; also see Pingree 1976: esp. 121), we have for the Sun:

$$\vartheta_S = \frac{1}{15} \cdot 6{,}500 \cdot \frac{4{,}320{,}000}{57{,}753{,}336} \cdot \frac{\omega_S^{\circ/d}}{0;59,8,16^{\circ/d}}$$
$$= 32;53\left[\approx 33;0\right] \cdot \omega_S^{\circ/d}$$

and for the Moon:

$$\vartheta_M = \frac{1}{15} \cdot 480 \cdot \frac{\omega_M{}^{\circ/d}}{13;10,35^{\circ/d}}$$
$$= 2;25,26 \left[\approx 2;26\right] \cdot \omega_M{}^{\circ/d}$$

where the results for ϑ's are in arc minutes.

As we see, after entering the numerical data we will have a constant in the above formulae, so we may rewrite (1) and (2) as

$$\vartheta = k \cdot \omega \quad (3)$$

The value of the constant, k, depends on the unit applied for ω, °/d or °/h. For the Sun, if ω_S is in °/d, then k_S = 0;33, and if ω_S is in °/h, then k_S = 13;12. For the Moon, if ω_M is in °/d, then k_M = 0;2,26, and if ω_M is in °/h, then k_M = 0;58,24. It is clear that by applying these values for k, the results of ϑ will be in degrees.

2.3 Medieval Procedure

Formula (3), above, was the standard formula for calculating the angular diameters of the Sun and Moon in medieval Islamic astronomy. It seems that medieval astronomers did not know the relationship between (1), (2) and (3), i.e. how (3) is derived from the two or how the constant k is produced, because they were clearly using different and various magnitudes for D_S and D_M. The Indian astronomical texts available to them (e.g. *Khaṇḍakhādyaka*) did not give any information about this. In his *India*, Bīrūnī (1964: 79–80) also only mentions the formulae without explaining them.[6]

Wābkanawī, however, accepts $\vartheta_S = 0;33 \cdot \omega_S$ as an approximate formula, but his principal method for determining ϑ_S and ϑ_M (which he calls the 'verified method') is fundamentally different from formula (3). His formula was in fact inherited from a distinguished astronomer named Muḥyī al-Dīn al-Maghribī (ca. d. AD 1283), who was active at the Maragha Observatory.

In spite of the works of the Indians, al-Battānī, Khāzinī and Kamālī, Muḥyī al-Dīn accepted the Ptolemaic assumption of the equality of the solar and the lunar apparent diameters when both bodies are at their apogees, i.e. when $C = \alpha = 0$. C is the 'solar true anomaly', i.e. the angular distance of the Sun at any moment counted from its apogee measured from the centre of the Earth, while α is the 'lunar true

[6] Prior to the publication of this paper, Neugebauer (1962: 57–58) had only discussed Indian formula (3), found in al-khwārizmī's *zīj*, which was based on the *Khaṇḍakhādyaka*. The first edition of the latter work was published in 1934 (see Brahmagupta 1934 in the reference list), but for this study I have used the more recent edition (Brahmagupta 1970: 62 and 118–120).

anomaly', i.e. the magnitude of the arc on the epicycle between the centre of the Moon and its true apogee.[7]

Based on either actual observations, say, those reported by Bīrūnī (see Sect. 3.2.3) or the Indian formulae, the Ptolemaic assumption of $\theta_S = \theta_M$ at the apogees of the Sun and Moon must no longer had been followed by the medieval astronomers. Nevertheless, Muḥyī al-Dīn al-Maghribī and a number of other astronomers from the medieval period (and even later—e.g. see Kepler 1990: 876) did accept it.[8] This was simply because the equality of the angular apparent diameters of the Sun and Moon acted as a fundamental assumption, whereby the Sun-Earth distance was calculated from the Moon-Earth distance (*Almagest*, V, 15; cf. Neugebauer 1975: 109–112; Pedersen 1974: 209–213).[9] Moreover, Aristotelian natural philosophy had rejected the existence of a vacuum in the spaces between the celestial spheres; therefore, the minimum distance of an upper planet from the Earth was assumed to be equal to the maximum distance of a lower planet from the Earth. From these two considerations, the successive distances of the planets could be established, so that Mercury and Venus lay between the Moon and the Sun, and the other planets were located in their own proper places above the Sun. Therefore, to remove that fundamental assumption led directly to a collapse of the cosmology founded by Ptolemy in the *Planetary Hypotheses*, from which an essential part of the medieval Astronomy—the so-called "Science of distances and bodies"—had evolved.

The other note is that Muḥyī al-Dīn introduces the value of 31′ 8″, instead of the Ptolemaic figure of 31′ 20″, for the minimum angular diameters of the Sun and Moon. The value 31′ 8″ cannot be derived from (3) with the afore-mentioned values for k and Muḥyī al-Dīn's value for the minimum solar velocity (Table 1). This was one of the non-Ptolemaic values for the minimum solar apparent diameter used in the medieval period.[10] In fact, surprisingly, the figure of 31′ 8″ is the result of data pre-

[7] The Ptolemaic solar and lunar models have been studied and described extensively in the secondary literature and for this reason we need not deal with them here. Two standard references are Neugebauer (1975: Volume 1) and Pedersen (1974).

[8] For instance, Kepler denies that the eclipse of AD 1567 April 9 observed by Clavius was annular because at the time the Moon was about midway between apogee and perigee and the Sun was drawing towards apogee. Thus, the Sun must appear smaller than the Moon (see Lynn 1896: 333). However, modern computations indicate that the solar and lunar apparent diameters were almost identical (see Stephenson 1997: 411, including Fig. 11.7).

[9] It is of interest to note that the value of 1,210 terrestrial radii that Ptolemy reported in *Almagest*, V, 14 for the distance to the Sun was assumed in later Greek writings to be its mean distance to the Earth. As far as the Ptolemaic assumption was concerned that the angular diameter of the Sun was always equal to 31′ 20″, this result was of little consequence.

[10] Elementary Islamic astronomical treatises often mentioned the rounded values of 31′ and 33′ respectively for the minimum and maximum apparent solar diameter; and 29′ and 36′ respectively, for the minimum and maximum apparent lunar diameter. For instance, see al-Ṭūsī's *Memoir* (1993: 236/237) and al-Shīrāzī's *Nihāya* (f. 134r). A scholar who was a contemporary of Wābkanawī was Niẓām al-Dīn' Aʿraj al-Nīshābūrī, and in his commentary on al-Ṭūsī's *Memoir*, titled *Sharḥ al-Tadhkira* (*Explanation of Memoir*, which was completed on AD 1311 July 18) he gives minimum and maximum values for the Sun's apparent diameter as 31′ 3″ and 33′ 33″, respectively (al-Nīshābūrī, f. 69v).

Table 1 Muḥyī al-Dīn's s extreme values of the velocities and the apparent diameters of the Sun and the Moon

	ω_{max} (°/h)	ω_{min} (°/h)	ϑ_{min}	ϑ_{max}
Sun	0;2,22,12	0;2,31,52	31′ 8″	33′ 20″
Moon	0;29,30	0;37,0	31′ 8″	35′ 20″

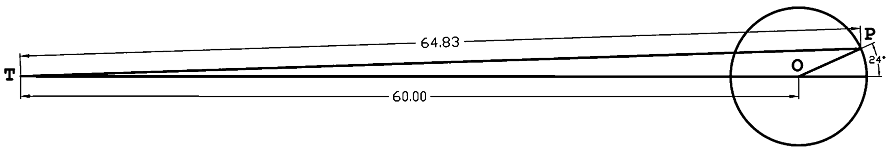

Fig. 1 The Moon revolves on its epicycle of radius 5;15^p clockwise (the lesser circle of the centre O), while O revolves counter–clockwise around the Earth's centre T. According to the Ptolemaic lunar model, if in a true syzygy (e.g., in the maximum phase of an eclipse, either solar or lunar) the Moon is 24° removed from its true apogee, its distance from the Earth's centre being around 64.83^p (≈64;50^p)

sented by Ptolemy himself! In *Almagest*, V, 14, Ptolemy calculates the apparent diameter of the Moon according to data obtained from Babylonian observations of two lunar eclipses that occurred on 21/22 April 621 BC and 16/17 July 523 BC (see Pedersen 1974: 208–209; Toomer 1998: 253–254). He derives the value of 31′ 20″ at the instant of the maximum phase of the two eclipses, which he assumed to be the "minimum lunar angular diameter". Based on data presented by Ptolemy, Muḥyī al-Dīn realized that from its orbital positions at the times of the two eclipses, the Moon was not at perigee, consequently the figure of 31′ 20″ could not be the value for the Moon's minimum apparent diameter. Then, he went on to calculate this figure himself. Based on Ptolemy's data, the angular distances of the Moon from its true epicyclic apogee at the time of the two eclipses were respectively 20° and 28°. The mean value of 24° meant that the Moon was placed at a distance of 64;50^p from the Earth. Note that in Ptolemaic astronomy the radius of the Moon's deferent was assumed to be 60^p (where ^{p} is an arbitrary length unit), and that of its epicycle 5;15^p. This is illustrated schematically in Fig. 1, which is drawn to scale. Thus, the apparent diameter of the Moon at its greatest distance from the Earth should be equal to (64;50×31′ 20″)/65;15=31′ 8″ (al-Maghribī, *Talkhīṣ*: f. 94r).

Actually, this value is questionable, because Muḥyī al-Dīn applied the figure of 2;5;59^p (if the radius of the Sun's deferent is assumed to be 60^p) for the eccentricity of the Sun, having obtained this value from three observations made in Maragha during AD 1264–1265 (al-Maghribī, *Talkhīṣ*: ff. 58v-61v; cf. Saliba 1994: 173f). That value is smaller than the Ptolemaic one of 2;30^p. As a result, the minimum solar diameter should be slightly larger than the Ptolemaic figure of 31′ 20″, rather than being smaller than it. The same logic applies for the measurement of the distance from the Sun to the Earth by al-Battānī, who used the figure of 2;4,45^p for the solar eccentricity, but his $\theta_{S,\min}$ has the Ptolemaic value of 31′ 20″. This strange situation has its roots in the very nature of the measurements of planetary distances in the medieval period, which, as we have said, lay within the framework established by Ptolemy in *Almagest* V, 14 and in his *Planetary Hypotheses*. The sequence of steps involved in calculating solar distances in medieval Islamic astronomy may be described as follows:

1. The minimum and maximum solar angular velocities were calculated with the aid of an acceptable figure for the solar eccentricity (which was often different from the Ptolemaic one of 2;30^p).
2. Then, these values were inserted in formula (3) listed above, along with the afore-mentioned values for the coefficient *k*.
3. The resulting values of θ were then used to geometrically determine the mean or maximum distance from the Earth to the Sun, based on the Ptolemaic method.

This process produced some rather strange outcomes. For example, the Ptolemaic maximum solar distance was 1,260 times the Earth's radius, and $\theta_{S,min}$ was 31′ 20″, while al-Battānī has the maximum solar distance at 1,146 terrestrial radii, but with the same value for $\theta_{S,min}$. This means that the true radius of the Sun must be about 9 % smaller than its Ptolemaic magnitude, but nowhere is such a thing mentioned. We do not need to discuss this problem here. It is sufficient to show that the Indian formulae were used not only in determining the angular diameters and the type and the magnitude of an eclipse, but also for measuring cosmic distances.

In order to determine ϑ_S and ϑ_M when C or $\alpha \neq 0$, Muḥyī al-Dīn employed the simple method of the linear interpolation, which can be expressed mathematically by the following formula:

$$\vartheta = \vartheta_{min} + \left(\vartheta_{max} - \vartheta_{min}\right)\frac{\omega - \omega_{min}}{\omega_{max} - \omega_{min}} = \vartheta_{min} + \left(\vartheta_{max} - \vartheta_{min}\right)\frac{C(\text{or}\,\alpha)}{180} \qquad (4)$$

in which his 'new' numerical values for the solar and lunar parameters shall be substituted (see Table 1). For Muḥyī al-Dīn (and also Wābkanawī), the variation in the solar apparent diameter was from 31′ 8″ to 33′ 20″, while for the Moon it was from 31′ 8″ to 35′ 20″.

Muḥyī al-Dīn's new values for ω are the results of using a new set of fundamental planetary parameters measured by him at Maragha Observatory during the 1260s:

The Sun's eccentricity $e = 2;5,59^p$ (Ptolemy: 2;30^p),
The Moon's epicycle radius $r = 5;12^p$ (Ptolemy: 5;15^p),
The moon's eccentricity $e = 9^p$ (Ptolemy: 10;19^p),

and the mean lunar velocities:

in longitude: $\omega_t = 13;10,35,1,52,46,45$°/d (Ptolemy: 13;10,34,58,33,30,30 °/d) and
in anomaly: $\omega_a = 13;\ 3,53,42,51,19,\ 0$ °/d (Ptolemy: 13; 3,53,56,17,51,59 °/d).

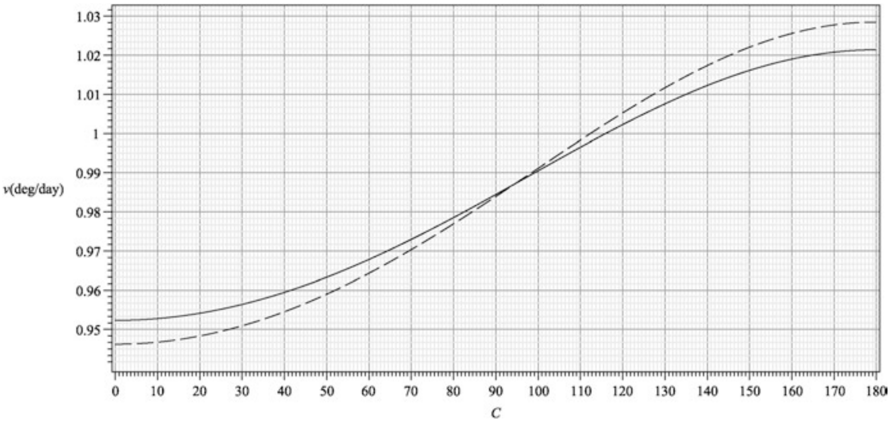

Fig. 2 The solar instantaneous velocity according to the parameters of Ptolemy (*dash curve*) and Muḥyī al-Dīn (*continuous curve*)

The equations needed to determine the true longitude of the Sun and Moon were calculated based on these parameters, which were tabulated in his *Zīj*. Then, the instantaneous velocities could be calculated based on the instructions given in the *Almagest*, VI, 4. Here, we do not deal with the rules for the calculation of instantaneous planetary velocities within the Ptolemaic model (which are discussed in Neugebauer 1975: 122 and Pedersen 1974: 223–224; for a medieval improvement over Ptolemy's method, see Goldstein 1996). A recalculation using Muḥyī al-Dīn's tables of planetary equations yields the following values for the instantaneous angular velocities:

$$\text{Sun}: \text{minimum} = 0;2,22,50° / \text{d}, \text{maximum} = 0;2,33,14° / \text{d}$$

$$\text{Moon}: \text{minimum} = 0;29,40,31° / \text{d}, \text{maximum} = 0;36,49,49° / \text{d}.$$

This indicates that Muḥyī al-Dīn applied rounded values in the case of the Moon. The graphs in Figs. 2 and 3 show the variations in the solar and lunar angular velocities when applying Muḥyī al-Dīn's parameters, compared with Ptolemy's in each case. Now, we can calculate the apparent diameters directly from the anomalies of the Sun and Moon, C and α. Figure 4 shows the variation in θ as a function of anomaly. Clearly, Muḥyī al-Dīn's theory of eclipses shows a limitation in predicting annular eclipses. For example, when $C = 92°$ (i.e. when the Sun is located at its mean distance from the Earth) α must be <68° or >292° at the instant of the true conjunction if the eclipse is to be annular; if $C = 15°$: α <10° or >350°; if $C = 145°$: α <96° or > 264°; and so on.[11]

[11] Note that the optical limitation of the visibility of a solar eclipse in the modern sense is not the case here. However, a similar kind of limitation existed in medieval astronomy, and dates back to India—see Sect. "3.2.4" (5).

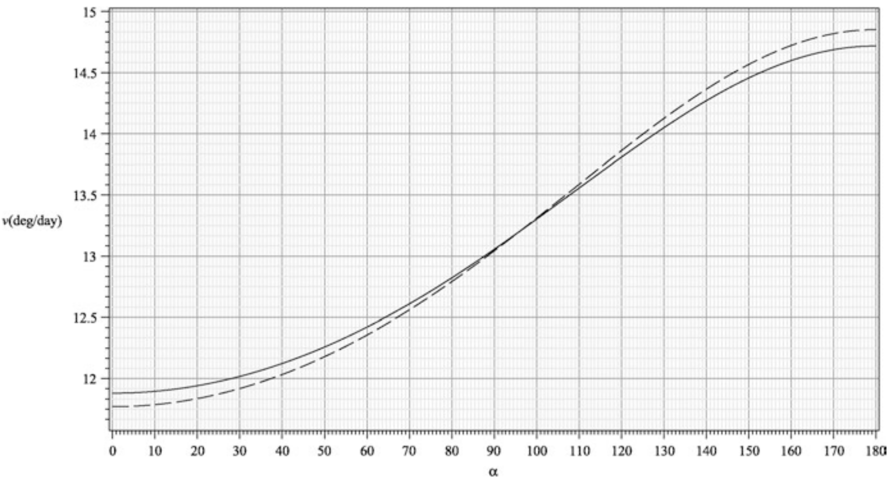

Fig. 3 The lunar instantaneous velocity according to the parameters of Ptolemy (*dash curve*) and Muḥyī al-Dīn (*continuous curve*)

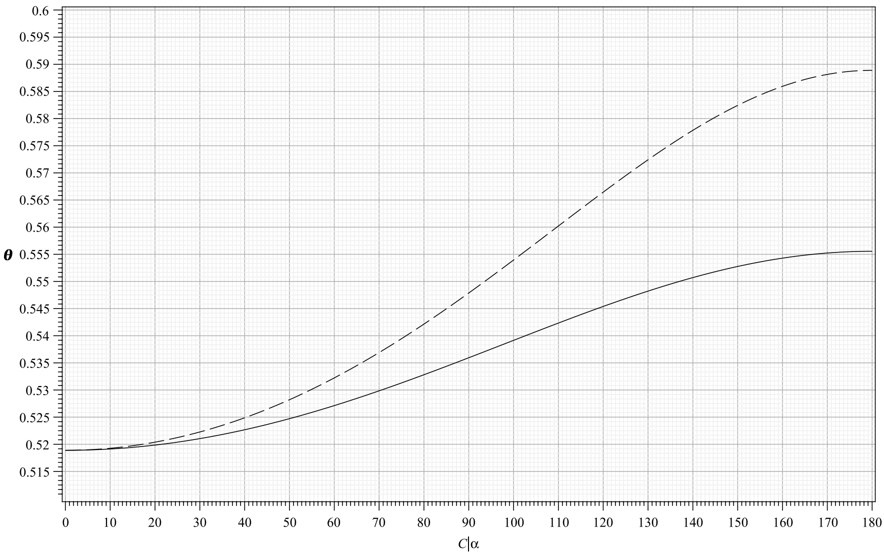

Fig. 4 The angular diameters of the luminaries (Sun: *continuous curve*, Moon: *dash curve*) as a function of their anomalies (*C* or α) based on Muḥyī al-Dīn's parameters

2.4 The Results in an Historical Context

Now, we attempt to place these data, in the case of the Sun, in an historical context. It is interesting to compare them with some systematic measurements and calculations made during the medieval period (Table 2):

Table 2 Values of the angular diameters of the Sun after Ptolemy and obtained during the medieval period

ϑ_S	Min	Max	Mean
Ptolemy	31′ 20″	31′ 20″	31′ 20″
al-Khwārizmī	31′ 20″ [P]	33′ 48″ [C]	32′ 34″
al-Battānī	31′ 20″ [P]	33′ 40″ [C]	32′ 32″
Muḥyī al-Dīn	31′ 08″ [C]	33′ 20″ [C]	32′ 14″
Levi b. Gerson	27′ 51″ [O]	30′ [O]	—
Ibn al-Shāṭir	29′ 05″ [O]	36′ 55″ [O]	32′ 32″
Kepler	30′ [O]	31′ [O]	—
Modern	31′ 29″	32′ 39″	32′ 04″

Key: [*P*] Ptolemaic, [*O*] observation, [*C*] calculation. The calculated values have mostly based been derived from the Indian formulae by applying the values for the solar velocities as listed in Table 3 to them, or have been computed with the aid of linear interpolation. The exception is Muḥyī al-Dīn's value of $\theta_{S,min}$, which, as already mentioned, is based on Ptolemy's recorded data

Table 3 Some values for ω_S in the Islamic medieval astronomy

ω_S	Min (°/h)	Max (°/h)
al-Khwārizmī	0;2,22	0;2,34
al-Battānī	0;2,23	0;2,33
Muḥyī al-Dīn	0;2,22,12	0;2,31,52

– The measurements of ϑ_S made by Levi b. Gerson (Gersonides, AD 1288–1344) by utilizing the camera obscura at the times of the summer and winter solstices on 14 June and 13 December 1334 were 27′ 51″ and 30′ (Mancha 1992: 292). These differ from the correct values by about 2.5′ and 3.5′, respectively.
– Ibn al-Shāṭir of Damascus (AD 1305–1375) determined the variation range of ϑ_S as 29′ 05″ to 36′ 55″, and the mean solar diameter as 32′ 32″, based, he claims, on direct observations, but he makes no mention of his methods or the instrument(s) that he used (Saliba 1987: 41).
– Gemma Frisius (AD 1508–1555), reports ϑ_S = 33′ on 27 October 1544, before sunset (Goldstein 1987: 172–173). On that day the time of sunset in Louvain, his observing site (ϕ = 50° 53′ N and L = 4° 42′ E), was about $19^h\ 38^m$. The true value of ϑ_S on that date was 32′ 53″.
– We also find Kepler's values for the maximum and the minimum apparent solar diameter of 31′ and 30′ respectively, based on direct observations made with the aid of a camera obscura. The differences from the true (modern) ones are 89″ and 99″. Kepler, as with Copernicus, knew of al-Battānī's work (Sigismondi and Fraschetti 2001).

These values were compared with each other and with the true range of variation of the solar diameter (31′ 29″–32′ 39″),[12] and the results are summarized in Table 2. As we can see, the difference between the observationally-derived values and the

[12] However, the Sun is a gaseous sphere without fixed and stable boundaries. In addition, a number of researchers have shown that changes have occurred in the solar diameter during recent centuries, and have suggested that some modification is required to its accepted range of 1924″ ± 35″ (e.g. see Toulmonde 1997; Wittmann 1977).

true modern ones diminished perceivably with the passage of time. An interesting thing to note is that the methods of Indian origin, and their modified versions, gave relatively accurate results when compared with the values obtained from direct observations. However, the superiority of the theoretical approach over direct observations was solely due to the systematic errors associated with the instruments used by Levi and Kepler, namely the Jacob Staff and the camera obscura respectively (e.g. see the analysis in Sigismondi and Fraschetti 2001).

It is noteworthy that Ibn al-Shāṭir's values listed in Table 2 lie outside the true range, yet he and Levi are historically of importance because both were known as reformers of Ptolemy's planetary models. Ibn al-Shāṭir claims that he founded his own solar model on the basis of his observations of the apparent diameters of the Sun and Moon, but it seems that he actually invented values for ϑ_S in order to demonstrate the correctness of his model. On the one hand he most likely knew about the afore-mentioned Indian-originated formulae that had been used by Islamic astronomers for 400 years and he probably was aware that they were relatively consistent with observations but, conversely, did not support his solar model. On the other hand, his value for ϑ_S when the Sun was at its mean distance from the Earth suggests that he made use of formula (3) rather than conducting his own observations, because $\vartheta_S = 0.33 \times (360/365.25) = 32'\ 31.54'' \approx 32'\ 32''$.

3 Discussion

3.1 Annular and Hybrid Eclipses

Annular and hybrid solar eclipses are more frequent than total solar eclipses (statistically, computations show that during the past 5,000 years there have been ~25 % more annular and hybrid eclipses than total solar eclipses). Nevertheless, as we have seen, throughout history annular and hybrid eclipses were not a main topic of discussion amongst astronomers, and often were treated with indifference, or neglected altogether. There were probably historical and astronomical reasons for this. We have already discussed the former, while the latter involved a diminution of light during an annular eclipse that often was so small that it did not attract much attention (e.g. see Stephenson 1997: 62).

3.2 Indian and Greek Astronomical Traditions in Relation to Annular Eclipses

3.2.1 The Role of Indian Astronomical Theory in Justification of the Phenomenon

The fundamental hypotheses of any scientific tradition determine what a scholar is able, or should expect, to see. In the case of annular eclipses, the Indian hypotheses, in particular, were very valuable, because they provided a suitable context within which an astronomer was able to observe certain celestial phenomena, including annular eclipses, which it was not possible to observe in the Ptolemaic tradition. But the medieval Islamic astronomers used the traditions of both their Western and Eastern neighbours. Thus, they used Ptolemy's model to determine the majority of the eclipses' positional parameters, and then by applying the Indian formulae, they could estimate the angular diameter of the Sun and Moon and then determine if an annular eclipse would occur. If the power of a theory depended upon its ability to forecast future phenomena, then the Indian hypotheses relating to variations in the angular diameters of the Sun and Moon were invaluable, owing to the fact that they gave rise to the justification or establishment of a phenomenon in the context of medieval astronomy.

3.2.2 The Phenomenon: A Case of the Synthesis of Indian and Greek Astronomy

The calculation of θ depends on the instantaneous angular velocity. Although the medieval formulae for calculating the angular diameters originated in India, but the angular velocities of the Sun and Moon—as we saw—were calculated on the basis of Ptolemaic method outlined in the *Almagest* (VI, 4), implemented with a minor refinement made during the medieval period. Therefore, we see here a synthesis of Indian and Greek astronomy, or strictly speaking, a successful mixing of the relatively simple formulae with a carefully-calculated variable. In medieval astronomy there were some precedents for syntheses like this (e.g. using crude Indian formulae to determine planetary latitudes with the basic parameters supplied in Ptolemy's *Handy Tables* in *Zīj al-Mumtaḥan*—see Viladrich 1988: 266), but none of them was as successful as in the case of the annular solar eclipses.

3.2.3 Bīrūnī's Treatment of the Phenomenon

It is usually assumed that the influence of Indian astronomy on Islamic astronomy was restricted to the early periods and quickly disappeared after the adoption of Ptolemy's *Syntaxis* by the Islamic world, but as we have seen Indian methods of astronomical calculation continued to be used by Islamic astronomers right up to the thirteen century. It seems that the observation of the annular eclipse of AD 873, which revealed the defects of Ptolemy's considerations of the apparent diameter of the Sun, paved the way for the continued use in the Islamic world of Indian hypotheses concerning the angular diameters of the Sun and Moon. Support comes from Bīrūnī's *al-Qānūn al-masᶜūdī*. Besides the annular eclipse, other evidence also guided the medieval astronomers to cast doubt on the Ptolemaic hypotheses of the angular diameters of the Sun and Moon. According to what a medieval astronomer could understand from the *Almagest*, except for the total solar eclipse in which both the Sun and the Moon were near their own apogees, all other eclipses *must* show an interval of darkness. For instance, when the

Moon is near its perigee, the difference in the angular diameters of the Sun and the Moon is 4′, and according to the tables of eclipses in the *Almagest*, VI, 8, the magnitude of a solar eclipse occurring under these conditions is 12 4/5 digits. As a result, such an eclipse must show a perceptible duration of darkness of around 8 min in places where the eclipse is central. Thus, in the table of solar eclipses in the *Almagest* (VI, 8), a fifth column with only one entry is needed to show the motion of the Moon from the instant of the complete immersion through to the instant of the maximum phase (like the procedure adopted for the lunar eclipse table in the *Almagest*). In fact, such an entry had already been included in the *Almagest*'s table of solar eclipses, but most Arabic copies of the *Almagest* have omitted this one-entry column (e.g. see Toomer 1998: 305, n. 63, tables on 306–307). As a result, the possibility exists that the medieval Islamic astronomers were wrongly assuming that Ptolemy neglected solar eclipses showing a perceptible duration of darkness as well as annular ones. In his *al-Qānūn al-Mas*ᶜ*ūdī*, before he reports on Īrānshahrī's observation of the annular eclipse of AD 873 Bīrūnī mentions as evidence the observation by Muḥammad b. Isḥāq al-Sarakhsī of a total solar eclipse on AD 876 May 27:

> On 12 Urdībihisht 245 Yazdgirdī era (=AD 876 May 27 or JDN 2041164), Muḥammad b.'Isḥāq al-Sarakhsī observed the full duration (*Makth*, lit. "staying") of the solar eclipse that occurred in his city. That does not contradict what Ptolemy said; rather it supports it. (Bīrūnī 1954: 2, 632).[13]

The duration of this eclipse in Sarakhs, a city located in the northeast of Iran ($\phi = 36°\,30'$ N and $L = 61°\,12'$ E), was around 3 minutes (magnitude of eclipse = 1.03), and on this date the Moon was at its minimal distance from the Earth.

Bīrūnī then reports Īrānshahrī's observation, and then makes the following comments:

> From that [i.e. Īrānshahrī's observation], it is clear that the apparent diameter of the Sun may be larger than that of the Moon. And, concepts in India[n astronomical tradition(s)] (*uṣūl al-hind*) testify to this … [and] The Indians obtain them [i.e. the apparent diameters of the Sun and Moon] only by a *theoretical* method (*min ṭarīq al-wujūd bi-l-i'tibārāt*). (ibid)

This phrase, "… by a *theoretical* method …" perhaps means through estimations, and probably emphasizes that there was no high level of certainty of precision. Whether or not Bīrūnī meant to reject the observation of the annular eclipse in India is a different topic (see Sect. 3.3).

Then, Bīrūnī returns to the problem of the perceptible duration of darkness in some solar eclipses and poses the possibility that

> The perceptible duration of darkness we mentioned in the solar eclipse may be due to [1.] the decrease [in the apparent diameter] of the Sun from its mean value, or [2.] the increase [in the apparent diameter] of the Moon [from its mean value, or [3.] both of them. (ibid).

[13] Note that Simplicius (1894: 505.7–8) also mentions solar eclipses showing a perceptible duration of darkness right before his account of the annular eclipse (cf. Bowen 2008: 74).

In the end, Bīrūnī concludes that he has enough evidence to reject the homocentric model of Abū Ja^{c}far al-Khāzin,[14] and "What Abū Ja'far mentioned about this issue … does not restrict us, but does Ptolemy." (ibid).

This section of the *al-Qānūn al-mas^{c}ūdī*, often without direct reference to Bīrūnī's book, appears so many times in latter treatises in connection with proving the eccentricity of the solar orbit, rejecting the Ptolemaic hypotheses of the equality of the angular diameters of the Sun and Moon at their greatest distances from the Earth, and/or setting new parameters for them. Examples are Quṭb al-Dīn al-Shīrāzī's *Tuḥfa al-Shāhīyya* (f. 37r; written in Arabic around 1285 AD) and *Ikhtīyārāt-i Muẓaffarī* (f. 49v, written in Persian around AD 1285–1305). However, al-Shīrāzī adds to Bīrūnī's account that (1) in the eclipse that Sarakhsī observed, the Sun had its minimum velocity; (2) in the eclipse Īrānshahrī observed, the Sun was in its period of increasing velocity; and (3) the distance of the Moon from the Earth on both occasions was the same. However, the two first statements seem clear with regard to the timing of the eclipses, but the last statement, of course, does not appear in the *al-Qānūn al-mas^{c}ūdī*. Al-Shīrāzī' then states:

> Thus, based on these facts, astronomers have recently inferred that when the Sun has its minimum velocity it is further from the Earth, and when it has its maximum velocity it is closer to the Earth. (ibid)

In fact, in adding the above-mentioned statement (3) to Bīrūnī's account, al-Shīrāzī cites the variations in the solar diameter as a proof of the way in which its distance to the Earth varies, and he then proceeds to emphasize that

> Although the *early astronomers did not find any difference in the apparent solar diameter* due to the remoteness or closeness of the Sun to the Earth, they also reached to the same conclusion [i.e. that the solar distance to the Earth varied]. Since the period when the Sun moves slowly in its orbit is longer than the period when it moves quickly, this is proof of it. (ibid.; my italics).

Finally, it is sufficient to say that Bīrūnī's clear reference to Indian astronomical tradition leaves no room to doubt the fact that observing annular eclipses in the medieval period resulted in adoption of the Indian formulae and hypotheses relating to the angular diameters of the Sun and Moon, but the medieval Islamic astronomers modified the formulae, then late in the medieval period they passed them on to European astronomers.

3.2.4 The Impact of Indian Astronomy on Islamic Astronomy

The effect of Indian astronomy on medieval Islamic astronomy was not just limited to the angular diameters of the Sun and Moon, and is worth noting here (but a detailed discussion lies beyond the scope of this paper).

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[14] This was just like Sosigenes who, after mentioning the solar eclipses showing a perceptible duration of darkness and annular eclipses, goes to prove the inequality in the *lunar* distance to the Earth (Simplicius 1894: 505, line 10f; cf. Bowen 2008: 74f). There is a strange parallel in the two texts even though they are more than 400 years apart.

Other examples that can be cited include:

1. The non-Ptolemaic constants for the arc of visibility of the planets were of Indian origin (e.g. see *Zīj al-Sanjarī*, XI, 5 (Khāzinī 2: f. 34r, Leichter 2004: 141), and *Zīj-i Ashrafī*, V, 7 (Kamālī, ff. 136r-136v). For a general study of this field see Kennedy and Agha (1970). See, also, Al-Ṣūfī (1995: 179, cap. 151) and Kennedy (1983: 412).
2. The colours of lunar eclipses, which are described—but not in much detail—in Ptolemy's *Tetrabiblos*, II, 10 (Ashmand 1822: 95–96); *Súrya Siddhánta*, VI, 23 (1861: 55), *Āryabha.tīya*, IV, 46 (1930: 81); cf. *Zīj al-Sanjarī* (Khāzinī 1: f. 79r) and Wābkanawī's *Zīj*, III, 12.10 (ff. 117r-117v).
3. Projection of eclipses (see *Súrya Siddhánta*, VI (1861: 52f); cf. Wābkanawī's *Zīj*, III, 12.9 and 13.26 (ff. 116r-117r and 127v-128r)).
4. Calculation of parallax: see Wābkanawī's *Zij* (III, 12.14 (ff. 123r-125r), where he compares and contrasts the Indian and Greek methods. See, also, Kennedy (1956b: 46–47).
5. Limitations on the visibility of eclipses: *Súrya Siddhánta*, VI, 13 (1861: 54), *Āryabha.tīya*, IV, 47 (81); cf. Wābkanawī's *Zīj*, IV, 15.8 (ff. 159r-159v).

3.3 Annular Eclipses in Indian Astronomy

As has been already seen, old Indian hypotheses about the angular diameters of the Sun and Moon proved that an annular eclipse was possible. Therefore, we would expect to find observational reports on these eclipses in the Indian astronomical literature, but in fact no such reports occur (see *Súrya Siddhánta* 1860: 174). Maybe the reason for this is that Bīrūnī, who spent more time in India studying local astronomical traditions than any other medieval astronomer, only mentions that the Indian hypotheses are in agreement with the fact that solar angular diameters may be smaller than the lunar ones, while the actual Indian formulae are *theoretical* (see Sect. 3.2.3). Also, Bīrūnī never said that an account of such a phenomenon in Indian astronomy was available to him. Therefore, we can conclude that in medieval Islamic astronomy the possible existence of the annular eclipse as an observational phenomenon was posed as a first step, and it was only later that an appeal was made to the Indian hypotheses in order to justify (or predict) it.

Yet not all medieval astronomers who were aware of the Indian formula for calculating the angular diameters of the Sun and Moon automatically accepted the possibility of annular eclipses. A good example is al-Battānī who was acquainted with the Indian formulae, and whose range for the variation of the angular diameters of both the Sun and the Moon was very different from Ptolemy's. On the one hand, he decreased the minimum lunar angular diameter to $29' \, 30''$, and, on the other hand, he extended the maximum solar angular diameter to $33'$. Yet he appears not to have see this as justifying the occurrence of annular eclipses, even if both the Sun and the Moon were at their apogees, since he never mentioned or referred to the phenomenon.

(To the best of my knowledge there is no hint of annular or hybrid eclipses in any astronomical records in the Islamic *Zīj* literature that pre-dates Khāzinī.)

4 Concluding Remarks

Although the non-Ptolemaic idea that the angular diameter of the Moon may sometimes be smaller than that of the Sun was widely accepted in early Islamic astronomy, it seems to have been in the late medieval Islamic period that the annular eclipse was accepted as a justified phenomenon. Wabkanawi's report in his *zīj* is a good example. By this time the *Kusūf ḥalqa al-nūr* (literally "bright ring eclipse") had become a well-known term for one of the three different kinds of solar eclipses (total, partial and annular), and was referred to even in elementary educational astronomical treatises.

It is notable that annular eclipses only returned to the astronomical agenda once the concept of homocentric planetary configurations arose, and then was used as conclusive evidence of its glaring deficiency, and thus to disprove it.

The discussion of annular eclipses and variations in the angular diameters of the Sun and Moon clearly illustrates the successful synthesis of different astronomical traditions, with their interaction proving, justifying or predicting these eclipses. Then, as we have seen, annular eclipses played a prominent role in testing the validity of different planetary models.

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The Investigation of Stars, Star Clusters and Nebulae in 'Abd al-Raḥmān al-Ṣūfī's *Book of the Fixed Stars*

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Abstract 'Abd al-Raḥmān al-Ṣūfī (AD 903–986) is justly famous for his *Book of the Fixed Stars*. This is an outstanding Medieval treatise on astronomy that was written in AD 964. This work was developed from Ptolemy's *Almagest*, but was based upon al-Ṣūfī's own stellar observations. The *Book of the Fixed Stars* has been copied down through the ages, and currently 35 copies are known to exist in various archival repositories around the world.

In this paper we begin with a brief introduction to the *Book of the Fixed Stars* and provide biographical material about al-Ṣūfī before reviewing his investigation of stars, star clusters, nebulae and galaxies in his book. We examine al-Ṣūfī's novel stellar magnitude system, his comments on star colours, and stars mentioned in his book but not in the *Almagest*. We conclude with a listing of star clusters, nebulae and galaxies, including the earliest-known mention of the Great Nebula in Andromeda.

1 Introduction to the *Book of the Fixed Stars*

The *Book of the Fixed Stars* was one of the most important books in the history of Arabic and Islamic astronomy (see Brown 2009; Hafez 2010; Hafez et al. 2011). It was written in Arabic around AD 964 by a Persian astronomer named ′Abd al-Raḥmān al-Ṣūfī. The original Arabic name of this book was '*Ṣuwar al-Kawākib al-Thamāniyah Wa al-Ārba'een*' which is translated as *The 48 Constellations*. However, it was later known by other names, the most famous of which was '*Kitāb al-Kawākib al-Thābitah*' or, in English, the *Book of the Fixed Stars*.

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The *Book of the Fixed Stars* contains an extensive star catalogue, which lists star co-ordinates and magnitude estimates. Al-Ṣūfī's original Arabic text contained 55 astronomical tables as well as star charts for 48 constellations. 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. The second group contained the 12 constellations of the zodiac, and the last group contained 15 southern constellations. The book also includes many other topics, such as descriptions of nebulae, notes on star colors, and a wealth of information on ancient Arabic folk astronomy.

Al-Ṣūfī's book was based on Ptolemy's classical work called the *Almagest,* which was written around AD 137 (Evans 1987; Grasshoff 1990; Swerdlow 1992). Al-Ṣūfī updated Ptolemy's stellar longitudes from 137 to 964 by adding 12° 42′ to Ptolemy's longitude values to allow for precession. Al-Ṣūfī starts his book with an introductory Chapter, which is a very important part of his work. He divides those who are interested in learning about the stars into two groups. The first group includes the actual astronomers, which he called '*al-Munajjemun'*. The other group is those who study the old Arabic *Anwā'* tradition. In this introductory chapter al-Ṣūfī criticizes the work of al-Battānī and al-Daīnawari, as well as other important scholars of the period. He mentions the reason he wrote his work, and he dedicates his book to 'Aḍud al-Dawla who was the most important Buyahid ruler at the time. He explains the method he used in calculating precession and explains why he made dual charts of each constellation, and the manner in which these charts should be used. Many scientists and astronomers have based their astronomical observations on al-Ṣūfī's work.

Throughout history al-Ṣūfī's name was sometimes mis-spelt or mis-written. He has been referred to by various names, such as *Esophi* by Leo Africanus and *Azophi* by the Spanish Jewish astronomer Ibn Ezra. He was also referred to as *Azophi* by the sixteenth century European map-makers Albrecht Durer and Peter Apian (Hafez 2010). Figure 1 is a star chart made by Durer, which shows four figures. The first is 'Aratus Cilix' (Aratus of Cilicia); the second 'Ptolemeus Aegyptus' (the Egyptian Ptolemy); the third 'M. Mamlius Romanus' (the Roman Marcus Manilius); and at the bottom right is 'Azophi Arabus' (the Arabic al-Ṣūfī).

There are many manuscript copies of al-Ṣūfī's book that are preserved in libraries throughout the world. In the course of our research, we managed to locate 35 different manuscripts in 16 different countries (Hafez 2010). These are listed in Table 1, grouped by country or the location of the library in which they are kept. There may also be additional, as yet unknown, manuscripts in other libraries or in private collections. The earliest-known manuscript of the *Book of the Fixed Stars* is Marsh144, which dates to AD 1009, just 23 years after al-Ṣūfī's death. This manuscript was actually written by al-Ṣūfī's son, and is now in the Bodleian Library in Oxford. Al-Ṣūfī's work has never been translated into English, but a French translation by Hans Karl Frederic Schjellerup was published in 1874.

Fig. 1 The sixteenth century star chart made by Albrecht Durer

2 Al-Ṣūfī: A Brief Biography

From the few historical records available we know that al-Ṣūfī's full name was ʼAbd al-Raḥmān, Ibn ʼUmar, Ibn Muḥammad, Ibn Sahl, al-Rāzī, otherwise known as Abū al-Ḥusaīn al-Ṣūfī. According to al-Qifṭī, al-Ṣūfī was born on Saturday the 14th of Muḥarram in the year AH 291. This date corresponds to Saturday 6 December in AD 903. He died on Tuesday the 13th of Muḥarram in the year AH 376, which corresponds to Tuesday 25 May in AD 986 (Hafez 2010).

The title '*al-Rāzī*' means that he was from the city of Rayy, south-east of the modern city of Tehran (see Fig. 2). Al-Ṣūfī's family was originally from Nisā or the

Table 1 List of known extant manuscripts of al-Ṣūfī's *Book of the Fixed Stars*

Oxford, Bodleian Library, England (3 MSS)
Istanbul, Topkapi Sarayi, Turkey (4)
Berlin, Ahlwardt, Germany (1)
Vatican, Rossi (1)
Paris, Bibliotheque Nationale, France (4)
Copenhagen, Royal Library, Denmark (1)
St Petersburg, Bibliotheque Imperiale, Russia (3)
New York, Metropolitan Museum of Art, U.S.A. (2)
Beirut, American University of Beirut, Lebanon (1)
London, British Library, England (5)
Madrid, Library Escurial, Spain (1)
Bologna, Collection Marsigli, Italy (1)
Tehran, Majles Library, Iran (2)
Tunisia (1)
Hyderabad, Asafiya Library, India (1)
Washington, Library of Congress, U.S.A. (1)
Cairo, Egyptian Dar books, Egypt (1)
Doha, Museum of Islamic Art, Qatar (1)
Princeton, Princeton University Library, U.S.A. (1)

city of Nisabour in western Khurasan Province in modern-day Iran. Al-Ṣūfī was a Persian not an Arab, even though he wrote all his works in Arabic, which was the preferred language of most scholars and writers at that time. The location of his death is not known, but most probably it was in Shiraz. He lived to be 83, which was a fairly good age for his time. From the introductory chapter in his *Book of the Fixed Stars* we know that he lived most of his life between the provinces of Rayy and Fars and in the cities of Rayy, Esfahan and Shiraz in Iran (see Fig. 2, which shows the provinces of Rayy and Fars in Iran).

In his *Book of the Fixed Stars* al-Ṣūfī wrote that he made his observations from Shiraz, where he established an observatory. He also wrote that he visited Dinawar, which is the home of the famous scholar and astronomer, Abū Ḥanīfa al-Danawari, and that he also visited Esfahan to research a celestial globe constructed by another important astronomer of the period.

3 Al-Ṣūfī's Treatment of the Stars

In his *Book of the Fixed Stars* al-Ṣūfī divides the constellations into 48 chapters, and starts with a detailed commentary for every constellation. In this commentary he describes in detail the number of stars, their locations and their magnitudes. At the end of these constellation chapters Al-Ṣūfī compiles a star catalog or tables for all of the stars that form the image of the constellation. He also draws maps for all the 48 constellations, which are considered a unique feature of his work. However, one

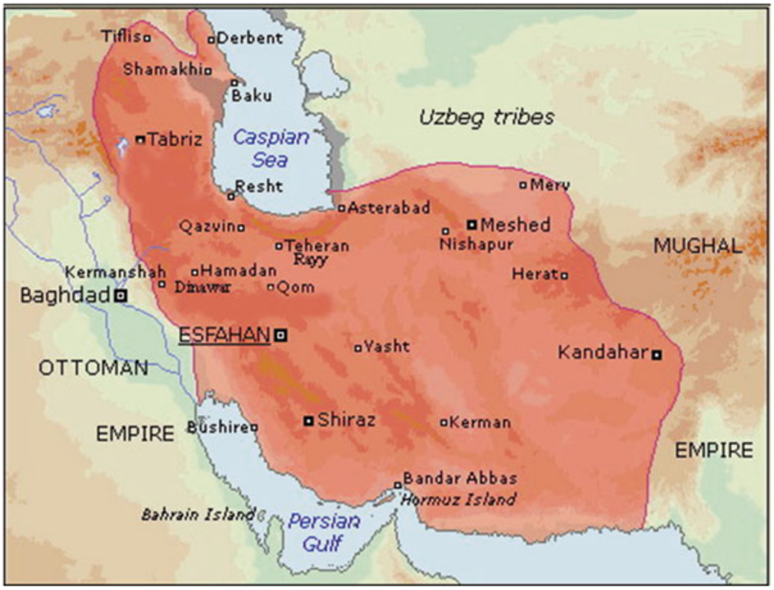

Fig. 2 Map showing the provinces of Rayy and Fars in Iran

of al-Ṣūfī's innovations in charting the stars was the production of dual illustrations for each of Ptolemy's constellations. One illustration was as portrayed on a celestial globe, while the other was as viewed directly in the night sky.

Figure 3 is a page taken from Paris manuscript MS5036 for the constellation Lepus. At the top of this page are the two illustrations of the constellation, and at the bottom is the star table. At the top of the table al-Ṣūfī notes that he added 12° 42′ to Ptolemy's longitudes to allow for precession. The first column in the table is the number of the star in the constellation. The second is the description or name of the star. The third group of columns lists the ecliptical longitude coordinates. The fourth is the latitude direction that positions the star in reference to the ecliptic. The fifth group of columns lists the latitude coordinates. The last column is the apparent magnitude estimates as al-Ṣūfī recorded them.

3.1 Al-Ṣūfī's Magnitude System

Al-Ṣūfī and Ptolemy both used intermediate values in the stellar magnitude systems that they developed. Ptolemy mentioned the words "more-bright" and "less-bright" for certain stars (see Grasshoff 1990; Schmidt 1994). However, al-Ṣūfī expressed these intermediate magnitude values by the words "*AṢghareh*" which means "less", "*Akbareh*" which means "greater" and "*A'ẓameh*" which means "much-greater".

Fig. 3 Paris manuscript MS5036 of the *Book of the Fixed Stars*, showing the constellation Lepus

Most scholars who have studied al-Ṣūfī's work do not differentiate between the two words "*Akbareh*" and "*A'ẓameh"* (e.g. see Fujiwara and Yamaoka 2005; Knobel 1885; Kunitzsch 1986; Lundmark 1926). However, when we look at al-Ṣūfī's text in detail it is evident that he made a clear distinction between three intermediate magnitudes. We believe that al-Ṣūfī used what we have termed a '3-step intermediate magnitude system', which was more accurate than Ptolemy's 2-step system. We think that with this system al-Ṣūfī was able to express all magnitude values by a constant difference of 0.25.

In order to analyze al-Ṣūfī's novel magnitude system all the magnitude values from his book were collected. We then conducted an accuracy analysis for al-Ṣūfī's

Table 2 Statistical results of the magnitude analysis

Statistical data	Mean	Standard deviation
Al-Ṣūfī 3-step	–0.06	0.59
Al-Ṣūfī 2-step	–0.09	0.59
Ptolemy	+0.07	0.71

magnitude values in comparison with those of Ptolemy. Then we calculated the difference between these values and the modern visual magnitudes. The statistical results of this analysis are summarized in Table 2, which shows the mean and the standard deviation for all stars combined.

From these values it seems that the mean for al-Ṣūfī's 3-step system is slightly better than his 2-step system, or the system used by Ptolemy. The standard deviation is the same whether we apply the 3-step or the 2-step system, whereas it is higher with Ptolemy. The dispersion in al-Ṣūfī's data is thus significantly less than in Ptolemy's data. Even though these statistical results might not seem entirely conclusive to some people, we believe that al-Ṣūfī intended to use a 3-step system. The main reason for this assumption is in the way al-Ṣūfī expressed or described the values of the stellar magnitudes in his book. From the many descriptions of the magnitude values found in the constellation commentaries we see that al-Ṣūfī made a clear distinction between the words "*Akbareh*" meaning "greater" and "*A'ẓameh"* meaning "much greater". In many instances we see that he expressed these terms consecutively. As for the term "*Aṣghareh"*, al-Ṣūfī only used this to indicate "less". He mentioned "*Aṣghareh"* on many occasions throughout the work. Therefore, from a literary analysis of al-Ṣūfī's work we have the impression that he was not really concerned with word repetition or correct sentence structure. If he was, then he would not have used the term "*Aṣghareh*", because there were many other Arabic words which could have been used instead, whereas he deliberately switched between the two terms "*Akbareh*" and "*A'ẓameh*". For further details of al-Ṣūfī's unique magnitude system see Hafez et al. (2015).

3.2 *The Colors of the Stars in al-Ṣūfī's Book*

The colors of the stars were never an important topic for ancient observers of the sky. There are very few ancient records on this subject or in ancient star catalogs. 'Red' was the color that attracted the most attention, whilst other colors such as 'white' or 'blue' were rarely mentioned. Ptolemy assigned the color red to the following six stars in his catalog: Aldebaran, Arcturus, Betelgeuse, Pollux, Antares and, strangely enough, Sirius (Toomer 1984). One of the first Arabic and Islamic authors to mention the colors of the stars was al-Farghānī. In his discussion of Ptolemy's book al-Farghānī mentioned only the color of three red stars, Antares, Pollux and Aldebaran (see Tekin and Tekin 1998). On the other hand, al-Battānī did not attribute colors to any of the stars in his star catalog (Nallino 1997), whereas Ulugh Bēg mentioned the color of four red stars, Antares, Pollux, Betelgeuse and Aldebaran, but neglected Arcturus and Alpha Hydrae (Knobel and Peters 1917). The Alfonsine authors do not include any remarks on the colors of stars, except for the red color of Antares (Samso and Comes 1988). By the time we reach the catalog of Tycho Brahe we find that it only mentions the color of Antares, as 'ruby red' (See 1927).

In the *Book of the Fixed Stars* al-Ṣūfī described seven distinctly red stars: Aldebaran, Arcturus, Betelgeuse, Pollux, Alpha Hydrae, Algol and Antares. However, he was silent about the color of Sirius, merely describing it as a bright star on the mouth (of the Dog) called *al-Kalb*. In Table 3 we give a brief summary of each of these eight stars, along with what al-Ṣūfī says about them. These stars were sometimes mentioned in the tables and at other times in his comments on the constellations.

Table 3 Colors of the stars according to al-Ṣūfī

Number	Modern star name and (HR) and color index	Star numbers according to al-Ṣūfī	Description according to al-Ṣūfī
1.	Aldebaran	14 Taurus	From the table:
	HR1457		The bright star, the reddish one of the letter (Δ) *al-Dāl* on the southern eye and it is *al-Dabarān*
			From the comments:
	B-V = 1.54		The fourteenth is the large bright red (star) on the south edge of the stars that resemble *al-Dāl*. It is located on the south eye and is drawn on *al-Īsterlāb* (the Astrolabe). It is called *al-Dabarān* and '*Ayn al-Thawr* (the eye of Taurus) and is of the 1st magnitude
2.	Arcturus	23 Bootes	From the table:
			The star between the thighs called *al-Simāk al-Rāmiḥ*
	HR5340		From the comments:
	B-V = 1.23		As for the one outside the constellation image it is the bright red star between the thighs. It is of the 1st magnitude and it is drawn on the *al-Īsterlāb* (Astrolabe). It is called *al-Simāk al-Rāmiḥ*
3.	Betelgeuse	2 Orion	From the table:
			The bright reddish star on the right shoulder
	HR2061		From the comments:
	B-V = 1.84		The second is the great bright red star located on the right *Mankib* (shoulder). It is less than the 1st magnitude. The distance between it and the three stars on the head is three *dhirā'*. It is (one of the stars that are) drawn on an Astrolabe. It is called *Mankib al-Jauzā'* (the shoulder of Orion) and also *Yad al-Jauzā'* (the hand of Orion)
4.	Pollux	2 Gemini	From the table:
			The reddish star on the head of the rear twin
	HR2990		From the comments:
	B-V = 1.00		The second (star) follows the first on the head of the rear twin. It is a little south (of the first) with a distance of more than two *dhirā'* between them. It is also of the 2nd magnitude

(continued)

Table 3 (continued)

Number	Modern star name and (HR) and color index	Star numbers according to al-Ṣūfī	Description according to al-Ṣūfī
5.	Alpha Hydrae	12 Hydra	From the table:
			The bright one of these two close stars called *al-Fard*
	HR3748		From the comments:
	B-V = 1.45		The twelfth star is the bright red star at the end of the neck and at the beginning of the back. It is of the 2nd magnitude. It is drawn on the *al-Īsterlāb* (Astrolabe). It is called '*Unuk al-Shujā*' (the Neck of Hydra). It is also called *al-Fard*
6.	Algol	12 Perseus	From the table:
			Stars in the Gorgon's head: the bright one
	HR936		From the comments:
	B-V = –0.05		The twelfth star is the bright red star less than 2nd magnitude. Ptolemy mentioned it is exactly of the 2nd magnitude. It is on the Gorgon's head. It is further than the eleventh star by two *dhirā*. It is drawn on the Astrolabe. It is called *Rae's al-Ghūl* (Gorgon's Head)
7.	Antares	8 Scorpio	From the table:
	HR6134		The middle one of these which is reddish and called *Qalb al-'Aqrab* (Antares)
	B-V = 1.84		From the comments:
			The eighth is the bright red (star) that is close to the seventh. It is of the 2nd magnitude. It is (one of the stars that are) drawn on an Astrolabe. It is called *Qalb al-'Aqrab* (the heart of Scorpio). It is in the eighteenth of the lunar mansions
8.	Sirius	1 Canis Major	From the table:
	HR2491		The star in the mouth, the brightest, which is called *al-Kalb* (Dog) and *al-Shi'ra al-Yamāniya* and *al-'Abūr*
			From the comments:
	B-V = 0.00		The first star is the great bright star on the mouth. It is drawn on the Astrolabe. It is called *al-Yamāniya*

The color index is a numerical expression that determines the color of a stellar object and thus its temperature. These indices are measured by determining the magnitude of an object using different filters: the U filter which transmits ultraviolet rays, the B filter blue light, and the V filter visible (green-yellow) light. The difference in magnitudes found with these filters is called the U-B or B-V color index. The smaller the color index, the bluer (or hotter) the object is. Conversely, the larger the color index, the redder (or cooler) the object is. Starting from the least red color (B-V) index of 1.0 for the star Pollux to the high color index of 1.84 for both the stars Betelgeuse and Antares, the above color indices are obvious evidence of the reliability of the data for most of these stars—except when it comes to the two stars Sirius and Algol.

The problem of Sirius and the subsequent historical debate has been adequately dealt with by Ceragioli (1995), Chapman-Rietschi (1995), Holberg (2007), See (1927) and others, and will not be discussed in this paper. As for the color of Algol, it is surprising that an acute observer like al-Ṣūfī should assign a red color to this star. Algol is a short-period close binary eclipsing system that has a period of about 10 hours, and also exhibits changes in apparent visual magnitude from a maximum of 2.12 to a minimum of 3.39 in the course of a few days, but the color index scarcely varies (see al-Naimiy et al. 1985; Borgman 1962). Al-Ṣūfī considered this star to be a bright star of less than 2nd magnitude (2.25), while Ptolemy assigned it the 2nd magnitude. Therefore, the nature of the variability of this star is not a reason which explains the error of assigning the red color to this star. The only other explanation is that al-Ṣūfī was mistaken in this regard. A similar mistake also was made by Julius Schmidt who was the Director of Athens Observatory. He also observed Algol to be 'reddish yellow' in 1841 (Ceragioli 1995).

3.3 Stars Mentioned by Al-Ṣūfī and Not in the Almagest

In his written comments on the constellations, al-Ṣūfī mentioned some additional stars that were not included in Ptolemy's star catalog. However, it is surprising that al-Ṣūfī did not include these stars in his tables even though he identified many of them in detail and described their magnitudes and he even estimated their locations. One reason why al-Ṣūfī did not include these additional stars might have been out of respect for Ptolemy, whose catalogue had long been a standard reference work in this field. In his introductory chapter al-Ṣūfī's clearly stated that the tables he produced were made according to Ptolemy's work. Therefore he might have been inclined to follow the classical tradition to which he and all other scholars before him were used.

It is also surprising that there are very few Arabic or Islamic historical sources that mention these additional stars. However, the one major text that does make reference to these stars is the *Alfonsine IIII Libros de la Ochaua Espera* (*Four Books of the Eight Spheres*), which was also called *Libros de las Estrellas Fixas* (*Books on the Fixed Stars*). These works were produced in Toledo in AD 1256, but were based on al-Ṣūfī's *Book of the Fixed Stars*. Book four of these *Alfonsine* texts was a statistical summary which included the number of stars in each constellation as well as Arabic names of stars according to Arabic folk astronomy (see Samso and Comes 1988). This book also included a general list of 84 stars taken from al-Ṣūfī's work which were not mentioned by Ptolemy.

In this part of the paper we have identified 132 of these additional stars; 64 were located in the Northern constellations, 41 in the Zodiac constellations and 27 in the Southern constellations. Al-Ṣūfī mentioned these stars in his constellation commentaries but not in the tables and he clearly said that "… these stars were not mentioned by Ptolemy." In many instances al-Ṣūfī mentions that in several areas of the sky there are many stars but he fails to mention a definite number because of their large numbers. For example, in his comments on the constellation Ursa Major he wrote: "Throughout (the main image of the) constellation and outside of it, there are many stars of the 5th and 6th magnitudes. Additionally there is an infinite number of dim (stars) which are fainter than the 6th magnitude (classification)."

In Tables 4, 5, and 6 we identify all of these major 'missing stars' that are mentioned by al-Ṣūfī. We also try to identify these stars by their HR number, and we include the magnitudes that al-Ṣūfī assigned them together with their modern magnitudes. In the star number column, we continue with the sequence of the star number as per al-Ṣūfī's sequence.

3.4 The Nebulae, Galaxies and Star Clusters in al-Ṣūfī's Book

The term 'nebula' comes from the Latin word for cloud. In the past the term nebula was also used for distant galaxies, clusters and any other hazy patches of light that resembled a cloud among the stars. With the application of spectroscopy and photography to astronomy in the nineteenth century, it was possible to distinguish real nebulae from galaxies (e.g. see Clerke 1903; Hearnshaw 1986; Lankford 1984).

The Arab and Islamic astronomers observed and identified several nebulae very early in their scientific endeavours. The Arabic term used for a nebula was *al-Saḥābi*, which also means a cloud. In his major astronomical treatise (*al-Qānūn al-Mas'ūdī Fi al-Hay'a Wa al-Nujūm*), al-Brn (2002) describes *al- Saḥābiāt* (plural for nebula) in these words:

> In the sky there are objects which do not resemble the stars in their round shape and by the bright light which they have. These are the *al-Laṭkhāt al-Bīḍ* [the white smears] called *al-Saḥābiya* [nebula]. Some believe that these [nebulae] are part of the [the Milky Way] galaxy; however they are both alike and both resemble clouds. These [nebulae[are believed to be an *Ishtibāk* [a mass[of small stars grouped together.

Al-Būrūnī (ibid.) clearly distinguished between nebulae and the Milky Way and he described the nature of these nebulae as a concentration or group of stars. As for the Milky Way it was called *al-Majarra* in Arabic, which is directly translated as just 'the Galaxy'. According to al-Marzq (1997), in his book *Kitāb al-Azmina Wa al-Amkina*, he said: "… the ancient Arabs called *al-Majarra*: *Um al-Nujūm* [the mother of all stars] because there is no area in the sky which has more stars then it." The Arabs also called the Milky Way *Sharj al-Sama'* (the dome of the sky) and *Nahr al-Majarra* (the galaxy river). However the name by which the Milky Way was mostly known was *Darb al-Tabbānah* (the path of straws). The term *Darb al-Tabbānah* describes a group of farmers returning home after planting their fields and dropping straw every once in a while, thus producing white patches on the ground. Abū Ḥanīfa al-Daīnawari (2001) also described the location of the galaxy in those words: "*al-Majarra* [the galaxy] is a connected circle like a ring. Even though it is narrow in some places and wide in others however this is due to its circular nature. It is most wide between [the Asterism] *Shawlat al-'Aqrab* [the tail of Scorpio] and *al-Nasrān* [the constellations of Lyra and Aquila]."

Table 4 Northern stars mentioned by Al-Ṣūfī but not by Ptolemy

Number	Star number (as per al-Ṣūfī)	Star/s (HR)	Al-Ṣūfī magnitude	Modern magnitude	Explanations and comments
1.	36 Ursa Major	5,062	Not mentioned	4.01	This is the star named Alcor. The Arabic name is *al-Suhā.* This star is not mentioned in Ptolemy; therefore it is not included in al-Ṣūfī's chart. However al-Ṣūfī mentions this star in his written explanation of this constellation
					This is a very famous star in Arabic tradition, as al-Ṣūfī explains that it was used to test eyesight
2.	37 Ursa Major	4,518	4	3.71	Al-Ṣūfī mentions this star in his written explanation of this constellation and he mentions that it was not included in Ptolemy
3–7.	38 Ursa Major	4,392	Al-Ṣūfī mentioned that these are of magnitude 5 or 6	4.99	Al-Ṣūfī mentions in the written explanation that there is a group of stars that together with the twenty-second star form a circle. These stars were not mentioned by Ptolemy. These stars are all part of Ursa Major
	39 Ursa Major	4,248		4.71	
	40 Ursa Major	4,277		5.05	
	41 Ursa Major	4,288		5.08	
	42 Ursa Major	4,380		4.78	
8.	43 Ursa Major	4,728	5.25	5.02	Al-Ṣūfī mentions that this star is between the second of the two (stars) outside of the constellation, close to *Kabd al-Asad* and (the star) on the knee-bend. It is fainter than the 5th magnitude. It is much closer to the second (star) that is outside of the constellation. This star is now included in the constellation of CVn
9.	44 Ursa Major	3,648		5.13	Al-Ṣūfī explains that this star together with the seventh and eighth form a triangle which together with the ninth and the tenth stars form another open angle (obtuse) triangle
10–11.	45 Ursa Major	5,023	6	5.15	Al-Ṣūfī claims that these two stars (5,023 and 5,112) are one *dhirā'* (2° 20′) distance from each other, which is remarkably close to the actual distance of 2° 26′
	46 Ursa Major	5,112	6	4.7	
12.	32 Draco	6,618	6	5.75	Al-Ṣūfī mentions that in the middle of the four stars which are the second, third, fourth, and fifth there is a very faint star which was not mentioned by Ptolemy and which the Arabs call *al-Ruba'*
13.	14 Cepheus	8,591	6	5.50	The Arabs call this star *Kalb al-Rā'ī* (shepherd's dog)
					Al-Ṣūfī mentions that this is a faint star located between the left and right leg, but closer to the left leg

14–17.	15,17,18,19 Cepheus	7,701	Not mentioned	5.39	Al-Ṣūfī mentions that the fifth and sixth stars together with other stars form a circle of stars between the constellations of Draco and Cygnus. This circle of stars was called *al-Qidr*. In his map Al-Ṣūfī drew four of these stars
		7,633		4.96	
		7,740		4.30	
		7,955		4.51	
18–21.	20,21,22,23 Cepheus	8,317	6(k) or 5(s)	4.56	Al-Ṣūfī mentions that there is a line of stars between the second and third stars whose magnitudes are either greater than 6th magnitude or less than 5th magnitude. We have tried to identify only a few of these stars. Al-Ṣūfī also mentions that there are many 5th and 6th magnitude stars on the body and between the legs, however these cannot be identified accurately since their locations are too vague
		8,468		4.79	
		8,615		5.08	
		8,819		4.41	
22–24.	24,25,26 Bootes	5,502	5	4.6	These stars are above the nineteenth star which is on the right heel, and they form a triangle
		5,544	5	4.55	
		5,575	6	5.71	
25–28.	27,28,29,30 Bootes	5,370	5	4.86	Al-Ṣūfī mentions that there is a line of stars between the constellation Bootes and Virgo; however he only identifies the magnitudes of four stars: three of the 5th magnitude and one of the 4th magnitude
		5,365	5	5.41	
		5,330	5	5.29	
		5,159	4	5.36	
29.	31 Hercules	6,159	6	4.84	
30–31	32,33 Hercules	6,355	6	4.91	
		6,337	6	4.98	
32–36.	34,35 Hercules	6,781	5(s) or 6	5.86	
		6,685	5(s) or 6	5.46	
		6,644	5(s) or 6	5.12	
		6,571	5(s) or 6	5.77	
		6,480	6(m)	5.74	
37.	36 Hercules	6,677	6	5.16	
	37,38 Hercules	6,793	Not mentioned	5.48	Al-Ṣūfī mentions that there are many 6th magnitude stars between the eighteenth star of Hercules and the constellation Lyra which were not mentioned by Ptolemy. He also mentions that there are many 6th magnitude stars between the twenty-fifth star of Hercules and the constellation Draco and one particular star of the 5th magnitude which is closer to the tip of the tongue of Draco; however it was not possible to identify this star with any certainty
		6,872		4.33	

(continued)

Table 4 (continued)

Number	Star number (as per al-Ṣūfī)	Star/s (HR)	Al-Ṣūfī magnitude	Modern magnitude	Explanations and comments
38.	11 Lyra	7,262	5	5.28	
39.	20 Cygnus	8,146	5	4.43	Al-Ṣūfī mentions that this star is between the two stars outside of the constellation (the eighteenth and the nineteenth) and the twelfth star
40–43.	21,22,23,24 Cygnus	7,834	4(s)	4.01	Al-Ṣūfī mentions that between these stars and the constellation Sagitta there are many stars of the 6th magnitude which were not mentioned by Ptolemy
		7,942	4(s)	4.22	
		7,866	6	4.61	
		7,806	5	4.43	
					Al-Ṣūfī mentions that between the twelfth star and the constellation Delphinus there are many stars of the 6th magnitude which were not mentioned by Ptolemy
44.	25 Cygnus	7,405	5	4.44	Al-Ṣūfī mentions that this star should have been on the beak and that it is brighter than the star on the head (the second star, which is of the 6th magnitude)
45–47.	14, 15,16 Cassiopia	580	4	3.98	Al-Ṣūfī mentions that there are three stars north of the seventh stars; two of the 4th magnitude and one of the 6th magnitudes. He also mentioned that next to these stars are many 6th magnitude stars which were not mentioned by Ptolemy
		575	4	4.54	
		548	6	4.99	
48.	14 Auriga	1,995	5	4.52	This forms a double star with the fifth star. Al-Ṣūfī does not mention its magnitude, however he states that the fifth star was of the 5th magnitude while Ptolemy mentioned it to be 4th magnitude. Al-Ṣūfī might have made a mistake here and switched the two stars
49.	30 Ophiuchus	6,493	5(m)	4.54	
50.	31 Ophiuchus	6,243	5	4.65	
51.	32 Ophiuchus	6,770	5 or 6	4.64	A double star with the twenty-ninth star of Ophiuchus. Al-Ṣūfī mentions that it is a small or faint star
52.	33 Ophiuchus	6,093	6	4.83	
53.	34 Ophiuchus	6,524	6	5.59	
54.	19 Serpens	5,843	5	5.33	

55.	20 Serpens	5,895	5 or 6	5.11	A double star with the eleventh star of the Serpens. Al-Ṣūfī mentions that it is a small or faint star
56.	17 Aquila	7,437	6	5.00	Al-Ṣūfī mentions that this star is between the nebula 16 Aquila and the constellation Sagitta
57.	18 Aquila	7,193	4(s)	4.02	
58.	19 Aquila	7,149	6	4.83	
59.	20 Aquila	7,063	5	4.22	
60.	21 Aquila	7,032	5	4.90	
61.	22 Aquila	7,020	5	4.72	
62.	23 Aquila	6,973	4(m)	3.85	
63.	24 Aquila	7,007	6	5.84	
64.	5 Triangulum	655	6	5.28	A double star with the fourth star of Triangulum

Table 5 Zodiac stars mentioned by al-Ṣūfī but not by Ptolemy

Number	Star number (as per Al-Ṣūfī)	Star/s (HR)	Al-Ṣūfī magnitude	Modern magnitude	Explanations and comments
1.	19 Aries	1,005	4	5.28	Al-Ṣūfī does not exactly specify a magnitude; however, he mentions that this star is similar to the tenth star which he states as 4th magnitude
2–3.	20 Aries	569	4(s) = 4.25	4.79	Al-Ṣūfī mentions that these two stars are similar in magnitude to the two stars on the muzzle, which are 4(s) and 5(s)
	21 Aries	623	5(s) = 5.25	4.98	
4.	22 Aries	613	6	5.03	Al-Ṣūfī mentions that this star is close to the star al-*Nāṭiḥ* (which is the fourteenth star of Aries)
5.	44 Taurus	1,153	6	5.35	
6.	45 Taurus	1,159	6	5.91	
7.	46 Taurus	1,268	5	5.20	
8.	47 Taurus	1,990	5(s) = 5.25	5.49	
9.	48 Taurus	1,253	6	5.33	
10.	49 Taurus	1,381	6	5.12	
11.	50 Taurus	1,389	6(m) = 5.5	4.29	
12.	51 Taurus	1,427	5(s) = 5.25	4.78	
13.	52 Taurus	1,394	6	4.49	
14.	53 Taurus	1,356	6	5.26	
15.	54 Taurus	1,149	Not mentioned	3.87	An additional star in the Pleiades
16.	55 Taurus	1,165	Not mentioned	2.87	An additional star in the Pleiades
17.	56 Taurus	1,142	Not mentioned	3.70	An additional star in the Pleiades
18.	26 Gemini	2,852	5	4.18	
19.	27 Gemini	2,973	5	4.28	
20–22.	28 Gemini	2,456	5	4.66	Al-Ṣūfī mentions that these three stars form an arc which is between the constellation Orion and the asterism *al-Han'a* (the 6th lunar mansion)
	29 Gemini	2,503	5	4.77	
	30 Gemini	2,506	5	4.47	
23.	33 Virgo	5,044	Not mentioned	5.37	A double star with HR 5019
24.	34 Virgo	4,824	6	6.19	Next to the eleventh star HR4828
25.	18 Libra	5,824	6	4.96	
26.	25 Scorpio	6,143	6	4.23	
27.	26 Scorpio	6,166	6	4.16	
28.	27 Scorpio	6,081	5(s) = 5.25	4.55	
29.	28 Scorpio	6,141	5(s) = 5.25	4.79	

(continued)

Table 5 (continued)

Number	Star number (as per Al-Ṣūfī)	Star/s (HR)	Al-Ṣūfī magnitude	Modern magnitude	Explanations and comments
30.	29 Scorpio	5,885	6	4.64	
31.	30 Scorpio	5,904	6	4.59	
32.	32 Sagittarius	7,120	Not mentioned	5.00	A double star with 8 Sagittarius HR7116
33.	33 Sagittarius	7,337	Not mentioned	4.01	A double star with 23 Sagittarius (HR7343)
34.	34 Sagittarius	–	3	–	Al-Ṣūfī mentions that there is a 3rd magnitude star between 23 Sagittarius and the constellation Piscis Australis; however the location is not precise enough for us to locate this star
35.	46 Aquarius	7,845	5	5.65	
36.	47 Aquarius	8,496	6	5.34	
37.	48 Aquarius	8,590	Not mentioned	5.89	Al-Ṣūfī mentions that this star is between 12 Aquarius and 23 Aquarius
38.	49 Aquarius	8,890	6	5.20	Al-Ṣūfī mentions that this star is north of 30 Aquarius
39.	50 Aquarius	8,987	6	5.28	A double star with 31 Aquarius (HR8968)
40.	39 Pisces	389	5	5.23	
41.	39 Pisces	274	5	5.42	

From the above descriptions, which we find in many historical references, we see that the ancient Arabs were well aware of these cloud-like objects. The Arabic and Islamic scholars and astronomers later described in detail the nature and location of these nebulae as well as the Milky Way which they could clearly see in the sky. Al-Ṣūfī also refers to the nebulae as *al-Laṭkhā al-Saḥābiya* (the nebulous smear or smudge) and *al-Ishtibāk al-Saḥābi* (the nebulous mass). As his work was based on Ptolemy's book, al-Ṣūfī again identifies the five nebulae that Ptolemy mentioned earlier. However al-Ṣūfī goes further and describes several additional nebulae, which he observed personally or which were previously identified by other Arabs.

Using al-Ṣūfī's descriptions, we identify in Table 7 all the nebulae, galaxies and star clusters found in the *Book of the Fixed Stars*. We have included the modern names or designations, which correspond to these objects. In the last column of Table 7 we include a brief summary of each of these objects as described by al-Ṣūfī. This summary includes all of the descriptions in al-Ṣūfī's book that are contained in the tables as well as in the comments in the constellations.

Included below are some comments on the above nebulae, galaxies and star clusters which were identified by al-Ṣūfī. The numbers associated with each object are those listed in column 1 in the above Table.

Table 6 Southern stars mentioned by al-Ṣūfī but not by Ptolemy

Number	Star number (as per Al-Ṣūfī)	Star/s (HR)	Al-Ṣūfī magnitude	Modern magnitude	Explanations and comments
1.	23 Cetus	775	5	6.21	Between 3 and 5 Cetus
2.	24 Cetus	531	5	4.67	Close to 14 Cetus
3.	25 Cetus	583	5	5.41	South of 13 Cetus
4.	26 Cetus	329	6	5.82	A double star with 16 Cetus (HR 334)
5.	39 Orion	2,130		5.14	A double star with 12 Orion (HR 2135)
6.	40 Orion	1,931	4	3.81	
7.	35 Eridanus	917	5	5.32	A double star with 15 Eridanus (HR925)
8.	36 Eridanus	994	4	4.88	A double star with 21 Eridanus (HR1003)
9.	37 Eridanus	794	4	4.11	
10.	38 Eridanus	789	5	4.75	
11.	39 Eridanus	1,008	4	4.27	
12.	40 Eridanus	963	3(s) = 3.25	3.87	
13.	46 Argo	3,307	3(s) = 3.25	1.86	
14.	47 Argo	2,787	Not mentioned	4.66	A double star with 12 Argo (HR2773)
15.	48 Argo	3,037	Not mentioned	5.23	A double star with 34 Argo (HR3055)
16.	28 Hydra	3,492	5	4.36	A double star with 3 Hydra (HR3482)
17.	29 Hydra	3,709	5	4.80	
18.	30 Hydra	3,706	5	4.79	
19.	31 Hydra	3,636	6	5.77	
20.	38 Centaurus	4,933		4.27	A double star with 22 Centaurus
21.	20 Lupus	5,457	6	6.07	Close to 2 Lupus
22.	21 Lupus	5,494	6	5.74	Close to 2 Lupus
23.	8 Ara	6,897	4	3.51	A double star with HR6934
24.	9 Ara	6,934	6	4.96	
25.	10 Ara	6,905	5	4.13	
26.	14 Corona Australis	6,938	5	5.07	
27.	12 Piscis Austrinus	8,447	Not mentioned	4.92	A double star with 6 Piscis Austrinus (HR8431)

1. The double clusters NGC884 and NGC869 were observed by the Greeks, the Indians and astronomers from many other cultures long before the time of al-Ṣūfī. These clusters were cataloged by Hipparchus as well as Ptolemy, and are bright enough to be clearly seen by the naked eye. In his comments al-Ṣūfī refers to the 'camel's thigh' which he mentions also in his description of the constellation Cassiopeia. Al-Ṣūfī mentions that the ancient Arabs described a

Table 7 Nebulae, galaxies and star clusters found in al-Ṣūfī's book

Number	Modern name and designation,	Star/Nebula according to al-Ṣūfī	Description according to al-Ṣūfī
1.	NGC 869/884	1 Perseus	From the table:
	Open clusters	Nebula	The nebulous mass on the right hand
			From the comments:
			The first of its stars is *al-Laṭkhā al-Saḥābiya* (nebulous smear) on the camel's thigh which we have talked about when we discussed the constellation Cassiopeia. It is on the edge of Perseus' right hand
2.	M44 (NGC 2632)	1 Cancer	From the table:
	Open cluster	Nebula	The middle of *al-Ishtibāk al-Saḥābi* (nebulous mass) in the chest, called *al-Mi'laf* (Praesepe)
			From the comments:
			The first of its stars is a *Laṭkhā* (smear) which resembles a piece of cloud surrounded by four close stars with the patch in the middle. Two stars are in front and two are behind
3.	M7 (NGC 6575)	22 Scorpio	From the table:
	Open cluster or NGC6441		The nebulous star to the rear of the sting
			From the comments:
	Globular cluster		As for the three stars outside of the constellation, the first is a star to the rear of *al-Shawla* and behind the nineteenth star which is on the seventh joint. It is less than 4th magnitude. Ptolemy mentioned that it is a nebulous object. The distance between it and the nineteenth star which is on the seventh *Kharaza* (joint) is a little more than one *dhirā'*. And the distance between it and *al-Shawla* is close to one and a half *dhirā'*
4.	HR7116	8 Sagittarius	From the table:
	HR7120	Nebula	The star on the eye, which is nebulous and double
	NGC6717		From the comments:
	Globular cluster		The eighth is the nebulous star on the eye of Sagittarius. It is towards the north from the sixth star by a distance of two *dhirā'*
5.	CR69	1 Orion	From the table:
	Open cluster	Nebula	The nebulous star in the head of Orion, which consists of three close stars
	HR1879		From the comments:
	HR1883 HR1876 HR1907		The first of its stars is the *Saḥābi* (nebula) on the head. This nebula is made up of three small stars close together forming a small *Muthallath* (triangle). Ptolemy mentioned it to be one star located in the middle of the triangle and he indicated its longitude and latitude in his book. It is located on the head between the two shoulders and further away towards the north but closer to the left shoulder

(continued)

Table 7 (continued)

Number	Modern name and designation,	Star/Nebula according to al-Ṣūfī	Description according to al-Ṣūfī
6.	CR399	16 Aquila	From the table:
	Open cluster	Nebula	(Description is only mentioned in the comments on the constellation Aquila)
			From the comments (Constellation Aquila):
			There is an image of a bowl (cup) with its stars beginning from the bright star on the tail, continuing towards the north-west then going to the east to the base of the bowl; then towards the south-east until it reaches a nebula located north of two stars in the notch of the constellation Sagitta. The distance between the nebula and the top of the bowl is two *dhirā'*; the nebula is located on the east edge and the bright star on the tail on its western edge and contains stars of the 4th, 5th and 6th magnitude, but most are of the 5th magnitude
7.	M31	–	From the table:
	Andromeda galaxy		(Description is only mentioned in the comments on the constellation Andromeda)
			From the comments:
			The Arabs mentioned two lines of stars surrounding an image resembling a large fish below the throat of the Camel. Some of these stars belong to this constellation (Andromeda) and others belong to the constellation Pisces which Ptolemy mentioned as the twelfth constellation of the Zodiac. These two lines of stars begin from the *al-Laṭkhā al-Saḥābiya* (nebulous smear) located close to the fourteenth star which is found at the right side of the three (stars) which are above the girdle
8.	IC2391 Omicron Velorum	49 Argo Navis	From the table:
	NGC2669		(Description is only mentioned in the comments on the constellation Argo Navis)
	Open cluster		From the comments:
			Above the thirty-seventh star at a distance of one *dhirā'* there is a nebulous star
9.	Large Magellanic Cloud	–	From the table:
			(Description is only mentioned in the comments on the constellation Argo Navis)
			From the comments:
			Some claim that under the star *Suhail* (the star Canopus) is a star called *Qaḍam Suhail* (feet of *Suhail*) and under *Qaḍam Suhail* are many bright white stars which are not seen from Iraq and *Najd* (the area north of Arabia). The people of *Tehāma* (the area south of Arabia) call them *al-Baqar* (Oxen). Ptolemy does not mention any of this and we do not know if this is right or wrong

(continued)

Table 7 (continued)

Number	Modern name and designation,	Star/Nebula according to al-Ṣūfī	Description according to al-Ṣūfī
10.	M45 Pleiades	29 Taurus	From the table:
	Open cluster	30 Taurus	The Pleiades: the northern end of the advanced side
		31 Taurus	The southern end of the advanced side
		32 Taurus	The rearmost and narrowest end of the Pleiades
			The small star outside the Pleiades towards the north
			From the comments:
			The Arabs called the twenty-ninth, the thirtieth, the thirty-first and the thirty-second, *al-Thurayyā* (the Pleiades). Inside (the Pleiades) are two stars or three together with the other four looking like a bunch of grapes that are close together. Therefore they considered them as one star and named it *al-Najem* (The Star) par excellence. They also named it *Nujm al-Thurayyā* (the stars of the Pleiades). It was called *al-Thurayyā* because they were blessed by it and by its rise, and they claimed that the rain which falls when it *Naw'* (sets) brings good luck
			(*al-Thurayyā)* means a small fortune (the diminutive noun for fortune). They (the Arabs) diminutised it because its stars are close and small. They mentioned in their books that it is located on the *Aliet* (the buttocks or the fat tail of a sheep) of (the constellation) Aries, (however) it is located on the *Sinām* (hump) of Taurus
			The distance between it and the last star on the buttocks of Aries is three *dhirā'* as is seen by the eye. It is in the third of *Manāzil al-Qamar* (the lunar mansions)

picture of a camel, which they identified between the constellations of Cassiopeia and Perseus.

2. The open cluster M44 is another nebula that was clearly seen by the naked eye and recognized a long time ago by the Greeks and those from other cultures.
3. Formerly the nebula that was associated with the star 22-Scorpio was considered to be the open cluster M7. It is interesting to note that al-Ṣūfī assigns a magnitude to the star 22-Scorpio of 4(s) = 4.25. For all other nebulae he only mentions that they are nebulous objects. This procedure was also used in the *Almagest*, therefore al-Ṣūfī again tried to adhere to Ptolemy's method of description in this regard except for the star 22-Scorpio. However for 22-Scorpio al-Ṣūfī might have been referring to the star HR6630 (magnitude 3.21) that also has next to it the globular cluster NGC6441. Al-Ṣūfī states that Ptolemy mentioned that this star was a nebulous object. He then goes on to determine the distance between this nebulous object and the nineteenth star that is on the

Table 8 Distances between two different nebulae and specific stars

Distance from NGC6441 to 19 Scorpio	Distance from NGC6441 to 21/20 Scorpio	Distance from M7 to 19 Scorpio	Distance from M7 to 21/20 Scorpio
2° 3′	3° 38′	4° 53′	5° 07′

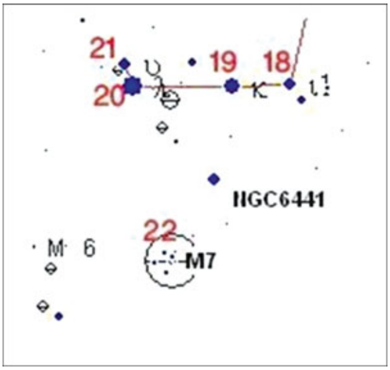

Fig. 4 A map showing the positions of NGC6441 and M7 relative to stars 19, 20 and 21 in Scorpio

seventh *Kharaza* (joint) as a little more than one *dhirā'*, and the distance between it and *al-Shawla* (stars 20/21 Scorpio) as close to one and a half *dhira'*. From these distance approximations this nebula should be about 2° 20′ from the nineteenth star of Scorpio and 3° 30′ from the twentieth and the twenty-first stars of Scorpio. We have calculated the distance between these nebulae and these stars and the results are indicated in Table 8.

From these approximate distances and the fact that one *dhirā'* is 2° 20′ according to al-Ṣūfī, it looks more likely that the nebula which al-Ṣūfī was referring to in this case is the globular cluster NGC6441 and not M7, as was initially supposed (see Fig. 4). This distinction was first recognized by Manitius (1912) then by Knobel and Peters (1915), and was later confirmed by Toomer (1984) in his translation of the *Almagest.*

4. Al-Ṣūfī mentions the star 8-Sagittarius as a double star together with a nebulous star. The two stars were identified as HR7116 and HR7120. Next to HR7120 is the NGC6717 globular cluster. Al-Ṣūfī might have been referring to these three objects collectively as a nebulous asterism.
6. The CR399 open cluster was first discovered by al-Ṣūfī and described in his Book of the Fixed Stars. It was later independently re-discovered by Giovanni Hodierna in 1654 (Jones 1991). It is also sometimes named Brocchi's Cluster after the astronomer D.F. Brocchi, who created a map of it in the 1920s (see Hall and Van Landingham 1970). It was included in Collinder's (1931) catalog of open clusters and given the designation of Collinder 399.
7. Messier 31 (M31) is the famous Andromeda Galaxy. It is the nearest large spiral galaxy to us. It was first discovered by al-Ṣūfī and described in his *Book of the Fixed Stars* (Fig. 5). It was later included in early European star catalogs,

Fig. 5 Al-Ṣūfī's illustration of the constellation of Andromeda. The Andromeda Galaxy was described as near the large star shown on her belt

such as those by Simon Marius in 1612, Giovanni Hodierna in 1654 and Charles Messier in 1764 (see Jones 1991).

8. The Omicron Velorum open cluster (NGC2669) was first discovered by al-Ṣūfī and described in his *Book of the Fixed Stars*. It was later re-discovered by N.L. de Lacaille in 1752 and he cataloged it as 'Lac II.5' (see de Lacaille 1763).
9. The Large Magellanic Cloud and its small neighbor the Small Magellanic Cloud are well-known objects in the Southern Hemisphere. They must have been very well recognized by ancient cultures living in the Southern Hemisphere. However there is very little preserved evidence to document these facts (but see Haynes 2000; Orchiston 2000). Some Arab researchers claim that the earliest documented proof of observation of the Magellanic Clouds might be found in al-Ṣūfī's *Book of the Fixed Stars* (Mujahed 1997). However, al-Ṣūfī only mentioned that there were stars under the stars of *Suhail* (Canopus) and *Qaḍam Suhail* (the feet of *Suhail*), which the Arabs called *al-Baqar* (oxen), but he did not mention that there were any nebulae. This recent claim is probably due to the fact that *al-Baqar* was mentioned by the fifteenth century Arab seafarer Ahmad Ibn Majid (1490) who referred to the Large Magellanic Cloud as a nebula and named it *al-Baqar* before Magellan documented it in AD 1519. However, al-Ṣūfī does not claim that he observed these stars himself, but rather

attributes them to the people of southern Arabia (from the region of *Tehāma*). He admits that he does not know if this is right or wrong. This is a tribute to al-Ṣūfī's scientific integrity whereby in the same paragraph he admits to making his observations from the city of Shiraz, which according to the measurements that he made with the Aḍudi Ring has a latitude of 29° 36′ N. The Magellanic Clouds were not visible from this latitude.

10. Al-Ṣūfī mentions that inside the Pleiades there are two stars or three together with the other four looking like a bunch of grapes. These additional stars are HR1149, HR1165 and HR1142. Therefore, together with the other four, al-Ṣūfī managed to observe seven stars in the Pleiades.

4 Concluding Remarks

As we have seen from this discussion, al-Ṣūfī and his *Book of the Fixed Stars* have a very important place in the history of Arabic and Islamic astronomy. Al-Ṣūfī

> … not only corrected observational errors in the works of his predecessors, like the famous Arab astronomer al-Battani, 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 he made himself." (Winter 1955: 128)

In his *Book of the Fixed Stars*, al-Ṣūfī also devised a new magnitude system; commented on star colors; documented 132 different stars that were not mentioned in the *Almagest*; and listed star clusters and nebulae, many of which were recorded for the first time. Like Ptolemy, he made a major contribution to stellar astronomy.

In the introduction to his French translation of al-Ṣūfī's book Schjellerup (1874: 5; our translation) mentions that:

> … these facts give to the work of al-Ṣūfī an importance which cannot be denied. Now the time has come when it shall be the duty of the future generations to study the work of the learned astronomers of the Levant and to reveal their importance and to draw conclusions from them.

Expanding upon these comments, we believe that much more effort needs to be directed towards locating the astronomical treasures hidden in Arabic books and manuscripts that are preserved in libraries and other repositories around the world. The start of this endeavor should be to begin translating these books from Arabic into English in order to make their contents more accessible to a wider audience of researchers. This will hopefully lead to the study and analysis of other works like al-Ṣūfī's *Book of the Fixed Stars.*

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'Abd al-Raḥmān al-Ṣūfī's 3-Step Magnitude System

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Abstract 'Abd al-Raḥmān al-Ṣūfī's *Book of the Fixed Stars* dates from around AD 964 and is one of the most important medieval Arabic treatises on astronomy. In this paper we begin with a very brief introduction to the *Book of the Fixed Stars.* This book contains an extensive star catalogue that lists star coordinates and magnitude estimates for all of the Ptolemaic stars. However, in his book al-Ṣūfī utilized three distinct intermediate magnitude values whereas Ptolemy only mentioned two. We believe that al-Ṣūfī used what we have termed a '3-step intermediate magnitude system,' which is more accurate than Ptolemy's 2-step intermediate system. In this paper we examine in detail the accuracy of this unique 3-step system in comparison with Ptolemy's and modern magnitude values.

1 Introduction to al-Ṣūfī and His *Book of the Fixed Stars*

ʼAbd al-Raḥmān al-Ṣūfī, Ibn ʼUmar, Ibn Muḥammad, Ibn Sahl, al-Rāzī, better known as 'Abd al-Raḥmān al-Ṣūfī, or simply al-Ṣūfī (AD 903–986), was a well-known tenth-century Persian astronomer (Hafez et al. 2015), and his *Book of the Fixed Stars* was one of the most important books in the history of Arabic and Islamic astronomy (see Brown 2009; Hafez 2010; Hafez et al. 2011). It was written in Arabic around AD 964 (al-Qifṭī 2005).

Al-Ṣūfī's book was based on Ptolemy's classical work, called the *Almagest,* which was written around AD 137 (Evans 1987; Grasshoff 1990; Swerdlow 1992; Toomer 1984). Al-Ṣūfī updated Ptolemy's stellar longitudes from 137 to 964 by adding 12° 42′ to Ptolemy's longitude values to allow for precession. The *Book of*

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the Fixed Stars contains an extensive star catalogue, which lists star co-ordinates and magnitude estimates. The book also includes many other topics, such as descriptions of nebulae, notes on star colors (e.g. see Hafez et al. 2015), and a wealth of information on ancient Arabic folk astronomy.

Al-Ṣūfī starts his book with an introductory Chapter, which is a very important part of his work. He then divides the constellations into 48 chapters, and starts with a detailed commentary for every constellation. In this commentary he describes in detail the number of stars, their locations and their magnitudes. At the end of these constellation chapters al-Ṣūfī compiles a star catalogue or tables for all the stars that form the image of the constellation. He also draws maps for all the 48 constellations, which are considered a unique feature of his work. One of al-Ṣūfī's innovations in charting the stars was the production of dual illustrations for each of Ptolemy's constellations. One illustration was as portrayed on a celestial globe. The other illustration was as viewed directly in the night sky. Many scientists and astronomers have based their astronomical observations on al-Ṣūfī's work, starting with al-Bīrūnī (2002), including the authors of the Alfonsine tables (Samso and Comes 1988) and the famous prince and astronomer Ulugh Bēg (Knobel and Peters 1917), and ending with more recent astronomers like Ideler (1809) and Knobel (1885).

There are many manuscript copies of al-Ṣūfī's book that are preserved in libraries throughout the world, and we managed to locate 35 different manuscripts in 16 different countries (Hafez 2010). There may also be additional, as yet unknown, manuscripts in other libraries or in personal collections. The earliest-known manuscript of the *Book of the Fixed Stars* is Marsh144, which dates to AD 1009, just 23 years after al-Ṣūfī's death. This manuscript was actually written by al-Ṣūfī's son, and is now in the Bodleian Library in Oxford (Wellesz 1959). Al-Ṣūfī's work has never been translated into English, but a French translation by Hans Karl Frederic Schjellerup was published in 1874.

2 Al-Sufi's Stellar Coordinates and Magnitude System

The study and analysis of al-Sufi's stellar data can be divided into two parts. The first is the study of the ecliptical longitude and latitude coordinates that are included in the stellar catalogue. The second is the analysis of magnitude values, which are found in both the chapters on the constellations as well as in the stellar catalogue.

2.1 Al-Ṣūfī's Ecliptical Coordinates

The study or analysis of al-Ṣūfī's star catalogue is closely related to the study of Ptolemy's classical work. Al-Ṣūfī relied heavily on Ptolemy's coordinate values, which he found in the *Almagest* (Kunitzsch 1970a, b). However, in many instances al-Ṣūfī mentions that the coordinates of Ptolemy are incorrect. For example, for the constellation Ursa Minor al-Ṣūfī states:

> In some of [Ptolemy's] stars both the latitude and longitude are incorrect. This is because if they are marked on a [celestial] globe according to [Ptolemy's] table of latitude and longitude, especially [the stars of] al-Na'esh, we notice that the image [of the constellation] in the heavens does not correspond with what is [seen] on the globe.

Such statements are repeated many times throughout the book, however it is a surprise that al-Ṣūfī did not follow up on these comments and correct what he thought to be Ptolemy's errors. This might have been out of respect of Ptolemy's work and in order to retain the data that were found in the *Almagest*.

For the epoch of his catalog al-Ṣūfī adopted the beginning of the year 1276 of the era of Thū al-Qarnaīn (Alexander the Great) which corresponds to the year AD 964 (Kunitzsch 1989). However, al-Ṣūfī mentions that Ptolemy used the observations of Menelaus who made his observations in the year 845 of the year of Nabūkhat Nassar. Al-Ṣūfī also mentions that: "The time difference between the observations of Menelaus and the date of Ptolemy is 41 years." He concluded that Ptolemy added 25 minutes to Menelaus' longitude values to account for precession. However it is still unknown why al-Ṣūfī makes this claim because at that time there was no evidence or available text that mentioned that Ptolemy used Menelaus' observations (Grasshoff 1990).

Al-Ṣūfī updated Ptolemy's stellar longitudes from A.D. 125 to A.D. 964 by adjusting for precession. In the introductory chapter of his book he describes the method 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 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 longitude value to allow for precession. Over the 839 years between the tables of Ptolemy and al-Ṣūfī, precession would actually amount to 11° 47′. Hence by using 12° 42′ al-Ṣūfī over-corrected Ptolemy's stellar longitudes by 55′. Of course Al-Ṣūfī would not have been aware of this over-correction because his calculations were based on the *Almagest* and thus he did not discover the systematic error in Ptolemy's longitudes even though Arabic and Islamic astronomers recognized earlier that Ptolemy's value for precession was false (see Evans 1998). Therefore, it would be unreasonable to compare the accuracy of al-Sufi's data with those of Ptolemy because of this over-correction, which renders al-Sufi's coordinates slightly more accurate then those of Ptolemy. As for the ecliptic latitudes, al-Ṣūfī mentions in his introductory chapter that: "… since they [the stars] rotate around the poles of the ecliptic therefore they do not ever change." The study of Ptolemy's coordinates has been covered in many research papers and books by prominent scholars such as Knobel, Peters, Newton, Toomer, Kunitsch and Grasshoff.

2.2 Al-Sufi's Magnitude Estimates

In the introductory chapter of his *Book of the Fixed Stars* al-Ṣūfī describes the magnitude system that he adopted when he estimated the brightness of the stars. He writes:

> … many people believe that the total number of stars in the sky, which are called fixed stars, is 1025 stars. However this is an obvious mistake because ancient astronomers observed this number of stars and they divided them into 6 divisions of brightness. They made the brightest 1st magnitude and those a little fainter 2nd magnitude then the ones below that 3rd magnitude until they reached the 6th magnitude. They found the number of stars below the 6th magnitude more than they could count so they left them.

This magnitude system was the same one used by ancient astronomers such as Ptolemy and Hipparchus many years before (Evans 1998). It is in these magnitude estimations that al-Ṣūfī excels as a capable observational astronomer. In this paper we review these magnitude estimations in order to illustrate the originality of al-Ṣūfī's observations and uniqueness of his magnitude system.

Al-Ṣūfī and Ptolemy both used intermediate values in their magnitude systems. Ptolemy mentioned the words "more-bright" and "less-bright" for certain stars (see Grasshoff 1990; Schmidt 1994). However, al-Ṣūfī expressed these intermediate magnitude values by the words "*Aṣghareh*," which means "less," "*Akbareh*," which means "greater," and "*A'ẓameh*," which means "much-greater." Almost all scholars who have studied al-Ṣūfī's work have not differentiated between the words "*Akbareh*" and "*A'ẓameh"* (e.g. see Fujiwara and Yamaoka 2005; Knobel 1885; Kunitzsch 1986; Lundmark 1926). Many have relied upon the French translation of the *Book of the Fixed Stars* by Schjellerup (1874), who also did not differentiate between "*Akbareh*" and "*A'ẓameh*." Schjellerup simply translated the intermediate magnitude values as a middle value. For example, he translated the expression "… much greater than 4th magnitude …" as magnitude 4–5. In their works on Ptolemy's catalogue, Knobel and Peters (1915), Grasshoff (1990) and Toomer (1998) all relied upon Schjellerup's translation for al-Ṣūfī's data, and they all expressed his intermediate magnitudes values on a 2-step system using the words "more" and "less" bright. This 2-step intermediate magnitude system was usually numerically interpreted by a constant difference of 0.33 of a magnitude.

However, when we look at al-Ṣūfī's text in detail, especially at the commentaries on the constellations, it is evident that he made a clear distinction between three intermediate magnitudes. We believe that al-Ṣūfī used what we have termed a '3-step intermediate magnitude system,' which is more accurate than Ptolemy's 2-step system. We think that with this 3-step system al-Ṣūfī managed to express all magnitude values by a constant difference of 0.25 of a magnitude. For example, the magnitude of the star 19 Ursa Major was expressed by al-Ṣūfī as "… much greater than 3rd magnitude." This can be interpreted on the 3-step scale as equal to magnitude 2.5, and the modern magnitude adopted for this star is 2.44, which is very similar. However if we interpret this description using a 2-step scale, we obtain a magnitude value of 2.7.

Therefore in this paper we make a detailed analysis of al-Ṣūfī's magnitude values, where the magnitude figures are numerically interpreted by a constant difference of 0.25 magnitudes: that is, +0.25 for "less," −0.25 for "greater" and −0.5 for "much-greater." Ptolemy's 2-step intermediate magnitude difference was interpreted by a constant of 0.3 magnitudes. All of the relevant data in al-Ṣūfī's book were collected in tables similar to Table 1, which is reproduced here by way of example and relates to the constellation Ursa Major. The first three columns in this table show the number and the number sequence of the stars and constellations. The 4th

Table 1 Table of coordinates, magnitudes and magnitude analysis for the constellation of Ursa Major

Seq	R.#	Cons.	Zodiac	Deg	min	D.	Lat	min	SM	SM1	SM2	PM	PMA	VIS	HR
1	9	UMa	3(90)	8	2	N	39	50	4	4.00	4.00	4	4.00	3.36	3,323
2	10	UMa	3(90)	8	32	N	43	5	5	5.00	5.00	5	5.00	5.47	3,354
3	11	UMa	3(90)	9	12	N	43	5	5	5.00	5.00	5	5.00	4.60	3,403
4	12	UMa	3(90)	8	52	N	47	10	5	5.00	5.00	5	5.00	4.76	3,576
5	13	UMa	3(90)	9	22	N	47	5	5	5.00	5.00	5	5.00	4.80	3,616
6	14	UMa	3(90)	10	52	N	50	30	5	5.00	5.00	5	5.00	4.56	3,771
7	15	UMa	3(90)	13	12	N	43	50	4(s)	4.25	4.30	4	4.00	4.67	3,624
8	16	UMa	3(90)	15	12	N	44	20	4	4.00	4.00	4	4.00	3.67	3,757
9	17	UMa	3(90)	21	42	N	42	5	4	4.00	4.00	4	4.00	3.80	3,888
10	18	UMa	3(90)	23	42	N	44	5	4(s)	4.25	4.30	4(s)	4.30	4.59	3,894
11	19	UMa	3(90)	23	22	N	35	5	3	3.00	3.00	3	3.00	3.17	3,775
12	20	UMa	3(90)	18	12	N	29	20	3(s)	3.25	3.30	3	3.00	3.14	3,569
13	21	UMa	3(90)	19	2	N	28	20	3(s)	3.25	3.30	3	3.00	3.60	3,594
14	22	UMa	3(90)	13	22	N	36	5	5(m)	4.50	4.70	4	4.00	4.83	3,662
15	23	UMa	3(90)	13	32	N	33	20	5(m)	4.50	4.70	4	4.00	4.48	3,619
16	24	UMa	4(120)	5	22	N	49	5	2	2.00	2.00	2	2.00	1.79	4,301
17	25	UMa	4(120)	4	52	N	44	30	3(m)	2.50	2.70	2	2.00	2.37	4,295
18	26	UMa	4(120)	15	52	N	51	5	3(s)	3.25	3.30	3	3.00	3.31	4,660
19	27	UMa	4(120)	15	42	N	46	30	3(m)	2.50	2.70	2	2.00	2.44	4,554
20	28	UMa	4(120)	5	22	N	29	20	3(s)	3.25	3.30	3	3.00	3.45	4,033
21	29	UMa	4(120)	6	52	N	28	15	3(s)	3.25	3.30	3	3.00	3.05	4,069
22	30	UMa	4(120)	14	22	N	35	15	3(s)	3.25	3.30	4(m)	3.70	3.01	4,335
23	31	UMa	4(120)	22	35	N	25	50	3(s)	3.25	3.30	3	3.00	3.48	4,377
24	32	UMa	4(120)	23	2	N	25	0	3(s)	3.25	3.30	3	3.00	3.66	4,375
25	33	UMa	4(120)	24	52	N	53	30	2	2.00	2.00	2	2.00	1.77	4,905
26	34	UMa	5(150)	0	42	N	55	40	2	2.00	2.00	2	2.00	2.27	5,054
27	35	UMa	5(150)	12	32	N	54	0	2	2.00	2.00	2	2.00	1.86	5,191
28	36	UMa	5(150)	10	32	N	39	45	3	3.00	3.00	3	3.00	2.90	4,915
29	37	UMa	5(150)	2	52	N	41	20	5	5.00	5.00	5	5.00	4.26	4,785
30	38	UMa	4(120)	27	42	N	17	15	4	4.00	4.00	4	4.00	3.13	3,705
31	39	UMa	4(120)	26	2	N	19	10	4	4.00	4.00	4	4.00	3.82	3,690
32	40	UMa	4(120)	25	52	N	20	0	6	6.00	6.00	F	6.00	4.55	3,800
33	41	UMa	4(120)	24	52	N	22	45	4	4.00	4.00	F	6.00	4.81	3,809
34	42	UMa	4(120)	23	52	N	20	20	6	6.00	6.00	F	6.00	4.56	3,612
35	43	UMa	4(120)	12	42	N	22	15	6	6.00	6.00	F	6.00	4.25	3,275

to the 9th columns are the coordinate values according to al-Ṣūfī's tables. The 10th column shows the magnitudes of the stars according to al-Ṣūfī, where we use the letters (s) for "less," (k) for "greater" and (m) for "much-greater." The 11th and 12th columns show the magnitudes after adjusting for the 3-step and the 2-step systems respectively. This was done by adding the values +0.25 for "less," –0.25 for "greater" and –0.5 for "much-greater" for the 3-step system, and +0.3 or –0.3 for the 2-step system. The 13th column shows the magnitude according to Ptolemy, where we used the magnitude that al-Ṣūfī attributed to Ptolemy. The 14th column shows Ptolemy's magnitudes after adjustment for the 2-step system. Finally, the 15th and 16th columns show the modern visual magnitude and the HR number for each star.

This table reveals that the magnitude values of 520 stars out of the total 1,022 stars (i.e. 51 %) have al-Ṣūfī's magnitude values that are identical with those derived by Ptolemy. Therefore one might first wonder whether al-Ṣūfī only re-estimated the magnitudes of about half of the stars observed by Ptolemy. However, upon a detailed comparison we found that of these 520 stars only 206 differ in value from the modern visual magnitude by >0.5 magnitude and only 56 stars differ in values >1 magnitude. The results also showed that out of these 56 stars 22 are of magnitude 5 or 6, which is understandable given the difficulty of visually estimating the magnitudes of faint stars. Therefore a level of accuracy of 0.5 magnitudes is more than can be expected for naked eye estimation, either by al-Ṣūfī or Ptolemy, for these faint stars. This conclusion is confirmed by the calculation of the standard error. Consequently, we believe that the best al-Ṣūfī could do was estimate the brightness of these faint stars to the nearest half-magnitude. Another study, conducted by Tomoko Fujiwara and Hitoshi Yamaoka (2005) on the magnitude estimates of old star catalogs, also confirms the above result. Fujiwara and Yamaoka found that the 1st and the 6th magnitude stars in the old star catalogs should not be used in determining the current magnitude system because they exhibited a Malmquist bias whereas all other stars magnitude in the old catalogs fit a logarithmic scale consistent with the light ratio of $R=2.512$. However, their findings do not reveal whether al-Ṣūfī personally re-estimated the magnitudes of all of the stars recorded by Ptolemy.

In order to analyze al-Ṣūfī's novel magnitude system and after all the magnitude values from al-Ṣūfī's book were collected we conducted an accuracy analysis for al-Ṣūfī's magnitude values in comparison with those of Ptolemy. Then we calculated the difference between these values and the modern visual magnitudes. The statistical results of this analysis are summarized in Table 2, which shows the mean and the standard deviation for all stars combined.

Given the values in Table 2 it would seem that the mean for the 3-step system is slightly better, but barely statistically significant. Meanwhile, note that the standard deviation is the same whether we apply the 3- or the 2-step system whereas it is higher for Ptolemy's magnitudes. The dispersion in al-Ṣūfī's data is thus significantly less than in Ptolemy's. While the statistical results in this table do not prove conclusively that al-Ṣūfī used a 3-step magnitude system in lieu of a 2-step system, we still believe that he did purposely adopt the 3-step system. The main reason for

Table 2 The statistical results of the magnitude analysis

Statistical data	Mean	Standard deviation
Al-Ṣūfī 3-step	–0.06	0.59
Al-Ṣūfī 2-step	–0.09	0.59
Ptolemy	+0.07	0.71

Table 3 Al-Ṣūfī's magnitudes for the constellation of Gemini

1	GEMINI	2
2	GEMINI	2
3	GEMINI	4(m)
4	GEMINI	4
5	GEMINI	4
6	GEMINI	4
7	GEMINI	4(k)
8	GEMINI	5(s)
9	GEMINI	5
10	GEMINI	3(s)
11	GEMINI	3
12	GEMINI	4(m)
13	GEMINI	3(s)
14	GEMINI	4(k)
15	GEMINI	4(k)
16	GEMINI	3(s)
17	GEMINI	3
18	GEMINI	4
19	GEMINI	4(s)
20	GEMINI	4(s)
21	GEMINI	5(s)
22	GEMINI	5(s)
23	GEMINI	5(s)
24	GEMINI	5(s)
25	GEMINI	4(s)

this conviction is in the way in which al-Ṣūfī expressed or described the values of the stellar magnitudes in his book. For example, if we look at the full range of magnitude values in the constellation of Gemini (Table 3) it is clear that he was referring to three separate intermediate magnitudes.

From this table, we can see that al-Ṣūfī made a clear distinction between (m) and (k). He was not really concerned with word repetition or correct sentence structure. The above examples show that al-Ṣūfī listed the magnitudes 4(m) and 3(s) consecutively then 4(k) twice. He also mentioned several 4(s) and 5(s) magnitudes in succession. These repetitions for the various terms are to be found in many places throughout the *Book of the Fixed Stars*. For example, in describing the constellation Taurus, al-Ṣūfī wrote:

> The third (star) is south of the second, close to it, and is much greater than 4th magnitude, but it was mentioned by Ptolemy as 4th magnitude exactly. The fourth (star) is the southernmost star of the four, south and close to the third, and is much greater then 4th magnitude, but it was mentioned by Ptolemy as 4th magnitude exactly.

Here the term "*A'ẓameh*" (much-greater) was used repeatedly in order to give the exact value that was intended. Therefore the assumption of word repetition is not valid in this case. Al-Ṣūfī also used the word "*Aṣghareh*" (less) throughout his entire work, and he repeated it many times consecutively in numerous locations throughout his book. Therefore, if al-Ṣūfī had been concerned about correct grammatical structure or word repetition he would not have used the term "*Aṣghareh*" (less) repetitively, especially since there were many other Arabic words that he could have been used instead.

These magnitude estimates only appear in his chapter commentaries, and the question now arises: why did al-Ṣūfī neglect to include these distinctions in his tables of the constellations? One answer might be that the original tables written by al-Ṣūfī did indeed include these comments, but they were omitted when the *Book of the Fixed Stars* was later copied—even by his son. But al-Ṣūfī also had great respect for Ptolemy and regard for his famous catalogue, so a more logical reason might be that he did not wish to deviate appreciably from the format of that catalogue. It is significant that in his *Book of the Fixed Stars* al-Ṣūfī specifically states that he is compiling his tables according to Ptolemy's *Almagest*.

3 Concluding Remarks

Al-Ṣūfī's *Book of the Fixed Stars* has a very important place in the history of Arabic and Islamic astronomy. Even though al-Ṣūfī's book was based on Ptolemy's *Almagest,* it is in the stellar magnitude estimates that al-Ṣūfī distinguished himself, and he corrected many of the values which were mentioned in previous catalogues (Winter 1955). Our analysis has revealed that al-Ṣūfī developed a unique system for expressing these magnitudes, which we have termed his '3-step intermediate magnitude system.' This new system was more accurate then the older 2-step system used by Ptolemy and others.

We have shown that the study and analysis of ancient works such as al-Ṣūfī's *Book of the Fixed Stars* can reveal new information that is of value to contemporary astronomers. Therefore, more effort should be directed towards locating and analyzing the astronomical treasures hidden in Arabic books and manuscripts that are preserved in repositories around the world.

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A Thorough Collation of Astronomical Records in the Twenty-Five Histories of China

Ciyuan Liu and Xueshun Liu

Abstract From the Spring and Autumn Period to the Qing Dynasty, people in China made numerous astronomical records, and a great majority of them are still kept in the Twenty-Five Histories. We have conducted textual research and done calculations with modern astronomical computing methods to test the validity of those records. Results of this collation are presented briefly in this paper.

1 Astronomical Records and the Twenty-Five Histories

It has been a tradition for Chinese people to record history. They have made huge quantities of historical records, among which the most authoritative ones are the Twenty-Five Histories. The first of the Twenty-Five Histories is the *Shiji, Records of the Grand Historian of China*, which was compiled by Sima Qian (BC 145–BC 90), an historian of the West Han Dynasty. He made public his version of the history from the era of the legendary Yellow Emperor to the time that he lived. The *Shiji* consists of chapters of *benji*, chronicles of emperors, *liezhuan*, biographies of aristocrats, officials and special commoners, and *zhi*, treatises on professional knowledge and institutions such as official ranks, geography, rituals, etc. From then on, the writing of Chinese official history was systematic. Historians who attended emperors daily wrote the *qiju zhu*, the official imperial diaries. After an emperor died, the next emperor compiled a *shilu* (chronicle) for him. When a dynasty was overthrown, its official history based on the *Shiji* was compiled by the next dynasty. That is how the Twenty-Five Histories came into existence, and they record Chinese history for several 1,000 years, without any chronological gaps.

Some of the Twenty-Five Histories were copied by hand more than once before the invention of printing, and different versions of these books have appeared.

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Moreover, before the founding of the Republic of China the punctuation in Chinese texts was extremely simple. As a result, it was difficult to read the Twenty-Five Histories, even though these were the most important Chinese historical texts available. In order to change this situation, after the People's Republic of China was founded the Zhonghua Book Company organized a group of senior scholars to collect different versions, conduct textual research and punctuate the Twenty-Five Histories. This project was suggested by the top-level leaders of China, and was supported by the government. In the end, a punctuated version of the Twenty-Five Histories was published by the Zhonghua Book Company between 1959 and 1977. Table 1 lists the name, dynasty or dynasties, dates of the dynasty or dynasties, and the number of pages of each History of this version.

However, the style and content of this punctuated version was imperfect because of two reasons. Firstly, the scholars involved with the project were influenced by contemporary political, economical and ideological conditions, and secondly, the project lasted a long time and there were major changes in the participants.

Table 1 Names and dates of the Twenty-Five Histories

No.	Book name	Dynasty	Period	Pages	Volume with astronomical records
1	Shiji	Western Han and before	−100	3,322	1
2	Hanshu	Western Han	−205 to 25	4,273	1
3	Houhanshu	Eastern Han	25–220	3,684	3
4	Sanguozhi	Wei, Shu, Wu	220–265	1,510	
5	Jinshu	Jin	265–420	3,306	3
6	Songshu	Song	420–479	2,471	4
7	Nanqishu	Southern Qi	479–502	1,038	2
8	Liangshu	Liang	502–557	870	
9	Chenshu	Chen	557–589	502	
10	Nanshi	Song, Qi, Liang, Chen	420–589	2,027	
11	Weishu	Northern Wei	386–550	3,065	4
12	Beiqishu	Northern Qi	550–577	698	
13	Zhoushu	Northern Zhou	557–581	932	
14	Beishi	Wei, Qi, Zhou, Sui	386–618	3,351	
15	Suishu	Sui	581–618	1,904	3
16	Jiutangshu	Tang	618–907	5,407	2
17	Xintangshu	Tang	618–907	6,472	3
18	Jiuwudaishi	Five dynasties	907–960	2,042	1
19	Xinwudaishi	Five dynasties	907–960	922	1
20	Songshi	Song	960–1279	14,263	13
21	Liaoshi	Liao	907–1125	1,560	
22	Jinshi	Jin	1115–1234	2,906	1
23	Yuanshi	Yuan	1279–1368	4,678	2
24	Mingshi	Ming	1368–1644	8,642	3
25	Qingshigao	Qing	1644–1911	14,740	14

Consequently, since 2007 the Zhonghua Book Company has arranged for scholars to thoroughly revise this punctuated version. It is called the Revising Punctuated Version of the Twenty-Four Histories and the *Qingshi Gao* Project, and eventually a new version of the Twenty-Five Histories will then be published.

The Twenty-Five Histories contain numerous astronomical records because astronomy was of special importance in China before the twentieth century. In Chinese history, observing celestial phenomena and issuing calendars were regarded as symbols of imperial power. Therefore, in the Twenty-Five Histories there are lengthy treatises on astronomy and calendars. Those treatises on calendars describe astronomical computing methods and those on astronomy include descriptions of celestial bodies and phenomena and astrological knowledge and records.

The source of astronomical records in the Twenty-Five Histories was the imperial observatories. To meet the needs of divination and calendrical calculations, the Chinese imperial observatories made a huge number of records of celestial phenomena, and these still exist. There is no other culture anywhere else in the world that has produced astronomical records with the same huge quantity, comprehensive variety, and for so long a time period. They are an indispensable resource when researching Chinese history, the history of technology, and even modern scientific research. The great majority of Chinese astronomical records are kept in treatises on astronomy of the Twenty-Five Histories, and the volume number of each treatise is listed in the last column in Table 1.

From the 'Treatise on Astronomy' in the *Hanshu* to the one in the *Qingshi Gao*, there is no obvious gap among astronomical records, although the frequency of such records differs from dynasty to dynasty. In the Twenty-Five Histories, descriptions of celestial phenomena also appear in chronicles of emperors. In these chronicles, records of the occurrence of solar eclipse are relatively complete. Records of comets and of "… stars appearing during the daytime …" are often seen as well. However, other astronomical records are rather rare. It should be pointed out that the amount of astronomical records in the chronicles of the emperors is far less than is found in the treatises on astronomy. In fact, most of the records that appear in the chronicles can also be found in the treatises on astronomy. In addition, occasionally, celestial records can be seen in the treatises on calendars. Although they are few in number, they often include details not contained in the treatises on astronomy, such as the time and magnitude of a solar eclipse. Astronomical records rarely were included in the biographies of the Twenty-Five Histories.

Besides the Twenty-Five Histories, other Chinese texts also contain astronomical records. For those extremely rare early records (namely before the Han Dynasty), a good source is the *Spring and Autumn Annals*, which retains 37 records of solar eclipses and some records of meteors and comets. Early astronomical records in other texts are extremely rare, and most lack details. From the Han Dynasty to the Yuan Dynasty, there are not many reliable astronomical records outside of the official histories. Some independent information exists only in texts like the *Tang Huiyao*, *Wenxian Tongkao*, *Song Huiyao Jigao*, etc. The *shilu* of the Ming and Qing Dynasties and many imperial archives of the Qing Dynasty are still preserved. Among these, there are many records that are not included in the treatises on astronomy in the official histories (Cui and Zhang 1997; He and Zhao 1986). Moreover, since the mid-Ming Dynasty, the practice of compiling local annals was very popular and quite a number of these local annals contain records of celestial phenomena, which can be divided into two categories: records that were copied from earlier texts and those that documented actual observations. Those records of actual observations of total solar eclipses, meteors and meteorites are of most value for scientific research.

In the late 1970s and early 1980s, astronomers and specialists in the historical texts in China conducted a comprehensive survey of astronomical records predating the twentieth century. Partial results of this survey were published in the *General Collection of Ancient Chinese Records of Celestial Phenomena* (Zhuang and Wang 1989). However, much more information is included in the *General Charts of Records of Ancient Chinese Records of Celestial Phenomena*, which as yet has not been officially published. It should be noted that neither of these books contains the huge quantity of records of the motion of the Moon and the five planets, and other kinds of celestial phenomena.

2 Summaries of the Astronomical Records

The quantity of Chinese astronomical records before the twentieth century is huge. However, its content is simple and formulaic. The common structure of one such record is as follows: reign name, year in that reign, month in that year, sexagesimal date and the astronomical phenomenon. For example, under the entry for the year 599 BC in the *Spring and Autumn Annals*, there is the following record: “Duke Xuan, the 10th year, the 4th month, day *bingchen*, the sun was eclipsed.”

Before the Tang Dynasty, there are prognostication and verification of most celestial records, which is an important characteristic of ancient Chinese astronomical records. Most astronomical phenomena were regarded as ill omens. Below are brief summaries of records of the different kinds of celestial phenomena.

2.1 Records of the Sun

Solar eclipses were taken most seriously in Chinese history. The earliest solar eclipse records with definite dates are the 37 records in the *Spring and Autumn Annals* from the eighth to the fifth centuries BC. During the several centuries that followed, solar eclipse records are scattered and do not contain much information. Then from the Western Han Dynasty, solar eclipse records become rather numerous; most actual eclipses were recorded. A small number of records even contain detailed information, such as the time, magnitude and the place where the eclipse was observed. Ciyuan Liu (2005) has arranged records of solar eclipses before 1500 AD in a computer-readable table that includes as much detailed information as possible.

Records of sunspots are included in the category of ‘abnormality of the Sun.’ This category also includes solar halos and clouds of a certain special shape that surround the Sun.

2.2 Records of the Moon

In contrast, lunar eclipses were not taken seriously. It was only in the fifth century AD that systematic records of lunar eclipses started to appear. Moreover, lunar eclipse records are far less complete than those of solar eclipses.

Among the records about the Moon, the most numerous ones are those that refer to the location of the Moon. When a moving or newly-appeared celestial body is close to another object (for example, when they are $<1°$ apart) this is called *fan*, or ‘invasion.’ Because the Moon moves comparatively quickly in the sky there are many chances for it to ‘invade’ different planets and stars, and many records of such events exist. Some *yan*, or occultations, were also recorded. Ciyuan Liu (1992) has analyzed the available data on the position of the Moon.

2.3 Records of the Planets

Records about the locations of the various planets are also very numerous. Ancient astronomers were happy to record the following phenomena: planets ‘invading’ each other or different stars, and when more than three planets were close to each other. A five-planet conjunction was considered an indication of an imminent dynasty change. Records about the locations of the Moon and the planets first appeared in the *Hanshu*.

During some dynasties, records about Venus appearing during the day are especially numerous. There even are some records about Jupiter appearing during the day. Obviously, climate factors contributed more than astronomical factors to the observation of these phenomena.

2.4 Records of Stars and Other Objects

Records of meteors are rather rich in content, often mentioning their color, size and their starting and finishing positions in the sky relative to specific stars. The phenomenon, ‘stars dropped like rain’ (e.g. during the occurrence of the Leonid meteor storm), was recorded many times. Comets often were recorded, with descriptions of their shape, changes in appearance, and the constellations they passed through. So-called ‘guest stars’ might include comets whose tails were not obvious, meteors with unusual tracks (i.e. that lie along the line of sight of the observer), and novae and supernovae.

In early Chinese capitals like Xi'an, Luoyang, and Nanjing it is not easy to see the star Canopus. However, throughout the different Chinese dynasties there was a custom to offer a sacrifice to Canopus in the Royal Court each year when it first appeared in the evening and morning sky, and many records about these ceremonies are still in existence. The appearance of Canopus was considered an auspicious omen.

Some records of 'night clouds' might refer to 'northern lights,' the *aurora borealis*.

Finally, there are some records that are difficult to interpret, such as "Tianxing reign period, the fourth year, the third month, day jiazi(401-4-18), *the Moon grew teeth*." (Weishu; our italics), and "Yuankang reign period, the second year, the second month(292-3-6——292-4-3), *the sky tore greatly in the northwest*." (Jinshu; our italics).

2.5 Statistics on the Astronomical Records in the 25 Histories

The classification of astronomical phenomena differs among the Twenty-Five Histories. Except that solar eclipses are listed separately, some histories record other celestial phenomena without employing any type of classification, while other histories use a large number of different categories to record them. For example, the *Qingshi Gao* divides astronomical phenomena into 43 different categories.

With modern astronomical computing methods we are able to test the validity of reports of solar and lunar eclipses, and the locations of the Moon and the different planets at any given time. Table 2 presents statistics on the astronomical records in the Twenty-Five Histories and the results of our tests. The first column lists the dynasty name, but some short dynasties are treated as one item. The total number of astronomical records of a dynasty, listed in the third column, includes all records appearing in the different books of those Twenty-Five Histories. The second column lists the time the astronomical observations were made, which is not always the same as that shown in Table 1. The number of testable records and the percentage of mistaken records in the testable records are listed in the fourth and fifth columns, respectively.

Figure 1 shows the quantities of astronomical records every 20 years: the bars represent the total number of records and the blacked sections indicate the number of testable records. It can be seen that the percentages of testable records within the total records differ from period to period, but generally speaking testable records account for the majority. Where two different governments coexisted, their data are indicated by 'a' and 'b' in Fig. 1.

3 Collation of Astronomical Records

During the transmission of the Twenty-Five Histories, it was unavoidable for textual mistakes to occur. As a result, collation has always been necessary. The first step of collation is to pick the best version. The next step is to compare the differences in words among the different versions; the differences in descriptions about the same

Table 2 Statistics and test results of astronomical records

Dynasty	Period	Total records	Average/ year	Testable records	Error ratio
Western Han	–205 to 10	174	0.8	94	27.7
Eastern Han	20–220	431	2.2	268	25.7
Wei, Shu, Wu	220–263	105	1.7	74	31.1
Jin	265–420	526	3.4	430	30.9
Southern dynasties	420–583	993	6.1	712	17.8
Northern dynasties	396–580	1,325	7.2	977	23.4[a]
Sui	581–618	49	1.3	19	63.2
Tang	618–907	1,049	3.6	683	26.2
Five dynasties	907–960	276	5.2	205	14.6
Song	960–1276	7,919	25.1	5,661	10.0
Jin	1129–1234	570	5.4	317	12.9
Yuan	1260–1367	1,875	17.5	1,528	4.3
Ming	1368–1644	2,115[b]	7.7	1,307	11.8
Qing	1644–1795	5,968[c]	39.5	1,858	3.6
Total		23,375		14,133	

[a]Among the 62 testable records during the Northern Wei (457–469), dates of 59 are one year off, but they are not counted as mistaken records here (Liu 2011b)

[b]For the Ming Dynasty, there are numerous records about the Moon invading stars in the *Ming Shilu* (He and Zhao 1986)

[c]The *Qingshi Gao* only includes astronomical records up to the end of Emperor Kangxi. There are some of these records kept in the official archives of the Qing Dynasty, and these have been published (Cui and Zhang 1997)

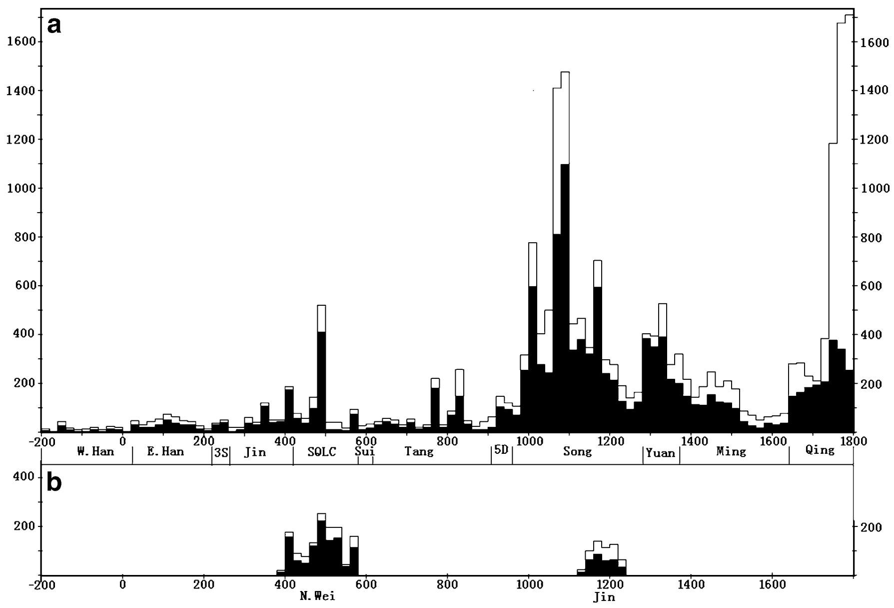

Fig. 1 The astronomical records in the Twenty-Five Histories

event at different places within the same book, and in other texts to find any obvious mistakes or missing words in the best version. After that, one may either correct the text, or write notes and insert them at the end of a volume, which are called *jiaokan ji* (collation notes). When the last collation of the Twenty-Five Histories was done, some problems with astronomical records were found, a great number of collation notes were made, and a small number of changes were made to the texts. However, because of the collators' limited ability to carry out astronomical computing at that time, it was impossible for them to find the vast majority of problems in these astronomical records.

Part of the work of those involved in the Collation of the Punctuated Twenty-Four Histories and the *Qingshi Gao* Project is to test all computable records of celestial phenomena using modern astronomical computing methods. In order to complete this task we had to develop special software. After dates are inserted according to the format recorded in the ancient texts, the software produces star maps and data lists to show the locations of the Sun, the Moon, and the planets. It is then very easy to compare them with the descriptions given in the texts and to judge whether these records are correct or not. As for incorrect records, special functions of the software can help us determine how those mistakes were made.

For an astronomical record to be included in an astronomical treatise of the Twenty-Five Histories, it normally had to go through the following steps: (1) The official astronomers observed the special celestial phenomena and wrote them down in the *houbu*, a notebook for astronomical observations; (2) important celestial phenomena were reported to the emperor and recorded in the *qiju zhu*, the official imperial diaries; (3) the compilers of the *shilu*, the official chronicle of an emperor, selected astronomical records from the *qiju zhu* and included them in the *shilu*; (4) when an official history was made for an overthrown dynasty, compilers again selected records from the *shilu* for the Astronomical Treatise; and (5) the Astronomical Treatise was passed down as part of the official history of the dynasty. During this long process, mistakes certainly could occur.

For most incorrect records the original version can be determined, and we call these records 'restorable.' During periods when records were made frequently, the dates of these records must be compatible, and it is relatively easy to restore the original texts. Take the record below as an example:

> Tianxi reign period, the fourth year, the first month, day *gengchen*, the Moon invaded the Pleiades. ('Astronomical Treatise' 6 of the *Songshi*).

On day *gengchen*, the 28th day of the first month (24 February 1020), the Moon was in the constellation Wei, and therefore was far away from the Pleiades. However, on day *gengshen*, the 8th day of the first month (4 February 1020), the Moon did indeed 'invade' the Pleiades. Therefore, it is clear that the original, *gengshen*, was mistakenly replaced by *gengchen*. Because the words *chen* and *shen* sounded similar, the mistake occurred when the text was being copied.

Upon analyzing the incorrect records, we found several common reasons for these errors, and they are discussed individually below.

3.1 Errors by Miscopying

Unlike other contents for historical texts, key words of the astronomical records are sexagesimal dates and numbers. Once they were copied wrongly, it was difficult to have a chance to correct them. The words *yi* and *ji*, *er* and *san* look so similar and *shen* and *chen*, *chou* and *you* sound so similar that it is very easy for people to mix them up. There is a very big chance for the second character of a sexagesimal date to be copied wrongly. The *gengshen* versus *gengchen* record mentioned above is a good example. As a matter of fact, we often made such errors ourselves when we typed sexagesimal dates during the process of testing the astronomical records.

Another often-seen miscopying error is missing characters. If a year or month is missing it usually is easy to find it by computation. If the date of a lunar invasion is missing, we often can find the appropriate date in the month. However, this kind of missing supplementary information is relatively inconspicuous and usually is not noticed. But if more parts of a record are missing at the same time—for instance the date *and* the description of a phenomenon—we have no way of restoring that astronomical record.

3.2 Errors by Miscompiling

Original astronomical records often were written together with other events in the chronicles of the emperors. In a chronicle, the reign name, year and month of those events usually appear once; only a sexagesimal date is given for a celestial phenomenon. When an astronomical record was selected to be included in an astronomical treatise, compilers needed to look for its month, year and reign name in the preceding section(s). During such a search, it was easy to make mistakes. The easiest mistake was to select a wrong month, especially when the text did not start a new paragraph at the beginning of a new month. We ourselves still have such difficulty when reading chronicles of emperors in the official histories.

Starting from the Eastern Han Dynasty, there often are some records of unobservable solar eclipses. According to our calculations, solar eclipse did indeed take place on these dates, but they were not observable in China. Apparently, such records were the results of inaccurate calculations. Perhaps, there already was a regular forecast of solar eclipses that guided the emperor to conduct sacrificial ritual when the eclipse actually occurred. When a predicated solar eclipse was not observed, the original texts would record notes as follows: this eclipse should have happened but did not happen, or this eclipse was not observed because it was cloudy. But often such notes were omitted when the official histories were compiled. As a result, unobservable solar eclipses are included in the Twenty-Five Histories. This is another kind of error by miscompiling.

3.3 Errors in the Original Texts

There are other errors that were obviously made, but not by miscopying or miscompiling. We call them errors in the original texts. Take records of 'invasion' for example. By definition, 'invasion' means that two celestial bodies are less than 1° apart (Liu 1992). But if they are less than 2° apart, that may still be called 'invasion.' For some records of 'invasion,' however, celestial bodies were separated by more than 2°, and by even as much as 5°. Because the ecliptic longitudes are in agreement and the differences between ecliptic latitudes are from 2° to 5°, it is obvious that people cannot say there are errors by miscopying or the dates of those records are incorrect. It may be that there are errors in the original texts. Because those bodies were so far apart, maybe the observer mistook a *he* 'conjunction' for a *fan* 'invasion.' It also was possible that the observer got the names of those celestial bodies wrong. For instance, according to the *Songshi*, the Moon invaded the determinative star in the constellation Bi twice at the end of the Shaoxing reign period. In reality, the Moon invaded the west end star of the constellation Bi. In some invasion records, the names of the planets are not correct. It is just possible that these errors could have been made by miscopying, but it is much more likely that the observers were mistaken and got names of the planets wrong.

Traditional Chinese calendars require that dates of the New Moon and the winter solstice be calculated accurately. However, that requirement could not be met easily. Calendar tables used in the current field of Chinese history, for example, the *Calendar Table for the Twenty Histories* by Yuan Chen (1962), are reconstructions based on treatises on the calendars in the official histories. These tables are not exactly the same as those actually used by people in history. During the process of testing astronomical records, we found 26 discrepancies between dates (Liu 2011a). Collecting such discrepancies between dates—which we detected by accident while reading the histories—is extremely important, if we wish to reconstruct the detailed calendar tables that were actually used throughout Chinese history.

4 Concluding Remarks

The errors we have found in the astronomical treatises of the Twenty-Five Histories and our collation notes are several-tens of times more than those in the punctuated version by the Zhonghua shuju. Our notes are so long that they cannot be included in the forthcoming punctuated version of the Twenty-Five Histories. Rather, they will be published as a book titled *Collation of Astronomical Records in Official Histories*, which will be a part of the *Series of Research Books related to Collation of the Twenty-Four Histories*. Based upon our calculations for all of the astronomical records seen in the chronicles of the emperors and the treatises on astronomy, and using modern astronomical computing methods, this book will include records that are incorrect but can be restored, and a small number of other explanatory notes. In total, it will include more than 2,000 items.

In the Twenty-Five Histories there are 23,375 astronomical records, and they constitute the vast majority of astronomical records from ancient China. Of those 23,375 records, 60 % are testable by modern astronomical computing methods, and of these testable records 12 % are incorrect. Fortunately, however, the original versions of most of the incorrect records can be reconstructed.

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Some Statistical Aspects of Historical Chinese Astronomy Records

Richard Strom

Abstract Ancient Chinese records of astronomical phenomena, which include visual observations of such diverse transient events as meteors, eclipses, comets and sunspots, have been used to investigate solar activity, returns of periodic comets, the rotation of the Earth and the ages of supernova remnants, to mention some of the most notable studies. The reliability of the recorded data has been tested using determinable events (such as planetary conjunctions) and is generally found to be good. The degree of completeness of the records is, however, extremely uneven. For Halley's Comet, all but one of the 29 returns since 240 BCE is described in Chinese annals (over 95 % complete), while in the case of sunspots far less than 1 % of the expected population has made it into the records. Looking at the sunspots in detail, the temporal sampling appears to be non-random: there are short periods when a fair number were noted, and long stretches (up to 250 years) without a single spot mentioned. This is in marked contrast to the comet and eclipse records, which both show a nearly uniform rate of events. However, examining the sunspot records from Korea and China in detail reveals striking similarities. I discuss a number of insights which can be gained from intercomparisons of the various ancient astronomical records.

1 Introduction

The records of astronomical phenomena collected by Chinese observers for over 2,000 years constitute a rich legacy which has been of considerable value to modern astrophysics. The observations, all of necessity done with the unaided eye, were of objects ranging from the Sun to distant supernovae. Here are a few examples. The orbit of Halley's Comet has been studied, using Chinese records, since as early as the first half of the nineteenth century (Biot 1843: 69; discussed by Yeomans and

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Kiang 1981). Yeomans and Kiang have summarized how orbit computations, combined with increasingly archaic records (as refined orbital parameters permitted extension of the comet's ephemeris to earlier epochs), were carried out from the 1840s until before the 1986 return. Although Halley's Comet is the most noteworthy example, other periodic comets, including 55P/Tempel-Tuttle (Marsden 1968: 314, 318) and 109P/Swift-Tuttle (Marsden et al. 1993), have been similarly traced in Oriental historical sources. Two-dozen candidate Kreutz sungrazers have also been suggested (Hasegawa and Nakano 2001). There have, moreover, been studies of the meteor showers associated with various periodic comets (see Hasegawa 1993).

A handful of historical supernovae observed and recorded in Chinese annals can be reliably linked to young remnants, of which the pair SN1054—Crab Nebula is probably the best known (Mayall and Oort 1942). Much of this work has been presented in two monographs (Clark and Stephenson 1977; Stephenson and Green 2002). The most important piece of information from such records is of course the age of the remnant, but in addition in some cases an estimate of the supernova brightness can also be extracted. A more common, yet even more spectacular phenomenon (if total) is the solar eclipse. Recorded eclipses provide a check on the rotation rate of the Earth, an area in which Richard Stephenson and his colleagues have been pioneers (Stephenson 2003). Also related to the Sun are sunspots, the most visible direct indicators of solar activity. Based upon catalogues of sunspots assembled by Clark and Stephenson (1978), Wittmann and Xu (1987), and Yau and Stephenson (1988), Stephenson, Willis and others have studied solar activity in the past (see Willis and Davis, these proceedings).

An important aspect of historical observations for the astronomer of today is the accuracy and reliability of the data. In some cases this can be checked: the positions of planets and the Moon can be determined by modern celestial mechanics to a high degree of accuracy over the entire period of Chinese records. Eclipses and conjunctions can thus be used as a check, and where this has been done the agreement is generally good (Clark and Stephenson 1977). This is not to say the data are free of errors (there are, in particular, apparent copying errors arising from characters with similar shapes; see Ho 1966), but there is little evidence of systematic falsification. While the data may be reliable and accurate, completeness can be another matter. Let us look in more detail at the problem of how complete the astronomical data are.

2 What Information Is There on the Completeness of Chinese Records?

The data sets available to us from historical sources are likely to be incomplete for a variety of reasons. Weather and other atmospheric conditions would in the past have been no less of an impediment to observing astronomical phenomena than they are today. An event can also have been missed by the astronomer 'on duty' (what might be termed observer incompetence). Original records (or early copies thereof) have succumbed to war, fire, insects, rodents and a variety of other hazards. Needless to say, original written annals from 2,000 years ago are extremely rare (though some do exist, for example from the *Mawangdui* tomb no. 3, dating from 168 BCE—see Loewe 1980). And since most of the material available has been edited and copied multiple times, we also have to contend with errors of transcription, and the whims of editorial choice. Let us consider some specific cases.

2.1 Halley's Comet

The periodic comet suggested as such by Edmond Halley returns to the inner solar system about every 76 years. Its appearance can be traced back to 240 BCE in Chinese sources (mainly the official dynastic histories). Of 29 returns to 1910, 28 were observed in China (Yeomans and Kiang 1981): the record is 97 % complete. While P/Halley is always a naked-eye object for one to two months, a factor which undoubtedly helps mitigate the effects of inclement weather, the high degree of completeness can be described as nothing short of remarkable. One can only speculate as to why only one return (that of 164 BCE) was not recorded, and be thankful for the information which has survived about all of the others. Such a complete set of data is, as we shall see, an exception and not the rule.

2.2 Supernovae

Some years ago, I investigated the completeness of ancient supernova (SN) records (Strom 1994). From 200 BCE to 1800 CE there have been eight SN candidates recorded (in 185, 386, 393, 1006, 1054, 1181, 1572 and 1604, all CE). Based upon distance estimates, size, kinematics and other relevant characteristics, ten supernova remnants (SNRs) can be identified within 5 kpc of the Sun, which are younger than about 2,200 years. From the overlap between the two samples, one can estimate that the Chinese record of SNe is about 70 % complete.

2.3 Comets Generally

The Chinese archives contain observations of thousands of night-time objects, including comets, novae and meteors. The latter, of short duration and by far the most numerous, are considered further below. While the overwhelming majority of the remainder are comets, the distinction between them and (super)novae is not always evident. Although terminology such as *huixing* (or 'broom star,' the most common of several Chinese names for comets) and *kexing* ('guest star,' the usual connotation for a new star) seems clear enough, a faint comet without a tail is sometimes mistakenly called a *kexing*. For example, the 66 CE appearance of Halley's

Comet is described as a 'guest star' in the *Hou Han Shu* (Ho 1962), even though the text also indicates that it was extended. The following discussion mainly refers to comets, though a tiny fraction of the objects may have actually been novae.

Let us consider the 1,000-year period from 600 to 1599 CE, when there were reliable astronomical records from both China and Japan. As has been noted elsewhere (Clark and Stephenson 1977), the capital cities of both countries (which changed on several occasions, and from where the observations were presumably made) were at similar latitudes during the period, so they would have observed practically the same sky. The Chinese observed and recorded 216 objects, the Japanese 146, of which 74 were common to both data sets. Hence a total of 216 + 146 − 74 = 288 objects was seen. How complete is such a sample? Can we estimate the degree of completeness? There is in fact a statistical method by which we can evaluate the size of the total ensemble (in our case, comets and new stars visible to the naked eye) from which the Chinese and Japanese samples have been drawn.

Introduced into meteor studies by Öpik (1922), the method depends upon samples independently drawn from the same parent population. This means that two (or more) observers view the same region of sky, and obviously they must not copy one another's data. If the parent population consisted of *N* objects, and Chinese observers recorded a fraction, *f*, of the ensemble, then the number they registered would be

$$n_C = f\,N \qquad (1)$$

If the fraction recorded by the Japanese was *g*, then we similarly have

$$n_\mathrm{J} = g\,N \qquad (2)$$

The overlap between the two samples is just

$$n_\mathrm{o} = f\,g\,N \qquad (3)$$

From our three equations we can eliminate *f* and *g*, to get

$$N = n_\mathrm{C}\;\; n_\mathrm{J}\,/\,n_\mathrm{o} \qquad (4)$$

Hence, from knowing the number of objects in each sample and how many are common to both, we have an estimate of the parent population. The existence of events not recorded, whether because they were missed in the first instance, or were edited out of the final records, can be construed from the estimated size of the parent population (though of course only in a non-specific statistical sense). This is true provided the missed objects in the two sample ensembles are uncorrelated. (The observing locations should, for example, be sufficiently separated that they do not systematically experience the same cloud cover at the same times.)

With this information, we are now in a position to estimate how many naked-eye comets and novae could have been observed in China and Japan from 600 to 1599 CE. From above, we have $n_\mathrm{C} = 216$, $n_\mathrm{J} = 146$ and $n_\mathrm{o} = 74$. For our estimate of the parent population, $N = 216 \times 146/74 = 426$, with a statistical uncertainty (based upon the sample size) of ≈ 10 %. From this we can conclude that the Chinese sample was 216/426 = 51 % complete and the Japanese recorded 34 % of the objects which should have been visible to them, while the combined (China+Japan) set was 288/426=68 % complete. These figures underline the uniqueness of the nearly complete Halley's Comet data set.

2.4 Sunspots and Meteors

Meteors and sunspots are among the most commonly-observed transient astronomical phenomena. On a clear night, several sporadic meteors are likely to be observed. Throughout the sunspot cycle, but especially when the Sun is active, naked-eye sunspots can be readily seen, as was quantified in a survey carried out by Mossman (1989). For over a year, shortly after solar maximum (1981–1982), Mossman daily observed the sun (weather permitting) and with the unaided eye saw about one sunspot every five days. Eddy et al. (1989) note that his detection rate, after correcting for and averaging over the solar cycle, exceeds that of the Oriental observers by a factor of 200: in 13 months Mossman saw more sunspots than the Chinese did in 1,800 years. Based upon a simple interpretation, the Chinese record is only complete at the 0.1–1 % level.

The situation regarding Chinese meteor records is slightly more complicated. There are periods of regular and frequent (weekly, for short periods daily) meteor sightings, alternating with extended stretches with a dearth of reports. Figure 1 shows the numbers of meteor records in 50 year intervals from 701 to 1600 CE. The variability is most dramatically illustrated by periods in the fourteenth and fifteenth centuries, separated by merely a century. From 1301 to 1350, just 11 meteor sightings were recorded, while during 1401–1450 there were 1186. If we take as a round figure a maximum possible rate of 200 meteors/year, then the latter period was about 12 % complete, while the former had a completeness rate near 0.1 %, similar to the value for sunspot records.

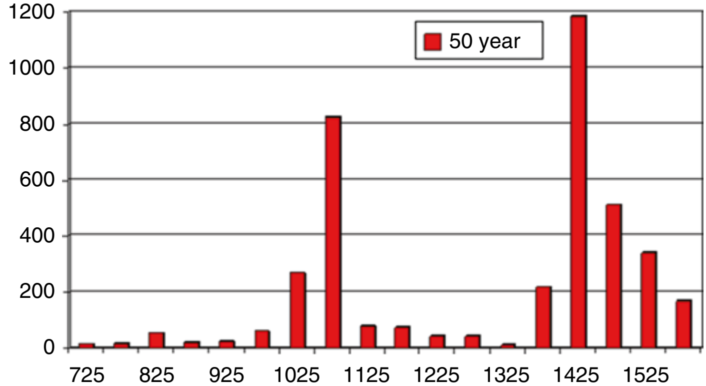

Fig. 1 Histogram showing the number of days on which meteors were recorded in 50 year intervals, from 701–1600 CE

2.5 Completeness for Different Types of Object

We can now summarize the degree of completeness in Chinese annals for the various kinds of object discussed above:

- P/Halley records: 97 % complete;
- Supernova records: 70 % complete;
- Comets (and novae) generally: 50 % complete;
- Meteor sightings: range from 12 to 0.1 % complete;
- Sunspot records: 1–0.1 % complete.

The low rate for meteors and sunspots may reflect the fact that they are fairly common phenomena. As Eddy et al. (1989: 72) noted about sunspots, perhaps they were so common that reports of them were usually discarded, "… much as one saves but a few of the seashells found … along the beach."

3 Chinese Sunspot Records

Let us now examine more carefully the sunspot observations recorded in Chinese and other Oriental sources. But before doing so, I will digress slightly to discuss what at first sight seems to be an apparently related phenomenon.

3.1 Peculiar 'Sunspot' Observations

Most Chinese astronomical records are brief and rather terse, and sunspot reports are no exception. A typical laconic report might read: There was a black spot on the sun. (日中有黑子。) While perusing the Beijing Astronomical Observatory (1988) compendium of sunspot records, I was rather surprised to read in an entry for 15 CE: 日中见星。(A star appeared within the sun.) I found fourteen other similar reports of "stars within the sun" in the BAO compendium. What, I wondered, could these records refer to, and were they really sunspots?

There were several possible explanations which could be eliminated. Venus in daylight, of which there are regular Chinese reports, is a potential candidate. However, on none of the occasions mentioned was Venus within 25° of the Sun, which appears to rule out this possibility. Parhelia (or sun dogs) are well-removed from the Sun, and were in any event well known to the ancient Chinese (Needham 1959: 473–477 and Plate LXX). Could this have been a bright supernova seen near the Sun? While possible, its *a priori* probability of occurring near the Sun is quite small, and it would remain visible for many months. Various possible explanations are discussed in some detail in Strom (2002). The Chinese descriptions reminded me of an event which I remembered once reading about.

On 7 August 1921 the Sun was setting over the Pacific as seen from Mt. Hamilton. Admiring the lovely scene was a unique quartet, including two of the most respected astronomers in the United States: W.W. Campbell, the Director of Lick Observatory (from where the spectacle was being viewed), and H.N. Russell, the Director of Princeton Observatory. They were joined by two men who must have had impeccable visual acuity: World War I ace pilots Major R. Chambers, and Captain E.V. Rickenbacher. While they admired the spectacle, Chambers broke the silence by asking: what star is that to the left of the Sun? Rickenbacher had already noticed it, but assumed that it must be a known star. At this point both astronomers also saw it. Through binoculars Campbell observed that it was star-like: there was no sign of extension. Shortly thereafter it set with the Sun.

Campbell and Russell checked the ephemeris and concluded that it could not be a planet, or any of the bright stars. From their scant observations, the star-like object was seen 3° from the Sun, on its southeastern side. It was brighter than Venus, but it set like the Sun so it could not be an atmospheric phenomenon. Given its brightness and location, a nova seemed unlikely. They concluded that it was most likely a sungrazing comet, and they telegraphed the information to Harvard Observatory and the *New York Times*, which published an article on the event shortly thereafter. From the publicity it transpired that several amateurs in the United Kingdom had probably observed the same object some six hours earlier, as the Sun set over the British Isles. There was also an observation made in southern Germany. (For a summary of what is known of the phenomenon, see Pearce 1921.)

I suggest that like the Mt. Hamilton object, the 'stars' which the Chinese observed were not sunspots, but were sungrazing comets. The descriptions given in the annals are slightly different for the two phenomena, and in 30 % of the cases the location given is the side (*pang*, 旁) of the Sun, which is seldom said of sunspots. There are also subtle differences in the language used to describe both phenomena, as I have noted elsewhere (Strom 2002). A major difference between the two is the time of year they were usually observed. While sunspot sightings peak in the winter/spring, the 'Sun stars' were more likely to be seen in the summer (when sunspots recorded were at a minimum). These differences can be readily seen in Fig. 2.

The pattern described above suggests Kreutz sungrazing comets. In the summer months their orbits lie behind the Sun, and as Marsden (1967: 1171) has pointed out, such a comet "… at perihelion between mid-May and mid-August will undoubtedly be missed, *unless it can be seen in daylight*." (my italics). At other times of the year, it would be possible to link the daylight 'star' to a night-time comet before or after perihelion. Kreutz sungrazers are known to be particularly bright as they near perihelion. Ikeya-Seki (1965 VIII) was readily visible in broad daylight, with an estimated visual magnitude of −10 to −11 as it neared the photosphere (Marsden 1965). Similarly, 1882 II (the Great September Comet) was a "… blazing star near the sun." (Clerke 2010: 402). For the remaining discussion, the 'sun stars' will not be considered further.

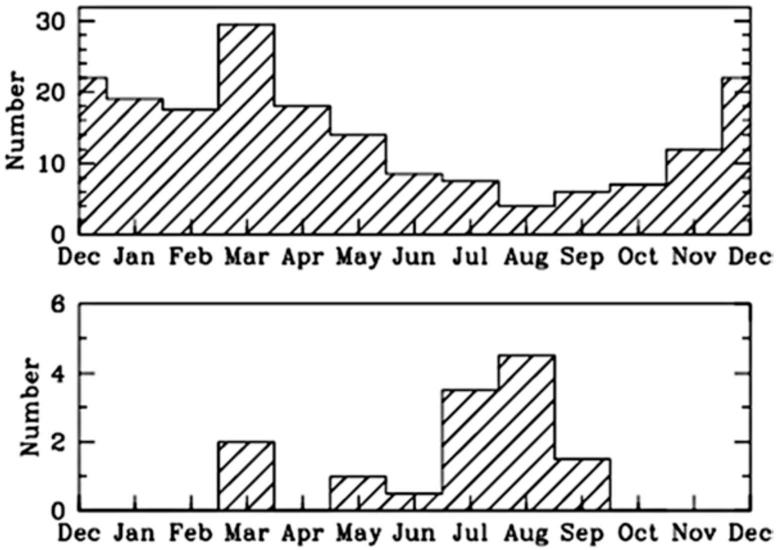

Fig. 2 Histograms showing (*top*) monthly sunspot numbers and (*bottom*) the recorded incidence of 'sun stars.' The summer dip in sunspot numbers is thought to reflect weather conditions unfavorable to direct observation of the solar disk. The anti-correlation between the two distributions makes it highly likely that we are dealing with two different phenomena (After Strom 2002)

3.2 The Oriental Record of Sunspots

Turning to sunspots as usually described in the Oriental records, most of the reports we have come from China. Apart from two reports from the early eighth century BCE (Zhou Period), regular sunspot sightings date from 179 BCE, and go on until 1917 with nearly 270 listed (BAO 1988), giving an implied rate of 0.13/year. Besides China, the only other major civilization reporting sunspots before 1610 was Korea (see Yau and Stephenson 1988). The Korean sunspots, however, only date from the period 1150–1750 CE, with 44 reported in all. There were, over the same period, 115 reported in China. Noting that there were only three sunspots common to both samples, we can once again estimate the total parent population: $N = n_C \; n_K/n_o = 115 \times 44/3 = 1687$. Note that the fact that only three objects were common to the two samples suggests sparsely-sampled data sets (rather than an intrinsically low number of sunspots). Spread over a 600 year period, the implied sunspot rate is (a still pretty meager) 2.8/year.

Before examining the data in more detail, let us consider the rate at which other, less common phenomena were reported. Figure 3 shows that solar eclipses were recorded at a fairly steady, slightly increasing rate over the same period. The pattern for comets (Fig. 4) is similar, though slightly more jagged than that for eclipses, and with a noticeably lower rate before the mid-fourteenth century. The same type of plot for sunspots from the Chinese annals is shown In Fig. 5, and it looks very different.

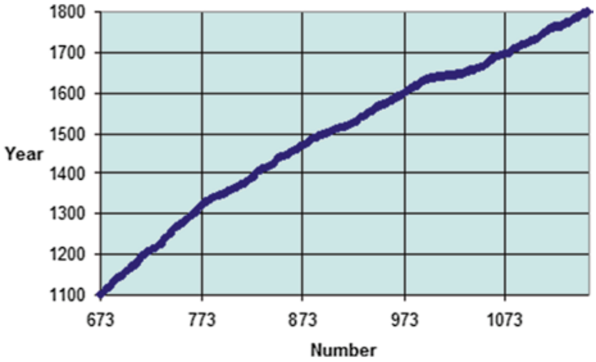

Fig. 3 Solar eclipses recorded from 1100 to 1700 in Chinese annals. This plot of date vs. sequence number would result in a *straight line* if the recorded eclipse rate were constant in time. The gradual flattening of the *curve* indicates an eclipse rate increasing with time

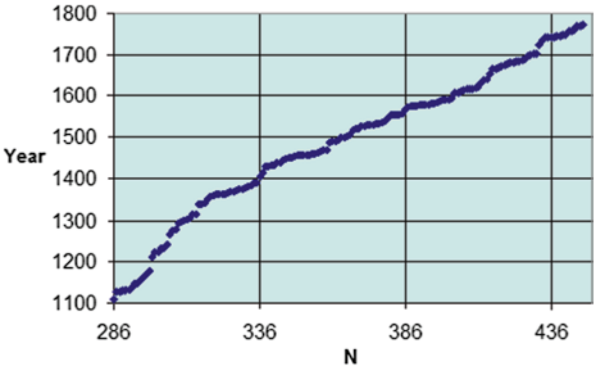

Fig. 4 Comets recorded in Chinese annals from 1100 to 1700. The format is the same as in Fig. 3

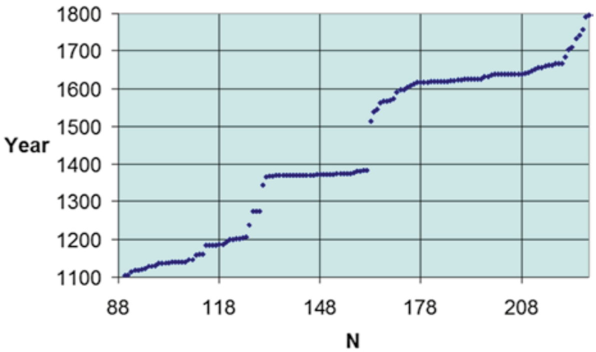

Fig. 5 Sunspots as recorded by Chinese observers from 1100 to 1700. Nearly vertical jumps are periods when few sunspots were noted

There are abrupt vertical jumps when few sunspots are reported, and short periods when they were readily seen. One might be tempted to attribute these sudden changes to non-solar (historical) events. However, the data for Korea (Fig. 6) reveal a strikingly similar pattern, suggesting that not history, but the Sun itself is the underlying cause.

A particularly noteworthy period is the almost horizontal segment in the late fourteenth century, clearly present in both the Chinese and Korean data sets.

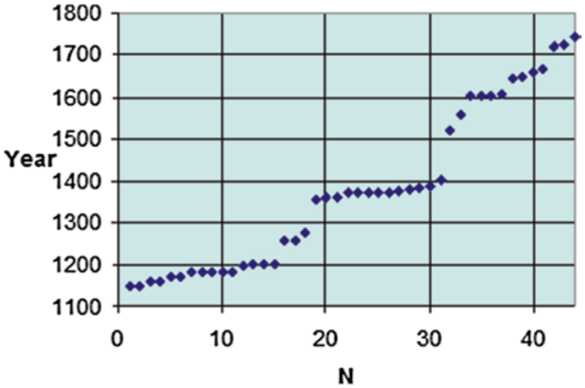

Fig. 6 Sunspot observations made by Japanese astronomers in the period 1100–1700. Note the similarity in shape to the Chinese records in the previous figure

From 1355 to 1388, the Chinese recorded 25 sunspots, 12 were reported from Korea, and two were common to both samples. The implied parent population was then, $N = n_C \; n_K/n_o = 25 \times 12/2 = 150$. For the whole period (three sunspot cycles) this gives an average rate of over 4 sunspots/year. We thus find rates in the fourteenth century and over the longer twelfth to eighteenth century period of from 20 to 35 times greater than that based upon the Chinese data alone. I note also that in the middle of the 11-year cycle of the fourteenth century data (i.e. from 1367 to 1378), when most of the spots were recorded, the implied average rate was about 10/year. This period of apparently higher than average solar activity can also be seen in sunspot numbers derived from ^{14}C data as a narrow peak between the Wolf and Spörer Minima (Usoskin et al. 2003). In a more extensive data set, extending back to before 9000 BCE (Usoskin et al. 2007), one sees a gradual decline in ^{14}C-derived sunspot numbers from the Western Han Dynasty (206 BCE – 9 CE) to the late Ming Dynasty (1368–1644 CE). After the Maunder Minimum, sunspot numbers increase until they reach the high values observed today (the highest since the ninth millennium BCE).

4 Concluding Remarks

The sunspot numbers we find in Chinese records clearly under-sample what can be observed with the unaided eye. Comparison of the Korean and Chinese sunspots both confirms this and provides a way of estimating the number of sunspots which could have been observed. Unfortunately, because of the small sample size, there is considerable uncertainty in the resulting estimate. (The statistical uncertainty will be dominated by the small number of overlaps, n_o. The statistics imply a 1 σ uncertainty of ±60 %.) The results described above, when compared with estimates based upon modern observations of sunspots, still suggest an under-sampling by at least an order of magnitude. This could be explained if the Oriental observers systematically failed to record sunspots during certain periods of time. The fact that the sunspot numbers during the twentieth century have been the highest for thousands of years (based upon ^{14}C data) should also be taken into consideration when trying to predict expected numbers from the distant past.

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Part III
Amateur Astronomy

The Clash Between William Herschel and the Great German 'Amateur' Astronomer Johann Schroeter

Clifford J. Cunningham and Wayne Orchiston

Abstract A distinction will first be made between the terms 'amateur' and 'professional' astronomer in the late eighteenth and early nineteenth century. William Herschel, who began his career as a musician but became a salaried employee of the British Crown, clashed metaphorical swords for many years with Germany's greatest amateur astronomer, Johann Schroeter. Each possessed the largest telescope in England and Germany, respectively. Schroeter began in the 1780s by purchasing telescopes made by Herschel, but his larger instruments were eventually made in Germany. Herschel began using his 20-foot telescope in 1783, but it would be another decade before Schroeter had a comparable instrument.

After briefly reviewing their correspondence from 1783 to 1804, their disagreements will be surveyed. These include very different measures of the diameter of Mars, and Herschel's critique of Schroeter's lunar, Venusian and Saturnian work. Their very different world views, as revealed by their telescopes, was the subject of a book by August Gelpke. Nowhere were these world views in starker juxtaposition than in their observations of and conclusions about Ceres and Pallas. They measured diameters in the same way, but came up with very different results. Schroeter also made a claim for a vast atmosphere around the objects, that caused variations in their light. These dual issues caused controversy and consternation among the entire astronomical community, and critiques from Carl Gauss, Wilhelm Olbers and Giuseppe Piazzi are noted. Schroeter's rejoinder to the diameter measurement debate is also given. Finally, Herschel and Schroeter clashed about the very nature of Ceres and Pallas. The former named them 'asteroids,' but Schroeter explicitly stated that they were planets, not asteroids.

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1 Introduction

By the late eighteenth century the divide between amateur and professional astronomers was becoming more clearly defined, although gray areas still existed. If one defines a professional astronomer as one employed at a state-run or university-run observatory, the list would include the following: Johann Bode (Berlin), Franz von Zach (Gotha), Nevil Maskelyne (Greenwich), Giuseppe Piazzi (Palermo), Barnaba Oriani (Milan), Joseph-Jerome Lalande (Paris), Marcin Poczobut (Vilnius) and Jan Sniadecki (Cracow).

Notable amateurs, namely those who operated their own observatories, included Friedrich von Hahn, Gottlieb Schrader, Heinrich Wilhelm Olbers and Ferdinand von Ende (all in Germany), and the Duke of Marlborough and Hans von Bruhl (in England). Straddling the divide was William Herschel (1738–1822; Fig. 1) who received funds from the state as the Court Astronomer to King George III of Great Britain, but who retained some independence by manufacturing telescopes for profit (see Cameron 2012), and making observations from his own property (Spaight 2004). In Germany, Johann Hieronymous Schroeter (1745–1816; Fig. 2) also drew

Fig. 1 William Herschel (en.wikipedia.org)

Fig. 2 Johann Schroeter (commons.wikimedia.org)

a salary in his position as a Government official (he was the Chief Magistrate of Lilienthal), but unlike Herschel's situation, his job was not related to astronomy. Thus, Schroeter may fairly be said to fall under the classification of an amateur astronomer, while Herschel may be classed as a professional astronomer.

2 The Telescopes of Herschel and Schroeter

By the size and power of the telescopes they possessed, Herschel and Schroeter obtained insights into the heavens that other astronomers of the age were unable to achieve. Their often contradictory observational results were reported in the journals and magazines of the day, and quoted as the most reliable data well into the nineteenth century (Hughes 1994) in everything from scientific journals to popular novels, including the work of Jules Verne (1865).

There were many parallels between the lives of William Herschel and Johann Schroeter. Both were German-born, and knew from their childhoods the meaning of penury. Both had a passionate fondness for music, and each enjoyed the tender care of a devoted sister. Each had command of the greatest telescope of his own country. Both were experts at mechanical contrivances; each was supremely energetic, patient, industrious and conscientious (Cunningham 2007).

Herschel began work with his 20-foot telescope (18.7-in mirror) in 1783, and used it (Fig. 3) for most of his observations, including the first scientific studies of Ceres and Pallas in early 1802. Herschel actually made Schroeter's first telescope, which was obtained through his brother, Dietrich Herschel, in 1779. In 1782 Schroeter bought two mirrors from William, with diameters of 4.7 and 6.5 inches. Immensely proud of the 7-foot telescope he made with the 6.5-inch, Schroeter (1788) devoted 55 pages to a description of it. Although quite modest by modern standards, it was the largest telescope in Germany at the time (Gargano 2012).

It was not until 1793 that Schroeter had a telescope to rival the one Herschel used. Although this 27-foot instrument had a mirror of 19.2 inches, it was a smaller 13-foot telescope with a 9.5-inch mirror that he employed to study Ceres and Pallas in 1802 (Leue 2002).

3 Correspondence Between Herschel and Schroeter

The Herschel Archives in the Royal Astronomical Society in London holds the extant correspondence between Schroeter and Herschel. Some of these letters, such as one dated 2 May 1792 (see Sect. 6.1 below), were written by Herschel to Schroeter, a copy having been made for Herschel's own records. Schroeter's own papers were destroyed long ago (Baum 1991; Denning 1904), so most of the existing correspondence is one-sided. The letter discussed in Sect. 6.3 was sent by Schroeter to Baron George Best (13.S.47). This begins with a cover letter from Best to

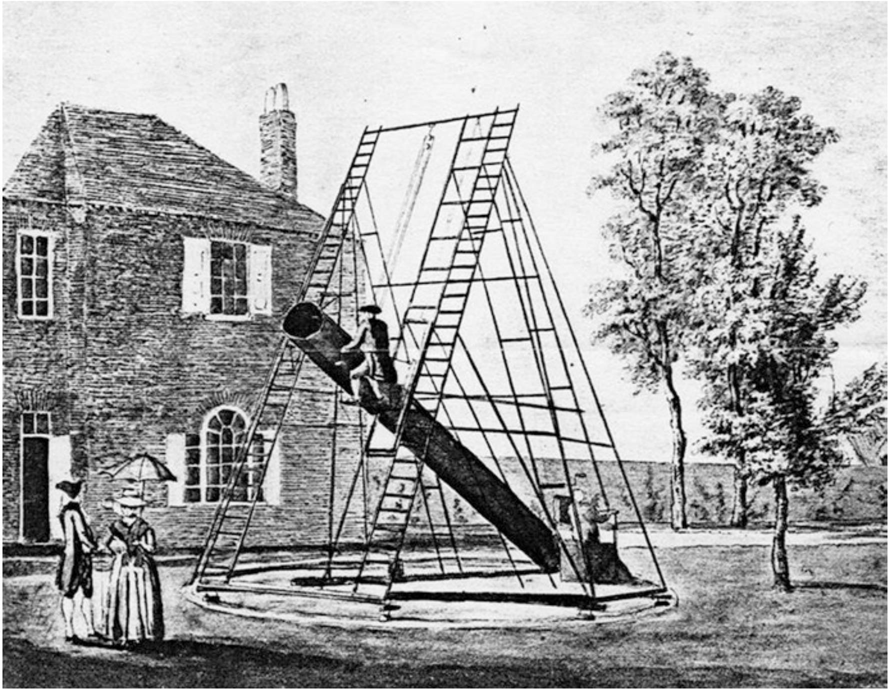


Fig. 3 Herschel's 20-foot telescope on the grounds of his residence at Slough, near Windsor (courtesy: Royal Astronomical Society Library)

Herschel dated 22 September 1804; what follows is a 2-page letter by Schroeter dated 11 September 1804. It is rendered in English by Best, and includes a page of positional data on Juno dating from 1 through 10 September 1804.

The letters are designated in the Archives as Herschel W. 1/13. S. 12–48, and listed in the official index as follows:

> 2 February 1783, 13.S.12; 27 February 1783, 13.S.13; 31 July 1783, 13.S.14; 14 January 1784, 13.S.15; 17 July 1784, 13.S.16; 27 October 1784, 13.S.17; 7 February 1785, 13.S.18; 1 June 1785, 13.S.19; 20 July 1785, 1, pp. 136–38; 29 August 1785,13.S.21; 12 September 1785, 13.S.20; 14 September 1785, 13.S.22; 29 October 1785, 13.S.23; 22 November 1785, 13.S.24; 24 January 1786, 13.S.25; 28 February 1786, 13.S.26; 20 July 1786, 13.S.27; 20/25 December 1786, 13.S.28; [February 1787], 1, pp. 156–57; 12 November 1787, 13.S.29; 2 May 1788, 13.S.30; 18 June 1788, 13.S.31; 15 September 1789, 13.S.32; 31 January 1790, 13.S.33; 12 May 1791, 13.S.34; 8 June 1791, 13.S.35; 16 December 1791, 13.S.36; 2 May 1792, 1, pp. 191–92; 16 September 1792, 13.S.37; 10 August 1793, 13.S.38; 20 August 1793, 1, pp. 195–96; 29 November 1793, 13.S.39; 4 January 1794, 1, pp. 198–99; 30 September 1796, 13.S.42; 30 March 1797, 13.S.43; a note concerning a letter of 22 May 1802, 1, p. 249; 30 October 1802 (attribution uncertain), 13.S.59; 12 February 1803, 13.S.45.

13.S.40, 13.S.41, and 13.S.44 are autograph tracts by Schroeter; another is included with 13.S.29. 13.S.47 is a copy of Schroeter's account of Harding's discovery of the planet Juno, sent to WH by G. Best on 22 September 1804. 13.S.48 is a single page, which is not in Schroeter's hand, but was with his letters.

4 Gelpke’s Book About Herschel and Schroeter

The fact that these were the two most celebrated observational astronomers of their day is not in dispute. Their respective and contrasting observations were the subject of a treatise by a teacher at the Collegium Carolinum in Brunswick, August Heinrich Christian Gelpke (1801; 2nd edition 1806). Gelpke (1769–1842; Fig. 4) became Professor of Natural History and Mathematics at the Carolinum in 1821, and authored an important early work in catastrophe theory (Gelpke 1835; cf. John 2004).

In the 1806 edition of his 294-page book (Fig. 5), Gelpke surveyed current astronomical knowledge on many topics including the Solar System and the asteroids, the fixed stars and nebula. Not surprisingly these were the very areas of research that most occupied Schroeter and Herschel. For example, Gelpke duly reported Schroeter’s discovery of the rotation period of Venus, and the presence of an atmosphere on the Moon. He also gave other interesting observational results, such as the solar parallax derived from observations of the 1769 transit of Venus.

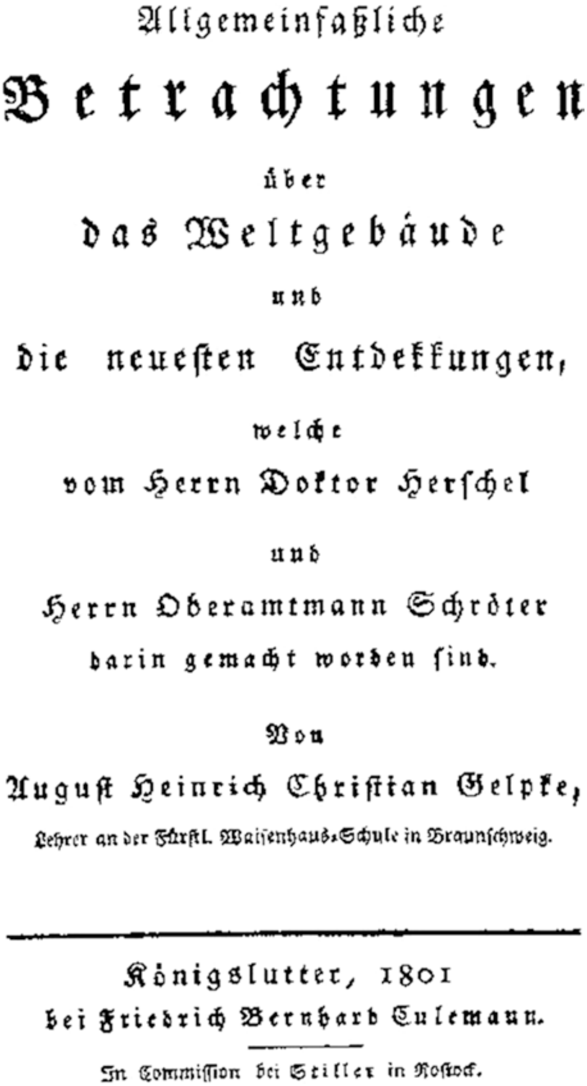
While the book offered no surprises, it was the best contemporary account available for the wider German-reading public about the cutting-edge research being undertaken by Herschel and Schroeter, whose 1805 book on Ceres and Pallas is available in English translation in Cunningham (2001, 2006).

5 Planetary Disagreements

5.1 Mars

As a matter of comparison, it is worthwhile looking at the diameter measurements of Mars made by both men. At the opposition of 1783, Herschel made micrometer observations on three nights and found an equatorial diameter of 9.13″ and a polar diameter of 8.57″. These figures were the first ever proving the oblateness of Mars, the ratio derived being 1:16.3 (Herschel 1784).

Fig. 4 August Gelpke (Braunschweigisches Landesmuseum)



Allgemeinfaßliche

Betrachtungen

über

das Weltgebäude

und

die neuesten Entdekkungen,

welche

vom Herrn Doktor Herschel

und

Herrn Oberamtmann Schröter

darin gemacht worden sind.

Von

August Heinrich Christian Gelpke,

Lehrer an der Fürstl. Waisenhaus-Schule in Braunschweig.

Königslutter, 1801

bei Friedrich Bernhard Culemann.

In Commission bei Stiller in Rostock.

Fig. 5 The title page of Gelpke's 1801 book *General Observations on the World and the Latest Discoveries made by Dr. Herschel and Counsellor of Justice Schroeter* (Cunningham Collection)

Also employing a micrometer, Schroeter observed Mars on 1 and 3 September 1798 when it was near opposition. His figures were 9.84″ and 9.72″, giving an oblateness of 1:81. Schroeter's Martian observations were published posthumously by H.G. van de Sande Bakhuyzen (1881).

In his study of 22 diameter measurements of Mars, See (1901) gives a mean value of 9.67″. He also notes that the filar micrometer is considered to be the best instrument for such a measurement. So we see that Herschel underestimated the diameter of Mars; in fact, of the 22 measurements given by See, Herschel's is by far the smallest, a figure of 9.47″ being the next closest (by Kaiser in 1862–1864).

While Schroeter’s measurement is higher than the mean, several others were larger still, with Lowell’s 1896 value of 9.92″ being the largest. Schroeter was also closer to the correct figure of the oblateness, the modern figure being 1:500.

Schroeter’s observations of the Martian surface led him to conclude that the dark areas were only atmospheric clouds, with changes occurring on time scales as short as an hour. This was despite the fact they were largely permanent surface features. This wholly incorrect interpretation of what he saw through his telescope was more the norm than the exception.

5.2 Venus, Jupiter and Saturn

The year 1792 was an important one in the relationship between Herschel and Schroeter, due to some extent to poor translation from German to English, as noted by Lynn (1892). In referring to recent observations of Venus, Lynn wrote:

> No one can read them without being struck by the fact to how great an extent they confirm the observations made by Schroeter a century ago, the accuracy of which was so strenuously contested by Herschel in the ‘Philosophical Transactions’ for 1793, and reasserted by Schroeter in 1795. My present purpose, however, in referring to this controversy is to point out the danger of trusting *translations* in matters of this kind and the importance of referring in disputed points to the originals. Amongst the observations of Schroeter to which Herschel alluded, in a tone which he must have afterwards regretted, were what he calls “flat spherical forms conspicuous on Saturn.” What Schroeter really wrote was “abgeplattete Kugelgestalt des Jupiter und Saturn,” meaning flattened spherical shape of the planets themselves, not of markings on them.

The 10 December 1797 letter (13.S.44), translated into English from Schroeter’s original (which is not extant), makes the remarkable claim that he had “… discovered dark spots in each of the four satellites of Jupiter.” Schroeter also laid claim to seeing very dark spots on Jupiter itself (Dobbins and Sheehan 1997). While these may very well have been real features, the fact that he saw dark spots on the satellites of Jupiter certainly prompts one to question it. Herschel was skeptical, but he confined his thoughts to a private note:

> Mr. Schroeter says that he has seen dark spots in each of the 4 satellites of Jupiter. He says that these spots are of the atmospheric kind.
>
> That these satellites turn on their axes I have shewn from their variation of light; & from the same phenomena I infer that the satellites have spots; but I have never seen spots. (Note dated 1797; Herschel Archives W.7/6; his underlining).

Herschel and Schroeter were clearly at odds about the supposed mountains of Venus (Baum 2007). Schroeter (1792) believed them to be five or six times as high as those on Earth. Before he read Herschel’s rather acidic commentary in the *Philosophical Transactions of the Royal Society* of 1793, Schroeter had written quite jauntily to Herschel: “I have good ground for hoping as well as wishing that my observations on Venus will in due course receive confirmation from you as well as from other authorities.” (Herschel Archives, 29 November 1793).

It was not to be, for Herschel (1793) wrote: "As to the mountains on Venus, I may venture to say that no eye which is not considerably better than mine, or assisted by much better instruments, will ever get a sight of them." He then goes on in quite scathing terms, but without once mentioning Schroeter by name:

> Even at this present time I should hesitate to give the following extracts if it did not seem incumbent on me to examine by what accident I came to overlook mountains in this planet of such enormous height as to exceed four, five, or even six times the perpendicular height of Chimboraço, the highest of our mountains … The same paper contains other particulars concerning Venus and Saturn. All of which being things of which I have never taken any notice, it will not be amiss to show, by what follows, that neither want of attention, nor a deficiency of instruments, would occasion my not perceiving these mountains of more than twenty-three miles in height, this jagged border of Venus, and these flat, spherical forms on Saturn. (ibid)

So from this time it was made plain that Herschel believed his telescope was the worlds' finest, and that Schroeter was seeing things that could not in fact be seen.

Schroeter (1795) wrote a rather pained rejoinder to Herschel's 1793 paper, asserting that it "… contains unreserved assertions, which may be easily injurious to the truth, for the very reason that they have truth for their object, and yet rest on no sufficient foundation."

Even though both men accepted the existence of a Venusian atmosphere (Baum 2010), the rotation period of Venus was another bone of contention between them. Schroeter accurately measured the period to be 23 hours, 20 minutes, 59 seconds. He further stated that Venus was inclined 75 degrees. Herschel thought the Venusian atmosphere to be opaque, and thus left the question of the rotation period open. Schroeter's rotation period was quoted as fact for many decades, and was even confirmed by Francescoe de Vico (like Herschel, an astronomer and musical composer) from Rome in 1841 (*The Illustrated London Almanack for 1863*, 51)! The correct value of the rotation period is 243 days, making Schroeter's 'precise' value an object lesson in scientific humility.

In 1900 See published a survey of diameter measurements of Venus, where he lists one by Herschel (1807), based on a single micrometer observation, of 18.790″. Based on a four-day study in 1792, Schroeter (1792) derived a diameter of 16.7″. See (1900) gives a value of 16.8″, based on 32 recent measurements made at the U.S. Naval Observatory, and this is almost identical to Schroeter's result.

The somewhat acrimonious exchange between Herschel and Schroeter was not confined to the pages of the *Philosophical Transactions of the Royal Society*, which had a limited scientific readership. It elicited a detailed commentary in the widely-read *The Critical Review …* (1796). Its articles were not signed, so the author of this particular critique of the Venusian book (Schroeter 1796) is unknown. While acknowledging that Schroeters' instruments are the inferior of the two, the writer says Herschel "… has no right to boast of his superior advantages. Dr. Herschel's instruments do not convey to us a proof of his ability to speak decisively on the subject; because the telescope of Schroeter had sufficient powers for all the observations which either party has made upon the planet Venus."

The reviewer considers whether Herschel's 'industry' in observing Venus may give him an advantage. "The number of observations made upon this planet by Dr.

Herschel, bears a very small proportion to the number of those made by his opponent. Consequently, in point of industry, we must acknowledge Mr. Schroeter to be the superior." The article in *The Critical Review* … even claims Schroeter has "… some grounds for his complaints against our astronomer, and he is evidently hurt at the reflections cast upon his observations." It concludes by enjoining Herschel to make more observations of Venus "… to enable us to account for the difference of opinion between him and his brother astronomer."

5.3 The Moon

Schroeter's (1791) book about the Moon (Fig. 6) was a massive 676 pages, with 43 copper plates engraved by Georg Tischbein, a Bremen artist. The publication of the work was paid for by Schroeter himself, and it was this work that made his European reputation (see Sheehan and Baum 1995), even though it was savaged in the British press. One contemporary review said it did not "… give pleasure to the reader: the *grand* fault is want of method; and of this the obvious consequences are confusion, prolixity, and innumerable repetitions." (*The Monthly Review*, 1792, volume 7, 481–487; their italics and underlining). Another used a sarcastic pun, saying that "… it contains no small portion of fanciful description; we will not say the author has altogether become a *lunatic*, but he pretends to a much more political, geographical, and domestic knowledge of the moon, than many of our politicians, geographers, and economists do with their own mother earth." (*The New Annual Register*, 1809, 416–417; their italics).

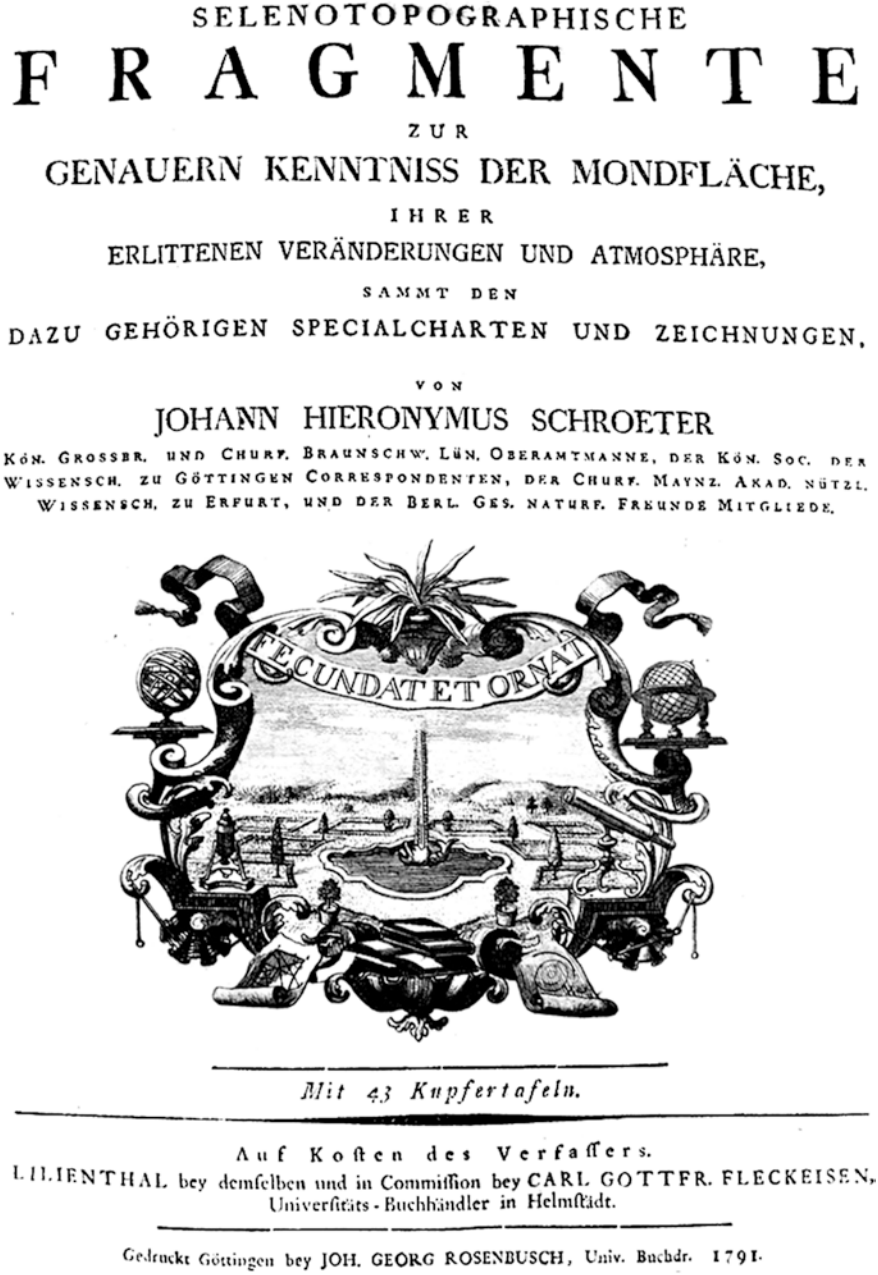
The book was carefully scrutinized by Herschel, who wrote a full page of notes about it. Even though the manuscript is undated, it was likely written in the mid-1790s (Herschel Archives, misc. papers 7/14). Most of the entries are critical of Schroeter's lunar work:

Page 8 Einleitung. The author mentions my name as one that has given one or two observations on the moon. Has he seen my measures of its mountains?
Page 60 section 24 I do not approve of the division of the light of the moon in 10. Instead of this I substitute given objects under given illuminations.
72 section 32. His way of naming I do not like.
73 Descriptions better than drawings.

Let us now examine each of these individually.

In his first comment, relating to page 8 in Schroeter's book, Herschel wonders if Schroeter had actually read about his lunar observations. This refers to one of his very earliest papers, "Mountains of the Moon," which was read before the Royal Society on 11 May 1780 and subsequently published in its *Philosophical Transactions* (see Herschel 1780).

On page 60 in his lunar book, Schroeter uses a 10-point scale to note the reflectivity of various areas on the surface of the Moon: "The darkest areas = 0; the central grey surfaces = 2; the light grey = 3; usually bright illuminated surface = 4; then far more than usually bright surfaces = 5, 6, 7 and 8; the greatest luminous intensity of



SELENOTOPOGRAPHISCHE

FRAGMENTE

ZUR

GENAUERN KENNTNISS DER MONDFLÄCHE,

IHRER

ERLITTENEN VERÄNDERUNGEN UND ATMOSPHÄRE,

SAMMT DEN

DAZU GEHÖRIGEN SPECIALCHARTEN UND ZEICHNUNGEN,

VON

JOHANN HIERONYMUS SCHROETER

KÖN. GROSSBR. UND CHURF. BRAUNSCHW. LÜN. OBERAMTMANNE, DER KÖN. SOC. DER WISSENSCH. ZU GÖTTINGEN CORRESPONDENTEN, DER CHURF. MAYNZ. AKAD. NÜTZL. WISSENSCH. ZU ERFURT, UND DER BERL. GES. NATURF. FREUNDE MITGLIEDE.

Mit 43 Kupfertafeln.

Auf Kosten des Verfassers.
LILIENTHAL bey demselben und in Commission bey CARL GOTTFR. FLECKEISEN, Universitäts-Buchhändler in Helmstädt.

Gedruckt Göttingen bey JOH. GEORG ROSENBUSCH, Univ. Buchdr. 1791.

Fig. 6 The title page of Schroeter's 1791 book *Lunar Topographical Fragments* (Cunningham Collection)

Proclus = 9; the greatest luminous intensity of Aristarchus = 10." Herschel takes exception to this, and he also explicitly states that he disagrees with Schroeter's system of lunar nomenclature, as outlined in section 32. Subsequently, nineteenth century selenologists also found Schroeter's scheme troublesome:

> In the course of his labours, Schroeter named a very considerable number of different formations, somewhere between seventy and eighty in number, but without any systematic method. In consequence of this he often attached a single name to two or more different formations, usually closely associated, it is true, whilst in other cases he named a region possessing little, if any, natural boundaries, and therefore little suited for the purpose of being named. (Neison 1876: 202)

That the drawings are somewhat lacking also finds confirmation in Neison's analysis: "Of the minute details of the lunar surface, it may be broadly stated that Schroeter shows nothing." Was it that Schroeter's telescopes "… lacked defining power …" as Goodacre (1917) asserted, or did Schroeter simply lack the necessary artistic talent? Nasmyth and Carpenter (1874: 66) comment on this:

> Schroeter was a fine observer, but his delineations show him to have been an indifferent draughtsman. Some of his drawings are but the rudest representations of the objects he intended to depict; many of the bolder features of conspicuous objects are scarcely recognizable in them. A bad artist is as likely to mislead posterity as a bad historian, and it cannot be surprising if observers of this or future generations, accepting Schroeter's drawings as faithful representations, should infer from them remarkable changes in the lunar details.

As is evident from a letter of 1793, Schroeter was quite frank with Herschel about their disagreements:

> It is to be expected that observers, who have only truth faithfully and eagerly at heart, should publish their observations, even if they give different results, without regard and without reference to persons. Thus will truth prevail, so in my Selenfragmente I have put forward my calculations, which differ greatly from yours, without mentioning yours, though well known to me, or even suggesting the conflict between them. Those who are well acquainted with the subject can then judge for themselves; and truth will not be obscured by partisanship. (29 November 1793; Herschel Archives).

6 The Asteroids

In a contemporary review of Schroeter's 1805 book about Ceres, Pallas and Juno, the great clash with Herschel was noted at the outset: "The observations themselves, Mr. Schroeter defends against every possible objection, especially against the measurements of Dr. Herschel, which are in strong opposition to them." (*The Eclectic Review,* 1807, volume 5, part 1, pages 182–183). These "measurements" were contained in a paper read before the Royal Society on 6 May 1802 (Fig. 7), which was the first scientific investigation of Ceres and Pallas (Herschel 1802; Cunningham 1984).

Fig. 7 The meeting room of The Royal Society at Somerset House in London where the papers of Herschel and Schroeter were read and discussed (Cunningham Collection)

6.1 The Diameter Measurements of Ceres and Pallas

Herschel found Ceres to be 161 miles across and showing a disk of just 0.22″. In contrast, Schroeter found Ceres to be 1,624 miles across, showing a disk including an extensive atmosphere fully 6″ across. Herschel found Pallas to be 70 miles across, with a disk somewhere between 0.13″ and 0.17″, while Schroeter found Pallas to be even larger than Ceres, at 2,099 miles in diameter, with a disk of 6.5″, which again included an atmosphere. For comparison, the modern values currently accepted for the diameters of Ceres and Pallas are 590 miles and 326 miles respectively (Hilton 2002).

That Herschel and Schroeter were well aware of each other's methods of measuring the size of celestial objects is apparent in a letter Herschel wrote to Schroeter a decade before the asteroid size controversy erupted. The letter appears to be a rather sarcastic swipe by Herschel, contrasting his 'old' method with Schroeter's 'new' method. Clearly, Herschel was not impressed by Schroeter's claims, either then or a decade later when they used their respective instruments to measure the asteroidal diameters:

> You mention your new Projection's Micrometer; as I suppose that you have undoubtedly taken notice of my camera-eye-piece etc: whereby I project objects on a sheet of paper, upon a wall, upon a measuring scale, upon a set of disks, peripheries, lucid points, draw

> images of objects, let the points of a pair of compasses that they will exactly fit into any two holes that a person makes upon a card fixed up at a distance etc. As I suppose you [are] acquainted with all these things I should be glad to know in which respects <u>your new</u> differs from <u>my old</u> Projection-micrometer. (2 May 1792; Herschel Archives; his underlining).

6.2 *Critiques of the Diameter Estimates*

Carl Gauss weighed in on the discrepancy between the Herschel and Schroeter diameter results, as reported by Zach:

> Gauss finds the diameter according to Dr. Herschel's own measurement slightly greater. Dr. Herschel gives on April 22 according to a fairly good observation the diameter = 0″.17; and Dr. Gauss calculated the true diameter 26½ German miles (the distance from earth = 1.562). [A German mile is 25,000 feet, compared to 5,280 feet in an English mile.] In his latest letter he expressed his astonishment about Dr. Herschel's and Dr. Schroeter's different results of the diameters because they were made according to one method. "I am very curious to learn what magnifications Dr. Herschel used. A magnification of 500 times would hardly turn an apparent diameter of 0″.17 into a disc, would it?" I, for my part, could not discern a trace of a disc at 300× magnification of neither Olbers' nor Piazzi's planet [i.e. Pallas and Ceres]. (*Monthly Corres*. August 1802, page 189).

Olbers sided with Herschel, although with reservations:

> The contrast between Schroeter's and Herschel's measurements is most surprising. Just between us, I trust neither of them. I believe Schroeter has included too much spurious light in his measurements, and he would have perhaps found a fixed star to be just as large.- And Herschel? – I mean, the eye could easily be misled in comparing such small dimensions. Even if he enlarged Pallas 500 times it would have appeared to him (according to his stated diameter) only as a 1′ 5″ – diameter disc appears to the naked eye. With such a diameter a disc actually still appears as a point, and whether one of two such small disks appears larger than the other depends only on the brightness of these small disks. The light from Pallas must certainly have become very feeble in the telescope after a 500-times magnification, and hence a <u>probably brighter</u>, though <u>much smaller</u>, disc could still appear as large as Pallas to the naked eye. - Nevertheless, I am convinced that Herschel is much nearer the truth than Schroeter. (Letter from Olbers to Gauss, 14 July 1802; Goettingen Archives; his underlining).

There is a longer section on Schroeter's observations and the critique he received from both Olbers and Gauss in Oestmann and Reich (2001).

6.3 *Schroeter's Rejoinder to the Diameter Controversy*

Schroeter examined Herschel's study of Ceres and Pallas, which he specifically says are "… not asteroids." In his letter to an unknown correspondent in England (possibly his friend Baron George Best), Schroeter makes his case quite forcefully, and begins by an absolute rejection of Herschel's designation of 'asteroid' to denote Ceres and Pallas (Cunningham et al 2009):

> After having read Mr. Herschel's paper on the two new planets (not asteroids) I discovered the reasons for his mistakes in measuring their diameters: Dr. Herschel measured the same way I did but

a) He positioned the projection disc at an immense distance from the eye, from 124 to 178 feet without realising that an illuminated body seen with the naked eye, except for a certain distance appears relatively the larger the farther it is removed from the eye. I made several tests with an identical illuminated disc of 1.2 inches by seeing it with one eye and with the other through a sextant's tube without glass. By this it appeared at a distance of 170 feet 5 times smaller than with the other naked eye. The more I was approaching the larger it became proportionate to that one seen with the naked eye and finally both agreed at eight feet. I changed the eyes; but it was and remained the same. Consequently, Dr. Herschel obtained, since he did not use the greater but the true and much smaller diameter for his calculation, a five times smaller diameter as product.

b) He did not measure, as I did, the nebulosity as well but only the brighter disc. And he used magnifications of 400 to 800, much too great for such a pale and comet-like planet. Due to lack of light and acridity he thus did not distinguish the entire disc with nebulosity but only its brighter centre part which he, as he himself says, saw as a cometary nucleus. Thus he saw the nebulosity's diameter sometimes six to seven times greater than this nucleus, which was not the case with my magnifications. A calculation for his errors produced his diameter of Pallas equally great as I found it. As a test I will soon measure the Georgian planet (Uranus) in the same way and Mr. [Karl] Harding, who is working incredibly eagerly, is writing a little work on it to which he will also attach a chart of the smallest stars of that celestial region which Pallas will pass next year to find it wherever possible. [30 October 1802; Herschel Archives; his underlining].

Was Schroeter correct in saying Herschel did not measure the projection disk properly? Herschel's diameter for Pallas was 70 miles. Applying Schroeter's correction factor of 5 gives a diameter of 350 miles. The actual diameter is 326 miles, very close indeed to the 'corrected' figure. His second point, regarding 'nebulosity' will be considered below in Sect. 6.4.

6.4 *Irradiation and Spurious Disks*

Herschel and Schroeter differed on the crucial question about the existence of atmospheres surrounding the asteroids. The issues involved can be formalised as an application of probability theory to variative induction. In the following quote from John Stuart Mill (1843), his words "animal or plant" have been replaced for the subject under discussion here by the word "planet":

> If we discover, for example, an unknown planet, resembling closely some known one in the greater number of the properties we observe in it, but differing in some few, we may reasonably expect to find in the unobserved remainder of its properties a general agreement with those of the former, but also a difference corresponding proportionately to the amount of the observed diversity.

This expectation to find properties in the "… unobserved remainder …" led Schroeter, Herschel and others to search for two properties in particular that are associated with the known planets—namely, satellites and an atmosphere. We concern ourselves here with the latter:

> Schroeter has, as he informs me, changed much in his work concerning the new planets based on ideas I had pointed out; I thus hope that you will no longer consider the calculation of the masses, densities, and gravitation at the surface of these small heavenly bodies. The

> determination of these details rests upon a totally erroneous application of an unprovable statement of [Daniel] Melanderhjelm. He had adopted the hypothesis that the planet's atmospheric density at the surface varies as the square of the gravitational force at the surface. Schroeter believed he could conclude the reverse, that the atmospheric density at the surface varied as the height of the visible portion of the atmosphere. For our Earth he adopted, along with La Hire, a height of 38,000 Toisen. Since his telescopic observations gave him the heights of Pallas' and Ceres' atmospheres from 100 to 150 miles, he thus decided on a high atmospheric density at the surface of both planets, and this the same for the gravitational force and density. The result is, e.g., that the density of Ceres is 4½ to 5½ times that of gold, etc.- I pointed out to him (1) that Melanderhjelm's so-called theory merely entails the somewhat strangely expressed theory that the ratio of the mass of the atmosphere of every planet to its total mass is always the same, and thus with every planet it would be about 1/800000 of its mass; (2) that this hypothesis, in itself very improbable, is refuted precisely by his observations of such large atmospheres surrounding such small heavenly bodies; and (3) that the heights of the visible atmospheres could by no means vary just like their density at the surface, etc. Just between us, I can't at all believe that Ceres and Pallas have these large atmospheres. Rather, I assume them to be due to irradiation in the telescope. (Letter from Olbers to Gauss, 4 April 1805; Goettingen Archives; his underlining).

That Schroeter held the belief that the density of Ceres was greater than that of gold is one measure of his credulity. Olbers had written to Gauss about the irradiation matter three years before:

> What kind of small planets are Pallas and Ceres? Herschel found an apparent diameter of Ceres, as Zach writes, of only 1″, and of Pallas, as Bode informs me from LaLande's letter, of only 1½″. In this way, speaking confidentially, irradiation must have interfered with our friend Schroeter's observations. I admit, I have always suspected this; for my very nice 5-foot Dollond, at 240-times magnification, does not even show an appreciable disc for either planet, nor is there a definite difference from a fixed star. (Letter from Olbers to Gauss, 8 May 1802; Goettingen Archives; his underlining).

As Olbers rightly pointed out, the theory upon which Schroeter based his conclusions was faulty. He also rightly identified irradiation as the cause of these unsupportable atmospheres (Oestmann 2002). The subject of spurious disks and irradiation was examined by Cooke (1896):

> Since the spurious disk is brightest at the centre, and really shades off into the dark ring, it is evident that its apparent linear extension will depend very intimately upon the brightness of the star in question, that the spurious disk formed when a bright star is viewed will appear larger than in the case of a dim one, although the maximum size can never amount to as much as the diameter of the first dark ring. To this must be added the effect of irradiation in the case of the brighter stars. As a matter of fact, it is notorious how much smaller the star-disks appear to be in the case of small (ie faint) stars than in the case of bright ones. In all objectives having their focal lengths equal to 15 times the aperture, then the linear diameter of the spurious disk may be said to average 0.0004 inches. With 6 inches aperture this corresponds to an angular diameter of 0.9 seconds, and in a 12-inch aperture to 0.45 seconds.

In his paper on Juno, Herschel (1807) repeatedly observed a disk of around 0.2 seconds of arc, using his 10-foot reflector with a 9-inch aperture [this instrument had a focal length 13.3 times the aperture, close to the 15 times figure used by Cooke]. But he finds a similar disk is apparent when he looks at stars of comparable brightness. He therefore concludes that the disk of Juno is almost certainly spurious, and he assigns no size to the object, merely saying it is also very small.

Herschel draws six corollaries relating to the identification of real or spurious disks, and claims that a real disk as small as a quarter second can be seen and distinguished from a spurious disk by the application of high power in the range of 500–600. If the disk is real, it is seen as a larger disk at high power; if it is spurious, higher power does not reveal a larger disk. This analysis was echoed by Giuseppe Piazzi, the discoverer of Ceres: “I have candidly to confess that I don’t see how we could explain the changes in light and magnitude by means of the atmosphere or nebulosity observed by Schroeter. If Ceres can be seen better with less strong telescopes, it is because of the little light it reflects, which diminishes in proportion to magnification.” (Piazzi 1802). Thus, Herschel recognized and rejected the very observational result that Schroeter accepted as evidence of extended atmospheres around the asteroids.

7 Concluding Remarks

Herschel’s negative critique of Schroeter’s work extended beyond the Solar System to the study of nebula. As Forbush (1980) has commented, “Herschel remained unimpressed by Schroeter’s originality, and commented in a personal note in 1797 (Herschel MSS, W.7/6): ‘Mr. Schroeter says he cannot consider every Nebula a distant Milky Way. I have already proved the same in my paper on Nebulous Stars and mention the Nebula in Orion among others as an instance.’”

Rarely, if ever, have two dedicated observational astronomers with similar instruments, observing contemporaneously, arrived at such disparate results about exactly the same celestial objects. Whether it was Venus (the mountains and the rotation period), the Moon (the best way to denote brightness of surface features, and nomenclature), or Ceres and Pallas (their diameters and atmospheres), the two men ‘saw’ the bodies of the Solar System in very different ways. Neither was wholly correct, but the judgment of history has given the plaudits to Herschel, and the nod of disapproval to Schroeter (Gerdes 1986).

As Crowe (1986) has correctly discerned, Schroeter was the victim of an insufficiently-developed critical sense: “Like Herschel, he was a pluralist with much imagination; unlike his more famous contemporary, Schroeter never learned that large telescopes and diligent observation are not of themselves sufficient to transform an amateur into a professional astronomer.”

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Henry Beighton's Eclipse Chart

Mike Frost

Abstract Henry Beighton, FRS (1687–1743) was a polymath who played an important role in the early days of the Industrial Revolution. He was born in Chilvers Coton, Warwickshire, and supervised the steam engines which enabled the exploitation of the Warwickshire coalfield; he then used this expertise in Oxclose Colliery, Washington Fell, County Durham. He was the editor of *The Ladies' Diary*, the only significant mathematical journal in England during the early eighteenth century, and he used continental surveying techniques to produce an early accurate map of Warwickshire. I first got to know about Beighton when I came across the beautiful chart in Warwickshire Country Archives that he used to predict the 18 February 1736–1737 solar eclipse. There is a probable connection to Thomas Wright of County Durham, another astronomer who charted the eclipses which crossed Britain during the eighteenth century.

1 Introduction

I came across the chart shown in Fig. 1 serendipitously one day in 2004 when I was in the Warwickshire County Archives researching the early life of the great Rugby-born solar astronomer Sir J. Norman Lockyer (Frost 2004). That day my researches into Lockyer were fruitless, but a speculative search for 'astronomy' in the card index revealed the presence of an eclipse map in the Archives (Class Mark CR136/B2551).

The map is a hand-drawn chart in ink and water colour, slightly larger than A4 in size, possibly quarto. What I like about it is that it is clearly a working document—the drawings of the eclipse escape into the margins at the lower right-hand corner—but it is still drawn with care and attention.

The title is "The Sun's Eclipse, Febr 18 1736–7 delineated for Coventry." The date requires some clarification; 1736–1737 is because in the early eighteenth century the year began on 25 March, and to avoid confusion dates between 1 January

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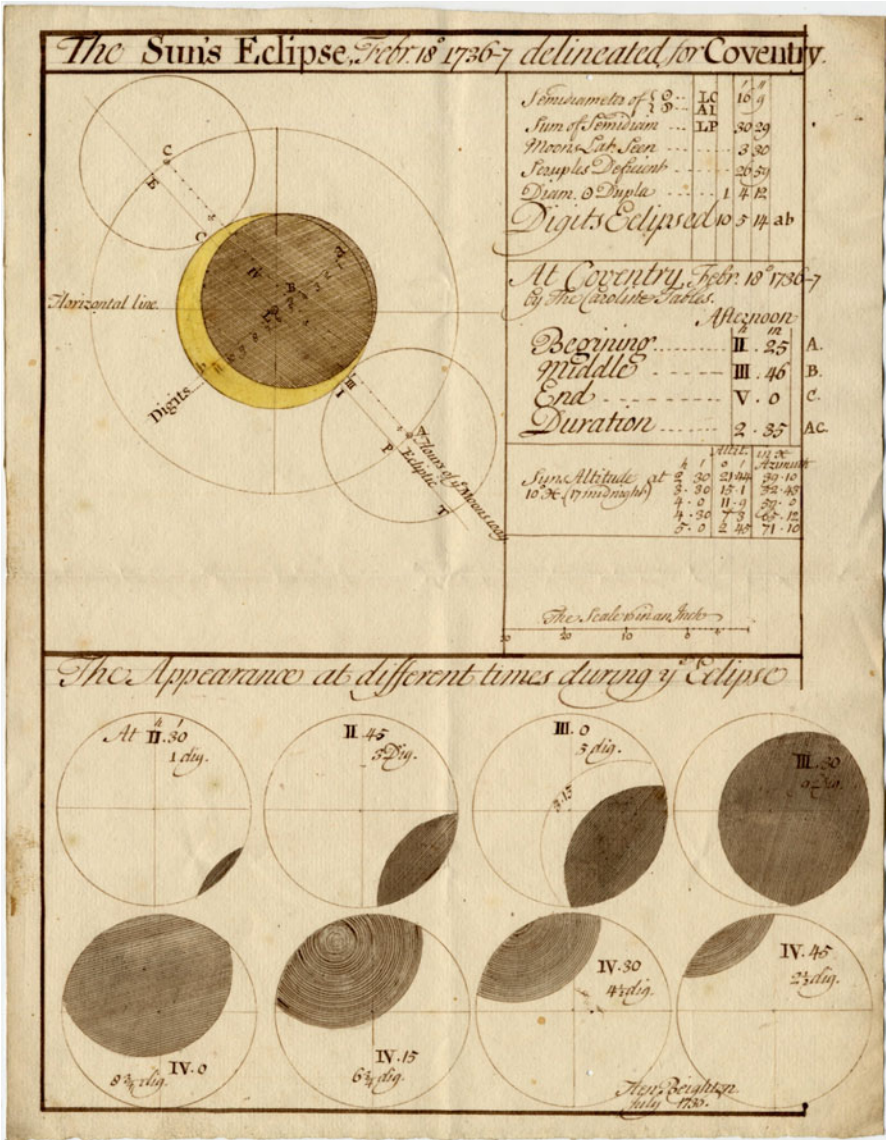

Fig. 1 "The Sun's Eclipse, Febr 18 1736–7 delineated for Coventry," by Henry Beighton, FRS

and 24 March were deemed to be 'between' the old and the new year, so 'Febr 18 1736-7' would now be considered as 18 February 1737. Note, too, that this was before the switch from the Gregorian to the Julian calendar, which took place in Britain in September 1752, so 11 days have to be added to give the equivalent date in the modern calendar. Most modern catalogues of eclipses (e.g. Espenak and Meeus 2009) give the date of this eclipse as 1 March 1737.

The top left hand diagram shows the Sun and Moon at the moment of maximum eclipse, and it can be seen that the eclipse was not central from Coventry (the centre-line was to the north and west). Moreover, the Moon is smaller in apparent size than the Sun, so this was an annular rather than a total eclipse. Southern Scotland and Northumberland saw an annular eclipse. The top right hand segment details the apparent diameters and offset from centre, concluding that ten-and-a-half "digits" (twelfths) of the Sun would be eclipsed.

The calculation continues "At Coventry, Febr 18 1736–7, By the Caroline Tables," indicating that Thomas Street's tables of planetary motion (used by Newton and Flamsteed, and re-published by Halley in 1710) were used. Coventry saw an afternoon eclipse, beginning, by Beighton's estimate, at 2:25 p.m., reaching maximum at 3:46 p.m., and concluding at 5:00 p.m., giving a duration of 2 hours and 35 minutes. The times are local, as there was no standardised time in Britain in 1737. The calculation summary concludes with a table of the Sun's altitude and azimuth at various times during the afternoon.

The third part of the chart, at the bottom, shows the appearance of the Moon on the Sun at eight different times during the eclipse, namely 2:30, 2:45, 3:00, 3:30, 3:45, 4:30, and 4:45, with estimates of how many digits of the Sun were covered at each time. Finally, there is the signature of the chart's draftsman, "Hen. Beighton, July 1736," showing that the chart was predictive, rather than a post-eclipse record of what had occurred.

Upon examining the chart a number of questions naturally occurred to me. For example, who was Henry Beighton? Who did the chart belong to, and how did it end up in the Warwickshire Archives? Was the chart accurate? And was the eclipse seen from Coventry, by Beighton or by anyone else? This paper answers some of these questions.

2 The Newdigates of Arbury Hall

Henry Beighton's eclipse chart is held in the archives of the Newdigate Family. There are other papers by Beighton, on astronomical surveying techniques, in the Newdigate archives; for example notes on the "Use of the Quadrant" and "The Lunar Method" (Class Mark CR136/B3026). Other items in the archive, while still scientific, are considerably less sophisticated. For example, there is a document on the workings of parabolic motion, which appears to be an attempt to understand basic Newtonian physics. We do not know who produced these, but they seem to be too elementary for Henry Beighton, and the likely author is a member of the Newdigate Family; however, there is no direct evidence that links any member of the Family to any sort of scientific career.

Nonetheless, the story of the Newdigate Family intertwines closely with Beighton's early life, so it is worth relating the family history. In 1586 John Newdigate, originally from Harefield Place, near Uxbridge, Middlesex, moved to Arbury Hall, to the west of Nuneaton and ten miles north of Coventry. His grandson, Sir Richard Newdigate (1602–1678), had a very successful career in law, rising to the post of Chief Justice during the Commonwealth, and was created a baronet by Charles II. He was also able to re-purchase Harefield House. Sir Richard's most significant contribution to Arbury Hall was to build a stable block in 1674, which was designed by Christopher Wren.

The Newdigates were a lucky family as the Arbury Estate sat on top of the Warwickshire coalfield. In 1714 a colliery was built at Griff, a hamlet to the south of Arbury Hall, and the third baronet, also Sir Richard Newdigate, went into business with entrepreneurs Richard and Stonier Parrott (father and son) and George Sparrow. These were the early days of the Industrial Revolution. The first working Newcomen steam engine was installed at Dudley Castle, in the English Midlands, and the second Newcomen engine was installed at Griff, to pump flood water out of the mine (see Rolt and Allen 1977).

When Sir Richard Newdigate died in 1727, his eldest son Sir Edward (b. 1716) became fourth baronet, but died in 1734. His younger brother, Sir Roger Newdigate (1719–1806), was only 14 years of age when he became fifth baronet. Roger's mother, the Dowager Lady Newdigate, ran the household until her son reached his majority. This was an important time for the family, as the Griff colliery reached the end of its working life. Nonetheless, the colliery had secured the finances of the Newdigates.

Sir Roger Newdigate undertook a Grand Tour of Europe, became a student at Oxford, and then a Member of Parliament; first for Middlesex, later for Oxford University. He married twice, first (in 1743) to Sophia Conyers and then in middle-age (1776) to Hester Mundy. Neither marriage produced children, but he and his second wife adopted a young girl from the Arbury estate, Sally Shilton, who had a beautiful singing voice. Many years later George Eliot, who was the daughter of the Arbury estate manager, told the story of Sally Shilton in her first published work, *Scenes from Clerical Life* (1857), in a story titled "Mr Gilfil's Love Story." Roger Newdigate makes an appearance, thinly disguised as Sir Christopher Cheverel of Cheverel Hall, "As fine a specimen of the old English gentleman as could well have been found in those venerable days of cocked-hats and pigtails …" (Chapter 2, page 1).

Roger Newdigate completely re-designed Arbury Hall, producing an elegant stately home which, unusually for the period, had a Gothic design; it is styled as 'The Gothic Gem of the Midlands.' In his later years Newdigate became increasingly reluctant to leave the estate. He was Lord of the Manor for 72 years. On his death, the baronetcy became extinct, but ownership of Arbury Hall passed to another branch of the family. The current owner of Arbury Hall, who lives there with his family, is the fourth Viscount Daventry, and I am grateful for his permission to use material from the family archives.[1]

[1] Arbury Hall and its grounds are occasionally open to the public—see www.arburyestate.co.uk for details.

3 Henry Beighton, FRS

Henry Beighton came from a lower social standing than the Newdigates (Cook 2009). He was born to a family of yeoman surveyors and engineers from Griff, a farming hamlet on the south side of the Arbury Hall estate, probably in 1687.[2] His father was Henry Beighton (1661–1710?), constable of Chilvers Coton, and his mother Ann Payne (1658–1710?). Beighton's second cousins included surveyors from Derbyshire. He married a woman named Elizabeth around 1720 and had a son, Marcellus, who pre-deceased him by a few months, and a daughter, probably named Celia.

Beighton first came to notice through his surveying of Warwickshire (Cook 1999). He was a talented draftsman, and also produced architectural drawings of Warwickshire houses, churches such as St. Michael's in Coventry, and other features such as the gilded Coventry Cross. One of his early projects was to survey Bedworth (in Warwickshire) in 1707.

In 1714, Henry Beighton became Editor of *The Ladies' Diary* (Fig. 2), an annual publication which was used to promote mathematics. The previous Editor, John Tipper, had introduced a variety of puzzles, but Beighton made them more difficult, and he introduced more practical and realistic problems (Costa 2002). As befitting the title, he positively encouraged contributions from women, and his (probable) daughter, Celia, was one of those who responded. Beighton edited *The Ladies' Diary* anonymously, as was the custom in almanacs of that period; however his role as Editor was known to his friends.

Beighton was a regular correspondent of the Royal Society, and in 1720 he became a Fellow. Subjects for correspondence included meteorology (for example, a detailed account of the hurricane of 1715), surveying and engineering, although I am not aware of any astronomical correspondence with the Royal Society.

He was friends with Revd. Doctor J.T. Desaguliers, the famous French-born natural philosopher and engineer (the only person to win the Royal Society's Copley medal three times). He and Desaguliers had suggested some modifications to the safety valve of the steam engine, and articles in *The Ladies' Diary* covered topics on the mathematics of pumping. So when coal was discovered on the Arbury estate, Beighton naturally took an interest. Lady Newdigate used his expertise to develop the colliery, and later, to advise when to close it.

Between 1717 and 1721 Beighton lived at Oxclose Fell, Washington, County Durham, and he installed a Newcomen engine there. His 1718 drawing of "The engine for raising water by means of fire" (Rolt and Allen 1977: 62), now in Worcester College, Oxford, is the earliest known depiction of a Newcomen steam engine, and is valued by industrial archaeologists for insights it offers into the development of the engineering.[3] Beighton had other mining interests in the north-east, including lead mines, though these were not successful and they led him into debt.

[2] It would appear that there was a boy born with the same name in 1686, but infant mortality is suspected. Beighton's date of baptism was 20 August 1687.

[3] Another drawing, by Desaguliers, of the Griff steam engine, is thought to date later than 1718.

Fig. 2 The Ladies' Diary (specialcollections.library.wisc.edu)

Beighton was not impressed with the quality of mapmaking in Britain during the early eighteenth century. Techniques of mapmaking lagged behind those used on the Continent, where triangulation was the norm, whereas in Britain surveyors tended to rely on a series of measurements from a linear feature such as a road (Costa 2002). Beighton decided that he was going to survey his own county of Warwickshire, and during the 1720's *The Ladies' Diary* regularly featured an advertisement seeking subscriptions for the map. Beighton carried out the survey between 1722 and 1725 and finally published the map in 1727 when it set a new standard for British mapmaking (see Fig. 3). The map was re-published in 1730 as part of the second edition of Sir William Dugdale's *Antiquities of Warwickshire*.

Henry Beighton died suddenly on 9 October 1743, having published his work in the *Philosophical Transactions of the Royal Society*, in Dugdale's *Antiquities of Warwickshire* and anonymously in *The Ladies' Diary*. He was buried at All Saints Church in Chilvers Coton, the same church George Eliot later worshipped at.

Fig. 3 A section of Henry Beighton's map of Warwickshire (barchestonhistory.info)

No memorial to him exists there, but there is a plaque commemorating gifts which he donated to the church in 1736. He was survived by his daughter and his widow, Elizabeth, who oversaw the publication of the second edition of the Warwickshire map in 1750.[4]

4 The Eclipse of 18 February 1737

The first half of the seventeenth century was a great time to be an astronomer in England. The preceding century had seen the establishment of institutions and academic posts at the heart of British astronomy—the Royal Greenwich Observatory (1675), the Royal Society (1660), the foundation of Savilian Chair of Astronomy at Oxford (1619) and the Plumian Chair in Cambridge (1704). The publication of Isaac Newton's *Principia Mathematica* in 1687 brought mathematical astronomy to a wide audience.

Observationally, the 50 years from 1715 to 1764 marked possibly the best half-century in the last two millennia for observing solar eclipses from the British mainland. Two total solar eclipses were visible from England in 1715 and 1724, followed by three annular eclipses in 1737, 1748, and 1764 (Williams 1996). Note that in the succeeding two-and-a-half centuries, there have only been a further two total eclipses visible from the British mainland (in 1927 and 1999) and five annular eclipses, the most recent having occurred in 2003.[5]

The total solar eclipse of 3 May 1715, the last total eclipse visible from London, is of considerable importance, because of the eclipse chart drawn by Edmond Halley, in advance of the eclipse, predicting the track of the eclipse (that is to say, which places would see totality and which would only see a partial eclipse). Halley

[4] Papers by Henry Beighton exist in a number of repositories. I have seen material by him in the Warwickshire Archives and at Durham University. Some papers by him are held in the British Library. I have not seen these but I'm grateful to Madeline Cox, who took a look at them at my request when she visited the British Library. Madeline tells me that they consist primarily of speculative writings on the nature of meteorological phenomena.

[5] Nor is the 'drought' over yet, as mainland Britain's next scheduled total eclipse is not until 23 September 2090 and the next annular eclipse is on 23 July 2093.

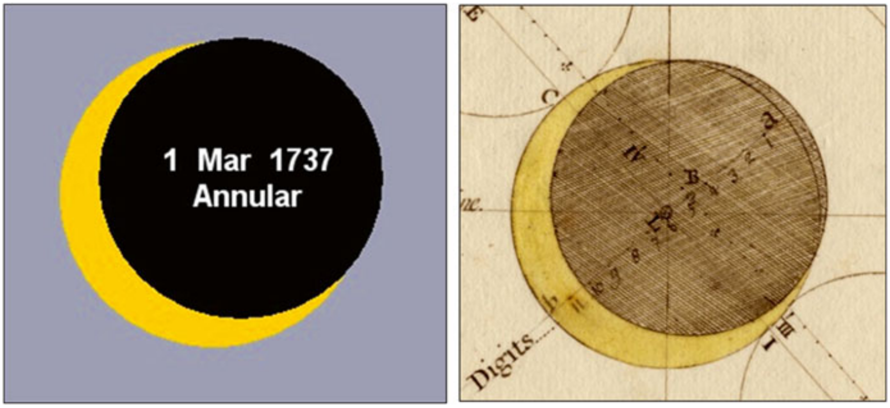

Fig. 4 On the left is a simulation by Sheridan Williams of the maximum eclipse phase at Coventry for the 1737 eclipse. On the right is an excerpt from Beighton's eclipse chart reproduced at the same scale. Note the excellent match

also pioneered the technique of showing the shape of the Moon's umbra along the track. Moreover, after the event Halley wrote to clergy in villages close to the edge of the totality track, asking who had seen a total eclipse and who had not. From this information he was able to refine the elements of the Moon's orbit around the Earth.

Halley's eclipse chart, engraved and published as a broadsheet by John Senex, was very popular, as was a second chart for the 1724 total eclipse (see Pasachoff 1999). Their commercial success, followed by the prospect of a string of eclipses, sparked a cottage industry in the production of eclipse charts (Armitage 1997). These tended to be of two types: first, charts like Halley's, which showed the progression of the Moon's shadow across the country; second, charts like Beighton's which concentrated on the progress of the eclipse at a specific location.

How accurate was Beighton's eclipse map? The left hand image in Fig. 4 was produced for me by Sheridan Williams, author of *UK Eclipses from Year 1* (1996), who had not seen Beighton's original chart. The match between the two diagrams of maximum eclipse is striking and so we can conclude that Beighton's chart was accurate. But did he see the eclipse? As yet I do not have an answer to this question, as it is still under investigation (see below).

Did Roger Newdigate see the eclipse of 1737? He would have been 17 on eclipse day. I was intrigued to see that there was a Newdigate diary in the Warwickshire Archives covering the year 1737 (Class Mark CR136/B3015/1), but unfortunately it turned out to be a very perfunctory document, simply noting significant events on a very few dates in the year. Nothing at all is noted for February 1737, although Newdigate was probably at Arbury Hall at the time, as he travelled there from nearby Astley Hall in January.

The annular eclipse was certainly seen from Scotland, as the Scottish mathematician Colin Maclaurin reported that

> A little before the annulus was complete, a remarkable point or speck of pale light appeared near the middle part of the Moon's circumference that was not yet come upon the disc of

> the Sun … During the appearance of the annulus the direct light of the Sun was still very considerable, but the places that were shaded from this light appeared gloomy. There was a dusk in the atmosphere, especially towards the north and east. In those chambers that had not their lights westwards the obscurity was considerable. Venus appeared plainly, and continued visible long after the annulus was dissolved, and I am told that other stars were seen by some. (Williams 1996: Chapter 6, page 8)

5 Henry Beighton and Thomas Wright

One reason why I was keen to deliver this paper at StephensonFest was because I knew that Henry Beighton had connections to the County Durham area, and that there were some possible Beighton papers in the Durham University Archives, held at Palace Green (next to Durham Cathedral). So I arrived in Durham early, in order to view these papers.

They were held in the archives of Thomas Wright (1711–1786), another polymath from the eighteenth century. Wright, although never quite part of the scientific establishment, had an extraordinary range of achievements (Gushee 1941; Hoskin 1970). He was an antiquary and architect, a landscape gardener, and studied meteorology and astronomy. He is perhaps best known for his novel assertion that the stars we know as the Milky Way are actually an 'Island Universe,' or galaxy, a viewpoint which was later popularised by Immanuel Kant (see Schaffer 1978).

Wright also drew an eclipse map for the 1737 eclipse. Wright's chart had elements of both the eclipse chart formats, showing the progress of the Moon's umbra across the Scottish Borders, but also detailing the appearance of the Sun and Moon at maximum eclipse for 52 locations around the British Isles (Armitage 1997: 17–19). A copy can be seen at www.eclipse-maps.com (Zeiler 2011).

In 1782, towards the end of his life, Thomas Wright wrote "Speculum Meteorum, or An Essay towards establishing a True Theory of the Weather," with the further sub-title "Analysis to that of the tides, or ebbing and flowing of the Sun, being Founded upon a Lunar Influence of the Sun and the Moon Upon the atmosphere of the Earth" (Class Mark GB033 WRM, 15/31-42). In other words, Wright was trying to spot a lunar cycle in the weather. This work, which was unfinished and was never published, contains the following: "An Extract of the Observations of the Weather at Coventry for several years successively made by Mr. Tipper, to which are added all the new and full Moons in ye same years…" The observations consist of four tables, one each for the years 1724, 1725, 1732, and 1733. Unfortunately, there is no table for 1737, so we have no clue as to whether the weather was co-operative on eclipse day. There is one entry for each day of the year, which the author annotated with either: R (rain), S (snow), W (wind), F (frost), T (thunder) or no entry. On 11 May 1724 there was a total eclipse potentially visible from mainland Britain to the south and west of Coventry, but there is no annotation in the 1724 table.

Wright attributes these tables to Beighton's fellow mathematician and former Editor of *The Ladies' Diary*, John Tipper, but he could not have produced the tables because he died in 1713. A note in the Wright files (dated 1979) by Professor Gordon Manley states: "The Meteorological Journal that is in this collection is almost certainly for Coventry or nearby, kept by Henry Beighton—a rather well known Mathematician-Draftsman." So we cannot be absolutely certain that the tables were prepared by Beighton, but we can agree with Professor Manley that he is the likely author. The handwriting is similar to Beighton's, but it is also similar to Wright's own handwriting, so we cannot determine whether the tables are originals or copies.

It might be expected that Beighton and Wright, two polymaths who had shared interests in meteorology and astronomy (especially eclipse charts), would have been acquainted, but Wright's lack of knowledge about the authorship of the Coventry data suggests otherwise. Although Beighton had business interests in the north-east of England right up until his death, his only recorded visit to the area occurred whilst Wright was still young.

6 Concluding Remarks

Preparing this paper has been a fulfilling experience. In the course of checking my facts I made contact with Beighton's biographer, Alan F. Cook. As well as writing an entry about Beighton for the *Dictionary of National Biography* (Cook 2009), Cook has published a brief biography and bibliography of Henry Beighton (see Cook 1999).

From Cook's biography, I found that the source that contained most of Henry Beighton's astronomical observations was *The Ladies' Diary*. This includes information about solar and lunar eclipses that occurred and potentially were visible from England during Beighton's editorship. The next step in my investigations of his life is to examine the complete run of *The Ladies' Diary* held in the Cambridge University Library. I am hopeful that this will finally allow me to answer the question which has been nagging at me ever since I first encountered Beighton's chart—did Henry Beighton see the eclipse he predicted for Coventry in February 1737?

Acknowledgements I would like to acknowledge the help of the following people: Viscount Daventry, who gave his permission to reproduce Henry Beighton's eclipse chart; Alan F. Cook, who has extensively researched the life of Beighton, and was kind enough to send me the mini-biography he wrote on Beighton; Sheridan Williams, author of *UK Solar Eclipses from Year 1*, who was able to verify the accuracy of Beighton's eclipse predictions for 1737; Chris Hicks, a friend and work-colleague of mine, who is a member of Rugby Local History Research Group, and assisted me with my researches; staff of the Warwickshire County Archive and the Durham University Archive; and Madeline Cox, who investigated Beighton's writings in the British Library for me.

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The Newdigate archive in the Warwickshire County archives contains the following:
CR136/B2551 Henry Beighton's eclipse chart
CR136/B3026 Henry Beighton's notes on lunar and quadrant measurements

CR136/B3015/1 Roger Newdigate's diary
Beighton's weather charts at Durham University have classmark GB 033 WRM, 15/31-42
Details of Thomas Wright's life and Durham University's collection of his work are held at: http://www.dur.ac.uk/library/asc/collect_information/cldload/?collno=142
The Arbury Hall website is www.arburyestate.co.uk. This contains a brief history of the family.
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Portuguese Amateur Astronomy (1850–1910)

Vitor Bonifácio and Isabel Malaquias

Abstract Although amateur astronomers have existed probably for as long as mankind has observed the sky their role has continued to adapt to different technological and social conditions. Throughout the nineteenth century two opposing trends were at play. On the one hand, the professionalisation of science and the rising cost of first class instruments led to a reduced number of research fields available to amateurs. On the other hand, an increased educated population with access to affordable small instruments led to the emergence of a growing number of middle class amateurs who founded institutions like the British Astronomical Association and the Société Astronomique de France, both of which still exist today.

While these developments have already been well studied for countries like the United Kingdom the same cannot be said of many others. We argue, nevertheless, that a global understanding of the evolution of amateur astronomy requires a comparison of different local dynamics, and that interesting insights into the history of astronomy, in particular, and human development, in general, may be gained in the process.

In this paper we present our ongoing research on the Portuguese amateur astronomical community between 1850 and 1910. We attempt to identify their members and analyse their research programs and relationships.

We conclude that while Portuguese developments followed the contemporaneous international trend the frailties of the educational system and science popularisation dynamics were probably responsible for the small number of amateur astronomers. The small size of this community in turn hindered the appearance of a local astronomical society so instead Portuguese amateurs joined and collaborated with international societies. Their contributions were well received by the astronomical community.

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1 Introduction

This paper is part of a research in progress in which we plan to characterise the Portuguese community of amateur astronomers during the time interval 1850–1910, analyse its development and place it in a national and an international context.

The time limit chosen is arbitrary but is associated with two important political changes that occurred in Portugal. In the 1850s there were attempts to modernise Portuguese institutional infrastructures, in general, and the astronomical ones, in particular. In 1851 a new government was elected and decades of political inconstancy were replaced by an epoch of stability that become known as the 'Renovation' ('Regeneração'). On 5 October 1910 the Portuguese monarchy was replaced by a republican regime and political instability ensued (Birmingham 1993; Bonifácio 2007, 2009; Bonifácio et al. 2009; Ramos 1993a).

Usually one finds enthusiasts with increasing degrees of involvement—from the casual, to the hobbyist, to the amateur. To avoid possible misconceptions we start by briefly defining these categories for the purposes of this paper. We will consider as an amateur astronomer someone that does astronomical research without being paid. This simply assumes that an amateur astronomer must be an astronomer, that is, his/her practice fits into the recognisable astronomical research pattern. In particular, an amateur has a serious intent to contribute to the advancement of science and shares his results with fellow astronomers (Williams 1988). Hobbyists, on the other hand, usually maintain long-lasting interests but are not motivated to contribute to the science. Finally casual, passive or 'armchair' enthusiasts have an interest in astronomy, may search for information in books and specialised journals, attend lectures, and join special societies. Both hobbyists and casual enthusiasts may also leisurely observe the sky (Williams 1988, 2000).

In this paper we will start (in Sect. 2) by analysing the international growth and development of amateur astronomy. In Sect. 3 we will outline the Portuguese context, then in Sect. 4 we will characterise the community of Portuguese astronomical enthusiasts and overview the life and work of Portuguese amateur astronomers working in the time period under consideration. Finally, in Sect. 5, we will discuss our findings and present our conclusions.

2 International Developments: A Growing Number of Enthusiasts

The number of individuals interested in science, in general, and astronomy, in particular, increased in the nineteenth century due to several factors. The expansion of the educational system led to a decrease in illiteracy. New printing technologies diminished the costs of newspapers, journals and books and accordingly the numbers published swelled throughout the century. The increase in readership helped sustaining science popularisation efforts that in turn enticed new readers. This created the positive feedback cycle represented in Fig. 1.

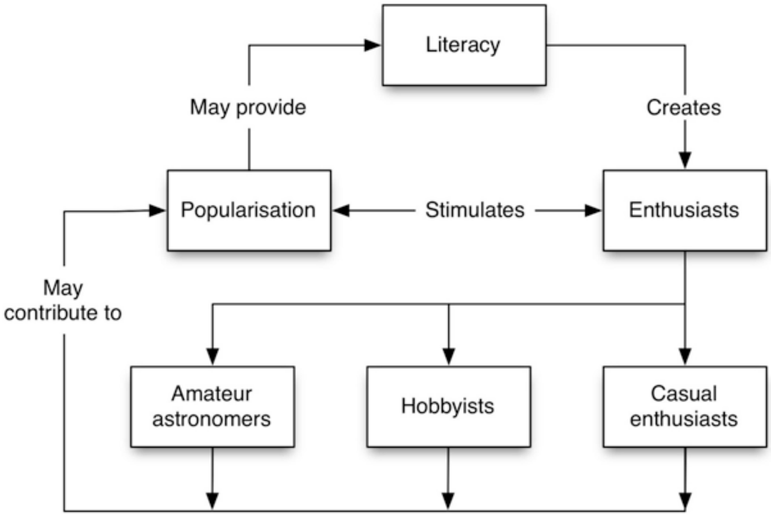

Fig. 1 A positive feedback cycle that increased the number of astronomical enthusiasts in the nineteenth century (After Bonifácio 2009)

Simultaneously, the price of small telescopes became proportionally cheaper. In 1880 (Flammarion 1880: 833, our translation) wrote:

> Advances in manufacturing have been so rapid, that we can today, by going directly to manufacturers, have good instruments at prices well below what we usually imagine.

The availability of small telescopes, with apertures of 11 cm or less, at reasonable prices proved popular. This in turn increased the number of enthusiasts. Since these small telescopes were unable to compete either in collecting power or in resolution with the largest telescopes available, amateur astronomers resorted to niche research fields that professionals were unable or did not want to fully tap into. Amateurs were particularly involved in the observation of solar, lunar and planetary surfaces and the study of variable stars.[1] In the field of variable stars a fruitful co-operation was established between the two communities.

As the number of enthusiasts grew the need for some type of formal organisation began to be felt. At the middle of the nineteenth century there was, apparently, a single society devoted to astronomy, the Royal Astronomical Society (RAS), but hobbyists, casual enthusiasts and women were *a priori* excluded from membership. To became a fellow one needed to be a reasonably well-to-do male usually with previous astronomical work of perceived merit. The creation of astronomical societies with less stringent admission rules proved to be a natural response to this situation.

[1] By 1880 the largest telescopes in the world were the 26-in. Alvan Clark refractor at the U.S. Naval Observatory in Washington (D.C.) and the 48-in. silver-on-glass reflector at the Paris Observatory. At Birr Castle in Ireland there was a 72-in. reflector with a speculum mirror, but this instrument used outdated technology (Clerke 1902).

Table 1 Amateur astronomical societies entitled ‘Flammarion’ created prior to 1885

Creation date		Society name	Country
January	1880	Société Scientifique Flammarion de Bogota	Colombia
January	1882	Société Scientifique Flammarion de Jaën	Spain
June	1882	Société Scientifique Flammarion à Argentan	France
March	1883	Société Scientifique Flammarion à Bruxelles	Belgium
May	1884	Société Scientifique Flammarion de Marseille	France

The first British amateur astronomical society was created in Leeds in 1859. Later that society would describe itself as “Founded 1859, Re-established, 1863, Re-organised 1892 …”, so one may suspect it had a small impact in its earlier years (Chapman 1998: 247). In the United States, the Chicago Astronomical Society was started in 1862 to support the Dearborn Observatory and “… diffuse astronomical knowledge.” (Anonymous n.d.; cf. Williams 2000). The *Astronomische Gesellschaft* was established in the following year and ‘friends of astronomy’ were considered for membership (Pfau 2000). Although each country possessed its own specifics, a turning point occurred around 1880, in part due to the efforts of the astronomer Camille Flammarion (1842–1925).[2] Flammarion was already a well known populariser when he started publishing *Astronomie Populaire* in installments in 1879. This book was an astounding success and according to his author in 1880 it attracted 30,000 subscribers (Flammarion 1880: 829). At the time Flammarion’s fame was so widespread that sometimes he was mistakenly believed to be the Director of the Paris Observatory, much to the displeasure of the true holder of the position, Amédée Mouchez (1821–1892) (see de La Cotardière and Fuentes 1994: 193). In this book, Flammarion proposes the construction of a public observatory with funds obtained by public subscription, the establishment of a journal “… to be used by all astronomical amateurs … [and] keep them up-to-date with the rapid evolution …” of astronomical science, and the creation of an astronomical society (Flammarion 1880: 831). The first issue of the journal *L’Astronomie* was published in March 1882, and in May Flammarion unsuccessfully renewed his appeal for the establishment of a society (de La Cotardière and Fuentes 1994: 189). Although the *Société Astronomique de France* (SAF) would only be founded in 1887, at least five societies inspired by Flammarion would be created before 1885 in four different countries (see Table 1) (Anonymous 1883; Lancaster 1886).

In 1886 the *Brussels Observatory Yearbook* listed eleven societies, plus the RAS and the professional *Società degli Spettroscopisti Italiani* (Lancaster 1886). It was also during the 1880s that some well known societies, still active today, first appeared:

Société Astronomique de France (SAF), 1887
Astronomical Society of the Pacific (ASAP), 1889
British Astronomical Association (BAA), 1890

[2] In Britain “… a growing body of fuel was being piled onto the amateur astronomical fire in the wake of Webb’s *Celestial Objects*, in the form of cheaper and more accessible telescopes and books, along, of course with journals like the *Astronomical Register* and the *English Mechanic*.” (Chapman 1998: 251).

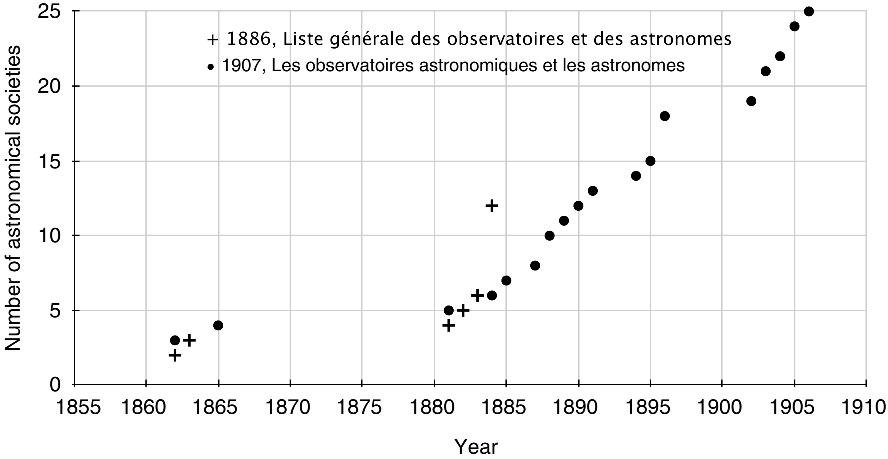

Fig. 2 Cumulative number of astronomical societies at a given year excluding those that only admitted professionals. Crosses are from the *Liste générale des observatoires et des astronomes* (1886) and dots from *Les observatoires astronomiques et les astronomes* (1907)

These amateur astronomical societies usually shared the following characteristics:

1. They allowed the exchange of information between their members via periodical meetings and/or the publication of a society journal;
2. They allowed their members to have access to a library with a wide range of publications;
3. Sometimes they owned an observatory and/or a collection of instruments that could be lend to the members.

The number of astronomical societies continued to grow throughout the nineteenth century, as shown in Fig. 2. These plots only provide a lower limit of the total number of societies at any given year since both data sets are biased towards decreasing the number of older societies. Both plots may also be affected by incomplete information and different methodological approaches. As a consequence significant discrepancies between the two plots occur. For example, for 1884 the number of societies differs by six, depending on the source. Both lists, nevertheless, point to a different society creation dynamic from 1880 onwards (Lancaster 1886; Stroobant et al. 1907). One should point out the number of professionals also kept growing throughout the century, as may be ascertained by the exponential increase of international astronomical observatories (see Herrmann 1973).

Another important quality of Flammarion's books was the departure from the typical French popularisation format. In her comparative study of London and Paris popular science periodicals published between 1820 and 1875 Susan Sheets-Pyenson (1985: 558) concluded that, despite the bi-directionally of influences across the English Channel and the similar aspirations of the publication promoters, there were "… two different low scientific cultures …" as a consequence of the different characteristics of readers, publishers and scientific communities. In fact, the most uniform feature of all French popular science periodicals was a report on the proceedings of the *Académie des Sciences*. French periodicals, then, did not try to stimulate amateur scientific pursuits, but instead eagerly followed the affairs and achievements of the world of professionalized and specialised 'high science' (ibid.).

This passive approach contrasted with the British periodicals that tended to encourage amateur pursuits and promoted the exchange of information among their readers. Portuguese popularisation efforts usually followed a passive model which is not surprising since France was, at the time, the dominant external cultural influence in the country.

Already in the last chapter of *Astronomie Populaire* in response to questions from readers, Flammarion advised several models of economic telescopes and indicated the observations that could be performed with each model, but it was "… impossible to go into any technical detail and provide the necessary elements for the study of astronomy …" (Flammarion 1880: 832). This was a topic that Flammarion would address in his 1882 book *Les Etoiles et les Curiosités du Ciel*, which was the natural 'complement' or 'supplement' to the *Astronomie Populaire*. According to Flammarion, previously there was no practical book a person could use to start a personal study of the astronomy, to which many readers aspired. He believed that the approximately 300 telescopes were sold to readers of his book between October 1879 and 1881, providing further evidence of this need (Flammarion 1882: 685, footnote 1). In its 792 pages, *Les Etoiles* attempted to fill "… this significant gap in public education in France."

3 Folque's Recommendation and the Portuguese Context

The first reference we found to amateur astronomers in Portugal during the period under review dates from 1857 and is a consequence of Carl Rümker's (1788–1862) arrival in Lisbon in order to improve his failing health.[3] For seven nights in April Rümker tracked Comet d'Arrest—currently known as C/1857 D1 (d'Arrest)—and his observations were published in May in the *Astronomische Nachrichten* (Rümker 1857). Filippe Folque (1800–1874), Director of Lisbon Naval Observatory, used the data to calculate the comet's orbital elements, which were later communicated by Rümker to the *Astronomische Nachrichten* (Folque 1857b). In a research paper written in June 1857 Folque presented the Rumker's comet observations and his calculations to the Lisbon Academy of Sciences (Academia das Sciencias de Lisboa). At the end of his communication Folque recommended

> … to the 'lovers' of astronomy Rümker's small refractor … It is a highly portable instrument, with various applications … and the results will be exact if conveniently installed … [and] it costs less than 180$000 [i.e. 180,000] réis. (Folque 1857a; our translation)

[3] Rümker passed away in 1862 and was buried in Lisbon, in the English cemetery, where his gravestone still stands.

Table 2 The population and levels of literacy in Portugal between 1878 and 1911

Date	Population	Literacy (%)
1878	4,550,699	21
1890	5,049,729	24
1900	5,423,132	27
1911	5,960,056	31

Folque's suggestion apparently had no effect since no Portuguese amateur astronomers are known before the 1880s. In our opinion three main causes contributed to this outcome: the low literacy of the population, the feeble popularisation dynamics and the costs associated with the acquisition of astronomical equipment.

Portugal was not immune to the cultural ideologies of the day and the multiple advantages gained by improving the 'public instruction' were vocally recognised by the country's elite. During the nineteenth century there was an effort to establish wide-ranging primary and secondary school systems. In 1836 the Government approved an ambitious network of secondary schools, but its practical implementation was impaired by political instability. Up to 1844 only 5 secondary schools had been created in the mainland, a number that had increased to 17 by 1853. In the 1880s industrial schools were created in Lisbon and Porto (Torgal 1993). These actions increased the literacy rate by 10 % between 1878 and 1911 while the country's population grew 31 % (see Table 2, which is based on Candeias et al. 2007, and references therein). By comparison, for the period 1870–1890, O'Rourke and Williamson (1997) estimate that literacy rates for the European basin (Italy, Portugal and Spain) and the industrial core areas (Belgium, France, Germany, Great Britain, Netherlands and Switzerland) were 40 % and 95 %, respectively.[4] The literacy rate of the European basin was approximately half that of the European average, which was 83 % (ibid.).

Following international developments, the number of Portuguese newspapers founded per decade, according to the Coimbra University catalog, increased from 21 in 1800–1810 to 240 in 1891–1899. This shows a growing publishing dynamism even if a lot of the publications were short-lived (Bonifácio 2009; Ramos 1993b). Several inexpensive collections of books, sometimes called 'libraries,' also were published: *Books for the people* (*Livros para o Povo*, 1859), *Popular Education* (*Educação Popular*, 1870), *Popular Library or Instruction for all Classes* (*Biblioteca Popular ou Instrução para todas as Classes*, 1870) and the hugely successful *People and Schools Library* (*Bibliotheca do Povo e das Escholas*, 1881) (see Torgal and Vargas 1993). Some collections were sold in installments, which made them an attractive proposition for newspaper readers since both media had similar prices and used the same distribution networks. This last aspect was important since, at the time, the popular classes usually did not patronise bookshops (Mollier 2003; Thiese 2000: 21).

[4] These estimates may have large uncertainties, as recognised by the authors. As an example, the Portuguese literacy rate quoted in the article is 38 %, a value that is substantially larger than the one presented in Table 2.

Some volumes also fulfilled a double function as they could be used as elementary textbooks, if approved by the Government.

In the specific case of the popularisation of astronomy the efforts made were apparently ephemeral and irregular. In particular, an extremely low number of astronomical books written by Portuguese authors was published in the second half of the nineteenth century. Two early twentieth century overviews of Portuguese mathematical publications only refers to four popular astronomy titles (Guimarães 1900, 1909), and a search of the National Library's (Biblioteca Nacional) legal deposit from 1805 does not significantly change this number. An exhaustive survey of Portuguese nineteenth century astronomical publications is still lacking, but from the available evidence we believe the small readership was unable to sustain these types of thematic publications for long. Worse still, since the publications were usually intended for a general audience they were unappealing to an expert who, having the necessary means, could access first-hand information directly from abroad.

In his 1857 comet observations Rumker (1857) used a comet-searcher ('chercheur des cométes') of 3 feet focal length and a Kellner eyepiece. We do not know the aperture of this telescope but an 1852 Troughton & Simms catalogue lists an achromatic telescope with a 3.25-in (82.55 mm) of 45 inches focal length (114.3 cm) and finder as costing £42 (Simms 1852), a figure that is similar to Folque's value of 180,000 réis (approximately £40).

Folque's suggestion to astronomy 'lovers' may appear to indicate that Rümker's telescope was an affordable purchase. The opposite is truth as 180,000 réis amounted to a substantial portion of the annual salary of a typical middle class public employee (54 % for a secondary school teacher; 44 % for an army captain and 22 % for a university professor). Table 3 compares the prices of the telescopes advised by Flammarion (1880) in the first edition of *Astronomie Populaire* with the 1880 annual salaries of several Portuguese public employees. The professions were chosen taking into account the main occupations of the Portuguese enthusiasts referred to in the following section. Small refractors became more affordable between 1857 and 1880, although for some professions the acquisition of a telescope was still a hefty investment.

Table 3 Comparison between telescope prices quoted in *Astronomie Populaire* and the annual salary of several professions in 1880. If a profession had a salary range the value chosen corresponds to the income group with the largest number of individuals. As such these values allow only a qualitative comparison

	No.	1	2	3	4	5
Telescope	Aperture (mm)	61	75	95	108	100
	Focal length (m)	0.9	1	1.3	1.60	
	Instrument maker	Molteni	Bardou	Molteni	Bardou	Secretan
	Price (French Francs)	150	200	400	600	500
Telescope prices as percentage of annual income	Primary school teacher	27	36	71	107	89
	Secondary school teacher	7.7	10	20	31	26
	Army Captain	6.4	8.5	17	26	21
	Navy commander	3.8	5.1	10	15	13
	Full university professor	3.3	4.5	8.9	13	11

4 The Portuguese Amateurs

In the 1880s the international middle class amateur astronomer movement was growing and self-organising. Flammarion's books mobilised his readers to pursue more actively their astronomical interests. In Portugal there was a peak of astronomical popularisation publications, amongst them a 74-page book, *In Various Worlds* (*Nos Varios Mundos*), published in 1883, written by Narciso de Lacerda (1858–1913) and inspired by Flammarion's *Les Etoiles et les Curiosités du Ciel*. Lacerda's goals were to indicate

1. the books in which the reader will easily acquire the notions that will awaken in him the love of astronomical science;
2. the beauty of the different planets and the main observations to make of each;
3. the most remarkable double stars;
4. and finally, the instruments necessary for the practical study of astronomy, and that today are available to all due to their extreme cheapness. (Lacerda 1883: 16, our translation).

Lacerda's book is dedicated to future hobbyists or amateur astronomers and as such differs from previous publications. Later, probably in 1893, the 1890 edition of Flammarion's *Astronomie Populaire* was translated and published in Portugal. This 1016-page volume was printed with similar size and quality than its French counterparts (Flammarion 1893a).

In 1887 the *Société Astronomique de France* (SAF) was created and its first Portuguese member joined in the following year. The conditions were ripe for the appearance of the first Portuguese amateur astronomers. In an 1890 overview of the developments made in the last decade Flammarion (1893a) mentions amongst the 64 persons from 25 countries who "… devote their spare time to the observation of the celestial wonders .." three Portuguese: "Narciso de Lacerda in Lisbon; J.C. de Castro Villas-Boas in Vianna do Castelo and Francisco Affonso Chaves in São Miguel Island, Azores." If one looks at these names several interesting things may be ascertained. Firstly, Affonso Chaves was the only SAF member; secondly, one finds observations by Lacerda and Chaves in the journal *L'Astronomie*, but none by Villas-Boas. Searching the Portuguese sources we found a reference to a certain João Coelho de Castro Villas-Boas from Vianna do Castello enrolled in the Porto Polytechnic School in the year 1889–1890. Unfortunately he shared the full name with his father and does not appear in the annual enrolments for the years 1888–1889, 1890–1891 and 1891–1892 (Anonymous 1889a, 1890, 1891). This illustrates a major difficulty encountered while trying to characterise a community of enthusiasts. While the amateurs can be traced by their paper trail, hobbyists and casual enthusiasts absent from national biographical references may easily slip into anonymity.

Due to the lack of biographical information we decided to look into the SAF and BAA yearly membership lists in order to derive a lower limit for the number of Portuguese enthusiasts at any given time. We also wanted to establish what sorts of links existed between the different members. Several difficulties prevent a quantitative analysis of the data collected. We had access to a incomplete data set of lists.

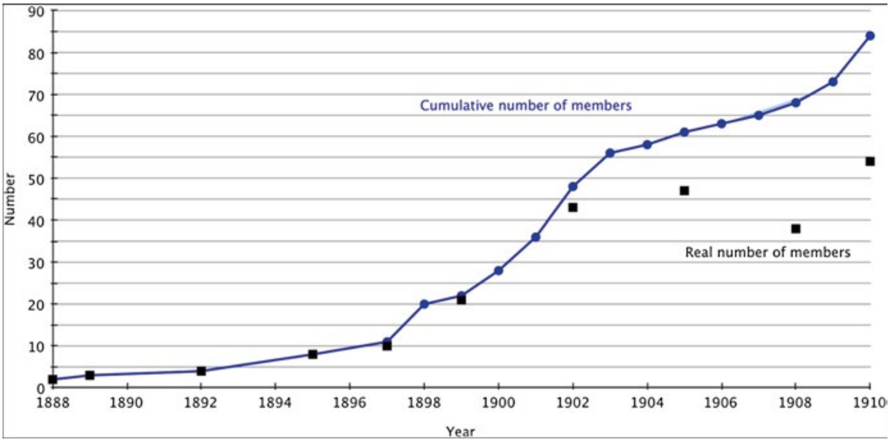

Fig. 3 Cumulative and actual number of Portuguese SAF members per year. Cumulative numbers are estimated from the membership lists for the years 1888, 1889, 1892, 1895, 1897, 1899, 1902, 1905, 1908, and 1910

Moreover, the SAF, as well as the BAA, do not indicate the nationalities of their members but only places of residence so, unless some extra information is available, it is impossible to distinguish between a Portuguese and a Brazilian living in Portugal, for example. We decided not to count members with foreign names living in Portugal or members with Portuguese names living abroad, except for those located in the former Portuguese African colonies. In addition, membership lists may also be incorrect. For example we found a person still on a list almost two years after he had passed away. Since the dates of election are known from a single yearly list one may construct the distribution of members per year. This provides a lower estimation for the number of yearly members. The cumulative Portuguese membership (see Fig. 3) was estimated from nine membership lists dating from 1889 to 1910, and separated at most by three years (SAF 1889, 1890, 1892, 1895, 1897, 1899, 1902, 1905, 1908, 1910; Anonymous 1889b).

SAF *Bulletins* provided yearly cumulative membership numbers, i.e. summing up all those that at any one time all those belonged to the society, and from 1898 onwards the actual number of members per year (see Fig. 4). From Figs. 3 and 4 one concludes that the total and Portuguese SAF membership numbers follow a broadly similar variation with time.

In 1910 the SAF had 54 Portuguese members of whom 50 were male and 4 were female. Their main occupations were low-ranking army officers, professors, physicians and public servants (see Table 4; SAF 1910). One should point out that the professions were self-defined by the members and as such may be misleading. For example, João de Moraes Pereira declared himself as an astronomer although he was a secondary school teacher. Large variations are also expected due to the small number of members.

Analysing the Portuguese membership of the BAA one realises this Association's almost negligible impact upon the Portuguese public, probably due to the strong

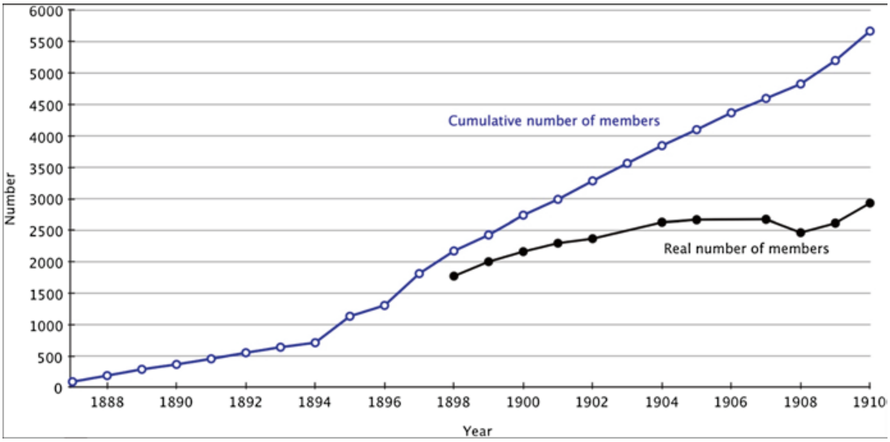

Fig. 4 Cumulative and actual number of total SAF members per year

Table 4 Distribution of professional occupations amongst the 1910 Portuguese SAF members (after SAF 1910)

Profession	Number	Observations
Armed forces	11	Low-ranking military officers
Professor	9	3 University or Polytechnic professors
Doctor/physician	7	
Others	7	3 public servants, 2 landowners, 1 journalist/writer, 1 priest
Undeclared	19	

Table 5 Number of Portuguese and Spanish members of the SAF, BAA and belonging to both societies

Date	Nationality	BAA	SAF	Both
1899	Portuguese	2	21	2
	Spanish	2	53	2
1902	Portuguese	3	43	3
	Spanish	2	73	2
1910	Portuguese	1	54	1
	Spanish	3	95	3

French cultural influence in Portugal and the language barrier. For instance, in *In Various Worlds* Lacerda (1883: 24; our translation) wrote “There is a very thorough book, which I have not yet referred because the English language is not widespread amongst us.” A similar situation is observed if one looks at the Spanish membership numbers (Table 5) (BAA 1899, 1902, 1910).

Interestingly with one exception, all Iberian members who belonged to both societies were at some point amateur astronomers, and all were first SAF members, although Moraes Pereira only for a month (Table 6; Anonymous 1892, 1893a, 1902, 1903; SAF 1905; BAA 1899, 1902, 1910).

In 1899 the SAF detailed the geographical distribution of the places of residence of its members (Flammarion 1900). For those European countries with more than

Table 6 Election dates of Iberian members who belonged to both the SAF and the BAA. Election dates as fellows of the Royal Astronomical Society (RAS) are also indicated

Name	Nationality	SAF	BAA	RAS
Comas Solá, José (1868–1937)	Spanish	1890	1897	1902
Pereira, João de Moraes (1855–1908)	Portuguese	1892	1892	
Patxot y Jubert, Rafael (1872–1964)	Spanish	1895	1897	1903
Simas, Manuel Soares de Mello e (1870–1934)	Portuguese	1895	1897	
Schindler, João Henrique (?–?)	Portuguese	1900	1901	

Table 7 Ratio of SAF members per million population at the end of 1899. The cross in the final column indicate a country with one or more astronomical societies active at the time, according to *Les Observatoires Astronomiques et les Astronomes* list (Stroobant et al. 1907). Population estimates were taken from McEvedy and Jones (1978)

Country	Members	Population (millions)	Ratio (per million)	Astronomical societies
France	1,210	41	30	×
Rússia	150	133	1.1	×
Roumania	63	11	5.7	
Spain	58	18.5	3.1	×
Italy	58	34	1.7	
UK	51	42	1.2	×
Belgium	41	7	5.9	×
Germany	37	43	0.9	×
Switzerland	36	3.25	11	
Austria	34	46	0.7	
Holland	17	5.25	3.2	
Portugal	15	5.4	2.8	

ten members we calculated the number of enthusiasts per population in order to try to get a perspective on the societal impact (see Table 7). Naturally France has the largest ratio but there is no clear-cut conclusion one can draw from the data. This was to be expected since the number of members from a given country depends on several variables, as we have been discussing for Portugal.

4.1 Narciso Manuel Correia de Lacerda

Narciso de Lacerda was born in Porto in 1858. At the age of 14 he followed his father's wishes and immigrated to Brazil in order to purse a trading career. Being unsuccessful Lacerda returned to Portugal three years later. He found employment in the railways and later in the mail company. In 1877 he met his life-long friend, the writer, journalist and polemicist José da Silva Pinto (1848–1911). In 1879 Silva

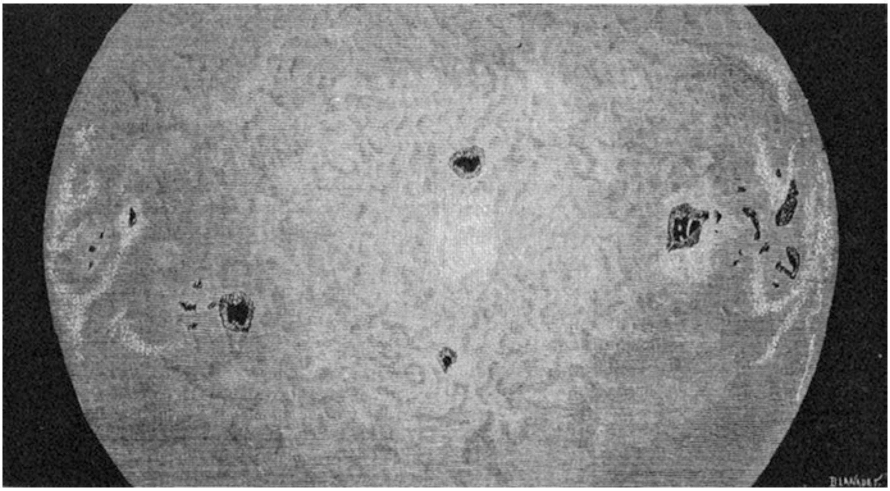

Fig. 5 Lacerda drawing of the solar surface on 22 December 1884 at 11h30m

Pinto's father, an industrialist, passed away leaving a small fortune to his son. Between 1880 and 1882 Lacerda published his first two poetry books and in 1883 *In Various Worlds* (*Nos varios mundos*). At the time he had a Bardou 108-mm refractor (Lacerda, 1883: 17), an acquisition well beyond a simple clerk's salary. In all likelihood Silva Pinto sponsored Lacerda's observatory (Lacerda 1885a).

Lacerda seems to have made good use of his observatory. His visual observations of Venus and Jupiter made in Lisbon during 1884 appeared in the journal *L'Astronomie* (Lacerda 1884a). These were his first published observations although a quote from *In Various Worlds* indicates that he was observing sunspots at least from 1883:

> Actually … the sun is in one of its best periods in this regard [i.e. sunspots], and almost no day passes by without a beautiful [sunspot] group. (Lacerda 1883: 54; our translation)

Throughout 1884 and 1885 we find several references in the journals *L'Astronomie* and *La Nature* to Lacerda's sunspot observations (see Lacerda 1884b, 1885a, b). In 1885, Gaston Tissandier, wrote in *La Nature* that "… the knowledgeable Portuguese amateur astronomer … studies sunspots with zeal and perseverance." (Lacerda 1885a; our translation). In this paper, illustrated here by Fig. 5, Lacerda hinted, incorrectly, at the existence of a possible correlation between sunspots and terrestrial phenomena such as high temperatures or unusual earthquakes.

During 1885, Lacerda observed Jupiter's satellites, a lunar rainbow and the November 27 meteor shower (Flammarion 1886; Lacerda 1885c, 1886). Still in 1885 he obtained a reasonable lunar photograph,[5] even though his telescope lacked a clock-drive (Tissandier 1886). In February 1888 Flammarion mentions that

[5] A copy of this still exists in the Historical Archive of the Lisbon Astronomical Observatory.

Lacerda had observed the previous 28 January lunar eclipse, but does not provide any details (Gérigny 1889a). This is the last reference to a Lacerda astronomical observations. We believe the end of Lacerda's astronomical activity was linked to another Silva Pinto reversal of fortunes. Having invested his father's inheritance in a factory that went bankrupt by the end of 1886 Silva Pinto was once more a pauper and had to resort to writing as a means of survival. He ended his life in poverty, borrowing money from friends. "He never knew the value of money …" said an acquaintance. In his later life Lacerda wrote and worked as a clerk, earning an annual salary of 60,000 réis. He passed away in 1913 (Bonifácio 2009 and references therein).

4.2 Francisco Affonso da Costa Chaves e Mello

The scientist and army officer commonly known as Affonso Chaves was born in Lisbon in 1857. As a young man he settled in the town of Ponta Delgada, São Miguel, in the Azores, where he died in 1926. Between 1875 and 1877 Affonso Chaves attended the Military Academy in Lisbon. He returned to São Miguel in 1879 where he played a pivotal role in the installation and development of the Azores meteorological service of which he became the first Director (Ferreira 1959; Tavares 2009).

In a letter published in February 1885 in the journal *L'Astronomie*, Affonso Chaves described an earthquake felt at his Ponta Delgada private observatory on 22 December 1884 (Mello 1886). Previously he wrote a few science popularisation articles in a local newspaper. In 1886, a series of public lectures was organised, intended to bring science "… within the reach of our [town's] less illustrated classes …," and astronomy was the lecture topic Affonso Chaves chose to speak about. Interestingly, as a complement to his lecture he proposed to provide 'astronomical notions' in his observatory to classes of 10 students. We do not know if anyone took advantage of this offer. Still in 1886, he observed the 29 August partial solar eclipse with a 108-mm telescope and detected "… a slight orange glow on the edge of the Moon." (Mello 1887). In 1888, he joined the newly-founded SAF and became its first Portuguese member (SAF 1889). Despite being a SAF member at least until 1913, we have found only two additional references to astronomical observations made by Affonso Chaves. On 7 August 1889 he observed an occultation of Jupiter by the Moon, and he timed the contacts of the 16 April 1893 solar eclipse (which was partial in the Azores) (Flammarion 1893b; Gérigny 1889b). His growing involvement with meteorology may explain the apparent decline in his astronomical activities. In 1893 Ponta Delgada became linked with Lisbon by a submarine telegraphic cable and the project to install an international weather center in the Azores gained momentum. Later that year Affonso Chaves was nominated Director of the Ponta Delgada's Meteorological Station (Ferreira 1959; Tavares 2009).

Although Chaves may best be described as a casual observer his activities may have played an important role in creating a small local network of enthusiasts, two of which, João de Moraes Pereira (1855–1908) and Manoel Soares de Mello e Simas (1870–1934) became amateur astronomers. In 1895 half of the eight SAF Portuguese members lived in Ponta Delgada (SAF 1895).

4.3 João de Moraes Pereira

Arguably the most important Portuguese amateur astronomer of the nineteenth and early twentieth centuries, João de Moraes Pereira, was born in Ponta Delgada in 1855. After finishing his education at the local secondary school in 1874 he became a shop assistant in his uncle's firm with an annual salary of 300,000 réis. He married in 1881 and had his only child in 1883 (Registo Paroquial de S. Sebastião, Ponta Delgada 1881, 1883). According to the firm records Moraes Pereira worked there at least until 1886 when he accepted an invitation to teach English at his former secondary school. Moraes Pereira never attended a higher instruction institution. We suspect his language skills were picked up within his family environment. His uncle traded with the local British community and made at least three trips to Britain. His grandmothers were also known for mastering the English language (Casa Comercial de José de Morais Pereira 1886; Rosário 2005). In 1886 the Government appointed Moraes Pereira as provisional English teacher, a status that changed to full teacher in 1889.

We could not identify the reasons that led a shop assistant/teacher to astronomy although Affonso Chaves appears to be the likely catalyst. They were both teachers at the same school in the 1880s and together observed the solar eclipse of April 1893, but by that time Moraes Pereira had already became an amateur astronomer (Pereira 1893). The earliest publication of a Moraes Pereira astronomical observation appeared in 1892 in the journal *L'Astronomie* when he was 36 years old. The article reports observations of double stars, the zodiacal light, and the 6 February conjunction of Venus and Jupiter (Armelin 1892). Still in 1892, Moraes Pereira joined the SAF and the BAA; drew the Moon (see Fig. 6), Mars, Jupiter and Saturn; and started observing variable stars (Bonifácio et al. 2010, and references therein). From 1892 to at least 1896 Moraes Pereira was an important contributor to the BAA's Variable Star Section, and his observations mainly appeared in the Section's Annual Reports.

Later he published a few variable star observations in the journal *English Mechanic* before started to contribute to the Harvard Observatory photometric program. Figure 7 summarises his variable star observations. At least between 1893 and 1898 Moraes Pereira was also a keen sunspot observer. Because of his geographical position he was able to assist in the 24-hour international monitoring of the solar surface, and thus contributed to a more complete BAA sunspot record which was generally appreciated. Moraes Pereira was also an exquisite draughtsman, as the lunar drawing in Fig. 6 shows. His images graced the pages of *L'Astronomie*, the BAA's Solar Section reports (see Table 8; Brown 1895, 1896, 1897, 1898, 1899; Cortie 1900) and Agnes Clerke's 1903 book *Problems in Astrophysics*.

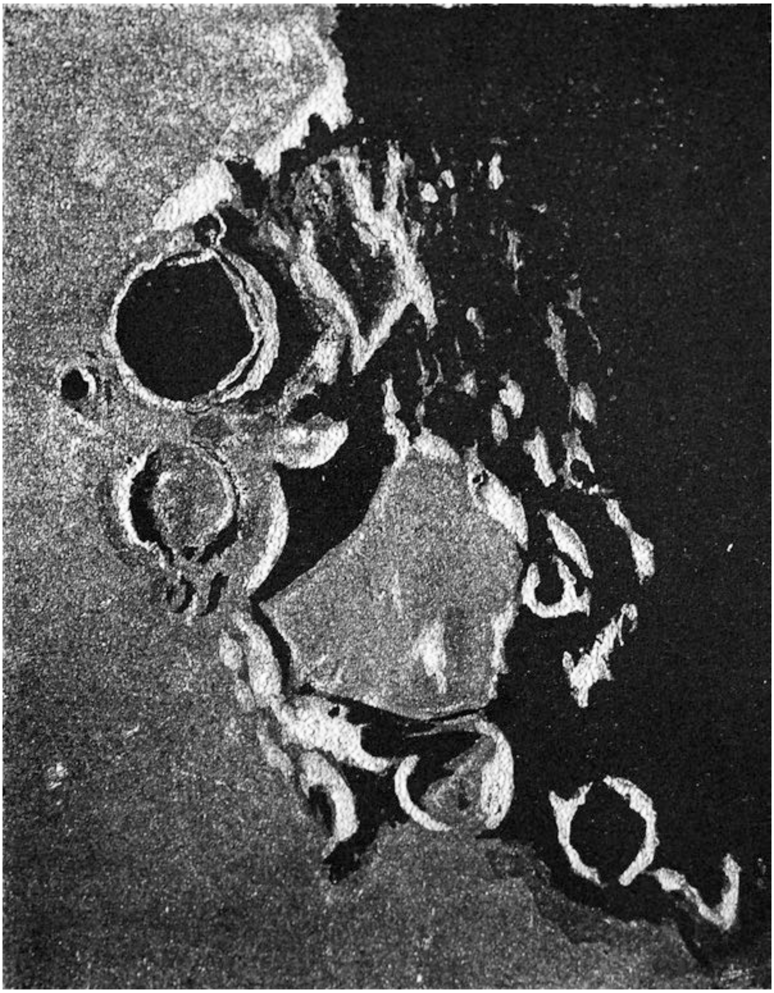

Fig. 6 Moraes Pereira drawing of the vicinity of the lunar crater Flammarion made on 2 July 1892 (Anonymous 1893b; Flammarion 1893c)

Throughout his astronomical 'career' Moraes Pereira made visual observations of the Moon, Mars, Jupiter and Saturn; timed transits, eclipse and occultations; determined longitudes by the telegraphic method; recorded the shape and position of sunspots; and studied the magnitudes of variable stars. Here we only briefly overviewed his contributions since a fuller account may be found elsewhere (see Bonifácio et al. 2010, 2011). One should point out that Moraes Pereira shied away from interpreting the data collected; at best he would describe his observations. To our knowledge he published, for instance, only a single variable star light curve. In this regard his approach was no different from that of many other amateur or professional astronomers at the time.

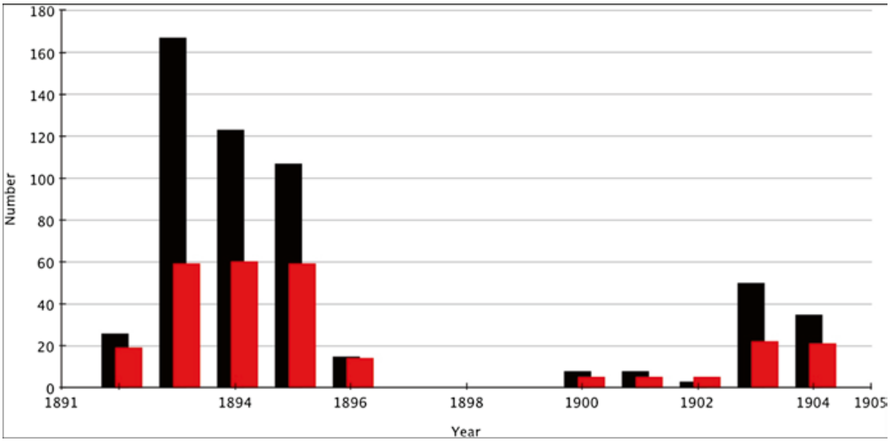

Fig. 7 Moraes Pereira's variable star observations per year, according to published sources. The black and red bars represent the number observation days and the number of stars observed, respectively (After Bonifácio et al. 2010)

Table 8 Authors and the number of sunspot drawings published in the British Astronomical Association's Solar Section reports between 1893 and 1898

	Observer	1893	1894	1895	1896	1897	1898	Total number of drawings
	Elisabeth Brown	15	18	13	22	12		80
	Moraes Pereira	3	10	3	3	5	2	26
	Henry Corder	1	1		1	1	2	6
	J. Bartlett	1				1		2
	J. Wykes			6		1		7
	E. M. Antoniadi					1		1
	T.H. Astbury						4	4
Solar Section observers	With published drawings	4	3	3	3	6	3	
	Total Number	10	8	8	11	9	15	

Nevertheless his enthusiasm was such that at one point he taught in his school, observed sunspots during the day and determined variable stars magnitudes at night. Another episode clearly reveals his commitment: while on holiday in Horta, a town of the Azores island of Fayal, he took advantage of the recently-installed submarine cable linking the island with Canada to telegraphically determine the longitude of Horta Castle. In the process, he became the first Portuguese to work out an international longitude difference by telegraphic means (Bonifácio et al. 2011).

In 1901, the Lisbon Astronomical Observatory astronomer Frederico Oom (1864–1930) met Moraes Pereira in Ponta Delgada. The letter he then wrote to the Lisbon Observatory Director is, we believe, revealing of Moraes Pereira's approach and abilities:

> … there is here an amateur [astronomer] … who is very competent, can calculate orbits of comets for fun and makes astronomical drawings of rare perfection. On all clear days he determines the time of his two chronometers (box-chrom) via the height of the sun, a sextant and an artificial horizon. It may be interesting to compare his time with the one from Tapada. (Oom 1901; our translation)

João de Moraes Pereira died suddenly and prematurely in Ponta Delgada in 1908. He was only in his mid-50s.

4.4 Manoel Soares de Mello e Simas

The other amateur from the Azores, Manoel Soares de Mello e Simas, was born in the town of Horta, Fayal Island, in 1870, into a well-to-do family. He studied at the local secondary school and in 1887 enrolled in Coimbra University to take the mandatory course to access the Military Academy. In 1889 he started the artillery course at the Military Academy in Lisbon.

As a youth he became interested in astronomy and while studying at Coimbra he already owned an 81-mm Bardou telescope that he used until at least 1907 (Arruda 2007; Stroobant et al. 1907). In February 1895 he became a SAF member and later that year sent the Society drawings of sunspots and Jupiter. In his communication, of which only a short note was published, he claimed a 12–13-year periodicity of Jupiter's equatorial brightness variations and proposed it was due to the influence of the Sun and the satellites (Anonymous 1895; Simas 1895).

Mello e Simas was already taking astronomy seriously before he was promoted to 1st Lieutenant and transferred to Ponta Delgada in November 1895. Upon his arrival he already knew of and admired João de Moraes Pereira from his SAF publications. At a social event they were introduced, and as a consequence

> For nine years, we [Mello e Simas and Moraes Pereira] saw each other almost every day, often spending forgotten hours through the night, in lecture and study. (Simas 1903a)

In 1896 he published an article titled "Methods to observe the Sun" where he presented practical solutions for determining the heliocentric elements of sunspots from their projection onto a target. He also concluded that

> … a good photograph would avoid a lot of work but a good shutter is essential for solar photography and it is very difficult to get one (Simas 1896)

In 1897 Mello e Simas became a BAA member, proposed by Moraes Pereira and the Director of the Solar Section, Elizabeth Brown (1830–1899) (Anonymous 1897). Probably due to the influence of Pereira Moraes, for a while he was interested in variable stars. His observations of *S Ceti* and *U Ceti* were published in the

Annals of Harvard College Observatory whereas the Nova Persei ones appeared in the *Astronomische Nachritchen*. He also observed the spectrum of *Nova Persei* (Wendell and Pickering 1902; Simas 1901). In 1901 he published his first paper on what turned out to be his preferred research topic—the determination of the orbital elements of comets and asteroids. Eight other papers were published prior to 1912 (Simas 1901, 1902a, b, 1903, 1905, 1906, 1907, 1910, 1911).

Still as an amateur, Mello e Simas began gravitating towards professional circles, and in 1907 he became a corresponding member of the Lisbon Academy of Sciences, to which he was elected a full member in 1931. In 1911 he offered to fill a supernumerary observer position at the Lisbon Astronomical Observatory and upon being accepted he became in practice a professional astronomer. However, he would turn out to have an irregular astronomical career, as a result of other commitments (Arruda 2007; Martins et al. 2000). For example, he served in the Portuguese expeditionary force in France between February 1917 and July 1919, was a Member of Parliament and, for a few months in 1923, was the Minister of Education.

At Lisbon Astronomical Observatory Mello e Simas observed Mars; determined the right ascension of stars; observed occultations, comets and asteroids; and calculated orbital elements (Arruda 2007, and references therein). In 1923, following a request published in the *Astronomische Nachrichten*, he unsuccessfully tried to measure Einstein's predicted gravitational deflection of light by observing the occultation of a star by Jupiter (Simas 1926). During his life Mello e Simas also wrote science popularisation articles and gave popular lectures. In 1931 he became Deputy Director of the Observatory. He passed away on 10 August 1934 while working at the Observatory (Arruda 2007).

5 Discussion and Conclusions

The previous four astronomical observers are archetypes of different kinds of astronomical enthusiasts. Affonso Chaves was the casual observer who by virtue of his popularisation efforts tried to enthuse those in his vicinity. Narciso de Lacerda's hobby was cut short by a change in life circumstances. Moraes Pereira was the typical middle class nineteenth century amateur astronomer. Finally, Mello e Simas was that rare amateur astronomer with a preference for calculations, who later made the transition to professional astronomy. Their main instruments, listed in Table 9, did not differ from those used abroad. In the 1890 edition of *Astronomie Populaire* Flammarion lists instruments owned by "frequent observers" and "private observatories." Of the

Table 9 Telescopes owned by Portugal's main astronomy enthusiasts

Observer	Aperture (mm)	Maker
Narciso de Lacerda	108	Bardou
Affonso Chaves	108	Secretan
Moraes Pereira	108	Bardou
Mello e Simas	81	Bardou

"frequent observers, 53 % (24 out of 45) had a 108-mm Bardou telescope, and only three observers had larger instruments.

In contrast, at private observatories, 34 % of the telescopes had larger apertures, but the 108-mm Bardou still accounted for 19.5 % of all models (8 out of 41) (Flammarion 1893a: 1004). Several famous astronomers amongst them, Camille Flammarion, Eugène Antoniadi and Jose Comas Solà, at a given time also had a 108-mm Bardou telescope (Dollfus 1988; Oliver 1997; Pernet 1988). One must not forget that this kind of acquisition was not for everyone's purse. Lacerda had a temporarily-wealthy friend, while Affonso Chaves and Mello e Simas belonged to well-to-do families, their fathers occupying the positions of Civil Governor of Ponta Delgada district and Administrator of the Municipality of Horta, respectively. We are unsure of Moraes Pereira's financial details, but the price of his telescope amounted to 22 % of his 1892 annual salary,[6] a lesser figure than previously (see Table 3), because salaries increased at a faster rate than the prices of telescopes.

We conclude that Portuguese developments in amateur astronomy mimicked the international trends but the low literacy levels, poor popularisation dynamics and the high cost of instruments prevented the appearance of a large number of astronomical enthusiasts. Even though the SAF ratio of Portuguese enthusiasts per population was reasonable in comparison (see Table 7), a small number of widely-dispersed persons did not have the critical mass to create a self-sustained dynamic. This in turn explains why no astronomical association was formed during the period under discussion. Yet the advantages to be gained by mutual support can be perceived in the results obtained by the tiny informal 'Azores network.'

The small numbers also make it difficult to ascertain the impact of some highly-visible astronomical events. In particular the solar eclipse 28 May 1900 whose path of totality crossed Portugal created, if one trusts the press reports, genuine excitement. The railway company reduced ticket prices to allow customers to travel to the totality area. Several secondary schools and higher education institutions organised trips to observe the eclipse and the Lisbon Royal Observatory (Tapada) published a widely-circulated book detailing the eclipse circumstances and summarising the available astronomical knowledge (Carolino and Simões 2012). Despite all this activity, there is no clear indication that the event led a measurable increase in the number of Portuguese amateur astronomy enthusiasts. Yet in neighbouring Spain, Ruiz-Castell (2008: 234) has shown that the eclipses of 1900 and 1905 certainly boosted Spanish astronomy.

In summary, between 1850 and 1910 there were very few Portuguese amateur astronomers, and none of them could be classed as a 'grand amateur'. Nevertheless, they promoted astronomy locally, joined foreign astronomical societies, participated in international observing programmes and published in foreign journals. As such they are the ancestors of the vibrant Portuguese amateur astronomical community that we have today.

[6] The price of a 108-mm Bardou refractor varied depending on the mounting and range of accessories. We are assuming that Moraes Pereira owned the less expensive version, if the telescope that we found in his secondary school is indeed his own (Bonifácio et al. 2011: Fig. 3).

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The Amateur-Turned-Professional Syndrome: Two Australian Case Studies

Wayne Orchiston

Abstract In the nineteenth century, and particularly during the era which saw the gradual replacement of positional astronomy by astrophysics, amateur astronomers were able to make an important contribution to international astronomy. Many were blessed with instruments comparable to those found in professional observatories; they pursued the same astronomical research programs as their professional colleagues; published in the same journals; received the same medals and awards; and played key roles in the formation of the earliest astronomical groups and societies. In this healthy environment of amateur-professional co-operation it was possible for talented amateur astronomers to transfer to professional ranks, and the 'amateur-turned-professional' (henceforth ATP) was a distinctive feature of late nineteenth century astronomy. In this paper we focus on two Australian-based ATPs, R.T.A. Innes and C.J. Merfield, and examine their contributions as amateur astronomers in Sydney before reviewing the circumstances surrounding their transfer to the Cape Observatory (South Africa) and Sydney Observatory, in 1896 and 1904, respectively.

1 Introduction

Unlike most other scientific disciplines, amateurs are still able to make a useful contribution to research astronomy, and this was no more so than during the nineteenth century, before astrophysics began to eclipse positional astronomy (e.g. see Ashbrook 1984b; Chapman 1998; Clerke 1893; Dunlop and Gerbaldi 1988; Lankford 1981a; Macpherson 1906; Meadows and Henbest 1981; Orchiston 1989b; Williams 1987). For the purposes of this paper, an amateur astronomer is defined as someone involved in astronomy *for the love of it*, who normally does not derive a *primary income* from astronomy.

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Back in the late 1970s, the University of Calgary sociologist, Robert A. Stebbins (1938), pioneered a whole new field of research, the sociology of 'amateurs' (e.g. Stebbins 1977, 1978, 1979, 1980a, 1992, 2004, 2007). Amateurs straddle the nebulous boundary between work and leisure. They are 'amators' in the strict sense in that they love their hobby and are happy to invest time, money and effort in it for the sake of the expected 'rewards' (see, also, Williams 1987). Five of Stebbins' later papers (1980b, 1981, 1982a, b, 1987) deal specifically with the avocation of amateur astronomy, and these form an important contribution to our discipline.

Using 'dedication' as a criterion, Stebbins distinguishes 'devotees' from 'dabblers'. Australia's leading amateur astronomers during the nineteenth century were all devotees, individuals who were happy to make a substantial commitment to the science in terms of both time and money. Using another dimension, 'knowledge and involvement', Stebbins differentiates between 'active' and 'armchair' amateur astronomers. In the nineteenth century, leading active amateur astronomers were engaged in observational and mathematical astronomy, and in instrument-making. Stebbins also was able to categorise individual active astronomers within an 'apprentice—journeyman—master' continuum. Apprentices were beginning their astronomical 'careers', while masters were the acknowledged experts who were making a meaningful contribution to science whatever their area(s) of astronomical involvement. Most of the Australian amateur astronomers mentioned in this paper were devotees who were active masters.

This paper examines a special group of amateur astronomers, those who were able to graduate from amateur to professional ranks and make their marks as professional astronomers. The amateur-turned-professional (ATP) sydrome was a distinctive feature of nineteenth century world astronomy, in an era when astrophysics began to eclipse positional astronomy as the preferred type of research pursued by professional observatories.

2 Developments in Late Nineteenth Century Australian Astronomy

In order to place the achievements of R.T.A. Innes and C.J. Merfield in a proper astronomical context it is important that we map the major developments that occurred in Australian astronomy during the late nineteenth century, and the role that amateur astronomers played in these.[1]

[1] Some of this section draws on material included in Orchiston 2002.

2.1 Fundamental Elements

The half-century from 1850 to 1900 should be viewed as a 'golden age' as Australian astronomy rapidly built on its fledgling international reputation established through the pioneering work carried out at Parramatta Observatory during the 1820s and 1830s (see Richardson 1835; Saunders 1990). Five different 'fundamental elements' can be identified in this evolutionary process, and each of these is discussed below.

2.1.1 Establishment of Professional Observatories

Apart from Phillip Parker King (1793–1856; Orchiston 1988f), no-one was particularly active in astronomy in Australia following the demise of Parramatta Observatory in 1847 and it was only in the 1850s that an urgent need for observatories emerged in both Sydney and Melbourne as the lure of the goldfields brought an avalanche of immigrants (for Australian localities mentioned in the text see Fig. 1). The primary demands of an accurate time-service and up-to-date meteorological data were best satisfied by the erection of an observatory.

Fig. 1 Australian localities mentioned in this paper

Fig. 2 Williamstown Observatory in 1862 (Orchiston Collection)

Thus it was that professional observatories proper were established in the various Australian colonies during the second half of the nineteenth century (see Haynes et al. 1996; Orchiston 1988a). The first of these was at Williamstown (near Melbourne), in 1853 (Fig. 2), and the last at Perth, in 1896 (see Table 1). Initially, only Adelaide (Fig. 3), Melbourne (Fig. 4) and Sydney (Fig. 5) Observatories contained sufficient staff and equipment to warrant ranking on an international scale, but Perth (Fig. 6) was able to join this trio soon after the turn of the century. Melbourne Observatory only came into existence when the Victorian Government decided to combine the functions of Flagstaff and Williamstown Observatories. The only other Australian institution with a substantial nineteenth century involvement in observational astronomy was the New South Wales Lands Department, which even created the official position of 'Field Astronomer' in 1886 (Orchiston 1987a).

Note that the work of all of the different 'astronomical observatories' in Table 1 went far beyond astronomy and time-keeping to involve—in varying degrees—geomagnetism, meteorology, seismology, tidal studies and trigonometrical survey work (see Baracchi 1914; Home and Livingston 1994; Todd 1893). While Adelaide, Melbourne, Perth, Sydney and Williamstown Observatories adopted more wide-ranging policies, the short-lived Flagstaff Observatory was concerned with geomagnetism and meteorology, while the observatories in Brisbane (Fig. 7) and Hobart focussed almost exclusively on meteorology and time-keeping. In addition, all of the observatories in Table 1 had important educational and informational roles to fulfil (see Orchiston 1991a). Because of chronic understaffing, and the emphasis that governments placed on public viewing nights, some of these institutions found their intended research programs severely disrupted.

Table 1 Australian professional observatories, 1850–1910

Name	Founding year	Main telescope(s)*	Officer(s)-in-charge	References
Williamstown	1853	11.4 cm OG	Ellery (1853–1863)	Andropoulos (2014), Ellery (1869)
Flagstaff	1858	Small OG	Neumayer (1858–1864)	Perdrix (1990), Weiderkehr (1988)
Melbourne	1863	1.22 m spec 20.3 cm OG 33 cm astr 20.3 cm tran	Ellery (1863–1895) Baracchi (1895)	Andropoulos (2014), Gascoigne (1992, 1995), Gillespie (2011), Perdrix (1961, 1970)
Sydney	1858	29.2 cm OG 18.4 cm OG 33 cm astr 15.2 cm tran	Scott (1856–1862) Smalley (1862–1870) Russell (1870–1905) Lenehan (1905–1908) Raymond (1908)	Bhathal (1991), Lomb (2011), Orchiston (1988b, 1998c, 2002), Wood (1958)
Adelaide	1874	20.3 cm OG	Todd (1855–1906) Griffiths (1907–1909) Dodwell (1909)	Edwards (1993, 1994)
Brisbane	1879	Small OG Small tran	MacDonnell (1879–1885) Wragge (1887–1891) McDowall (1891–1902) Spowers (1902)	Haynes et al. (1993, 1996)
Hobart	1882	Small tran	Shortt (1882–1892) Kingsmill (1893–1909)	Meteorological Department (1900)
Perth	1896	30.3 cm spec 33 cm astr	Cooke (1896)	Hutchison (1980, 1981), Utting (1989, 1992)

*Key: OG = refractor; spec = reflector; astr = astrograph; tran= transi t telescope

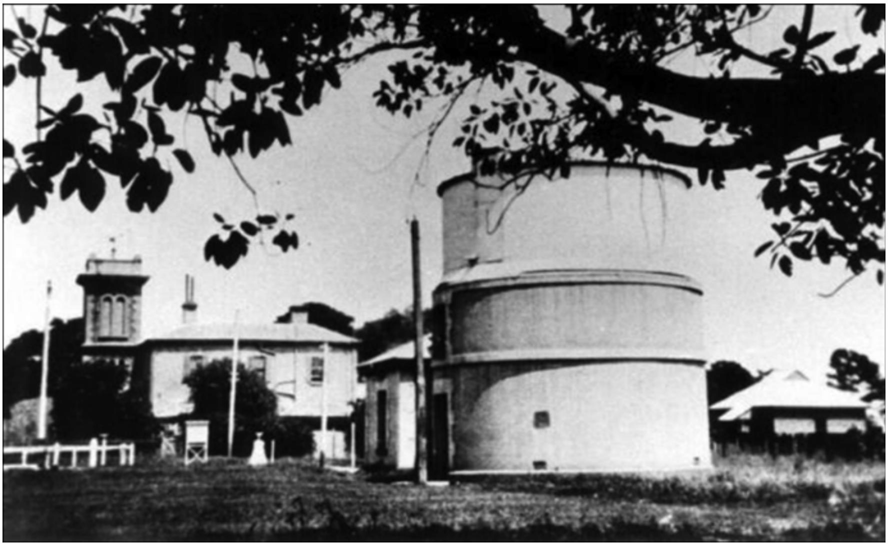


Fig. 3 Adelaide Observatory (Courtesy: setterfield.org)

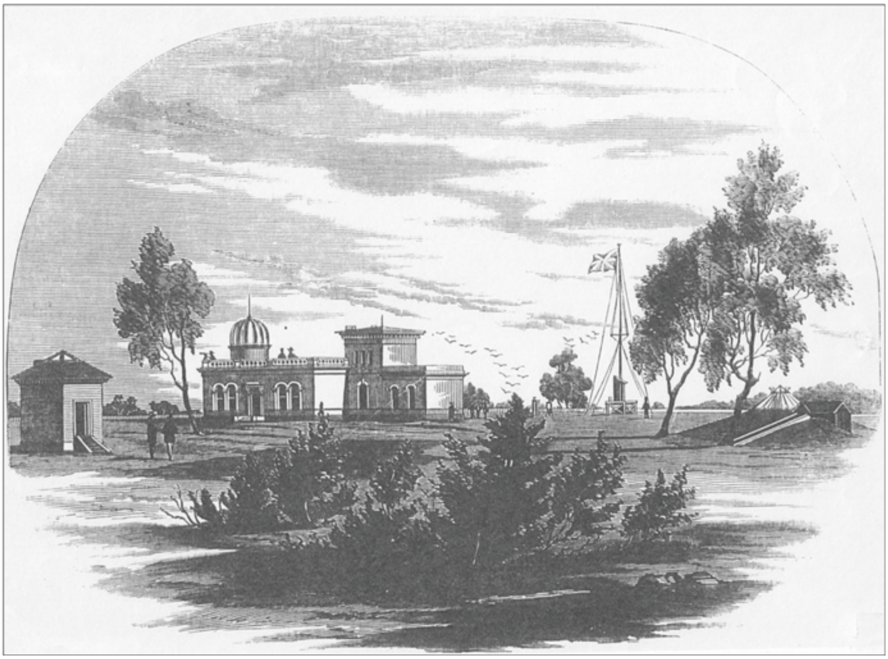


Fig. 4 Melbourne Observatory soon after it was founded (Orchiston Collection)

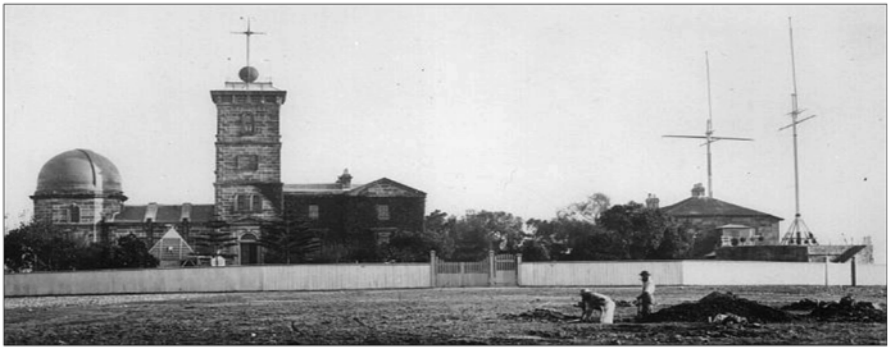


Fig. 5 Sydney Observatory (Courtesy: Royal Astronomical Society)

Fig. 6 Perth Observatory (Courtesy: westaussiewedding.typepad.com)

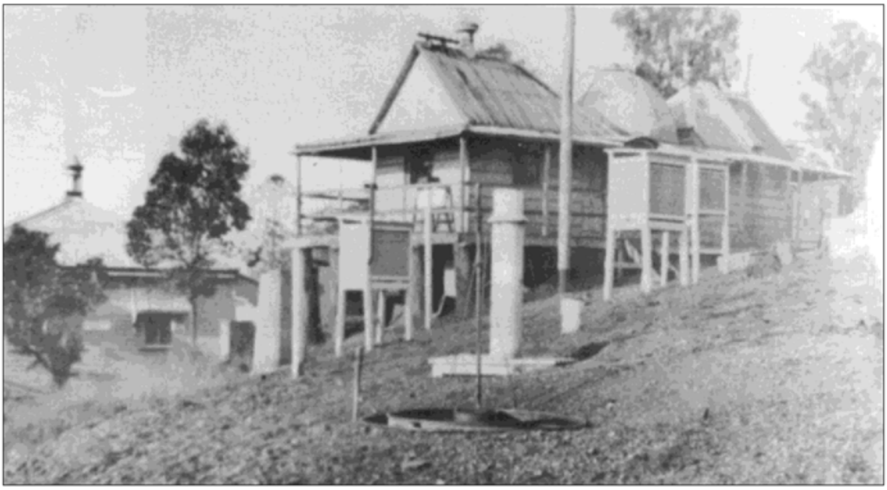


Fig. 7 Brisbane Observatory (After Haynes et al. 1993)

Fig. 8 Sir Charles Todd, founding Director of Adelaide Observatory (Courtesy: community.history.sa.gov.au)

Fig. 9 William Cooke, founding Director of Perth Observatory (Courtesy: www.perthobservatory.wa.gov.au/history.htm)

Research required the right combination of instruments and staff, and in this regard the four major Australian observatories were well served by international standards. The first two directors of Sydney Observatory were Cambridge mathematicians appointed by Airy (Orchiston 1988b, 1998c; Wood 1958), and all of the senior subordinate staff came with excellent newly-acquired academic qualifications or with substantial experience in observational and mathematical astronomy.

A properly-trained professional was also appointed to direct Adelaide Observatory in the person of Charles (later Sir Charles) Todd (Fig. 8; 1826–1910; Edwards 1993; Symes 1976), who had worked at both the Royal Observatory Greenwich and Cambridge Observatory. Todd was also the South Australian Superintendent of Telegraphs, and in 1870 added the post of Postmaster General to the list! Todd's assistant and understudy at Adelaide Observatory was an enthusiastic young local graduate named William Cooke (Fig. 9; 1863–1947; Hutchison 1980, 1981), who became founding Government Astronomer of Western Australia when Perth Observatory was opened in 1896, and eventually took charge of Sydney Observatory (Wood 1958).

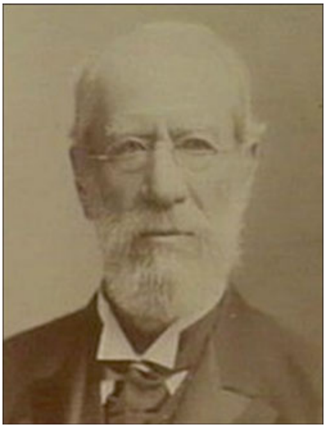


Fig. 10 Robert Ellery, founding Director of Melbourne Observatory (After Gascoigne 1992)

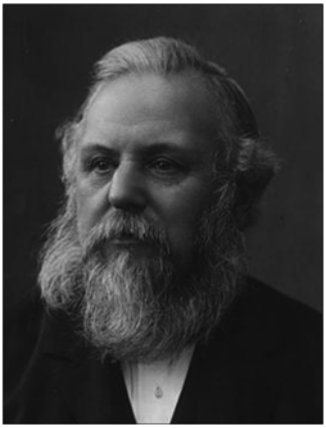


Fig. 11 Edward White, first assistant at Melbourne Observatory (Source: Museum Victoria)

For a long time, Melbourne was the only major Australian observatory without professionally-trained senior staff. Robert Ellery (Fig. 10; 1827–1908), Superintendent of Williamstown Observatory and subsequently founding Director of Melbourne Observatory, had trained as a medical practitioner (Gascoigne 1992) and had a background in amateur astronomy, as did his First Assistant, Edward John White (Fig. 11; 1831–1913). A professionally-trained individual (but in surveying, which included some practical observational astronomy) only joined the senior staff in 1882 when Pietro Baracchi (Fig. 12; 1851–1926) was appointed.

While the Directors at Adelaide, Melbourne, Perth and Sydney also served as the Government Astronomers of their respective colonies, Brisbane and Hobart Observatories were not so well blessed. From the start, these small observatories were placed in the care of their colony's respective Meteorological Observers, but at some point in time late in the century the Surveyor-General of Queensland took over responsibility for the Brisbane Observatory (see Haynes et al. 1993).

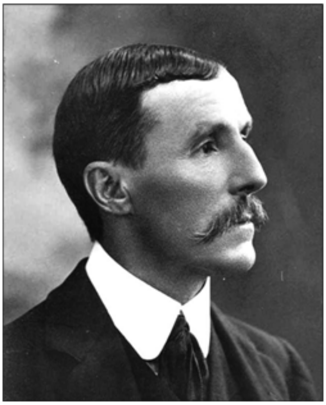


Fig. 12 Pietro Baracchi, second Director of Melbourne Observatory (Source: Museum Victoria)

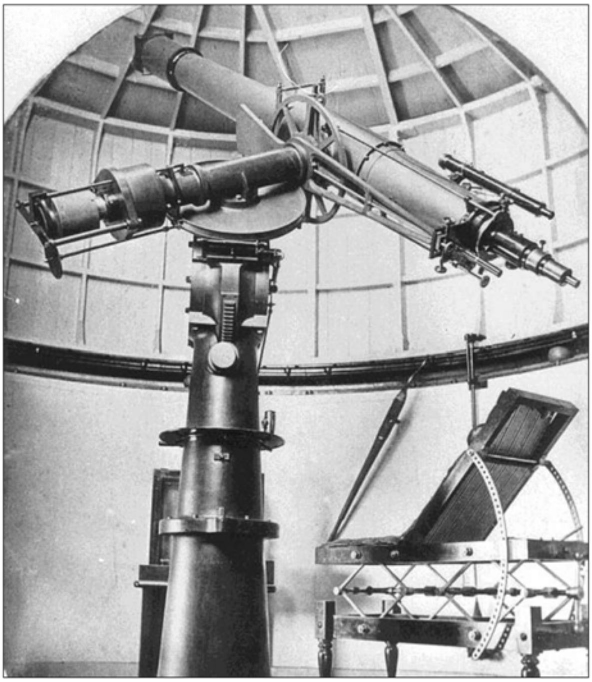


Fig. 13 The Adelaide Observatory 20.3 cm refractor (Source: Museum Victoria)

When it came to astronomical instruments, the major observatories were well equipped, partly due to the high public profile of the 1874 and 1882 transits of Venus (see Ellery 1901) and the pressure that the observatory directors therefore were able to apply to their respective Governments for special 'equipment funding'. The principal refractors at Adelaide (Fig. 13), Melbourne (Fig. 14) and Sydney Observatories were all acquired in this way. However, all were modest by world standards, the largest being the 29.2 cm Schroeder refractor in Sydney (Fig. 15). Each observatory

Fig. 14 The Melbourne Observatory 20.3 cm refractor (Orchiston Collection)

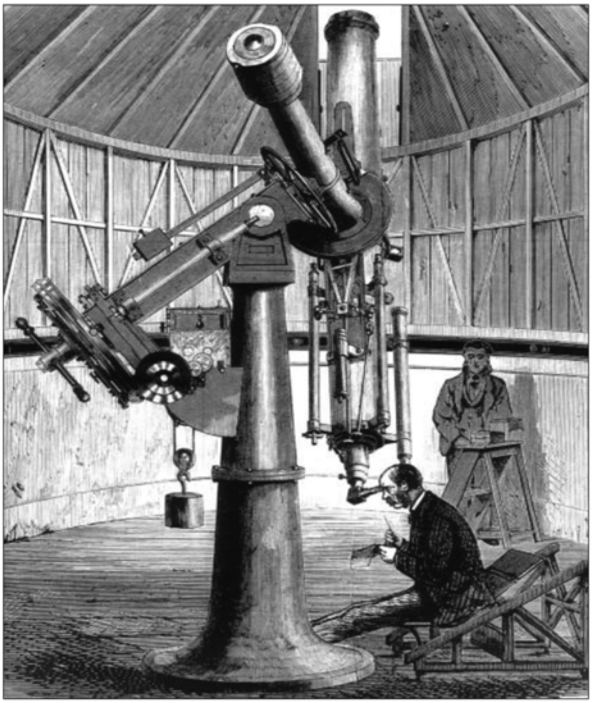
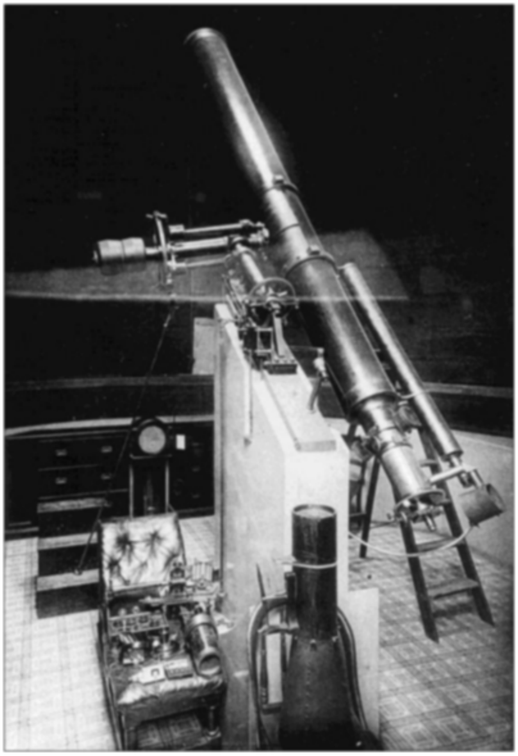


Fig. 15 The Sydney Observatory 29.2 cm refractor (After Russell 1892b)



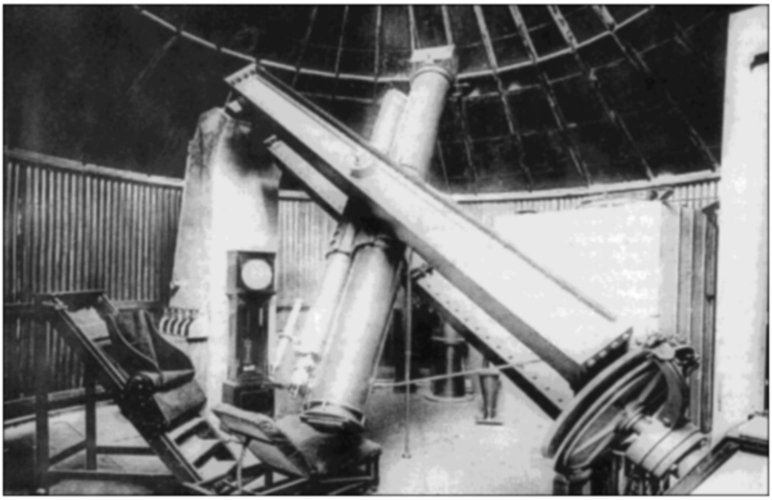


Fig. 16 The Sydney Observatory 33 cm astrograph and 26.7 cm guide scope (After Russell 1892a)

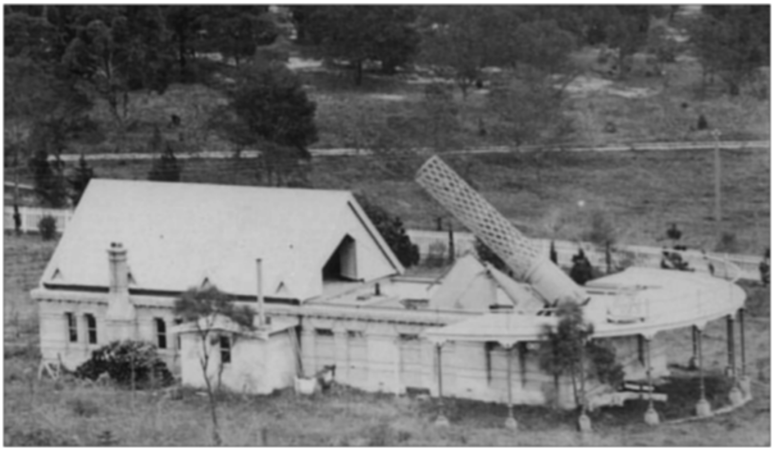


Fig. 17 The 'Great Melbourne Telescope' (Courtesy: Royal Astronomical Society)

also was supplied with one or more transit telescopes, and Melbourne, Perth and Sydney (Fig. 16) Observatories acquired Grubb astrographs (see Russell 1892a).

Of all the colonial observatory instruments, by far the most impressive was the Great Melbourne Telescope (Fig. 17), which became operational in 1869 (Gillespie 2011; Perdrix 1970). Its 1.22 m speculum mirror by Grubb made this the largest operational equatorially-mounted telescope in the world at the time (Robinson and

Table 2 Types of astronomical research programs most commonly undertaken by the leading Australian professional observatories, 1850–1910

Transitory events
Eclipses of the Moon
Eclipses of the Sun
Lunar occultations of planets
Lunar occultations of stars
Phenomena of Jupiter's satellites
Transits of Mercury
Transits of Venus
Short-term monitoring projects
Comets (positions and appearance)
Long-term monitoring projects
Double stars (separation and position angle)
Planets (appearance)
Sun (surface details)
Search programs
New double stars
Sky survey work
Star positions

Grubb 1869), but despite the promise it did not live up to expectations (Gascoigne 1995; Hyde 1987; Perdrix 1992; but cf. Orchiston et al. 2015). A large number of nebulae and star clusters were observed, and many of these featured in *Observations of the Southern Nebulae Made With the Great Melbourne Telescope* (Ellery 1885), but drawings based on naked eye observations of these tenuous yet complex objects were rapidly replaced during the last two decades of the nineteenth century by innovations in astronomical photography (e.g. see Bamard 1898; Lankford 1984; Norman 1938). With severe staff cuts during the depression of the 1890s and increased demands from the International Astrographic Project, the GMT was all but decommissioned, and thereafter was rarely used. From the start, had it been housed in a conventional dome rather than its roll-off roof observatory and a glass mirror of considerably shorter focal length been installed, then it could have been used extensively for spectroscopic and photographic studies and made a significant contribution to astrophysics. Instead, it proved to be a 'white elephant'.

The types of research undertaken at Australia's leading Government observatories are listed in Table 2. Adelaide, Melbourne, Perth, Sydney and Williamstown Observatories all succeeded in carrying out worthwhile research (see Haynes et al. 1996) and placing their names before the international astronomical community.

At Sydney Observatory Henry Russell (Fig. 18; 1836–1907) and his assistants discovered and measured many new southern double stars (see Innes 1899), and Russell was also one of these who pioneered astronomical photography in Australia (e.g. see Russell 1890a, b, 1891). In Adelaide, Edward P. Sells and then Cooke assembled a long series of drawings showing Jupiter's changing atmospheric features (Dodwell 1913), while during the 1870s Melbourne Observatory

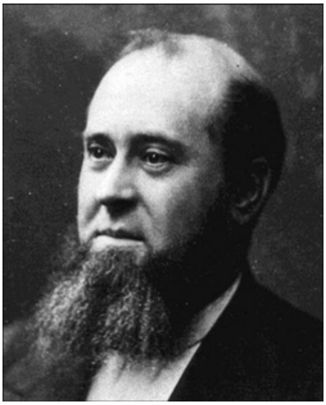


Fig. 18 Henry Russell, the third Director of Sydney Observatory (Orchiston Collection)

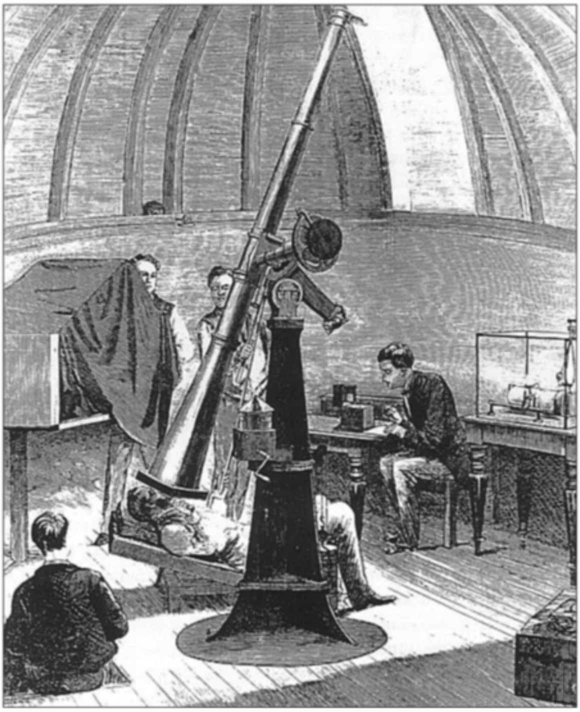


Fig. 19 The Melbourne Observatory 10.2 cm Dallmeyer photoheliograph (Orchiston Collection)

produced what Astronomer Royal, George Airy (1801–1892) at the time described as the "… best catalogue of stars of the Southern Hemisphere ever published." (Eleventh Report 1876: 8), and for twenty years, starting in 1874, weather permitting, daily solar photographs were taken with a 10.2 cm Dallmeyer photoheliograph (Fig. 19) and forwarded to Greenwich (Haynes et al. 1996). During the late

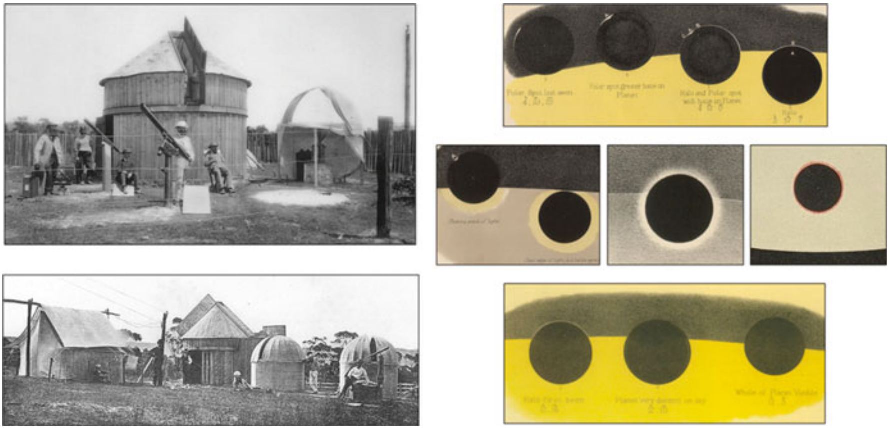


Fig. 20 Sydney Observatory's Eden (*top*) and Woodford (*bottom*) 1874 transit of Venus stations, and some drawings of the transit by astronomers involved in the Sydney program (After Russell 1892b)

1880s, Baracchi (1889) and Ellery (1889) carried out stellar spectroscopic observations with the 20.3 cm refractor (see Andropoulos and Orchiston 2006), while even earlier Albert Le Sueur had used the Great Melbourne Telescope to obtain the spectrum of Eta Argus (now Eta Carinae) and to carry out the first ever spectroscopic observation of an extragalactic object, 30 Doradus (Hearnshaw 1986; cf. Orchiston et al. 2013). In Sydney, Russell (1881) conducted a spectroscopic examination of the Great Comet of 1881 (C/1881 K 1). Staff from Adelaide, Melbourne and Sydney Observatories observed the 1874 transit of Venus (e.g. see Fig. 20; Baracchi 1914; Russell 1892b; cf. Orchiston 2004b), and the last two observatories were joined by Perth Observatory in the International Astrographic Project (see Turner 1912).

Research was not the only astronomical contribution made by the staff at the Australian colonial observatories, for both Ellery and Russell were active in grinding, polishing and figuring telescope mirrors. Ellery produced speculum metal mirrors (see Gascoigne 1992), while Russell experimented with glass, in 1880 completing his *piéce de rèsistance*, a mirror with a diameter of 38.1 cm. The associated telescope employed a novel equatorial mounting of Russell's own design, and somewhat reminiscent of that used later for the Great Palomar Telescope (see Orchiston 2000a; Orchiston and Bhathal 1982). Russell also developed a range of meteorological instruments (Bhathal 1991).

By the end of the nineteenth-century Australia was viewed—along with South Africa—as a major force in Southern Hemisphere astronomy, and Ellery, Russell and Todd were names well-known to Northern Hemisphere colleagues, particularly those committed to positional astronomy.

2.1.2 The Growth of Popular Interest in Astronomy

The period from 1850 to 1910 was blessed with an amazing succession of naked eye comets (Fig. 21), three total solar eclipses and two transits of Venus (see Table 3), all potentially visible from Australia. To add to the drama, three of these comets (C/1861 J1, C/1865 B1 and C/1881 K1) were discovered by Australians (see Figs. 22 and 23), and the two transits not only attracted Australian observers (amateur and professional) but also teams from Britain and the United States (e.g. see Orchiston 2004b; Orchiston and Buchanan 1993). All of these visually-appealing public spectacles listed in Table 3 demanded description and explanation. Australian professional and amateur astronomers used many means to bring information about these objects and events, and others, before the general public. They established public information services; offered viewing nights at their observatories; prepared press releases, reports, 'Letters to the Editor', and even regular 'Astronomy' columns for newspapers; published booklets, pamphlets, books and chapters of books on astronomy or aspects of the discipline; manufactured planispheres; presented public lectures on aspects astronomy; and delivered courses on astronomy (e.g. see Bonwick 1866; Orchiston 1991a, 1997a, 2003b). I refer to this collective corpus of activities and productions as 'public astronomy' (in contradistinction to 'research astronomy').

Fig. 21 Comet C/1880 C1, otherwise known as the Great Southern Comet of 1880, was independently discovered by Castlemaine's Dr William Bone, and attracted enormous public attention (Orchiston Collection)

Table 3 Impressive astronomical objects and events visible from Australia, 1850–1910 (After Orchiston 1997a)

Object/event	Year	Name/place visible*
Comet	1853	C/1853 G1 (Schweizer)
	1853	C/1853 L1 (Klinkerfues)
	1858–1859	C/1858 L1 (Donati)
	1860	C/1860 M1 (Great Comet)
	1861	C/1861 J1 (Tebbutt = Great Comet)
	1862	109P/Swift-Tuttle
	1864	C/1864 N1 (Tempel)
	1865	C/1865 B1 (Great Southern Comet)
	1874	C/1874 H1 (Coggia)
	1880	C/1880 C1 (Great Southern Comet)
	1881	C/1881 K1 (Tebbutt = Great Comet)
	1881	C/1881 N1 (Schaeberle)
	1882	C/1882 F1 (Wells)
	1882–1883	C/1882 R1 (Great Southern Comet)
	1887	C/1887 B1 (Great Southern Comet)
	1892	C/1892 E1 (Swift)
	1901	C/1901 G1 (Great Comet)
	1910	C/1910 A1 (Great January Comet)
	1910	1P/Halley (Great Comet)
Transit of Venus	1874	
	1882	
Total solar eclipse	1857	Sydney-Windsor
	1871	North Queensland
	1910	Tasmania

*Cometary nomenclature after Marsden and Williams (1996). Note that in Orchiston (1997c) I have made a case for the Great Comets of 1865 and 1880 to also be named after Hobart's Francis Abbott and Castlemain's Dr William Bone, respectively

All of the professional observatories were involved in these activities to a greater or lesser extent, but those who made the most significant contributions were William Scott (Fig. 24; 1825–1917) and Russell (Fig. 18) at Sydney Observatory, Ellery (Fig. 9) at Melbourne Observatory and Cooke (Fig. 8) at Perth Observatory (see Andropoulos 2014; Orchiston 1998c). However, the combined activities of the nation's amateurs brought astronomy to a much wider public audience (see Orchiston 1997a). The leading practitioners are listed in Table 4, but many others also contributed. One non-Australian who helped satisfy the public demand for astronomical information was the noted British populariser, Richard Proctor (1837–1888; North 1975), and in 1880 he undertook a lecture tour of Australia.

In any review of the achievement of Australia's amateur astronomers, the outstanding contribution that they collectively made to public astronomy cannot

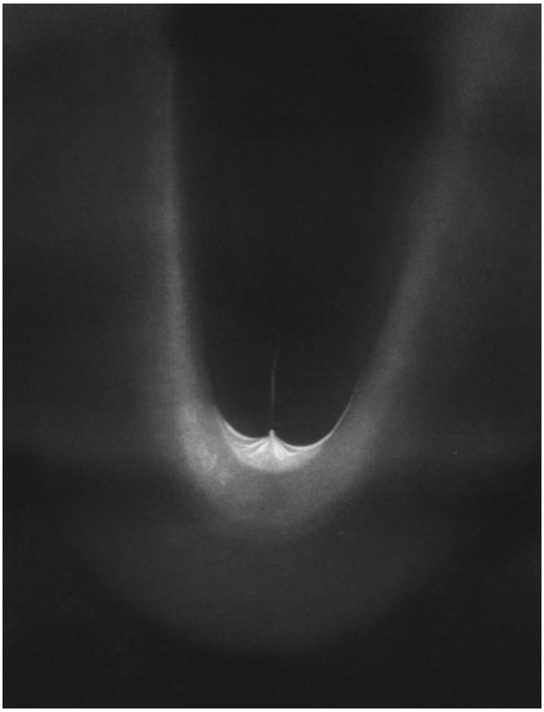


Fig. 22 Head of the Great Comet of 1861 (After Guillemin 1877: Frontispiece)

Fig. 23 Étienne Trouvelot's painting of the Great Comet of 1881, after it became visible in the northern sky (Courtesy: Chapin Library, Williams College)

Fig. 24 William Scott, founding Director of Sydney Observatory (Adapted from Russell 1892b)

Table 4 Leading Australian amateur astronomers actively involved in the popularisation of astronomy, 1850–1910 (After Orchiston 1997a)

Name	Location	Activities*	Other references
Abbott	Hobart	1, 2?, 3, 5, 7?	Orchiston (1992)
Baker	Ballarat	1, 2, 3?, 8	Burk (1986), Davis (1990)
Beattie	Sydney	1, 3	Orchiston, unpublished study
Biggs	Launceston	1, 2, 3, 7	Giordano (1995), Orchiston (1985)
Bone	Castlemaine	1, 2, 3, 7	Orchiston (1987b)
Butterfield	Sydney	1, 3, 6	Orchiston, unpublished study
Davidson	Mackay	1, 2, 3?	Baracchi (1914); Orchiston, unpublished study
Dobbie	Adelaide	1, 2, 3?	Orchiston and Bembrick (1995)
Gale	Sydney	1, 3, 7	Orchiston (1988c), Orchiston and Bembrick (1995, 1997)
Hawkins	Sydney	3	Orchiston (1987a), Orchiston and Bhathal (1991)
Innes	Sydney	1, 3	Orchiston (2001a, 2003c)
Jones	Bendigo	1, 2, 3?	Martin and Orchiston (1987)
Macdonnell	Port Macquarie Sydney	1, 2?, 3	Baracchi (1914), Orchiston (2001c)
Martin	Sydney	1, 7	Orchiston and Bhathal (1991)
Merfield	Sydney	1, 3	This paper
Roseby	Sydney	1, 2, 3, 7	Orchiston (1988c); Orchiston, unpublished study
Ross	Melbourne	1, 2?, 3	Orchiston and Brewer (1990)
Severn	Sydney/ Melbourne	1, 3	Orchiston and Bembrick (1995)
Tebbutt	Windsor	1, 2, 3, 5, 7	Bhathal (1993), Orchiston (1988g)
Thomson	Brisbane	1, 2?, 3, 8	Haynes et al. (1993), Page (1959)
Wooster	Ballarat	1, 2, 3, 4, 7	Orchiston, unpublished study

*Key:
1 = Supplier of astronomical information
2 = Offered public viewing nights
3 = Contributed newspaper reports, "Letters to the Editor"
4 = Contributed newspaper columns
5 = Prepared booklets, books, or chapters of books
6 = Manufactured planispheres
7 = Delivered public lectures
8 = Presented astronomy courses

be ignored. Through their activities, an understanding or at least heightened public awareness of astronomy reached many more people than the Government observatories alone could ever have serviced. In this respect, they supplemented the work of these official institutions, but all the while on a voluntary basis and at considerable personal sacrifice in terms of both time and money. In some towns and cities devoid of professional observatories, amateur astronomers ran their own institutions as small-scale de facto city observatories (Orchiston 1989b). Without these individuals, and others who focussed on the popularisation of astronomy through their local news media, the Australian public would have been far less astronomically literate than was indeed the case.

A notable outcome of this substantial amateur involvement in popularisation was the rapid growth in the number of active amateur astronomers during the second half of the nineteenth century (see Ellery 1901). The exponential growth curve that characterised the Sydney-Windsor region is shown in Fig. 25, and is based on data provided by Orchiston (1982a, 1987a, 1988c), Orchiston and Bhathal (1984, 1991) and Russell (1892b). It is likely that similar curves typify other major population centres, although the actual numbers in each case would have been smaller.

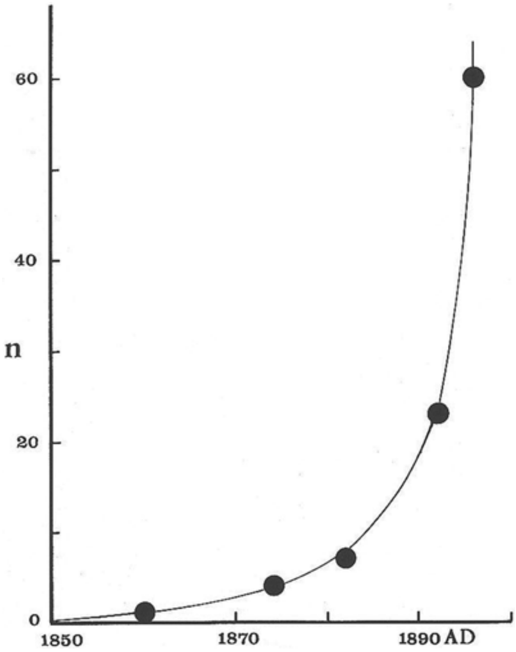


Fig. 25 Growth in the number of active amateur astronomers in the Sydney-Windsor region between 1850 and 1899 (After Orchiston 1991a)

2.1.3 Establishment of Significant Private Observatories

A particularly important feature of nineteenth century and early twentieth century Australian astronomy was the emergence of a network of private observatories across the nation, established by amateur astronomers involved in research (Haynes et al. 1996). Research observatories are listed in Table 5, and in the main were distributed along the eastern seaboard of the nation (Fig. 1), but with a marked concentration in the Sydney region. Their proliferation between 1880 and 1910 is immediately apparent.

Although the emphasis here is on research astronomy, some of the astronomers listed in this table emulated their professional colleagues and adopted a wider charter of operations. Thus, Francis Abbott (Fig. 26; 1799–1883), Ernest H. Beattie (1864–1931), Alfred B. Biggs (1825–1900), Dr William Bone (1836–1885), William J. Macdonnell (1842–1910) and John Tebbutt (Fig. 27; 1834–1916) all maintained local time services, while Abbott, Biggs, Bone and Tebbutt operated meteorological stations. In addition, Biggs was one of Australia's earliest seismologists (*Earth Tremors* 1984), and Tebbutt studied local floods and tides. About half of the astronomers listed in this table were committed to public astronomy.

Table 5 Significant private research observatories, 1850–1910 (After Orchiston 1989b)

Astronomer	Location	Founding decade	Main instruments*	Other references
Abbott	Hobart	1850s	11.4 cm OG	Orchiston (1992, 1997c)
Tebbutt	Windsor	1860s	11.4 cm OG, 20.3 cm OG	Orchiston (1982b, 2004a), White (1979)
Biggs	Launceston	1870s	21.6 cm spec	Orchiston (1985)
Bone	Castlemaine	1870s	20.3 cm OG	Orchiston (1987b, 1997b, c)
Colyer	Sydney	1870s	26.0 cm spec	Baracchi (1914), Haynes et al. (1996)
Macdonnell	Port Macquarie	1870s	15.2 cm OG	Haynes et al. (1996), Orchiston (2001c)
(Dr) Wright	Sydney	1870s	21.6 cm spec	Orchiston and Bhathal (1991)
Davidson	Mackay	1880s	15.2 cm OG	Baracchi (1914), Orchiston (1997b)
Morris	Sydney	1880s	21.6 cm spec	Orchiston (1987a)
Gale	Sydney	1880s	15.2 cm OG, 45.7 cm spec	Orchiston (1988c, 1997b), Orchiston and Bembrick (1995, 1997)
Innes	Sydney	1890s	15.6 cm OG, 41.9 cm spec	Orchiston (2001a, 2003c)
Macdonnell	Sydney	1890s	15.2 cm OG	Haynes et al. (1996), Orchiston (2001c)
Merfield	Sydney	1890s	17.8 cm spec	This paper.
Ross	Melbourne	1890s	30.5 cm spec	Orchiston (1999b), Orchiston and Brewer (1990)
(Mr) Wright	Sydney	1890s	21.6 cm spec	Orchiston (1988c)
Beattie	Sydney	1900s	15.9 cm OG	Orchiston (1997b); unpublished study
Nangle	Sydney	1900s	16.5 cm OG	Baracchi (1914), Orchiston (1997b)

*Key: OG = refractor; spec = reflector

Fig. 26 Francis Abbott of Hobart seated in a doorway, ca. 1860 (Courtesy: Allport Library and Museum of Fine Arts, Tasmanian Archives and Heritage Office)

Fig. 27 John Tebbutt of Windsor (Orchiston Collection)

All of the observatories represented in Table 5 were furnished with instruments that were similar in aperture to or only marginally smaller than those found in the major Australian Government observatories (the Great Melbourne Telescope excepted). Reflectors and refractors were favoured almost equally, and apart from the locally-manufactured reflectors owned by David Ross (1850–1930), Robert Innes (1861–1933) and Charles Merfield (1866–1931), and Walter Gale's (1865–1945) 45.1 cm instrument, all of the reflectors referred to in Table 5 were imported.

Table 6 Types of astronomical research programs most commonly undertaken by the leading Australian amateur observatories, 1850–1910

Transitory events	
	Eclipses of the Moon
	Eclipses of the Sun
	Lunar occultations of planets
	Lunar occultations of stars
	Phenomena of Jupiter's satellites
	Transits of Mercury
	Transits of Venus
Short-term monitoring projects	
	Comets (positions and appearance)
	Meteors (fireballs, and shower activity)
	Minor planets (positions)
	Planets (positions)
Long-term monitoring projects	
	Double stars (separation and position angle)
	Planets (appearance)
	Sun (surface details)
	Variable stars (magnitude variations)
Search programs	
	Coloured stars
	New double stars
	New variable stars (including novae)

Table 7 Publications by Henry Russell of Sydney Observatory and John Tebbutt of Windsor Observatory (After Orchiston 1989b: 20)

	1871–1880		1881–1890		1861–1870		1891–1900		1901–1910		1911–1920	Totals	
Discipline	R*	T	R	T	R	T	R	T	R	T	T	R	T
Astronomy	0	33	36	75	13	134	24	110	3	37	5	73	397
Meteorology	3	18	1	1	22	0	18	1	6	1	1	67	5
Other	0	3	0	0	7	1	3	1	0	0	0	13	2
Total	3	54	37	76	42	135	45	112	9	38	6	153	404

*Key: R = Russell; T = Tebbutt

As Table 6 illustrates, the types of research undertaken also closely mirrored that carried out at the major Government observatories, although the amateurs pursued more catholic Short-term Monitoring Projects and Search Programs.

Of all of the amateurs, Tebbutt was Australia's most prolific publisher of scientific papers (Orchiston 2004a), followed by Abbott, Merfield and Innes. Given the calibre of these and other leading Australian amateur astronomers, we should not underestimate their collective impact on research astronomy in Australia. Their combined publications far surpassed those of their professional colleagues (e.g. see Table 7), and like their Government counterparts they published in the same local and overseas journals. Most popular were *Astronomische Nachrichten*, *Journal of the British Astronomical Association*, *Monthly Notices of the Royal Astronomical Society* and *The Observatory*, all highly-respected international journals. Through the sheer quantity and quality of their publications, amateurs helped to cement Australia's international astronomical reputation.

2.1.4 Emergence of the First Notable Australian-Based Telescope-Makers

During the second half of the nineteenth century the number of amateur astronomers in major and regional population centres around the nation grew, and so too did the demand for telescopes. But astronomy would prove an expensive hobby for anyone contemplating serious telescopic work. Refracting telescopes by Cooke (Andrews 1992), Grubb (Andrews 1993) and Wray were preferred, but these precision instruments were highly priced and had to be imported from England. Quality British reflectors by Calver (Dall 1975) or With-Browning (Marriott 1996), equally desirable, also were beyond the price-range of most Australian amateur astronomers.

The only option for those without sufficient financial means was to manufacture their own reflecting telescopes or purchase locally-made ones, and this became a realistic proposition with the advent of the silver-on-glass reflector (see Tobin 1987). In Sydney, Government Astronomer of New South Wales, Henry Russell, was one of those who experimented successfully with telescope-making during the 1870s, and soon inspired some local amateur astronomers to follow his lead (Orchiston and Bembrick 1995). Their combined activities launched a local Australian telescope-making tradition that has continued through to the present day (see Orchiston 2003a).

During the last two decades of the nineteenth century many reflecting telescopes were produced by Australian amateur astronomers, and while most of these instruments were of modest aperture (typically in the 15–20 cm range), a number of amateurs succeeded in grinding, polishing and figuring much larger mirrors. The leading pioneers were F.D. Edmonds, Gale and Hans Madsen (1843–1937) in Sydney, Ross and Robert Wigmore (1856–1947) in Melbourne, and Alfred Dobbie (1843–1912) in Adelaide (Madsen 1886; Orchiston and Bembrick 1995), all of whom completed mirrors in the 30–46 cm range (e.g. see Fig. 28), but the doyen of Australian telescope-makers at this time was surely Henry Evans Baker (1816–1890) of Ballarat (Burk 1986; Davis 1990). In 1888 he completed the 66 cm reflector shown in Fig. 29, and for more than a century the "Leviathan of Ballarat' as it was popularly known held the record as the largest telescope in the state of Victoria!

It is interesting to note that most of these early large instruments were committed to the popularization of astronomy; only Ross (Fig. 30) and Gale (Fig. 31) employed their telescopes for serious observational programs (Orchiston and Brewer 1990), and although Innes did discover some new double stars with the 41.9 cm reflector made for him by Edmonds, he preferred to use a 15.9 cm refractor for his searches (see Innes 1895j).

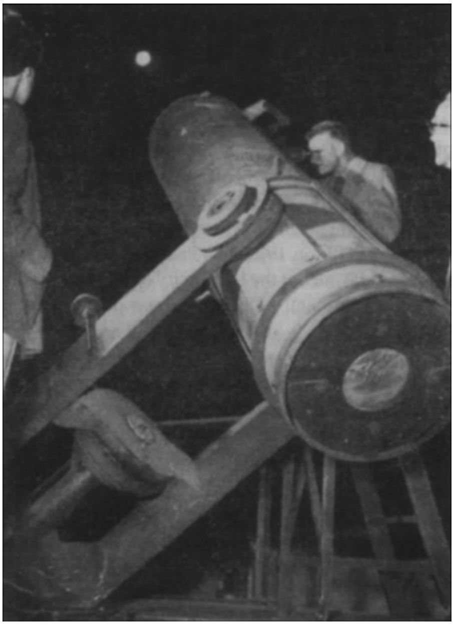


Fig. 28 The 46 cm reflector made by Robert Wigmore (After Journal of the Astronomical Society of Victoria 1959)

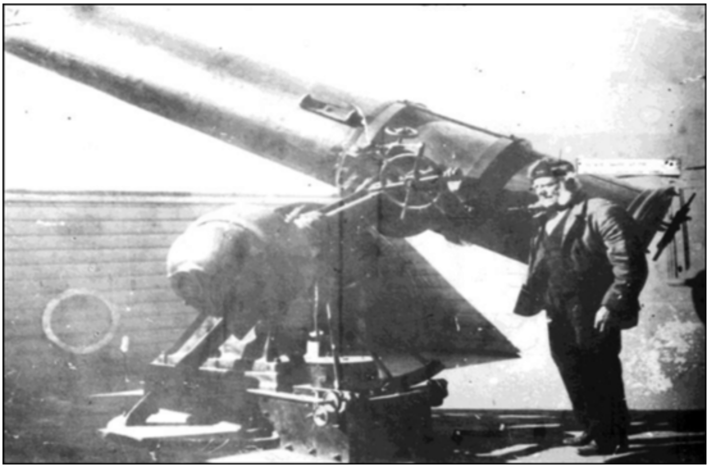


Fig. 29 The 66 cm reflector made by Henry Baker in 1888 (Orchiston Collection)

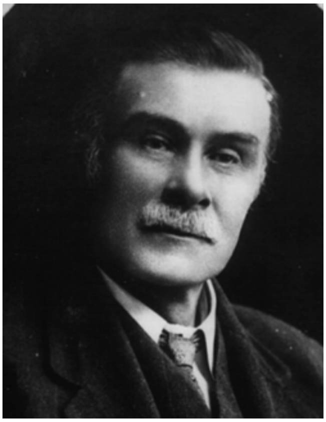


Fig. 30 David Ross, pioneer telescope-maker and astrophotographer (Orchiston Collection)

Fig. 31 A cartoon of Walter Gale, pioneer telescope-maker, founder of astronomical societies and veteran Mars observer (Orchiston Collection)

2.1.5 Formation of Astronomical Groups and Societies

The formation of organised groups and societies is a critical element in the evolution of any discipline, and in nineteenth century Australian astronomy this was important, given the vast geographical distances involved, physical isolation from the main international centres of astronomical research, and relatively small number of astronomers. Australia's earliest astronomical groups and societies are listed in Table 8, and amateurs and professionals both played key roles in their formation and operation (see Orchiston 1998a).

In addition to these groups, in 1892 Gale and Innes spent considerable time and energy planning the formation of the Australian Astronomical Society, but in the end they decided not to proceed with this (Orchiston and Bhathal 1984). If they had chosen otherwise and this initiative had proved a success then Australia would have gained its first national generalist astronomical society, which could take its rightful place in Table 7.

The Sydney and Melbourne Observatory Directors, Henry Russell and Robert Ellery, were the driving forces behind the short-lived Astronomy Sections of the Royal Societies of New South Wales and Victoria, respectively, but amateur astronomers operating alone or in collaboration with professionals were involved in the formation of all of the other groups listed in Table 8 (Ellery 1901; Baracchi 1914). While amateur astronomers also were responsible for forming the Astronomical Section of the Royal Society of South Australia and the Victoria Branch of the British Astronomical Association, it was not long before professional astronomers from the Adelaide and Melbourne Observatories respectively were playing important roles in these two groups (see Orchiston 1998a; Orchiston and Perdrix 1990, 2002).

As we can see from Table 8, it was only in the 1890s that Australia's first enduring astronomical groups were formed. These were generalist in focus in that they dealt with all aspects of astronomy (unlike Tebbutt's earlier, short-lived, specialist Comet Corps), and they focussed on localised rather than national audiences. By this time, Australian astronomy had evolved to the stage where a number of cities could sustain their own astronomical groups: there were adequate numbers of active amateur astronomers present; support from both amateurs and professionals was forthcoming; and there were prominent astronomers who could act as ideal role models and were willing to provide the required leadership.

With the possible exception of the Brisbane Astronomical Society, all of the groups listed in Table 8 played an important role in formalising astronomy in

Table 8 Australia's earliest formal astronomical groups and societies

Duration	Founder(s)*	Name of group	References
1876–1881	Russell (p)	Royal Society of New South Wales, Section A	Orchiston and Bhathal (1991)
1879–?	Ellery (p)	Royal Society of Victoria, Astronomy Section	Orchiston (1998a)
1882–1883	Tebbutt (a)	Australian Comet Corps	Orchiston (1982a, 1998a)
1892	Farr (a)	Royal Society of South Australia, Astronomy Section	Waters (1980)
1895–1995	Gale (a) & Innes (a)	British Astronomical Association, New South Wales Branch	Orchiston (1988c), Orchiston and Perdrix (1990, 2002)
1895–1901.1	76 (a)	Brisbane Astronomical Society	Orchiston (1998a)
1897–1907	Ross (a) & Wigmore (a)	British Astronomical Association, Victoria Branch	Orchiston and Perdrix (1990, 2002)
1912–1928	Curlewis (p) & Hilton (a)	Astronomical Society of Western Australia	WA Astronomical Society (1914)

* Key: p = professional astronomer; a = amateur astronomer

Australia. They gave newcomers a structured way of easing themselves into astronomy, and provided all members with regular meetings, library facilities, and avenues for publication. They also encouraging members to participate in observational programs. These groups served to reinforce the close relations that for the most part existed between the nation's amateur and professional astronomers (for further details see Orchiston 1998a).

2.2 *The Impact of the Leading Amateurs on Nineteenth Century Australian Astronomy*

Elsewhere (Orchiston 1989b) I have suggested that Windsor's John Tebbutt (Fig. 27) was Australia's leading amateur astronomer, with Francis Abbott (Fig. 26) of Hobart coming in second, based on the quality and quantity of his publications, followed by the subjects of this paper, C.J. Merfield (Fig. 32) and R.T.A. Innes (Fig. 33). All four astronomers, together with Beattie and James Nangle (Fig. 34; 1868–1941), were of professional standard in both intellect and mathematical prowess. In this regard, it

Fig. 32 Charles Merfield (Courtesy: Royal Astronomical Society)

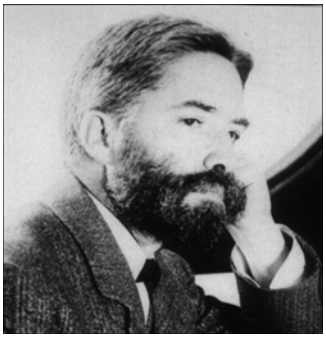


Fig. 33 Robert Innes (Courtesy: National Research Foundation/South African Astronomical Observatory)

Fig. 34 James Nangle (Collection: Powerhouse Museum, Sydney)

is illuminating that with the passage of time Merfield, Innes and Nangle all became professional astronomers, while Tebbutt was offered this option but declined (see Orchiston 1988e, 1998c). Meanwhile, following the close-down of the geomagnetic and meteorological Rossbank Observatory (see Savours and McConnell 1982), for more than twenty-five years Abbott ran his own observatory as Tasmania's de facto 'Government observatory', performing all of the functions expected of a professional colonial observatory. Because Abbott was so successful, the colony only felt obliged to establish an actual Government observatory, in Hobart, when increasing age forced Abbott close down his observatory (see Meteorological Department 1900; Orchiston 1992).

In some instances, amateur astronomers were responsible for the actual founding of Government observatories. Sydney Observatory (Fig. 35) resulted from the untiring efforts of Phillip Parker King (see Orchiston 1988f), while Robert Ellery agitated successfully for a colonial observatory in Melbourne (Andropoulos 2014), and was rewarded when the Government formed the Williamstown Observatory (Fig. 2) and subsequently appointed his as its Director. In addition, lobbying, by groups of amateur astronomers in both Brisbane and Hobart eventually led to the establishment of small government observatories in these cities.

Amateur astronomy then provided a recruiting ground, albeit a limited one, for professional astronomy. Ellery (Fig. 10) and White (Fig. 11) of Melbourne Observatory made the transition early without having established international reputations as amateur astronomers but this was not so of Innes and Merfield (Baracchi 1914), as we shall see in this paper.

However, most Australian amateur astronomers never graduated to professional ranks. Yet many were able to offer invaluable assistance to their Government observatory colleagues by providing much-needed observations (in both astronomy and meteorology), and by serving as willing collaborators when manpower was required for transit of Mercury, transit of Venus and solar eclipse expeditions. For example, some of those manning the country stations established by the Sydney Observatory for the 1874 transit of Venus were prominent amateur astronomers (see Fig. 36; Russell 1892b; Orchiston 2004b).

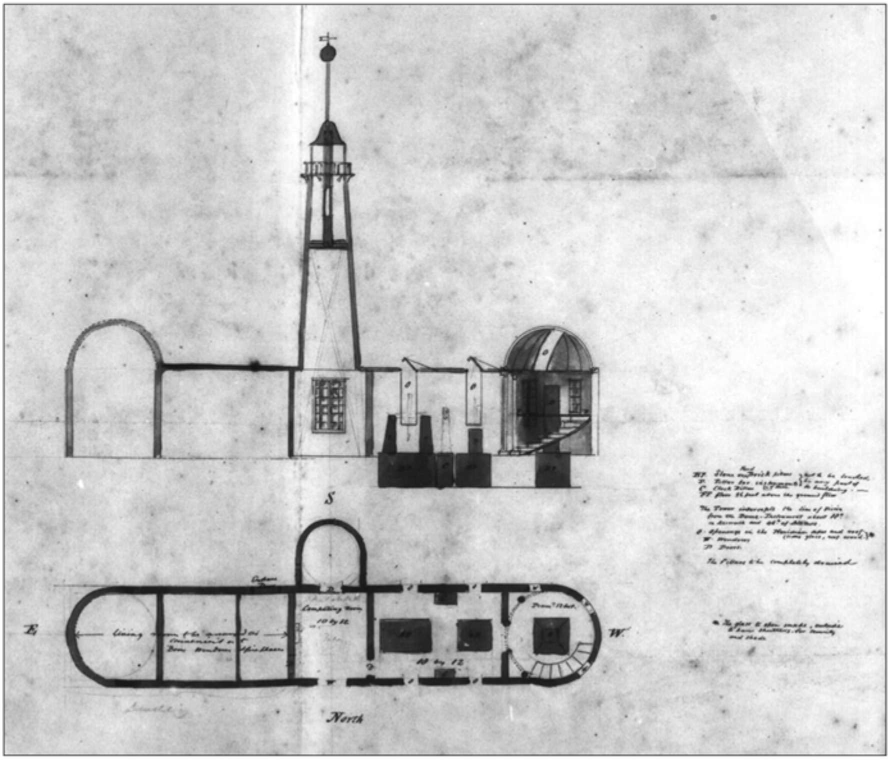


Fig. 35 One of the designs for Sydney Observatory proposed by P.P. King in December 1853 (Courtesy: State Records NSW)

Occasionally amateurs also were able to contribute to professional astronomy by serving as sources of instruments. Thus, when Captain Henry O'Reilly died in Brisbane in 1879, the Queensland Government purchased his observatory in toto and used it as a basis for a new colonial observatory (Fig. 7; see Haynes et al. 1993). Similarly, in 1910 James Oddie (1824–1911) gifted his 23 cm Grubb refractor (Fig. 37) to the Commonwealth, and after being used for site testing it became the founding instrument of the Commonwealth Solar Observatory at Mount Stromlo, near the national capital, Canberra (Allen 1987; Baracchi 1914; Morris-Kennedy 1989).

At times, professional astronomers also relied on amateur instruments for the success of their research programs. For instance, one of the telescopes used by the Woodford transit of Venus observing team in 1874 was a fine 12.9 cm Schroeder refractor provided by Alfred Fairfax (see Fig. 36), on whose property the party was stationed (Orchiston 2004b), while the team based at the Sydney Observatory had the use of J.C.U. Colyer's 26 cm reflector (Russell 1892b).

As a group, Australian amateur astronomers also had a political role to play. Late in the nineteenth century they became a force to be reckoned with as watchdog bodies over Government support for professional astronomy, and the activities of the

Fig. 36 Participants in the Sydney Observatory 1874 transit of Venus program. Fairfax, Hirst, Macdonnell and Wright all were prominent amateur astronomers (After Russell 1892b)

professional observatories themselves. During the 1880s, Russell increasingly turned the focus of Sydney Observatory away from astronomy towards meteorology, and in so doing estranged himself from many in the powerful Sydney astronomical fraternity, much to the consternation of some of his own staff (e.g. see Orchiston 1987a). Matters only came to a head when Tebbutt intervened and made this a public issue (Orchiston 2002).

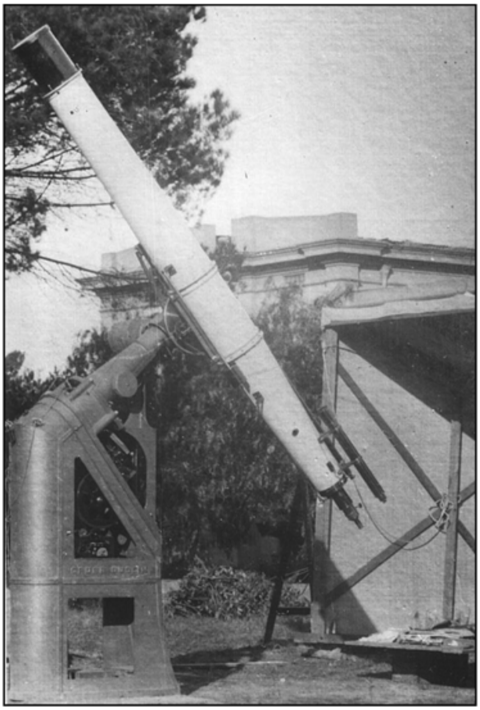


Fig. 37 The 23 cm 'Oddie Refractor' at Melbourne Observatory prior to its transfer to Mount Stromlo for site testing (Orchiston Collection)

As we have seen in the section on "Fundamental Elements", amateur astronomers also played a major part in establishing and reinforcing Australia's reputation in research astronomy, and in bringing astronomy to the public, thus complementing the activities of their professional colleagues. Australian amateur astronomers also were responsible for forming and running the nation's earliest astronomical groups and societies, while other amateurs contributed to astronomy by providing some of their colleagues with access to affordable telescopes that were used for educational activities and for serious observational programs.

Because of the numerical strength and the prodigious publications output of the Australian amateur astronomy fraternity during the late nineteenth century, and Tebbutt's anomalous position as the nation's foremost astronomer, the distinctions between Australian professional astronomers and serious amateurs were blurred. Until Melbourne, Perth and Sydney Observatories became involved in the International Astrographic Project, the nation's serious amateurs carried out much the same range of observations as their professional counterparts, with instruments of similar size and precision; published similar papers, in the same journals; joined the same scientific societies; served on the same committees; vied for the same prizes and awards; and used the very same tactics to promote a popular interest in their chosen discipline. In general, the intellectual and academic backgrounds of the two groups were not dissimilar and transfer from amateur to professional ranks was sometimes possible—as Innes and Merfield would demonstrate.

Mobility along the amateur-professional continuum was possible in late nineteenth century Australia because the forces that emerged to separate amateur and professional astronomers once and for all in other parts of the world between 1880 and 1920 simply by-passed Australia altogether at this time. The professional penchant for giant refractors (with apertures >50 cm) was nowhere apparent, and the widely-held view that reflectors were simply 'playthings' of the amateur never took hold. To the contrary, nineteenth century Australian professional astronomers had a certain (uncharacteristic) fondness for mirrors, and at a time of giant refractor domination worldwide, Australia remained one of the few professional bastions of the beleaguered reflector.

The other prime reason for the rapid separation of amateur and professional astronomers elsewhere was the emergence of astrophysics, involving advanced training in mathematics and physics, access to elaborate instrumentation and research funding, and subject specialization. No longer could a professional astronomer afford to be a generalist. As Orchiston et al. (2015) recount, Baracchi, Ellery, le Sueur and Russell all had fleeting spectroscopic escapades, but their exploits were matched in part by the Launceston amateur astronomer, A.B. Biggs (Fig. 38; see Biggs 1884a, b). Meanwhile, a few years earlier, Hobart's Francis Abbott (Fig. 26) had published three popular booklets on astronomy (Abbott 1878, 1879, 1880), and the first two contained a great deal of useful material on astronomical spectroscopy (see Orchiston 1992).

The only major international trend to impact on Australian professional astronomy towards the end of the nineteenth century was the International Astrographic Project (see Fig. 16; Turner 1912), but this did not lead to immediate obvious differences between the nation's amateur and professional astronomers for the Government observatories also continued their non-astrographic work, while a number of amateurs experimented successfully with astrophotography. The most notable of these were David Ross (Fig. 30) of Melbourne (Orchiston and Brewer 1990) and Sydney's Walter Gale (Fig. 31; Reports of the Branches 1895). Amateur-professional communication was preserved, notwithstanding this innovation.

Fig. 38 Alfred Barratt Biggs, who experimented with astronomical spectroscopy during the 1880s (Orchiston Collection)

Thus, in Australia amateur-professional co-operation and collaboration continued because the forces that emerged to separate the two classes of astronomers in the United Kingdom and the USA between 1880 and 1920 (e.g. see Hetherington 1976; Lankford 1979, 1981a, b; and Rothenberg 1981) simply by-passed Australia altogether at this time. They only surfaced after World War II (Orchiston 1989a), with the emergence of non-solar astronomy at Mt Stromlo Observatory (Frame and Faulkner 2003; Gascoigne 1984; Hyland and Faulkner 1989; Orchiston 1989a) and the phenomenal growth of radio astronomy in Sydney (see Haynes et al. 1996; Robertson 1992; Orchiston and Slee 2005).

3 The ATP Syndrome: The Case of R.T.A. Innes[2]

3.1 Robert Thorburn Ayton Innes: A Brief Biographical Sketch

Robert Thorburn Ayton Innes (Fig. 33) was born in Edinburgh on 10 November 1861, and went to school in Dublin. He acquired an early interest in astronomy (Obituary 1933), and showed such aptitude for mathematical astronomy that he was elected a Fellow of the Royal Astronomical Society at the age of 17 years and 2 months (Obituaries 1934).

Later he began observing double and variable stars, and this combination of observational and mathematical attributes particularly impressed his future employer, Sir David Gill (1843–1914; Fig. 39), the Director of the Royal Observatory at the Cape of Good Hope:

> Thus at the Cape Observatory, as has always been the case elsewhere, the subject of double star measurement on any great scale waited for the proper man to undertake it … It is a special faculty, an inborn capacity, a delight in the exercise of exceptional acuteness of eyesight and natural dexterity, coupled with the gift of imagination as to the true meaning of what he observes, that imparts to the observer the requisite enthusiasm for double star observing. No amount of training or direction could have created the Struves, a Dawes, a Dembowski or a Burnham. The great double star observer is born, not made, and I believe that no extensive series of double star discovery and measurement will ever emanate from a regular observatory through successive directorates, unless men are specially selected who have previously distinguished themselves in that field of work and who were originally driven to it from sheer compulsion of inborn taste. (Gill 1905: preface)

Gill (ibid.) identified Innes as just such a man.

Throughout his life, Innes was known for his unconventional views, and "… his unaffected manner of expressing them made Innes a charming companion in daily life …" (Obituaries 1933). Young astronomers and their wives were always welcome at his house, particularly during his later years (Obituaries 1934). A letter Innes wrote to John Tebbutt in 1895 about an incorrect report which appeared in a

[2] This section draws on material in Orchiston 2001a and 2003c.

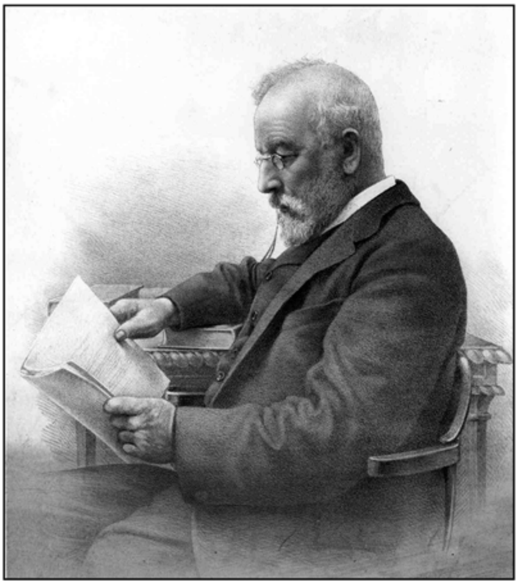


Fig. 39 Sir David Gill, Director of the Royal Observatory, Cape of Good Hope (Courtesy: Royal Astronomical Society)

Sydney newspaper reveals something of this sense of sociability and his wonderful way with words: "Whilst the Reporter was in my cellar we found a severe local drought and irrigated accordingly and I fear between the wine, astronomy & meteorology the poor reporter got mixed up." (Innes 1895i).

Innes

> … was an extreme individualist, who did not yield an inch once he had made a decision or taken a stand … Once he decided never to wear a tie again, the Transvaal heat being what it was. Thereafter he wore open-necked shirts, and was even presented at the Dutch court wearing tails—without a tie. (Scientiae 1968)

He also possessed strong socialist views, and while living in Sydney participated in party politics (Merfield 1895a). At one time Tebbutt made some comment about anarchy in one of his letters, and Innes (1894c) was summarily dismissive of this concept.

Innes married young, and if we are to believe the author of Obituaries (1934)

> … his marriage was a model of simple domestic happiness. The delight with which he and Mrs Innes watched the development of their [three] boys when they were growing up, and later their success in life, the atmosphere of quiet love and happiness that they created around them, made their house the ideal home, to which friends often came …

However, this idyllic picture masks the true nature of Innes' affections for when he moved to South Africa in 1896 he and his sons were accompanied by his mistress, his wife having previously been bundled off to an asylum. Later she was released and joined him in Cape Town, where they apparently all lived in harmony (see Vermeulen 2006).

On 13 March 1933, while he was visiting London on a visit, Robert Innes died suddenly from a heart attack. He was survived by his wife and his three sons (Obituaries 1934).

3.2 The Sydney Sojourn: Escapades on Observational Astronomy

On 29 August 1890 Robert Innes and his wife sailed from Scotland for Australia (Innes 1890a), and they settled in Sydney where he established a business as a wine and spirit merchant, a venture that would ultimately prove to be very successful. Once in Sydney, Innes was keen to reactivate his astronomical interests, and he already was aware of the astronomical work being carried out at the New South Wales Government's Sydney Observatory and at the private observatory of Australia's foremost astronomer, John Tebbutt, of nearby Windsor. Innes (1890b) came armed with a letter from W.H. Wesley (1841–1922), Secretary of the Royal Astronomical Society, to Sydney Observatory Director, Henry Russell.

After meeting Russell (Innes 1890c) Innes contacted John Tebbutt (Innes 1890d), and just two days later he wrote again (Innes 1890e), asking to meet him. Then one week later he wrote yet again, offering to help Tebbutt with the reduction of his observations (Innes 1890f).

Early in January 1891 Innes (1891b) visited Windsor Observatory (Fig. 40) for the first time, and reported on what proved to be a thoroughly enjoyable outing in *The Observatory* (Innes 1891g). This indicates that Innes was most impressed:

> In a country where astronomy is but little thought of, it is pleasing to come across such a bright exception as Mr. Tebbutt … who truly loves astronomy for its own sake, and who has pursued it with unflagging devotion for now nigh on 30 years, and, as he modestly remarks, "doubtless with some service to the cause of Astronomy."
>
> The long list of contributions to the pages of *The Observatory*, *Monthly Notices* … and *Astronomische Nachrichten* testify to this latter fact. We may remark, too, that not only has he equipped and kept up the observatory, at his own expense, but he has also made all the observations and himself computed nearly all the reductions; and this, for an unbroken period of over a quarter of a century, and so far distant from those taking an interest in his pursuits that it creates, as he plaintively remarked, a feeling of isolation …

Fig. 40 The general appearance of Windsor Observatory at the time of Innes' visit (Courtesy: Royal Astronomical Society)

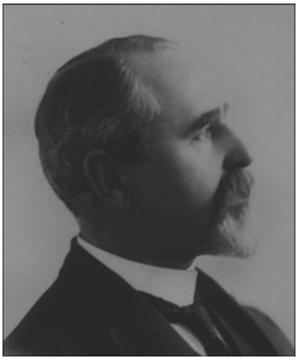


Fig. 41 Walter Gale (Courtesy: British Astronomical Association)

> The amount of work accomplished by Mr. Tebbutt shows what private observers can do if their enthusiasm is tempered with system. (ibid.).

Not long before he visited Windsor Observatory, Innes (1891a) wrote to Wesley that "There are but few people here interested in Astronomy." But he gained a more realistic perspective four months later after attending a meeting of the Royal Society of New South Wales and meeting some of the local astronomical fraternity (Innes 1891c). He also became aware of the strained relations that existed between Russell and Tebbutt, which by this time had led to the estrangement of the Observatory from the local amateur astronomical community (e.g. see Orchiston 2002).

One of these whom Innes met at the Royal Society of New South Wales meeting was Walter Gale (Fig. 41), and the two struck up an instant friendship. Born in Sydney on 27 November 1865, Gale was just four years Innes' junior. After completing his schooling, Gale worked for five years in the insurance and commercial fields before joining the Savings Bank of New South Wales in 1888, and he remained with the Bank until 1925, rising ultimately to the position of Manager and Chief Inspector at Head Office (Wood 1981). Gale had inherited an early interest in astronomy from his father, but it was the Great Comet of 1882 (C/1882 R1) (Fig. 42) which launched his life-long commitment to astronomy (Sun 1943).

In 1884 Gale made a 17.8 cm reflecting telescope (Gale 1928), which was destined to be the first of many (Wood 1981); the largest had an aperture of 30.5 cm (Obituary 1945). Gale was later to reminisce about "… how I had to strive for ten years of the best part of my young manhood to equip myself with a decent telescope, after "messing about" with mirrors of my own grinding mounted on "bits of board"." (Gale 1928). Later he would become one of Australia's leading 'telescope-brokers' and reputedly "… knew the history and characteristics of every astronomical instrument in Australia, and could tell many anecdotes relating to them." (Obituary 1945). Over the years many telescopes passed through his hands (e.g. see Orchiston 1991b, 1997b), and these included the ex-Tebbutt 20.3 cm refractor (Orchiston 1982b; Orchiston and Bembrick 1997) and two different 45.7 cm reflectors (Orchiston and Bembrick 1995) and a 50.8 cm Grubb reflector (Fig. 43; see Orchiston 2010).

Fig. 42 Photograph of the Great Comet of 1882 taken at the Cape Observatory (Courtesy: National Research Foundation/South African Astronomical Observatory)

Fig. 43 The 50.8 cm Grubb reflector, colloquially known as the 'Catts Telescope', which at one time was owned by Walter Gale (Orchiston Collection)

Gale also was interested in observational astronomy and took part in several solar eclipse expeditions (Obituary 1945). He also enjoyed comet-searching and independently discovered seven different comets, three of which (C/1894 G1, C/1912 R1 and 34P/Gale) now bear his name (Wood 1946). He also used his telescopes to study the planets, but particularly Mars, Jupiter and Saturn (Wood 1981), and he believed that the 'canals' of Mars were genuine naturally-occurring surface features and that the planet "… may be inhabited by a race of sentient beings, perhaps not cast in the same mould as we are, but of a type suited to the conditions of the planet …" (Gale 1921). Gale also discovered a number of double stars and a planetary nebula (Wood 1981), and he experimented successfully with astronomical photography (Obituary 1945).

For twenty-eight years Gale was on the Board of Visitors of the Sydney Observatory (Wood 1946), and in 1935 he was awarded the Jackson-Gwilt Medal and Gift by the Royal Astronomical Society for "… his discoveries of comets and his work for astronomy in New South Wales." (Wood 1981), thus emulating Tebbutt (who was the third recipient of the Medal and Gift). Gale's long and productive life finally came to a sudden end on 1 June 1945 when he suffered a heart attack (Wood 1981), and he was remembered by his many friends for his "… personal qualities of helpfulness, enthusiasm, kindness, tolerance and understanding …" (Obituary 1945). These were qualities that Innes valued so much.

After settling in Sydney, lnnes began to immerse himself in mathematical astronomy, and soon he produced a paper on the secular perturbations of the Earth by Mars which was published late in 1891 (see Innes 1891f). In November 1891 he and Gale arranged a visit Tebbutt at Windsor Observatory, and both men were impressed. In thanking Tebbutt for his hospitality Innes (1891d) specifically mentions that "… the little lesson I had in practical astronomy will serve to complement my bookish theoric." Obviously this visit inspired Innes to contemplate doing some observational astronomy, for less than two weeks later he wrote Tebbutt that he was planning to obtain a 21.6 cm altazimuth-mounted reflector through Gale, although he would only use it "… for amusement as I prefer computation and analysis." (Innes 1891e). However, earlier in the year Innes (1891g) had remarked on the "… intense purity …" of the Australian skies, and soon they were to seduce him and convert him into an observational astronomer.

It is not clear whether Innes actually acquired the afore-mentioned reflector from Gale or someone else, but by May 1892 he was busy using the telescope to learn the constellations (Innes 1892b), and soon was using it for comet-sweeping (Innes 1892c). He also reported observing a meteor shower (Innes 1892d). This was quite a transition for someone previously committed solely to mathematical astronomy, but Innes did not abandon this prior interest for he published a follow-up note to his earlier paper on secular perturbations (see Innes 1892g), and he also decided to try his hand at computing the orbital elements of a comet (Innes 1892e). However, Innes (1892f) would later admit that his first attempt was unsuccessful. In November and December he returned to observational astronomy and tracked periodic Comet 17P/Holmes, which was known colloquially at the time as 'Biela's Comet' or the 'Andromeda Comet' (Innes 1892a).

The foregoing review shows that within a year of visiting Windsor Observatory and meeting Tebbutt. Innes had gained a great deal of practical experience in observational astronomy. As future developments would later reveal, it was this new orientation that would play a critical role in his eventual transition from the ranks of the amateur astronomer to the professional.

In addition to his observational astronomy, during 1892 Innes teamed up with Gale in planning the formation of the nation's first generalist formal astronomical group—which they named the Australian Astronomical Society—but eventually they decided not to proceed (see Orchiston and Bhathal 1984). Had this abortive initiative succeeded then Australia would have gained its second national astronomical society, following in the footsteps of Tebbutt's short-lived Australian Comet Corps which was formed in 1882 (see Orchiston 1982a, 1998a).

While little is heard of Innes' observational activities in 1893, he did prepare a further paper on secular perturbations of the Earth, and this was published in the *Monthly Notices of the Royal Astronomical Society* (Innes 1893d). This also was the year when Innes had a philosophical difference of opinion with Tebbutt: Innes (1893a) wanted to put Gale up for membership of the Royal Astronomical Society and asked Tebbutt to support the application but Tebbutt refused. Tebbutt believed that a FRAS should be reserved for someone who had *already made* a contribution to astronomy (whether by observational work or mathematical investigations), and he judged that Gale had yet to achieve this. Innes (1893c) begged to differ and was not afraid to debate the issue with Tebbutt: he thought Tebbutt's view was too myopic, and he saw the Royal Astronomical Society as a group of men interested in astronomy who collectively *wished to advance the science, although many of them did not end up doing so individually*. On these grounds he was certain that Gale was a suitable candidate, and so he proceeded with the nomination (Innes 1893b), which was duly accepted.

In 1894 Innes (1894j) published a further mathematical paper, but Gale's discovery of a new comet on 1 April provided an excellent opportunity for him to combine his observational and mathematical interests. Consequently, four day later he wrote to Tebbutt and asked him for positional observations so that he could attempt an orbital computation (Innes 1894d). Innes' elements were eventually published in *Astronomische Nachrichten* (Innes 1894a), and on 20 April he was pleased to advise Tebbutt that they were similar to those computed by Baracchi (Fig. 12) at Melbourne Observatory (Innes 1894e). Despite his abortive start in 1892, in the interim Innes obviously had mastered these complex calculations.

Late in 1894 Innes and Gale succeeded in forming the New South Wales Branch of the British Astronomical Association (Orchiston and Perdrix 1990), less than five years after the establishment of the parent body in London (see Kelly 1948; McKim 1990). As I have documented elsewhere (Orchiston 1988c, 1998a), during its early years the new Branch was to prove a cohesive force for the large, vibrant amateur astronomical community in Sydney, but only later—following Russell's retirement—were professional astronomers from Sydney Observatory able to become active within its ranks. At the inaugural meeting of the Branch Innes was elected Vice-President, Gale Secretary and Tebbutt President.

Towards the end of 1894 Innes also immersed himself in observational astronomy once more, this time with a refractor loaned to him for two months by Gale. This

> … had a 6¼-inch object glass, made by T. Cooke, York, in 1851, and was mounted on a rough equatorial without circles. The eyepiece used gave a power of about 360. (Innes 1895p)

Although it had a crude mounting and lacked a drive (see Innes 1895b), Innes used this historic refractor to systematically search for new double stars during October–November 1894. He also prepared a newspaper report on a transit of Mercury (Innes 1894b, f) and observed an occultation of Antares (Innes 1895q). In his letter to the Royal Astronomical Society that accompanied the occultation paper, Innes expressed concern about the fact that he saw the companion of Antares at the time whereas Tebbutt apparently did not (see Tebbutt 1894b), and included the following P.S.: "l hope it wont be thought that I am trying to discredit Mr Tebbutt's observation but the best of us are caught napping now & then." (Innes 1895b). These observations reveal Innes' visual acuity, for Tebbutt was known internationally as an experienced and careful observer.

In December 1894 Innes wrote Tebbutt that he was busy preparing a 'working catalogue' of southern double stars (Innes 1894h; i). Eventually this was published in the *Monthly Notices of the Royal Astronomical Society* (Innes 1895p), and upon examination proved to be a little research paper listing details of 26 different double stars that Innes had 'discovered' in the course of about 30 hours of systematic searching. But an addendum at the end of the paper reveals that shortly after submitting the manuscript Innes learnt that three of these stars had previously been observed by others, and fellow BAA Branch member Hugh Wright (1868–1957) then pointed out that a further 'discovery' had in fact been noted as a double by astronomers at the Cordoba Observatory back in 1875 (see Innes 1896b).

As a result of these discoveries, Innes became embroiled in local astronomical politics when R.P. Sellors at Sydney Observatory privately informed him that the Director, Henry Russell, would not allow him to measure any of Innes' new double stars (Innes 1895d). An enraged Innes complained to Russell, who several months later had a change of heart, leaving Sellors free to make the observations (Innes 1895f). Soon after settling in Sydney Innes had become aware of the tension that existed between Russell and Tebbutt (see Orchiston 2002), and had realised that if he wished to pursue astronomy, even as an amateur, it would be almost impossible for him to remain neutral. Clearly he had great admiration for Tebbutt—despite their occasional differences—and consequently this made for strained relations with Russell.

As it turned out, the two months when he had access to Gale's old refractor were a turning point for Innes, as he recognised that observational astronomy could sit comfortably alongside his earlier interest in mathematical astronomy. Moreover, he had discovered his observational *forté* in the form of double stars, and had even prepared a research paper on them for a leading international astronomical journal. It was during this critical period that Innes (1894g) also began thinking about abandoning his successful career in the wine and spirits trade and becoming a professional astronomer.

Innes also realised that if he wished to continue his observational astronomy then he needed a telescope of his own, so he commissioned one of his Sydney amateur astronomy colleagues, F.D. Edmonds, to construct a 42 cm reflector for him (Innes 1896b). On 21 January 1895 Innes proudly told Tebbutt that: "l got the 16½-inch telescope to work … but unsilvered & not finally corrected …" (Innes 1895a). Thereafter, it did not take long to make the telescope fully operational (Innes 1895c), and after the 46 cm reflectors owned by Gale and Madsen (see Orchiston and Bembrick 1995) this was the third-largest telescope in Sydney.

Armed with the increased light-grasp that it offered, Innes (1895e) then began searching for new double stars, and in 1896 published a list of 16 new discoveries made with this telescope (Innes 1896b). An additional discovery was made with this telescope the following year (Innes 1897), bringing the total number of new double stars Innes detected while in Sydney to 39. Years later James Nangle (1936) commented: "Many of us … remember the enthusiasm with which he [Innes] carried on his double star observations and we also remember our delight when he discovered new pairs." Originally Nangle (Fig. 32) was a leading amateur astronomer in Sydney, but later he was appointed Government Astronomer of New South Wales, yet another Australian example of an ATP.

Innes also used the new reflecting telescope for other observations. On 16 October 1895 he discovered a 9th magnitude nebula measuring about 3 by 5 seconds of arc in size, which "… looks like a double star a little out of focus." (Innes 1896a), and in the paper reporting this discovery he also described three nebulae recorded by Schmidt in Corona Australis and confirmed the variability of a star embedded in one of them on the basis of six observations that he made between 7 October and 16 November.

But this was not the only observational astronomy undertaken by Innes in 1895. Between 8 January and 29 April he made 50 naked eye observations of the well-known variable star I Carinae, and also published these in the aforementioned Innes 1896a research paper. First he presented a light curve, then he used his own observations and those made earlier by other astronomers to investigate the magnitude range and the period (*P*). He derived a value for *P* of 35.506 days, which is remarkably close to the currently-accepted value of 35.5225 days (Rowlands 1984). This was a significant improvement on the earlier values published by Gould and by Roberts.

Innes (1896a) also spent the first seven months of 1895 observing the bright red variable, N Velorum. He found that it varied between 3.2 and 3.8, but could not detect any period: "l regret I cannot trace any semblance of a period in this star's changes. That it does vary is undoubted, but it is very irregular." (ibid.). In this same paper Innes also included seven observations of a suspected variable, q Carinae, made between 8 January and 2 July. The magnitude estimates ranged between 3.3 and 3.8, confirming that the star was indeed a variable.

Early in 1895 Innes also began an ambitious library-based project: to compile "… a very considerable catalogue of binaries from observations in the southern hemisphere with many original measures by Mr. Gale and himself, and a paper thereon."

(Double Star Section 1895; cf. Innes 1895g). When he finished this paper Innes forwarded it to the *Journal of British Astronomical Association*, and must have been disappointed when the manuscript was returned to him. The problem was not the usefulness of the catalogue or the scholarship involved; it was simply too expensive for the Association to publish (see Double Star Section 1895; Merfield 1895b). Innes then thought about whether the newly-formed New South Wales Branch of the Association could publish it (Innes 1895h), but other more pressing matters intervened and he decided not to pursue this option. However, in the long run all his efforts would not prove to be in vain, for his catalogue would eventually get published, but through connections which at that time were only starting to enter his imagination. Meanwhile, as some small consolation, late in 1895 he prepared a research note on the proper motion of the known double star Lacaille 4336, and eventually this was published in *Monthly Notices of the Royal Astronomical Society* (lnnes 1895r).

Notwithstanding his success in detecting new double stars, Innes found the large altazimuth-mounted reflector difficult to use for systematic observations and he actually preferred to use the much smaller refracting telescope loaned him earlier by Gale! So eventually he decided to sell the amateur-made reflector and replace it with an professionally-made equatorially-mounted refractor. At this time the well-known amateur astronomer, W.J. Macdonnell (Orchiston 2001c), wished to move from Port Macquarie (see Fig. 1) back to Sydney and replace his 15.2 cm Grubb refractor with a smaller telescope (see Orchiston 1997b), and on 17 September 1895 Innes (1895j) wrote Tebbutt that he had arranged to the purchase the Grubb refractor. Innes (ibid.) then advertised his large reflector for sale, pointing out to Tebbutt that it really was no use for double star searches, "… but for the ordinary star-gazing amateur it will be an efficient instrument." (ibid.).

While Innes was busy arranging to buy Macdonnell's refractor and trying to publish his double star catalogue an opportunity emerged which he thought might offer him an appointment in professional astronomy. This involved the founding Directorship of Perth Observatory (see Fig. 6), where the successful applicant would also serve as the Government Astronomer of Western Australia (following the pattern already set in both New South Wales and Victoria). Western Australia was the last of the Australian colonies to establish a Government astronomical observatory, and the initiative came from the Premier, Sir John Forrest (1847–1918), with support from the Government Astronomer of South Australia, Sir Charles Todd (Fig. 8; Utting 1991).

By this time Innes (1895i) was keen to quit commercial life, and on 13 September he wrote to the Western Australian Government asking for information about the post and indicating that he would like to apply. In a letter to Tebbutt written at this time he was brimming with confidence: "… such a post I believe I could fill with credit to the Colony and do much real work to advance our Science." (ibid.). He requested a letter of support from Tebbutt, and sent this and his own letter of application off to Sir John Forrest (Innes 1895j, k).

3.3 Flight from Commercial Life: The Cape Appointment

However, Innes did not believe in 'putting all his eggs in one basket', so he had been pursuing other employment possibilities. One of those he contacted was Sir David Gill (Fig. 39), Director of the Royal Observatory at the Cape of Good Hope (henceforth Cape Observatory) in South Africa (see Forbes 1916; Warner 1979), who was later to write:

> Mr lnnes wrote to me from Sydney, expressing a strong desire to obtain a post under me.
>
> He explained that he was engaged in business, but his tastes were wholly for Astronomy and had always been so but he never had an opportunity to devote himself entirely to it.
>
> His name was familiar to me from several excellent papers published by him in the Monthly Notices of the RL Astronomical Society, proving not only competent theoretical knowledge but practical skill as an observer.
>
> *Mr Innes was obviously a man to keep an eye on*. (Gill 1897; my italics).

Unfortunately, at this time there were no scientific vacancies at the Cape Observatory), and besides, at 34 years of age Innes (1895n) was already too old to enter the South African Civil Service. All that Gill could offer was a lowly clerical post which carried financial and other responsibilities, but Gill was not certain that Innes was the right man for this job. His interesting solution to this dilemma was to employ Tebbutt as both referee and arbiter, and on 18 October 1895 he wrote a long letter to the Windsor astronomer.

Gill began:

> Although I have not the pleasure of knowing you personally I at least know enough of you and your work to form some notion of what manner of man you are, and I feel sure that I can implicitly trust you in a very delicate matter. (Gill 1895b).

He (ibid.) then went on to explain that all he could offer Innes was the post of "… Secretary & in charge of accounts, library and M.S.S …", but that there would be opportunities for him to carry out astronomical work in his spare time. Gill then listed the qualities required for this non-scientific post: Innes should have natural tact, possess business qualities, have the ability to remain silent on confidential matters, possess presentable manners and have a presentable appearance, be honourable and reliable, and finally, be sober, steady and industrious. Elsewhere I have commented that "This is quite an attribute list for a simple clerical position!" (Orchiston 2001a: 322).

Gill (1895b) also pointed out to Tebbutt that he had no doubts about Innes' astronomical interests and background, but when it came to personal qualities these could only be judged on the spot. He then went on to assign the responsibility for this appointment to Tebbutt:

> Is it too much to ask you whether you consider that Mr. Innes would be a suitable man for me in such a post.
>
> Under these circumstances I have ventured to enclose my letter for Innes to you. The letter is left open, and I wish you kindly to decide whether it should be delivered or not. If you believe Mr Innes to be the kind of man fitted to perform the duties there described, send my letter on to him—if you think otherwise then please destroy my letter to Mr Innes or return it to me.

Gill (ibid.) concluded by stressing that if "… in a social and moral point of view his habits of life are beyond reproach, then he wd be just the sort of man I want. But if you have any doubts at all then return the letter of offer or else destroy it." Gill stressed that since Innes knew nothing of this matter Tebbutt's "… hands are therefore perfectly free."

Along with Gill's letter to Innes was a short letter from a Mr J. Power (whose position Innes was being offered) supplying Innes with the name of a friend in Sydney who could provide details of living costs and conditions in South Africa.

We are fortunate that Tebbutt proceeded to made a copy of the letter from Gill to Innes, as this reveals more details of the position. In part it reads:

> I am now in a position … to offer you employment here [at a] … Salary £150, with the opportunity to earn from £30 to £50 for overtime or extra-computing, or other work, but I ought to add that I see no prospect of being able to increase this. The post is not that of a covenanted servant … and I can hold out no prospect whatever of your getting an appointment on the permanent staff or a pension. The duties … beyond a knowledge of bookkeeping and general knowledge of Astronomical literature involves no special qualifications …
>
> I think that you have the qualities and qualifications necessary. I do not know whether the terms I have offered are sufficient to induce you to come but they are the only ones in my power to offer you. (Gill 1895a).

This letter also reveals that Gill received letters of enquiry from Innes on three earlier occasions (on 20 November 1894 and on 1 and 16 June 1895) but Gill had nothing to offer him at these times. Gill (ibid.) also suggested that if Innes did accept the Cape Observatory post then he should aim to reach Cape Town by the end of the year, but Tebbutt only received these letters on 18 November so this was obviously a logistical impossibility.

Tebbutt was now placed in a delicate position for Innes' future was literally in his hands, and after carefully considering the situation he decided to pass the two letters on to Innes. Actually, this proved timely, as Innes (1895m) had just heard that W.E. Cooke had been offered and had accepted the Perth post. Just two years Innes' junior, William Ernest Cooke (Fig. 9) had faithfully served as Todd's assistant at Adelaide Observatory (Fig. 3), and subsequently he went on to distinguish himself at Perth Observatory (see Hutchison 1980, 1981; Utting 1989, 1992) and later as Director of the Sydney Observatory (Orchiston 1988b; Wood 1958).

From Innes' point of view this unsatisfactory outcome helped decide the matter, as any job in astronomy—no matter how tenuous and tedious—was preferable to none at all. Accordingly, on 24 November 1895 Innes wrote Tebbutt:

> Dr Gill's offer is not as you remark "very encouraging" but if Mr Power's friend tells me that Iiving is not more expensive there than here I will accept it. I am very anxious to have an Astronomical life and money is not of much account to me, I mean I don't care for it, not that I have a lot. *And if I please Dr Gill he may help me to some position elsewhere*. (Innes 1895m; my italics

At the time, Innes could not have imagined just how prophetic this last sentence would prove to be.

In the meantime, Innes (ibid.) thanked Tebbutt for his support, while Tebbutt wrote to Gill about his action in this matter:

> l have known Mr. Innes for five years and I have always found him a worthy member of society. He has … I believe, from his youth been accustomed to accounts. I believe he may be trusted in the confidential post which you have offered to him. He is a fair mathematician, has a good knowledge of astronomy and is exceptionally anxious to quit his present occupation and fill some position in which he can engage in astronomical work. He has not had many opportunities for observational work, but any deficiency in this respect I feel assured he would soon make up. As I feel satisfied he will turn out to be a suitable man for the post which you offer I have handed to him the letters which you have enclosed to me. After some hesitation he expressed his willingness to accept the offer, but he finds it impossible to reach the Cape by the close of the year …
>
> I heartily wish him every success in his new undertaking and I trust that you yourself will have no cause to regret having accepted his services. (Tebbutt 1895).

As it was now far too late to arrive in South Africa by the end of the year, Innes undertook to reach Cape Town by 30 March 1896 (ibid.).

Innes now faced the frantic preparation for a new life, and over the next two months he had to wind up his partnership in the liquor trade, arrange for the transfer of his family's effects and belongings to South Africa, and prepare for employment in a professional observatory. And as he told RAS Secretary, Wesley, in a letter dated 14 December 1895 he also had to forget about purchasing Macdonnell's Grubb refractor:

> Well on the very day I was going to send him a cheque, I received an offer of a minor appointment from Dr. Gill, through Mr. Tebbutt. I cannot say I dislike commerce but I began to feel with each succeeding year that I was not doing right to Astronomy … I may say that Mr. MacDonnell very kindly released me from my bargain. (lnnes 1895n)

Always accommodating, Macdonnell was not too concerned, and six months later sold the telescope to Gale (Brooks 1896). Subsequently, it did excellent service in the hands of E.H. Beattie (see Baracchi 1914).

During the very busy months leading up to his departure for Cape Town, Innes somehow also found time for further observational astronomy: between 30 November 1895 and 22 February 1896 he used the naked eye, binoculars and when necessary the large reflector to carry out a great many observations of the variable stars l Carinae, R Carinae, R Doradus, Eta 1 Hydri, Episilon Leporis and N Velorum, and a few of Brisbane 2371, Gould 14766, Epsilon Muscae and Rho Phoenicis (see Innes 1896d). Between 9 January and 22 February 1896 he also observed the star Lac. 3904 and discovered that it was variable: its apparent visual magnitude ranged between 6.5 and 7.1, but there was no clear evidence of periodicity (ibid.).

After hearing of his South African appointment Innes completed one final research paper while in Sydney, and this was a mathematical treatment of achromatic telescope lenses. Eventually, this was published in the *Journal of the British Astronomical Association* (Innes 1896c).

At the end of February 1896, Robert Innes was farewelled by friends and colleagues from the local astronomical community before sailing for Cape Town and a new career. An article in the *Sydney Morning Herald* (1896) reports that a banquet as held for him in Mr Quong Tart's rooms in King Street and was attended, amongst others, by Dr Megginson and Messrs Bedford, Craven, Edmonds, Furber, Knibbs, Merfield and Wright, all prominent members of the New South Wales Branch of the British Astronomical Association (see Orchiston 1988c). Branch Vice-President George (later Sir George) Handley Knibbs proposed a toast, and Innes was called upon to reply, but his response was brief:

> He decried the encomiums of the chairman, so far as he was concerned, and endeavoured to show that many members of the local branch of the association had done as much or more in the interests of astronomical research as he had. (Sydney Morning Herald 1896)

Shortly before he was due to depart for South Africa Innes (1896e) informed Tebbutt that he had committed his wife to Callum Park Hospital for the Insane, and at the same time Merfield and Roseby (1896) made Tebbutt aware of Innes' sexual "delinquencies …" Subsequently, Innes and his mistress—along with his three young sons—embarked for Cape Town (Gale 1896b), armed with a letter of support signed by members of the Sydney astronomical community, many of whom were unaware of Innes' affair (Gale 1896a; Merfield 1896c). Tebbutt was both embarrassed and appalled to learn about Innes' affair, for he had already assured Gill that Innes' social and moral "… habits of life are beyond reproach …", so he immediately wrote Gill and recommended that Innes' letter of appointment be withdrawn (Innes 1896f; Roseby 1896). However, Gill was absent when Innes reached the Cape Observatory and by the time he returned and was able to read Tebbutt's letter Innes had already succeeded in convincing him that the accusations were all false (Gill 1898). Furthermore, Gill was very happy to keep Innes on the staff so long as he performed his clerical job efficiently and effectively and so long as he also furthered the Observatory's research objectives (which he certainly did).[3]

Later the author of the Innes obituary that appeared in the *Journal of the Astronomical Society of Southern Africa* claimed that Innes sought employment at the Cape Observatory because he wanted access to larger instruments than the two 'small' telescopes he was using in Sydney (Obituary 1933). This simply is not true. In fact, all he wanted was an opportunity to work full-time in astronomy, and while the mounting of his large reflector may have left much to be desired, its light grasp was only marginally inferior to the largest telescope then at the Cape, which was the 46 cm McClean Refractor.

After Innes left Sydney he was sorely missed by some in the local astronomical community. This is reflected in the letter that Hugh Wright wrote Tebbutt on 19 September 1896 where he commented on the apathetic attitude of members at the latest meeting of the New South Wales Branch of the British Astronomical Association:

> We need a real live man among us in Sydney, who will work and induce others to do the same. In Mr. Innes we lost such a man, and the breach has not yet been filled. (Wright 1896)

[3] Innes' hankering for heavenly bodies of a non-celestial kind apparently was common knowledge after he moved to Johannesburg and is even discussed in Vermeulen's 2006 history of the Transvaal-Union-Republic Observatory.

Because of the stand Tebbutt took on Innes' affair immediately before he left for South Africa Innes' letters to Tebbutt were infrequent after he settled into his new post at the Cape Observatory. Nonetheless, Innes continued to see Tebbutt as an inspiration, and just three years before Tebbutt's death he wrote: "… you know what a high opinion I have always had of your astronomical work and of your invaluable services to astronomy in Australia." (Innes 1913). Ironically, it was partly as a result of these "invaluable services" that Innes ended up in the ranks of the professional astronomer.

3.4 A Post at a Professional Observatory: Secretary-Astronomer at the Cape

By international standards the Royal Observatory at the Cape of Good Hope was a major one (see Fig. 44), and in scale it far surpassed any of the Australian Government observatories. Although Innes had accepted a non-research post, he devoted all of his spare time to observational astronomy, with emphasis on double stars, lunar occultations of stars, comets and variable stars (Obituaries 1934). He also revised the *Cape Photographic Durchmusterung*—a mammoth project—in the process discovered some new double and variable stars (Obituaries 1933). Finally, he returned to and completed his *Reference Catalogue of Southern Double Stars*, which included observations he made in Sydney and observations by other Australian amateur and professional astronomers, and this 328-page monograph was published by the Cape Observatory (Innes 1899). As the following except illustrates, in the Preface Sir David Gill speaks of Innes in glowing terms:

> Mr R.T.A. Innes, the author of the present work, joined the staff of the Cape Observatory in 1896 as Secretary, Librarian, and Accountant. It formed no part of his official duties either to engage in astronomical observing or to contribute in any way to the publications of the Cape Observatory. But previous to his arrival at the Cape … he had discovered about forty new double stars, and published their estimated distances and position angles. He had also made some progress in the preparation of a card catalogue of reference to the known double

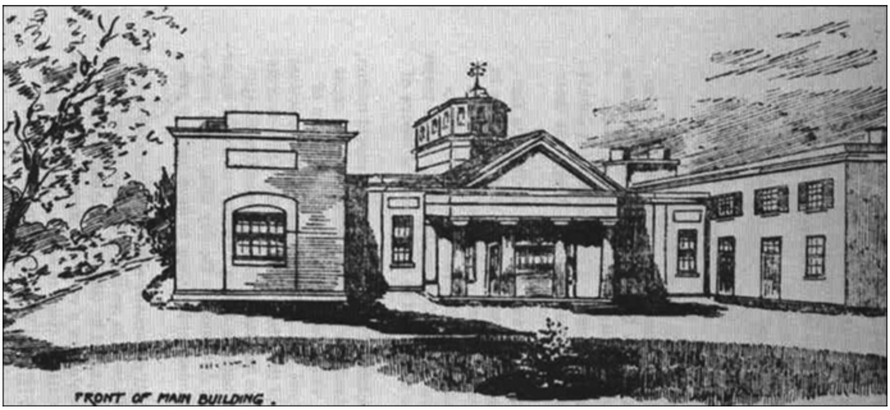


Fig. 44 Sketch of the Cape Observatory soon after Innes joined the staff (After *The Cape Times* 1908)

> stars of the Southern Hemisphere. This catalogue he has not only completed within the past two years in the intervals of his leisure time, but he has discovered upwards of 280 new double stars with the 7-inch equatorial …

This was the first catalogue of southern hemisphere double stars, and one of its most valuable attributes is the 41-page chronologically-arranged Bibliography at the end of the volume.

For many years this catalogue remained the standard reference work in this field and, as might be expected, it was particularly well received by Innes' former colleagues in Sydney (e.g. see Merfield 1900b; Roseby 1901),

3.5 A Professional Appointment at Long Last: The Transvaal Directorship

When the Boer War ended the South African Government decided to establish an observatory at Johannesburg "…. which, in the first place at least, was to be devoted to meteorology; but it necessarily included a time department which, in energetic hands, could be developed into a regular astronomical observatory." (Gill 1913). Or as W.S. Finsen (n.d.), a former Director of the Union Observatory, so aptly put it:

> The Transvaal, after the South African war, decided that it needed a meteorological service for the farmers, and Gill suggested Innes. Now, Innes was not interested in meteorology, and Gill knew that. But he also knew that if he could get Innes up here, he would do his met. duties in the same way as he had done his clerical duties in the Cape, quickly, efficiently, and then get on to astronomy.

Johannesburg was an ideal location for an observatory as it was at altitude, had an ideal climate and offered excellent seeing (see Evans 1988).

With Gill's (1897) support lnnes was appointed Founding Director of the new Transvaal Observatory, and in 1903 he left the Cape Observatory and moved to Johannesburg. As anticipated, initially the Observatory focussed only on meteorology, but this changed in 1907 with the acquisition of a 22.9 cm Grubb refractor. Then in 1909 Mr J. Franklin-Adams (1843–1912) gifted the Observatory a 25.4 cm astrograph, and in this same year, the local Minister of Lands approved the purchase of a 66 cm Grubb refractor, but this instrument only became operational in 1925, because of production problems at Grubb's works and the intervention of WWI. By this time the Observatory was a purely astronomical institution, as in 1912 the Government had set up a separate meteorological branch, and in the process the Transvaal Observatory was renamed the Union Observatory (see Hers 1987a, b, c; Moore and Collins 1977; Vermeulen 2006). Figure 45 shows Innes during the time he was Director of the Union Observatory.

From its start, the Union Observatory focussed on the observation and theoretical study of double stars, the observation of Jovian satellite phenomena the study of proper motions of stars (Obituaries … 1934), and Innes contributed to all three fields. In the course of his life, Innes discovered about 1,500 new double stars or multiple star systems, arguably the most notable of these being Proxima Centauri which he detected in 1917 (see Glass 2008). Perhaps it was this penchant for observing that

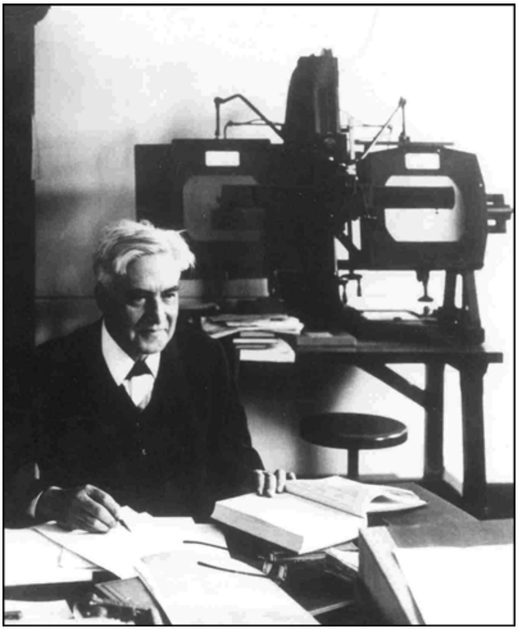


Fig. 45 Robert Innes at his desk at the Union Observatory (Courtesy: National Research Foundation/South African Astronomical Observatory)

prompted one writer to characterise Innes as a "… typical amateur …" and point out that he effectively remained one "… even when he was a professional astronomer and head of a government observatory." (Obituaries 1934). Yet Innes liked to describe himself as an observer by necessity but a mathematical astronomer by choice. Nonetheless, he was seen by many as an exceptional observer with a very keen eye (ibid.). In 1923 Leiden University recognised Innes' lifelong astronomical work by awarding him an honorary D.Sc.

In addition to his research work, Innes enriched the local professional astronomical community in Johannesburg by inviting many overseas astronomers to the Union Observatory (Scientiae 1968), and at the national level he also made a very substantial contribution to astronomy:

> … it seems certain that the very important position that South Africa occupies in the astronomical world to-day is due in great part to Innes, to his persistence in drawing attention to the splendid climate, and to his influence in persuading the authorities to welcome the foundation of southern stations by northern observatories. He was formerly convinced that the interests of astronomy urgently demanded more observations in the southern hemisphere. (Obituaries 1934)

Innes also played a leading role in the Astronomical Society of South Africa; he was a foundation member, a one-time President, and was the Director of the Computing Section (Obituary 1933).

At the end of 1927 Innes retired from the Union Observatory and less than six years later he was dead (Obituaries 1934), bringing to an end the remarkable career of an ATP who contributed in a notable way to both Australian and South African astronomy (Orchiston 2001a, 2003c).

4 The ATP Syndrome: The Case of C.J. Merfield

4.1 Charles James Merfield: A Brief Biographical Sketch

Charles James Merfield (Fig. 32) was born in Ararat, Western Victoria (see Fig. 1) on 28 April 1866. After completing his secondary education at Stawell Grammar School, he trained in mathematics, surveying and engineering and for a number of years was employed by the Government supervising "… the construction of new railway lines through the then virgin territory of Victoria." (Obituaries 1932).

Merfield then moved to Sydney, and on 1 October 1890 was employed as a 'Temporary Draftsman' by the Public Works Department (New South Wales. Blue Book 1893), and was assigned to the Railway Construction Department (Merfield 1896d) where his mathematical prowess was particularly valued (see Obituaries 1932). This was to prove his *entree* into astronomy.

Merfield had a long-standing interest in astronomy, but this only came to the fore in Sydney, initially through the influence of his friend and neighbour, the Reverend Dr Thomas Roseby. This is referred to in a letter that Roseby wrote Tebbutt in 1901:

> It is interesting to notice how the aid of one man helps to make the career of another. It was your help 12 years ago that encouraged me, and mine (in the first instance) that helped to stimulate the genius & enthusiasm of my neighbour. (Roseby 1901)

Roseby was born in Sydney in 1844, and educated at the University of Sydney where he completed an M.A., an LL.B. and an LL.D. (Phillips 1976). In 1872 he went to Dunedin, New Zealand, as a Congregational minister, and then spent from 1885 to 1889 in Ballarat, Victoria, before returning to Sydney (Dun 1919; Phillips 1976). Although active in astronomy while in Dunedin (see Roseby 1882), Roseby came into his element with the founding of the New South Wales Branch of the British Astronomical Association in 1895 (see Orchiston 1988c). He was interested in comets, but his forté was the popularization of astronomy (Leavitt 1887; Orchiston 1997a). Tebbutt (1894a) was pleased to support Roseby's application for membership of the Royal Astronomical Society "After the amount of *real* interest which you have shown for our science …" Thomas Roseby died on 16 December 1918 (Obituaries 1920).

Through Roseby, Merfield got to meet those in the local astronomical fraternity, and he soon built up a close friendship with John Tebbutt which was characterized by occasional visits and a very healthy correspondence. Unlike Innes, Merfield (1896e) was no great lover of formal social occasions; rather, he was the studious type who thrived under Tebbutt's influence:

> Your kindly influence upon me the last few years, through the medium of your letters and occasionally in person, has tended towards the cultivation of strict habits, indeed, as you observe, the planets in their courses teach us good lessons. Indeed it has been mainly through your advice and encouragement; that I have attained a certain knowledge for which I shall ever feel grateful … (Merfield 1901h)

As his international reputation in mathematical astronomy grew, Merfield (1904p) was happy to assign most of the credit to his friend, mentor and inspiration, John Tebbutt. In 1905, he reminded Tebbutt that "My desire has always been to attempt to continue on your great work in Australia …" (Merfield 1905e).

Merfield went on and did just this, first in Sydney and later as a staff member of Melbourne Observatory, and by 1916 had acquired "… quite an international reputation as a cometary computer." (Cooke 1916). On 23 January 1931, less than three months before his planned retirement, he was tragically killed in a motor accident, a sad loss for Australian astronomy and international cometary astronomy (Crommelin 1932; Mr. C.J. Merfield 1932; Obituaries 1932).

4.2 Calculations and Observations: A Burgeoning Interest in Astronomy

Fieldwork, or "living under canvas" as he called it, kept Merfield away from Sydney and the chance to indulge his latent astronomical interests until about 1894 when he came under the influence of both Innes and Roseby. It was Innes who first discussed ways of channeling his mathematical interests into astronomy (Merfield 1896c).

Like Innes, Merfield had a passion for mathematical astronomy, and after Comet C/1894 G1 (Gale) was discovered in 1894 he decided to apply this to the calculation of the orbital elements. Subsequently, Merfield, Innes and Roseby worked together on the computations (Merfield 1894a) and after two months of intermittent effort came up with final results (Merfield et al. 1894). Roseby (1894a) indicates that most of the workload fell on Merfield's shoulders, and that he has "… the highest admiration for his skill … [and] his genius for hard work." Their results were forwarded to Tebbutt, with a query as to where they should be published, and it must have been disappointing when he suggested instead that they add extra data (from a longer arc of the orbit) and repeat their calculations (Roseby 1894b).

Perhaps it was this exercise which prompted Merfield to consider trying his hand at observational astronomy, for by November 1894 he was the proud owner of a 19 cm reflector. Soon after, he admitted to Tebbutt: "… I don't care a great deal for the reflector, but being within my means I am able to speculate." (Merfield 1894c). Merfield (1894b) was able to use this telescope to observe the 10 November transit of Mercury.

An important event for Sydney astronomy at the start of 1895 was the founding of the New South Branch of the British Astronomical Association (see Orchiston 1988c), and Merfield was one of those who was particularly involved. In fact, he was elected Director of the first observing section, which was devoted to Star Colours (see Reports of the Branches 1895), and this gave him a new observational focus. By year's end, he had observed 101 different southern stars and estimated the colour of each (see Merfield 1896g). He also observed an occultation of Antares on 10 May 1895, and subsequently published a note about this in the *Journal of the British Astronomical Association* (Merfield 1895c). This was his first publication in astronomy.

Merfield got to meet Tebbutt at the meetings of the Branch, which prompted him to arrange his first visit to the Windsor Observatory, in April 1895 (Merfield 1895d). This experience must have fired him with further enthusiasm for observational astronomy, given his obvious regard for Tebbutt. It may also have inspired him to consider the possibility of a career in professional astronomy, and in February 1896 he visited Melbourne Observatory and discussed this concept with Ellery and Baracchi, both of whom thought he should apply for Cooke's old position at Adelaide Observatory (Merfield 1896b). That he did not do so would suggest that he felt he still had to establish a viable track record as both an observational astronomer and an astronomical mathematician.

Once back in Sydney, Merfield was able to work on the first of these deficiencies by expanding his observational repertoire. On 28 February 1896 he observed a partial eclipse of the Moon (Merfield 1896f), and on nine evenings during February and March he carried out observations of three conspicuous dark spots on Jupiter's North Tropical Zone (Merfield 1896a).

The year 1897 offered similar observational possibilities to the previous year. On 2 February Merfield observed a partial solar eclipse, already in progress at sunrise, and published a note on this (Merfield 1897b). Meanwhile, Merfield and his collaborators continued their star colour work. A report published in the *Journal of the British Astronomical Association* (Merfield 1897j) indicates that Merfield made observations of 344 different southern stars. Later in the year, he revealed his great interest in minor planets to Tebbutt (see Merfield 1897g), stressing that he would like to carry out research on them if and when the opportunity arose. At the Annual General Meeting of the New South Wales Branch held on 21 December 1897 the President, G.H. Knibbs, made special mention of Merfield's work during the year:

> The President, after reviewing the progress of the branch during the session, referred in laudatory terms to the valuable astronomical work achieved during the same period by Mr. J. Tebbutt and Mr. C.J. Merfield … (Reports of the Branches 1898)

Nor did Merfield neglect his mathematical interests in 1897. His first challenge was to calculate the orbital elements of Comet C/1896 V1 (Perrine) which had appeared in late 1896, and these were published locally (Merfield 1897a) and in both *Monthly Notices of the Royal Astronomical Society* and *Astronomische Nachrichten* (Merfield 1897c, i). Although these were only short, they were his first papers in these two prestigious international journals. Meanwhile, in February and March he was busy coaching the visiting Queenslander, J. Ewen Davidson (1841–1923) and fellow Sydney Branch member Dr A.M. Megginson on the niceties of these orbital computations (Wright 1897a, b). He was also very aware of the mental burden which the on-going reduction of observations posed for John Tebbutt as he approached 70 years of age, and volunteered to sacrifice some of his own precious evenings in order to assist with these computations (see Merfield 1897e).

4.3 *Endless Frustration: That All-Too-Elusive Professional Post*

With his astronomy progressing admirably throughout 1897, Merfield must have been frustrated by the lack of promotional opportunities within the Railway Construction Department, and although his career aspirations lay squarely in astronomy he did contemplate other interim options including a move to a commercial engineering firm (Merfield 1897d). But he decided to persevere, and his patience appears to have been rewarded towards the end of the year when he was identified by the Public Service Board as the replacement for R.P. Sellors who was anxious to leave Sydney Observatory (Merfield 1897h). This was very welcome news.

Although there was no further word about the Sydney Observatory post in 1898, Merfield's astronomy employment prospects did show a marked improvement in January when he was offered a new post at the Perth Observatory (Fig. 6). On 16 January he wrote excitedly to Tebbutt:

> The position of first assistant of the Perth Observatory has been offered to me, but the salary to start is only £200 without residence, this is hardly tempting enough, as living is high, but I would have been pleased to take it, if there had been a residence or in lieu say £50, I am indeed sorry that I will have to refuse, for the observatory routine is what I require. Mr Cooke said he will use his best endeavours to have the salary increased, but I have lived on promises the last few years, and must now have matters fixed in a definite manner. (Merfield 1898b)

The "promises" he refers to were those made by H.C. Russell regarding Sellors' position at Sydney Observatory. Baracchi was delighted for Merfield, but realizing that the salary was insufficient he wrote Cooke with a view to having it increased (Merfield 1898c). For his part, Merfield (ibid.) explained to Tebbutt that "… I do not want a large salary, but I would like sufficient, so that I might have a few pounds remaining after paying for the necessities of life."

It would appear that Merfield did little on the observational front in 1898, perhaps because he lacked the telescope and auxiliary instrumentation to carry out precise micrometric observations:

> … as soon as I can afford the outlay I intend getting a five or six inch refractor to do some of the minor planet and comet work, the small reflector that I have is quite unsuited for the work of measurement. (Merfield 1898d)

What he did do was write a paper on the proper motions of eight stars in Aquarius, which was published in *Monthly Notices of the Royal Astronomical Society* (Merfield 1898f), and a popular two-part article about solar eclipses for *The Surveyor* (Merfield 1898a). He also worked up short papers providing provisional orbital elements of Comet C/1898 L1 (Coddington-Pauly) for *Astronomische Nachrichten* (Merfield 1898e; 1899m), and when further observations came to hand prepared more precise elements (Merfield 1899k). When he realized that this comet would come within range of northern telescopes in 1899 he prepared two relevant ephemerides and published these also in *Astronomische Nachrichten* (Merfield 1899a, b). It was at this time that Professor Heinrich Kreutz (Fig. 46; 1854–1907), the Editor of *Astronomische Nachrichten*, complimented Merfield on the accuracy of his computations (see Merfield 1899c). This must have been a welcome letter for, like Tebbutt (see Elkington 1901), Merfield recognised the supremacy of German science at the time (Bernal 1986) and the importance assigned there to positional astronomy.

Merfield continued his romance with mathematical astronomy in 1899 following the discovery of Comet C/1899 E1 (Swift) in March, and went on to publish short papers on its orbital elements in *Astronomische Nachrichten* (Merfield 1899i) and the *Journal and Proceedings of the Royal Society of New South Wales* (Merfield 1899j).

Fig. 46 Heinrich Kreutz, Editor of the *Astronomische Nachrichten* (en.wikipedia.org)

And as further observations were made around the world (in many cases thanks to his ephemerides), he began pooling these in order to derive precise orbital elements, and also published these in *Astronomische Nachrichten* (Merfield 1900h). During early 1899, he also prepared a second paper on stellar proper motions (see Merfield 1899n), a by-product of reductions that he had been carrying out for Tebbutt.

At last Merfield was starting to be noticed internationally through his expanding list of cometary publications:

> Attention should be called to the very valuable computations on cometary orbits which have been carried on by Mr. C.J. Merfield, of Sydney, N.S.W. His work goes admirably hand in hand with Mr. Tebbutt's observational work. (Reports of the Sections 1900)

Given Merfield's special regard for Tebbutt (e.g. see Merfield 1897f), he must have been very pleased to see his name linked with that of his mentor.

By now Merfield was totally committed to a full-time position in astronomy as indicated in his letter to Tebbutt of 15 March 1899: "I only trust that your remarks will come true so that I can devote the whole of my time & attention to the science of astronomy." (Merfield 1899d). All that was missing was that all-important salary. In May he provided Tebbutt with a progress report on the Sydney Observatory option:

> I have heard nothing officially with regard to the appointment at the observatory, but the Director Mr. H.C. Russell has my office ready and anticipates my coming to his department. (Merfield 1899e)

As if it were some small consolation, Merfield had his Public Works salary increased by £30 at about this time (ibid.)!

With an offer already from Perth and no progress at Sydney, that left only Melbourne Observatory (where he was on excellent terms with Baracchi) and on 8 July Merfield wrote Tebbutt about the post of Chief Assistant which paid a salary of between £315 and 340:

> … the position is vacant, and I am making enquiries with regard to the future intention of the authorities, the assistant also has dwelling provided in addition to the emolument mentioned. (Merfield 1899f)

Tebbutt offered to do what he could to help Merfield obtain this post (see Merfield 1899g) and subsequently wrote to Baracchi (Merfield 1899h). Meanwhile, at the end of October Merfield advised Tebbutt that there was still no news on his "… intended transfer to the Sydney Obs. …" (ibid.).

This must have been a trying time for Merfield with two possible positions apparently in the offing, but on 5 November 1899 Baracchi felt obliged to write Tebbutt and 'set the record straight' regarding the Melbourne option:

> I regret to say that I do not see any prospects of the appointment being made by the Government during the current financial year, and Mr Merfield may not perhaps be willing to wait for such an uncertain opportunity. I may say however that I am quite aware of the great value Mr Merfield would be to me and as, in the interests of the Observatory, the best man available will be selected for the position so far, at any rate, as my power will go in regard to the appointment, when the opportunity comes, he may rest assured that his claims will receive the fullest consideration, which means that as far as I know at present, he would have the best chance. (Baracchi 1899)

This was all very flattering for Merfield, but it did not absolutely guarantee him a position at the Observatory, nor did it indicate a likely time-frame for the appointment.

Instead, just over one month later a new employment opportunity unexpectedly emerged, at the Perth Observatory. In a letter written to Merfield, Cooke (Fig. 9) explained that since Baracchi had led Merfield to expect an offer of a position at the Perth Observatory he deserved to know the current situation (Cooke 1899). Although the sum of £250 for a new position was in the estimates and it had been approved by Government, Cooke was dismayed to find that they would not permit him to fill the post. He did, however, conclude on a more optimistic note:

> I am badly in need of a first class computer and still hope to be able to induce the Govt. to alter their minds before the close of the financial year.
>
> Should this happen it would be a convenience to me to know whether you would entertain the proposal. (ibid.).

Here again was another virtual 'job offer', but once more without a meaningful time-frame, yet it must have been pleasing to Merfield to realize that he was so much in demand. Despite this, he decided to refuse the offer, for he felt the salary was inadequate if Cooke really wished to attract "… a good man …". (Merfield 1899i)

Would 1900 turn out to be his year? Merfield certainly hoped so as he continued to pursue the various job options. While he was holidaying in Melbourne early in the year he took advantage of the opportunity and lobbied a number of members of the Melbourne Observatory Board of Visitors. He was told the vacancy would be discussed at the next meeting of the Board. Merfield was hopeful, because "Mr Baracchi seems very anxious to have me at the observatory and will do all he can to advance my case at the proper time …" (Merfield 1900a). From what he was told, there would be two other candidates for the position. Despite such promising prospects, nothing more was heard of the vacancy in the course of the year.

What of the promised post at the Sydney Observatory? On 30 March 1900 Merfield (1900c) wrote Tebbutt that Sellors had already been transferred to the Trigonometrical Survey, but that

> The position I understand is not to be filled, Mr. Russell has recommended that two youths be employed to reduce the star places … this recommendation of course may be upset and the position filled, but the above is what Mr. Russell was pleased to tell me.

Merfield must have been disgusted by this outcome, but given his close friendship with Tebbutt and long-standing agitation against the apparent astronomical inactivity at the Sydney Observatory it would have been naive of him to expect anything else. He was, after all, 'tarred with the Tebbutt brush'! Although disappointed, he was still optimistic:

> I trust that some day I will be able to devote some attention to the observation of these interesting bodies [i.e. minor planets], & I trust that my "Maker" will grant me health and strength to carry out the plans that I have made for myself. (Merfield 1900d)

As if to drown his sorrows, Merfield threw his energies into cometary computations once more, and began his most challenging project to date: to produce the definitive orbital elements of Comet C/1898 L1 (Coddington-Pauly), using *every known* published observation. By 1 July this was completed and forwarded to *Astronomische Nachrichten* (Merfield 1900e), and it appeared in print the following year as a 20-page paper (Merfield 1901c). In his introduction, Merfield pays a special tribute to his friend and mentor, John Tebbutt:

> The largest series of observations are by Mr. J. Tebbutt of Windsor. The work of this astronomer extends over the period 1898 June 15 to 1899 Feb. 15, and comprises one hundred and two nights work, seven hundred and sixty eight comparisons being made, and one hundred and thirty seven stars of reference used. The provisional elements of this comet, published by the author in A.N. 3546, depend almost entirely on the observations of Mr. Tebbutt who is to be congratulated not only on the general accuracy of the observations, but also on the careful manner in which the reductions have been prepared for publication. (Merfield 1901c: 230)

At the 18 September 1900 meeting of the New South Wales Branch of the British Astronomical Association Merfield gave a talk on this paper, and at its completion Roseby made the following flattering but thoroughly deserved comments:

> … the definitive orbit elements which Mr. Merfield had computed were a long way in advance of all that has ever been done in Australia before. Indeed, the computation of precise orbits is a matter of comparative rarity, even in the older countries, where extra assistance is so readily attainable. The result now achieved has involved the collection of data from observatories all over the world; it has involved the collation of 430 different observations, and their reduction and correction; and it may be said to be the coping-stone to the mathematical astronomy of Australia up to the close of the century. (Reports of the Branches 1900)

Tebbutt was equally lavish in his praise:

> Owing to the very large number of published positions of this comet, the definitive investigation has been exceedingly laborious, and the author is to be congratulated on its successful issue. It is a work which cannot fail to be appreciated by astronomers, and it will form an important item in our local astronomical literature. It plainly shows that if the author be only blessed with good health, and the necessary opportunities, he will have a brilliant astronomical career before him, and one which will do honour to the State of which he is a member. (Tebbutt 1901)

When Merfield's paper appeared in print it created such an impression that it was even commented on in other astronomical journals. For example, the following appeared in the *Journal of the British Astronomical Association*:

> Mr. Merfield is to be congratulated on having brought this laborious piece of work to a successful conclusion … The final result, to which he has devoted his leisure hours for several months, is probably as close an approach to the true path of this body as the observations admit of. (Comet Notes 1901)

With the 1898 comet 'off his plate', Merfield (1900f) began a similar treatment for Comet C/1899 E1 (Swift), and at year's end advised Tebbutt that he was still working on this project (Merfield 1900g).

Early in 1901, the appearance of the Great Comet of 1901 (C/1901 G1) inspired Merfield to begin observing again (see Reports of the Branches 1901), and he later prepared notes for publication in *Astronomische Nachrichten* and *Journal of the British Astronomical Association*. The former lists positional observations made on five nights in May (Merfield 1901q), while the latter includes two sketches of the tail configurations and the following description: "The nucleus is a fine stellar point, and very bright, as also is the tail, that appears to the eye to extend some 8° …" (Merfield 1901b). Meanwhile, he was somewhat amused by some of Walter Gale's statements about this impressive new visitor:

> I cannot understand Gale in his statement about perihelion passage; having one observation to tell us most emphatically that the comet has passed the nearest point to the Sun, wonderful? … I am afraid that Mr. Gale's education, in these depts. of astronomy, has been neglected; Mr Gales [*sic*.] statement is a huge guess … (Merfield 1901g)

As would be expected, Merfield (1901a, d) also calculated preliminary and then more precise orbital elements for this comet, based in both instances upon observations supplied by Tebbutt, and he provided observers with an ephemeris for September–October 1901 (Merfield 1901d). He also found time to assist George Knibbs (destined for a knighthood and to become the Commonwealth Statistician—see Obituaries 1930) with computations for a paper on the Sun's motion in space (Merfield 1901e) which he was preparing as his Presidential Address to the New South Wales Branch of the British Astronomical Association (see Knibbs 1900) and to try and teach John Grigg (Fig. 47) how to compute cometary orbital elements (Merfield 1901k)—but by correspondence! Grigg (1838–1920) was New Zealand's leading amateur astronomer at this time, and this tuition was particularly appropriate—if a little belated—since he was a compulsive cometary observer and was soon to become even more widely known through his discovery of three different comets (see Orchiston 1993). Grigg also was a pioneer of astronomical photography in New Zealand (Orchiston 1995), and an avid popularizer of astronomy.

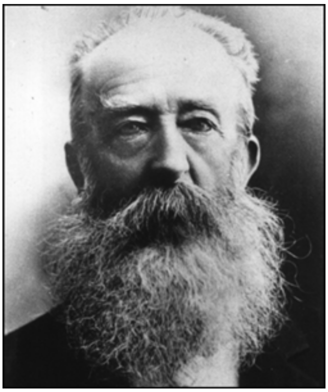


Fig. 47 John Grigg of Thames, New Zealand's foremost amateur astronomer (Orchiston Collection)

During 1901, Merfield also continued his definitive orbital analysis for Comet C/1899 E1 (Swift), but had to curtail this during September and October when he was sent out of Sydney to supervise the Grafton to Casino railway survey (see Fig. 1). In discussing this with Tebbutt, he writes that he was too tired of an evening to do any of the necessary computations (Merfield 1901m).

Nor did Merfield abandon his quest for a full-time astronomical position in 1901. Early in April he received a letter from Baracchi who advised that the Chief Assistant's position was going to be discussed at the next meeting of the Board and he "… hopes to have something definite to tell me at an early date." (Merfield 1901f). Of course Merfield had heard all this before, so in the interim he boldly requested permission to use the Sydney Observatory 29.2 cm Schroeder refractor (Fig. 15) for micrometric observations of comets and minor planets. Since the telescope was being overhauled and therefore was inoperative, Russell was happy to approve! Then in June, Merfield (1901i) received another letter from Baracchi advising the Melbourne Observatory appointment had gone up to the Government for approval.

No further word on the appointment had been received by October 1901 when Tebbutt paid a visit to the Melbourne Observatory, and although he was not very impressed with what he saw, he again interceded on Merfield's behalf. Merfield was grateful for this support and for Tebbutt's comments:

> As you say this observatory is a perfect museum for instruments, for a paltry £300 or £400 per annum that the Govt. of Victoria seem unwilling to devote to the salary of an Assistant astronomer, the fine instruments are idle. I must indeed thank you, Mr. Tebbutt for any remarks that you have been pleased to make to the Victorian Astronomers, I thought that some appointment would have been made before this … (Merfield 1901n)

During November, Merfield was back in Melbourne on holiday (his wife's parents lived there), and he took the opportunity to visit Baracchi himself and to discuss the vacancy. Baracchi told Merfield quite candidly that the position was not in the Budget Estimates at the time, but that when it did come up he would fight very hard to have him appointed (Merfield 1901p).

In the midst of this Melbourne Observatory job saga, Merfield (1901j) wrote and thanked Tebbutt for his encouragement which "… has been of great assistance to me in my work and studies."

If 1901 had been a frustrating year for Merfield on the job front, then 1902 turned out to be even more so. Because of what he perceived to be broken promises from Russell at the Sydney Observatory and Baracchi at Melbourne, Merfield had become rather cynical, and on 20 January wrote to Tebbutt:

> It is useless to expect any encouragement as in most cases the gentlemen in charge are more interested in collecting their salaries than in astronomy. Indeed I have often said that if you eliminate your work for astronomy in these climes, then there is very little left to say any thing about. (Merfield 1902c)

By September Merfield (1902e) had given up any hope of hearing from Russell, and in early November he wrote Tebbutt musing over what had become of Baracchi. Had he gone to the South Pole? Merfield continued:

> As far as our so called Govt. Astronomers are concerned they might as well be there, as we hear very little of them, and when they do open out in print they nearly always make high laughing stocks of themselves, to those who know their work. (Merfield 1902f)

In the course of 1902 Merfield spent more than six and a half months away from Sydney overseeing the construction of two different railway lines: two and a half months during February-April (Merfield 1902d) and the balance during July–November (Merfield 1902e, f). Despite this, he prepared an ephemeris for Comet C/1902 G1 (Brooks) for local members of the British Astronomical Association (Reports of the Branches 1902), and in mid-June he managed to complete his work on the definitive orbit of Comet C/1899 E1 (Swift) and sent this off to *Astronomische Nachrichten* for publication (Merfield 1902b). Once again we are looking at a long paper (22 pages) involving a vast amount of computation. Of the 579 observations utilized, 35 came from Windsor Observatory. This represents just 6 % of the total, well down on the 18 % that Tebbutt contributed for Merfield's Comet Coddington-Pauly analysis, but the earlier comet was better placed for southern viewing. Later in the year, a new issue of *Astronomische Nachrichten* provided Merfield with an additional 33 observations, and these were dealt with separately in a short supplementary paper (Merfield 1902a).

Although he was obviously tired of an evening while in the field, during the second half of the year Merfield pressed on with his next, his third, definitive orbital analysis. This time, the target object was Great Comet of 1901 (which he had actually published observations of), and at the very end of the year he wrote Tebbutt that this challenging project was nearing completion (Merfield 1902g). His paper was published in 1903 (Merfield 1903a), and reflected the same exacting standards of scholarship that were represented in its two predecessors. After this paper went to press, Merfield became aware of a further 18 observations that should have been included, and he was forced to deal with these in a separate little paper (Merfield 1904a).

Unfortunately, 1903 provided no relief on the astronomical employment front, with no further word from either Sydney or Melbourne Observatories. However, towards the end of the year Russell went off on sick leave and Henry A. Lenehan (1843–1908; Fig. 48) was appointed Acting Director. When Merfield learnt of this he wrote to the Public Service Board advising them that he wished to apply for Russell's position when it was advertised, but in a letter to Tebbutt he noted that "… there are however certain influences at work in the Sydney Observatory that require diplomacy to get over …" (Merfield 1903i).

In contrast to this frustrating situation, Merfield was upwardly mobile in the Public Service at the time, having been promoted to the position of Assistant Engineer (Merfield 1903b). The downside to this was that it involved further field-work, and he was obliged to spend most of 1903 based in Tumut in far-off southern New South Wales (see Fig. 1). Mathematical astronomy offered intellectual relief when the opportunity permitted, and the discovery (in April) of a new comet (C/1903 H1) by his New Zealand colleague John Grigg gave an added excuse.

Merfield used three of Tebbutt's ever-reliable observations to compute the orbital elements, and forwarded these to Baracchi, Grigg, Tebbutt, and Wright, amongst others (Merfield 1903c, d). Wright (1903) immediately arranged for them to be published in the Sydney newspapers. Merfield (1903d) also prepared an ephemeris for this comet, and subsequently received a letter from Grigg which included his observations and orbital elements that were computed on the basis of these (Merfield 1903e). Grigg was concerned that there was a "considerable difference" between his own elements and those of Merfield, but this is only to be expected given that his positional data derived from readings of the right ascension and declination circles rather than micrometric observations (see Orchiston 1993).

Merfield had already developed a jaundiced view of Baracchi, but this was exacerbated during 1903 by the latter's actions—or rather lack of them—regarding Comet C/1903 H1 (Grigg). As the 'national point of contact', it was Baracchi's responsibility to pass discovery information and subsequent observations from Australia and New Zealand on to Kiel (which was then the world centre) and also to disseminate such information among Australian and New Zealand observers. Merfield, Tebbutt and Grigg (amongst others), felt that Baracchi had acted unprofessionally or at very least irresponsibly. On 26 July Merfield (1903g) wrote to Tebbutt about this: "I cannot understand Mr. Baracchi, these little annoyances occur so often that one is apt to fancy that they are done for a purpose …"

In a later letter, he refers again to Baracchi's mistakes and how "… his methods of procedure are peculiar and irritating to those of us who are careful and exact." (Merfield 1903h)—and this about the Director of the very institution he was still hoping to work at! Further details of the 1903 Grigg Comet incident are provided in Orchiston (1999b).

Late in 1903, and while still at Tumut, Merfield (1903i) was visited for two days by Professor W.J. Hussey (1862–1926) from Lick Observatory, who was in New South Wales "… for the purpose of testing certain places in reference to astronomical observation." (Boss 1903). Although Australia did not secure this southern station, that Hussey should spent time with Merfield is a reflection of his growing reputation in the world of professional astronomy.

One other development of note that occurred in 1903 was that Merfield for the first time had a research paper published in the French scientific journal, *Comptes Rendus* (Merfield 1903f), yet further evidence of his international visibility as an astronomer.

Merfield was still based at Tumut as 1904 dawned, but his prospects of returning to Sydney and a post at the Observatory looked brighter. At the end of December he had spent three days in Sydney, and took the opportunity to visit Lenehan and discuss the directorship (Merfield 1904b). He learnt that other aspirants for the position were the surveyor and fellow-Branch member Thomas F. Furber (1855–1925), Walter Gale, R.P. Sellors, and possibly George Knibbs.

He also learnt that Lenehan was about to offer a number of redundant telescopes for tender, including three 15.2 cm (6 inch) refractors, and that if he wanted one he should be able to secure it for just £40. Merfield (ibid.) wrote excitedly to Tebbutt about this:

> … it is the chance that I may never get again of getting a good instrument at such a small price, the object glass alone in cell is quite worth the money.

Each telescope came with an equatorial mounting and eyepieces, and had been in storage since the 1882 transit of Venus.

Merfield already had half of the purchase price and aimed to raise the balance. Six days later Tebbutt's return letter arrived, and Merfield was surprised, and thoroughly delighted, to find it accompanied by a cheque for £20. Tebbutt explained that this was a loan, to be repaid during 1904, and was specifically for the purchase of the telescope. (Merfield 1904c).

The Tumut posting was due to end in mid-April 1904, and at that time Merfield (1904d) hoped to transfer to the Sydney Observatory, so he was extremely disappointed to learn instead that he was to be made redundant (Merfield 1904e)—a far from welcome 38th birthday present! But first, from 1 May, he was required to take his accrued annual leave (which he estimated to total 5–6 months). This must have been a very bitter blow, after 14 years in the New South Wales Public Service. The only good news, which arrived at about the same time, was that he had tendered successfully for one of the three refractors (a Cooke), and this instrument is shown in Fig. 49. At least he would now be able to carry out those long-intended observations of comets and minor planets (ibid.), but his first priority, quite naturally, was to find alternative employment.

During the last two weeks of April, while still at Tumut, Merfield was deeply involved in correspondence, and trying to obtain some sort of post at Sydney Observatory. Meanwhile, when Cooke heard of his plight, he wrote that

> … he could find me work but he was sorry to say that the salary was not what he would like to offer me, it is only £220 per annum however this would be better than nothing. (Merfield 1904f)

At about the same time, Merfield also received an "extraordinary letter" from Gale (Fig. 30) saying that there was a chance of a position at the Sydney Observatory and that he would help Merfield secure this. Merfield was very suspicious of Gale and his motives as the following letter to John Tebbutt reveals:

> … after careful study of his letter I came to the conclusion that this gentleman had some unknown motive in thus writing so that I had to reply to his letter in an evasive manner, and from which he would gain very little information about my movements in the direction for which I am working. I am quite sure that he is one that would not like to see me a member of the staff of the Sydney Observatory as it would not suit his ideas of the future. I am quite convinced that his letter was written to me with some ulterior motive to suit his own ends, and not from a friendly motive. (ibid.).

Fig. 48 Henry Lenehan, who eventually followed Russell as Director of Sydney Observatory (Adapted from Russell 1892b)

4.4 Good Fortune at Long Last: Life Under Lenehan at Sydney Observatory

When next Tebbutt heard from Merfield, on 21 June 1904, he was at last ensconced at Sydney Observatory (see Merfield 1904g)! After more than eight years of trying, he finally made the transfer to professional ranks, though the claim by Haynes et al. (1996) that this transition came "easily" understates the lengthy succession of frustrations that Merfield was forced to endure.

Nor was this to be the end of such disappointments, for his post was a temporary one: he was simply replacing a "young gentleman" who was on sick leave. Moreover, his salary was a meagre £180 per annum (Merfield 1904h). However, Merfield (1904g) saw this as a start, and hoped that it would lead to a permanent appointment. Lenehan was still recommending Merfield's appointment as Assistant Astronomer and was working to try and convince a new Minister to support this, but he was subsequently informed that new appointments would only be considered after Russell retired (Merfield 1904h).

Under these circumstances, Merfield (1904i) was uneasy about his immediate future prospects at the Observatory, and must have been relieved when he learnt that he would be kept on after the young man returned from sick leave (Merfield 1904j). He had hopes of using the 29.2 cm Schroeder refractor for minor planet observations (ibid.), but as a safeguard was pressing ahead with plans to erect a private observatory for his Cooke refractor (Merfield 1904g), and he discussed the design and construction with Tebbutt (e.g. see Merfield 1904h).

In mid-September 1904, Merfield (1904k) wrote Tebbutt that he was still pursuing the permanent position at the Observatory and that chances seemed to be opening, but

> … there is much intrigue that requires much watchful care to combat. Some who aspire to the position of astronomer of the state are office seekers, the salary attached and not the love for astronomy is their object.

This would suggest that he was still more interested in the top position, once Russell officially retired, rather than the Assistant's post which Lenehan was working hard to secure for him. Merfield (1904m, n) then sought, and received, a letter of support from Tebbutt. He also solicited similar letters from Cooke and Todd, but was disgusted with Baracchi from whom he heard nothing (Merfield 1904p). Merfield certainly had powerful supporters, and he was convinced that if appointed Government Astronomer of New South Wales (and Director of the Sydney Observatory) his energy would enable him to "… give an impetus to our science in this country, that would bring it out of the mire that it has been in for so long …" (Merfield 1904m). In his naivety, perhaps he overestimated his own ability to combat the inertia and political niceties of the New South Wales Public Service! Yet as further evidence of his growing international reputation, Merfield (1904n) heard at about this time that he had been nominated a Fellow of the Astronomischen Gesellschaft in Berlin.

By the end of 1904 there had still not been any progress on the directorship, but at least Merfield (1904q) had heard that he would be kept on at the Observatory

Fig. 49 Charles Merfield and the 15.2 cm Cooke refractor (Courtesy: Melbourne Camera Club)

"… for the time being …", whatever that might mean. He therefore redoubled his efforts to make his Cooke telescope operational, and on 21 December wrote Tebbutt that he had acquired a chronograph and small transit telescope (with an aperture of only 4.1 cm) and had successfully mounted the latter (ibid.), as shown in Fig. 49. He also explained that because of uncertainties over his future at the Sydney Observatory he had been loath to spend money on his own observatory, which was thoroughly understandable.

And so the saga of the Directorship dragged into 1905, and as Russell's retirement approached progress was eagerly anticipated. On 9 February Merfield (1905b) wrote that he had heard that Gale was working away behind the scenes, even though Lenehan was expected to get the post. If this should eventuate, then Merfield assured Tebbutt that he would be happy to serve as Assistant Astronomer.

On 15 March Merfield (1905c) advised that the following decisions had been made: Lenehan would remain in charge but the post of Government Astronomer (and Director) would be kept vacant, and Merfield would be in charge of non-meridian work and on a salary of £300 per annum. There was also a chance that he may get some financial compensation for the poor salary which he had received during the previous nine months. Lenehan (1905) wrote Tebbutt the same day confirming all this. Although the appointments were not yet finalized, he was certain that Merfield would get a permanent position and be responsible for equatorial work.

After such a long struggle this must have been heartening news, even if it did relegate him to number three (rather than two) in the staffing 'hierarchy', but Merfield (1905c) cautioned that these arrangements had still to be formally announced. This caution proved to be justified, for more than two months later Lenehan and the Public Service Board were still at loggerheads over Merfield's appointment. In absolute frustration, Merfield (1905d) wrote to the Board asking for a decision to be made, which may not have endeared him to those already opposed to his appointment.

This whole disgraceful saga dragged on throughout 1905 and played havoc with Merfield's extra-curricula astronomical activities. The computation of definitive orbits of selected comets became a thing of the past and he did not proceed with the construction of his own observatory. What he did do was publish two papers on his work at the Observatory (Merfield 1905a, f) and immerse himself in the activities of the local Branch of the British Astronomical Association. At the 17 October Annual General Meeting, he was rewarded when elected to the Presidency for what would turn out to be two sessions (Reports of the Branches 1905; 1906). After following in the footsteps of such notables as Tebbutt, Knibbs, Roseby, Gale and Macdonnell, all people Merfield knew well and (in most cases) respected, this was a considerable honour, and he threw himself into revitalizing the Branch. More than half way through his second session, Merfield (1907f) was able to claim, with some pride, that

> … there has been much improvement in the work being done by the members and I trust that those interested in Mars will do some good work [during the forthcoming opposition]. I find that our members generally have no idea of the real work of astronomy. I may say however that I have induced several to go in for some work in measurement, as several have very good micrometers.

Towards the end of 1905 he also began to indulge that long-standing interest in minor planets, and initiated a study of the secular perturbation of Eros. This was completed in February 1907 and was published in *Astronomische Nachrichten* (Merfield 1907m), his first substantial mathematical astronomy paper in this journal since 1902. This study tugged affectionately at the heartstrings of Merfield's great love, mathematical astronomy, and after the vocational frustrations of the last few years it was just the research tonic he needed.

As Russell lingered on decisions about Sydney Observatory appointments were postponed, and it was only in May 1906 that Merfield (1906) heard officially that he was to join the permanent staff, but by this time his salary had slipped another £50 to just £250 per annum. It is not hard to imagine his frustration and despair, yet he persevered with his minor planet work and completed two further papers, both about Ceres. One dealt with the actions of all eight major planets and appeared in *Monthly Notices of the Royal Astronomical Society* (Merfield 1907a), while the other examined Jovian influences alone and was published in *Astronomische Nachrichten* (Merfield 1907k).

For Merfield, 1907 proved to be an important year from a number of viewpoints. In February Russell died (Obituary 1907), and when Lenehan was appointed Government Astronomer that put paid to any lingering hopes that Merfield may have entertained in that direction. But at least he still had a position in professional astronomy, even if it was not well paid (Wright 1907a).

The year also produced two new comets which succeeded in dragging Merfield back into cometary astronomy once more. On 8 April John Grigg discovered C/1907 G1 (Grigg-Mellish), his third comet (see Orchiston 1993, for details), and sent his crude positions to Merfield (1907b) who computed preliminary orbital elements

(Comet Notes 1907; Grigg 1907). Grigg also sent a letter to Lenehan announcing the discovery, and Lenehan responded by advising Grigg that the object could not be a comet as its motion was too great! When he learned of this Merfield (1907c) was astonished; this certainly seemed to support his view that Lenehan's knowledge of astronomy was not all it should be.

This 1907 comet also generated further deep concerns over Baracchi's role, for although Grigg cabled him information about the discovery on 10 April this was not disseminated to Australian observers and by the time they got to hear about the comet when it was too far north to observe (ibid.). For his part, Baracchi (1907) was concerned about the imprecise positions supplied by Grigg and so decided to send this information to Kiel by letter rather than cable. But his greatest *faux pas* was that he did not provide Australian observers with details of the discovery so that others could obtain the necessary micrometric positions. In the past, these observations had generally been supplied by Tebbutt (see Grigg 1907) but since his retirement it would seem that no alternative *modus operandi* had been developed.

Merfield, Tebbutt and others decided that something had to be done to rectify this situation, and at the 21 May 1907 meeting of the New South Wales Branch of the British Astronomical Association they discussed Baracchi's "… remissness and want of courtesy …" over the previous ten years (Merfield 1907d) and his recent "… shabby treatment …" of Grigg, Ross and Tebbutt (Wright 1907b). But the meeting, under Merfield's chairmanship, went further, and passed the following motion:

> That the Committee be requested to write to Astronomical Headquarters at Kiel and suggest that Sydney be in future the Australian centre for the dissemination of information concerning comets and other astronomical news. (Merfield 1907e)

The Committee then prepared a long letter to Professor Kreutz at Keil Observatory outlining the nature of the problem, and specifically the "… indifference on the part of the Melbourne Observatory … [which] has been the means of losing many valuable observations." (ibid.). The letter concluded with the recommendation that Sydney Observatory become the recognized Australian 'Central Bureau' (ibid.). By the time the letter reached Germany Kreutz had died and it was Professor Hermann Kobold (1858–1942) who acceded to this request and on 4 August wrote Merfield accordingly (Kobold 1907). Merfield (1907h) immediately sent an English translation of this letter to Tebbutt. Further details of this transfer and the circumstances leading up to it are discussed in Orchiston (1999b).

The other comet to intrude on Merfield's sky and his time in 1907 was Comet C/1907 L2 (Daniel), which was discovered on 10 June 1907 (Marsden and Williams 1996). This subsequently became a spectacular naked eye object, and was observed by many of the Sydney astronomers. On 30 July Merfield described it as like "… a hazy 4th mag. star. In the telescope a well-defined nucleus was seen, surrounded by a coma 5′ in diameter, tail 2½° long, pointing towards Aldebaran." (Crommelin 1908). As might be expected, Merfield went ahead and computed the orbital elements (see Ross 1907), prompting David Ross of Melbourne to write that "Mr Merfield has had a lot of worry with lots of comets appearing on the scene …"

(ibid.). Ross (see Fig. 30) was one of Australia's foremost comet-seeker at this time (see Orchiston and Brewer 1990), and over the years a healthy rivalry had developed between him and the New Zealander, John Grigg.

Back at the Sydney Observatory an important new project emerged which took Merfield and other staff away from observational astronomy, and this was the quest for a new dark sky site (Merfield 1907d). In June Merfield (1907f) advised Tebbutt that Mt. Canoblas (see Fig. 1) had been selected for site testing and that cost estimates had gone up to the Government for consideration. Under Lenehan's gentle guidance, it looked as though the Observatory might finally escape from the severe light-pollution of its city site. But the Government was prepared to go further, for in September Lenehan (1907a) submitted a recommendation for a Grubb 38.1 cm refractor to replace the 29.2 cm telescope and in December this was included in the budget estimates which were passed (Lenehan 1907b). During the brief interval that he had been Government Astronomer of New South Wales Lenehan had made remarkable progress.

But while these promising developments were occurring at the Observatory, Merfield's relationship with Lenehan began to deteriorate. The cause was the 1908 total solar eclipse which Merfield wished to observe, and by September 1907 he had accepted an invitation from Professor William Wallace Campbell (1862–1938) to join the Lick Observatory Expedition to Flint Island in the Pacific Ocean (Merfield 1907g). Lenehan was totally opposed to this and told Merfield that he would place every obstacle in his way. Merfield (1907j) was angered by this, and complained that Lenehan "… is anything but a firm man in his dealings, and is often led into doing things that cause him to regret having done so." Merfield ended up going to Flint Island—without Lenehan's blessing—and helped the Lick party obtain a valuable photographic record of the eclipse (see Merfield 1908a; cf. Pearson 2009; Pearson and Orchiston 2008).

With mounting uncertainty over his future at the Sydney Observatory, Merfield (1907i) thought it prudent to defer construction of his own observatory, even though his friend and architect, James Nangle, had completed the plans for this (Reports of the Branches 1907).

The situation at the Observatory changed dramatically in early 1908 when Lenehan fell ill, and he died on 2 May (Obituary 1908). Although the post of Government Astronomer was vacant (Merfield 1908b), the Public Service Board decided instead that because of seniority the Assistant Astronomer, W.E. Raymond (d. 1912), should be appointed Officer-in-Charge. Merfield (1908c) ever tactful, protested this decision, and was quick to point out to Tebbutt that Raymond knew nothing about astronomy. Merfield still hoped that the Board would eventually appoint a new Government Astronomer and although Todd sent a strong letter of support to the Minister this came to nothing.

Then suddenly another employment opportunity emerged from a long-abandoned quarter: on 21 June Merfield (1908d) excitedly write Tebbutt that

> Mr. Baracchi has offered me a position at £300 per annum in the Melbourne observatory and I feel very much inclined to accept it.

Less than a week later, Merfield (1908e) had a long conversation with the Minister for Public Instruction in Sydney, and indicated that he was leaving Sydney Observatory, but that he wished to be considered for the post of Government Astronomer when it arose. He also recommended that the order for the 38.1 cm Grubb refractor should be cancelled, and this was done.

4.5 With Baracchi and Baldwin: A Stable Future at Melbourne Observatory

On 1 July 1908 C.J. Merfield returned to the home town of his wife's family and started work at Melbourne Observatory under Baracchi. Pietro Paolo Giovanni Ernesto Baracchi (Fig. 12) was born to wealthy parents in Florence, Italy, on 25 February 1851 and studied mathematics and astronomy at school before completing a degree in Civil Engineering. He then served briefly in the Italian Army as an engineer. In 1876 Baracchi and two friends emigrated to New Zealand, but soon moved on to Melbourne. For a short time Baracchi worked at the Melbourne Observatory, but in early 1877 he was transferred to the Department of Lands and Survey as a draftsman and subsequently trained as a surveyor. In October 1882 he was transferred back to the Observatory as Third Assistant. Baracchi was promoted to First Assistant in 1892, and when Ellery retired in 1895 he became Acting Director. It was only at the end of 1900 that his formal appointment as Government Astronomer of Victoria was confirmed. Baracchi was described as a man of "… particularly likeable disposition, with a genius for making friends." (Perdrix 1979: 167). Already of independent means, Baracchi had married the daughter of a wealthy Melbourne citizen (Merfield 1915), and after retiring in 1915 he lived in luxury until succumbing to cancer on 23 July 1926 (Perdrix 1979).

Several months after arriving in Melbourne Merfield wrote to the Secretary of the Royal Astronomical Society:

> I desire to inform you that I have left the Sydney Observatory in complete disgust. I have taken charge of the meridian circle work of the Melbourne Observatory. I am delighted to get into an astronomical observatory, for some time past Mr. Baracchi has been offering inducements to join him so I have at last made the step. I regret that I had to leave a sinking ship, but I have done my best to try and save the wreckage and found the task hopeless. I still trust that my many arguments with the present Minister for Public Instruction will bear fruit. (Merfield 1908g)

Despite this jaundiced point of view, just three months after taking up his Melbourne appointment Merfield noticed an advertisement in the newspapers for the post of Government Astronomer of New South Wales, and although he professed to be very happy in Melbourne he did submit an application. However, given his track record in Sydney, he was not overly optimistic for "… I have been so disappointed, times without number." (Merfield 1908f).

And this proved to be the case once again. The applications were referred by the Public Service Board to the Astronomer Royal. The Board then decided to defer the appointment while the Federal Government deliberated over whether or not it

Fig. 50 Charles Merfield, while at Melbourne Observatory (Courtesy: Melbourne Camera Club)

should take over the State observatories. When it decided not to, the New South Wales Government began its own review of Sydney Observatory's operations, and it was only in 1912 that William E. Cooke (from Perth Observatory) was appointed Government Astronomer of New South Wales (see Orchiston 1988b; Wood 1958).

Meanwhile, Merfield (Fig. 50) settled in happily at Melbourne Observatory and despite some misgivings that Hugh Wright voiced (Public Service Board 1909) about his administration skills he eventually rose to the position of Deputy Director, and served from time to time as Acting Director (see Andropoulos 2014). He continued to carry out his mathematical investigations of minor planets (e.g. Merfield 1909b), to observe comets and compute their orbital elements (e.g. Merfield 1909a, 1913), and to observe solar eclipses (Mr. C.J. Merfield 1932). And, as in Sydney with the fledgling branch of the British Astronomical Association, he played a leading role in the development of the Astronomical Society of Victoria following its formation on 10 June 1922 (see Perdrix 1972).

As we have already noted, Merfield died tragically in a motor accident on 23 January 1931, thus bringing to a premature end the important contribution to Australian astronomy and international mathematical astronomy of yet another ATP.

5 Discussion

When we review examples of prominent non-Australian ATPs mentioned, for example, by Ashbrook (1984b), Chapman (1998), Clerke (1893), Dunlop and Gerbaldi (1988) and Williams (1987, 1988) we note that by the time they transferred to professional ranks most of them already possessed telescopes capable of serious research; that their research programs mirrored those of some of their professional colleagues; and that they published at least some of the results of their research in the leading astronomical journals of the day, *Astronomische Nachrichten* and *Monthly Notices of the Royal Astronomical Society*. In addition, many of these ATPs were involved in the formation or early development of astronomical societies in England, the Continent and the USA, and some received honours, awards and other forms of recognition for their distinguished contributions to astronomy from these same societies. Furthermore, in cities devoid of professional astronomers, before they became professionals these ATPs often ran their private observatories as de facto city observatories, offering the full range of services and facilities normally available from government- or university-funded public observatories: public viewing nights; astronomical and meteorological information (particularly through the local media); a local time service; and public lectures, or even courses, on astronomy. In other words, before they became ATPs, in most respects these leading amateur astronomers were behaving as though they were already professional astronomers, even though they were not yet employed as such, and they were viewed by many of their colleagues and interested members of the general public as de facto professional astronomers. To all intents and purposes, they were professional astronomers in all but name only!

Does this scenario also apply to nineteenth and early twentieth century Australia, where positional astronomy reigned supreme and where professional astronomers were late in recognizing the research potential of astrophysics—both factors that should ideally have enhanced the prospect of leading amateur astronomers joining the ranks of their professional colleagues? Apart from Innes and Merfield, other Australia ATPs were Ellery, White and Nangle, while in 1862 Tebbutt was offered but declined the Directorship of Sydney Observatory and with it the title of Government Astronomer of New South Wales. Who were these astronomers, and what had they accomplished internationally in astronomy when they became professional astronomers or were offered this option?

Robert John Lewis Ellery (Fig. 10) was born at Cranleigh (Surrey) in 1827, the son of a surgeon (W.T.L. 1908). His uncle also was a doctor. After completing his schooling Ellery studied medicine as an apprentice at his uncle's medical practice in London, and subsequently at hospitals in London (Robert John Lewis Ellery 1868). He then worked as a doctor in London, but through friends at the Royal Observatory, Greenwich, developed a keen interest in astronomy and meteorology (Gascoigne 1992).

In 1851 fabulous stories of gold discoveries in Victoria lured Ellery to Australia, and two year later, after successfully lobbying the Government to set up a facility to maintain a local time-service and provide meteorological data he was rewarded when Williamstown Observatory (Fig. 2) was established near Melbourne and he soon became its Superintendent. Note that there is no evidence that he carried out systematic astronomical observations, or promoted the popularization of astronomy through local newspapers prior to this. In 1863 both Williamstown and Flagstaff Observatories closed, and the astronomical, time-keeping, meteorological, geomagnetic and trigonometrical survey functions of the two institutions were centralized in a larger facility, Melbourne Observatory (Fig. 4; Andropoulos 2014). By this time Ellery was the Government Astronomer of Victoria, and he assumed the directorship of this new institution, continuing in this capacity until his retirement in 1895. During this time, Melbourne Observatory snared the 'Great Melbourne Telescope' (Fig. 17; see Gillespie 2011; Warner 1982), and Ellery built his institution into the most prestigious Government-funded observatory in Australia (see Haynes et al. 1996; Orchiston 1988a).

In addition to astronomy, Ellery was particularly active in meteorology and trigonometrical survey work (he was Director of the Geodetic Survey from 1858 to 1874). He was also a leading force in the Royal Society of Victoria, serving on its Council from 1863 to 1905 and as President between 1867 and 1884. He had earlier (in 1859) been elected a Fellow of the Royal Astronomical Society, and in 1873 was honoured when appointed a Fellow of the Royal Society (Obituaries 1909). In addition to his formal duties at the Observatory, Ellery organized and for a time commanded the Victorian Torpedo Corps, and retired in 1889 with the rank of Lieutenant-Colonel (Gascoigne 1992). In this same year he was appointed a Companion of the Order of St Michael and St George (Queen's Birthday Honours 1889). Robert Lewis John Ellery passed away on 14 January 1908, and was survived by his second wife.

Edward John White (Fig. 11) was born in Bristol (England) in 1831, and while working at the Avondale Engine Works in Bristol developed a strong interest in astronomy and added a small telescope to his existing astronomical equipment. He then filled his evenings making astronomical observations (White 1860). In January 1853 White sailed for Australia, like Ellery lured by the Victorian gold fields. But upon arrival in Australia he spent several years living in Melbourne before moving to Bendigo gold field. Once there, he trained as an engineer while supervising the erection of mining machinery (Andropoulos 2014).

Bendigo also offered White a chance to pursue his astronomical interests with the appearance in 1858 of Donati's Comet (C/1858 L1), which was a spectacular naked eye object (see Fig. 51). White made several observations, and sent reports on these to the *Bendigo Mercury*. Late in 1858 he also observed a partial lunar eclipse and an occultation of Venus by the Moon, and once again reports on these were published in the newspaper, which appointed him its Astronomical Correspondent.

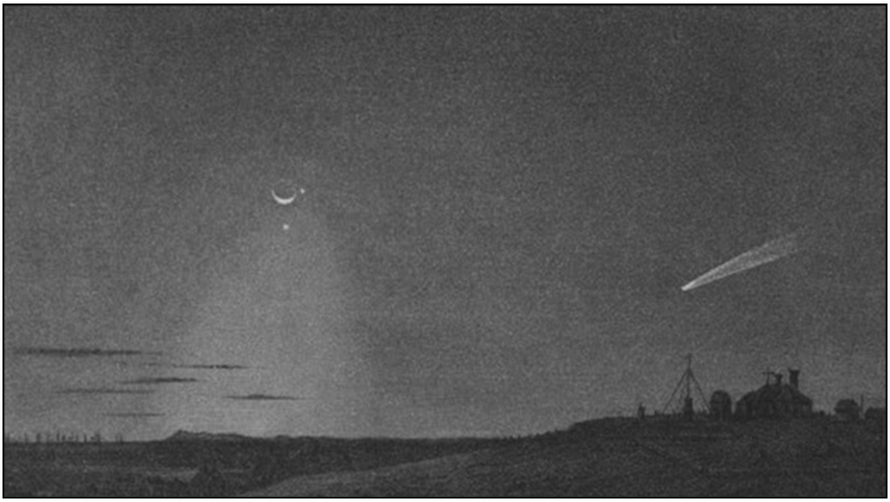


Fig. 51 Comet C/1858 L1 (Donati) was a spectacular naked eye object in Victorian skies (Orchiston Collection)

But these observations brought White an even greater reward, for in 1860 he was offered a position at the Williamstown Observatory (ibid.). Then when Melbourne Observatory was opened, White was appointed Chief Assistant Astronomer, and he subsequently served as Acting Government Astronomer when Ellery was on leave and travelled to Europe for a year in 1874–1875. Like Ellery, White played a key role in the history of the Royal Society of Victoria, serving as the President in 1902–1903 (Personal 1913). He died in 1913.

James Nangle (Fig. 34) was born in Sydney in 1868 and after leaving school at the age of eleven studied architecture at Sydney Technical College (Baracchi 1914; Cobb 1986; The late James Nangle 1941; Mr. James Nangle 1907; Obituary 1942; Orchiston 1988b; Wood 1958). From 1890 he practised as an architect, and in 1905 was appointed Lecturer-in-Charge of the Architecture Department at his old *alma mater*. In 1913 Nangle became Superintendent of Technical Education for the State of New South Wales, and proceeded to totally reorganize technical education.

Nangle had a long-standing passion for astronomy, and maintained a private observatory with a 16.5 cm refractor (see Orchiston 1997b). This was used for a variety of observational programs, but with the emphasis on double stars. Nangle wrote a number of descriptive papers on his work, and these were published in the *Journal of the British Astronomical Association*.

After Cook's resignation from Sydney Observatory in 1925 the Board of Visitors appointed Nangle to succeed him as Director, and it is largely to his credit that the institution was able to survive the difficult years of the Great Depression (Wood 1958). Nangle also was interested in popularizing astronomy, and while at Sydney Observatory he wrote his well-known book, *Stars of the Southern Heavens* (Nangle 1929).

James Nangle (or 'Jimmy' to his friends) was a Fellow of the Royal Astronomical Society, and in 1920 received an Order of the British Empire. He served one session as President of the Royal Society of New South Wales and as President of the Royal Australian Institute of Architects, and was a Fellow of the Royal Institute of British Architects. He died in 1941 while still in office at Sydney Observatory, having exerted "… important influence in this State [New South Wales] in the fields of architecture, education and astronomy." (Obituary 1942).

Although an amateur and self-taught, John Tebbutt (1834–1916; Fig. 27) was Australia's leading astronomer during the last three decades of the nineteenth century (see Ashbrook 1984a; Bhathal 1993; Orchiston 1988g; White 1979). He lived on the outskirts of Windsor, an historic town about 60 km north-west of Sydney, where he combined a lifetime interest in astronomy with farming. During the 1850s he used the naked eye, a marine telescope and a sextant to observe sunspots, aurorae, meteors, lunar eclipses and occultation's, Jupiter's satellites, comets, and the variable star Algol. He also taught himself the mathematics required to compute comet orbits, and began publishing astronomical reports in the Sydney newspapers (Orchiston 1998c).

On 13 May 1861, Tebbutt detected a faint nebulous object in Eridanus. Comet C/1861 J1, otherwise known as the Great Comet of 1861 (see Fig. 22), developed into one of the most magnificent comets of the century, featuring a tail more than 100 degrees in length at its prime (see Orchiston 1998b). It was publicity relating to

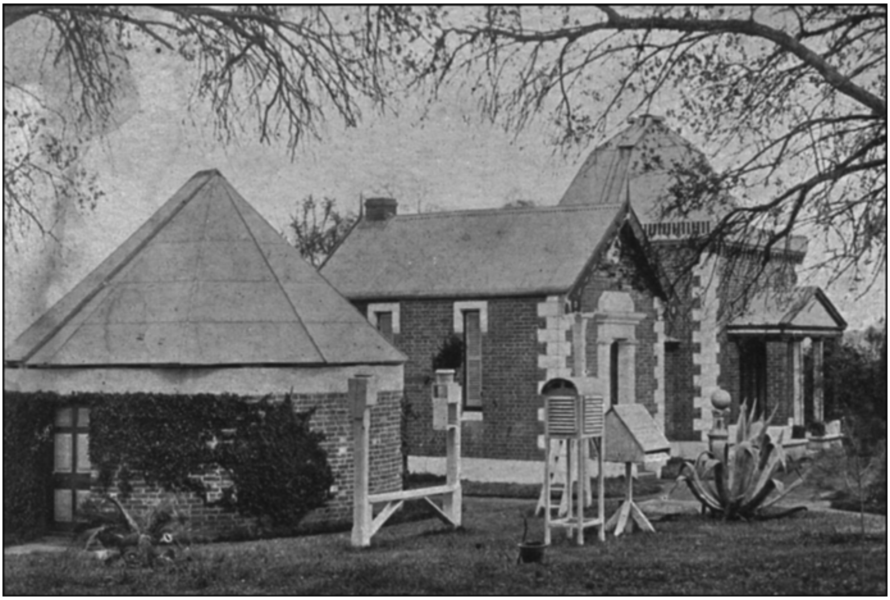


Fig. 52 Two of the three Windsor Observatory buildings in 1908. The foreground dome housed a 20.3 cm Grubb refractor (Orchiston Collection)

this discovery and Tebbutt's previous observational track record in astronomy that led to the offer of the Sydney Observatory Directorship (see Orchiston 1988e, 1998c), and it also inspired Tebbutt to purchase a small English-made refractor and construct the first of the four buildings that would comprise the Windsor Observatory (Fig. 52; Orchiston 1988d).

Subsequently, Tebbutt furnished his observatory with ever-larger refracting and transit telescopes and ancillary instrumentation (see Orchiston 2001b for details); installed a full suite of meteorological instruments; established a local time service; and between 1863 and 1903 conducted an amazing range of observational programs that continued thereafter intermittently through to 1915, one year before his death (Orchiston 1982b, 2004a). His main interest was in comets, and he discovered another 'Great Comet' in 1881 (Fig. 23; Orchiston 1999a), but he also regularly observed lunar occultations, asteroids, the planets, double stars, variable stars (e.g. Fig. 53; Orchiston 2000b), solar and lunar eclipses, and much less frequently lunar occultations of planets, and transits of Mercury and Venus (e.g. Fig. 54; see Orchiston 2004b).

Tebbutt reported his observations and developments at Windsor Observatory in two books and 323 research papers (many of which were published in *Astronomische Nachrichten* and *Monthly Notices of the Royal Astronomical Society*). His *Annual Reports* of the Windsor Observatory were produced as booklets from 1888 to 1903 (inclusive). He also authored two chapters for books by other authors, eight meteorological monographs, a number of booklets on the relationship between astronomy

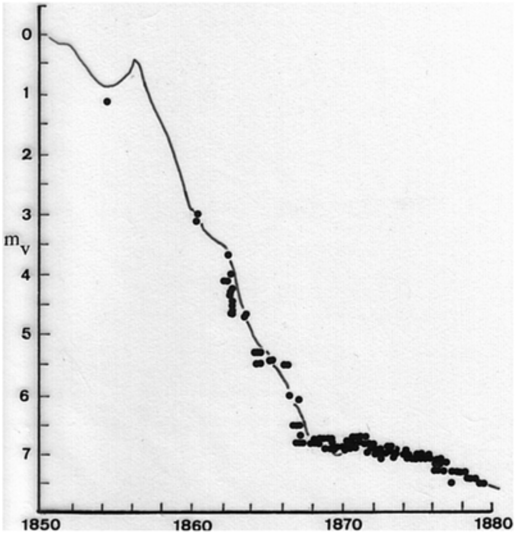


Fig. 53 Tebbutt's observations of the luminous blue variable, Eta Carinae (After Orchiston 2000b)

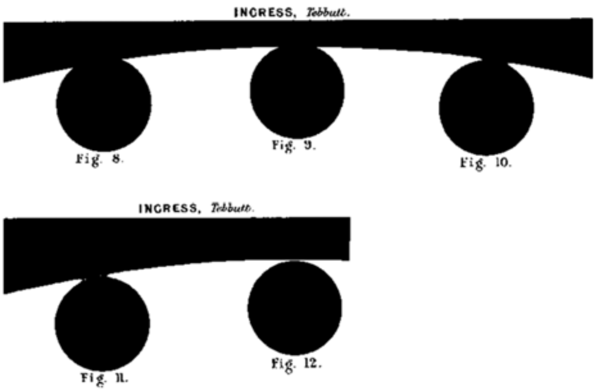


Fig. 54 Tebbutt's observations of the ingress of the 1874 transit of Venus (After Tebbutt 1883)

and religion, and hundreds of newspaper articles to popularize astronomy, altogether a phenomenal output for a one-man observatory (see Orchiston 1997a, 2004a).

Tebbutt was a member of the Philosophical (later the Royal) Society of New South Wales from 1861 and a stalwart of its short-lived Astronomy Section (see Orchiston and Bhathal 1991), and a Fellow of the Royal Astronomical Society from 1873. In 1882 he founded Australia's first formal specialist national astronomical group, the short-lived Australian Comet Corps (Orchiston 1982a, 1998a). When the New South Wales Branch of the British Astronomical Association was founded in 1895, he was elected its inaugural President (Orchiston 1988c). By 1869 the Windsor Observatory was included in the *Nautical Almanac's* listing of world observatories. In 1867 the Government presented Tebbutt with a Silver Medal and in 1905 he was awarded the Jackson-Gwilt Medal and Gift by the Royal Astronomical Society. Much later, in 1973, the International Astronomical Union arranged for lunar crater Picard G to be renamed Tebbutt, and in 1984 Tebbutt's portrait featured on a new Australian $100 bank note.

From the 1870s, Tebbutt's status as Australia's leading astronomer led increasingly to a bitter feud with the then Director of Sydney Observatory, Henry Chamberlain Russell (Fig. 18), that only ended in 1907 with Russell's death (for details, see Orchiston 2002). Despite modest equipment, Tebbutt was able to make valuable contributions to observational astronomy, and he played an important role in the development of Australian astronomical groups and societies and more than any other nineteenth century Australian astronomer helped popularize astronomy. He was a remarkable scientist, running his Windsor Observatory as a "… one-man Greenwich Observatory in the Southern Hemisphere." (Ashbrook 1984a). It is clear that Tebbutt could have made the transition to professional astronomy any time subsequent to 1862, if he wished to and if again given the opportunity. But to most Australian and many overseas astronomers, Tebbutt was a professional in all but name only, and that, presumably, was enough for him.

Let us now refer to Table 9, which summarizes the distinctive attributes that characterized the afore-mentioned Australian amateur astronomers when they made the transfer to professional ranks, or in Tebbutt's case were offered this option. The astronomers are listed chronologically, with the year they became or could have become at ATP shown below each name. The table then summarizes the following attributes, as at the ATP date in each case:

(1) Did they have a private observatory and/or astronomical instruments that were comparable to those found at the time in the Australian Government observatories?
(2) Had they been carrying out serious astronomical observations or other research?
(3) Were they publishing their results of their research in the leading astronomical journals of the day?
(4) Were they involved in establishing and/or fostering the subsequent development of new formal astronomical groups?
(5) Did they conduct public viewing nights at their observatories?
(6) Did they maintain meteorological stations at their observatories, and make results available through the local media?
(7) Did they offer public lectures and/or courses of lectures on astronomy and/or allied disciplines?
(8) Did they offer astronomical (and perhaps other scientific) information to the public and/or other astronomers through personal contacts and the local media?
(9) Did they maintain an astronomical clock which was regulated by regular transit telescope observations, and offer a time service for citizens of and visitors to their city or town?
(10) Were they involved in lobbying the Government to set up or maintain a local properly-equipped and professionally-staffed astronomical observatory?

Table 9 Criteria involved in the transfer or potential transfer of Australian amateur astronomers to professional ranks

Criterion		Ellery (1853)	White (1859)	Tebbutt (1862)	Innes (1896)	Merfield (1904)	Nangle (1925)
(1)	Observatory and/or instrumentation	x	✓	✓	✓	✓	✓
(2)	Serious observing or research programs	x	✓	✓	✓	✓	✓
(3)	Publications in leading journals	x	x	x	✓	✓	✓
(4)	Society involvement	x	x	x	✓	✓	✓
(5)	Public viewing nights	x	x	x	(x)	(x)	(x)
(6)	Meteorological centre	x	x	x	(x)	(x)	(x)
(7)	Public lectures/courses	x	x	x	x	x	✓
(8)	Information source	x	✓	✓	✓	✓	✓
(9)	Local time service	x	?	x	(x)	(x)	(x)
(10)	Political lobbying	✓	x	x	✓	x	✓

The crosses in brackets shown in the Innes, Merfield and Nangle columns for attributes (5), (6), and (9) indicate that since these three astronomers resided in Sydney and Sydney Observatory already offered these public facilities there was little logic in their also offering them.

When we review the entries in Table 9 it is apparent that timing, the available competition for newly-created positions and an element of good luck, rather than a distinguished international record in astronomy, were sometimes enough to allow one to move along the ATP continuum. Thus, Robert Ellery was able to secure the directorship of one of Australia's earliest government-funded observatories by astutely using the media to lobby the Victorian Government to establish a time-service for the rapidly-growing population of Melbourne and Williamstown, even though he could display no prior published track record in observational astronomy or in the public promotion of astronomy. But as an intelligent man with a knowledge of astronomy, friends at the Royal Observatory in Greenwich, and some observational experience acquired in England, he was the right man in the right place at the right time, and in the absence of any other obvious contenders was the obvious choice as Superintendent of this important new facility. Thus he relatively quickly and easily was able to achieve the goal that he had set himself when he emigrated to Australia, of abandoning medicine and obtaining a professional position in astronomy (see Robert John Lewis Ellery 1868).

Likewise, Edward White was in the right place at the right time. Ellery needed an Assistant at the Williamstown Observatory, and White's accounts of his astronomical observations that appeared in the Bendigo and Melbourne newspapers in 1858—especially of Donati's Comet which by this time was a spectacular object and was attracting considerable public attention (Fig. 51)—showed that he was the ideal man for the job. Yet, like Ellery, at this time White had no international visibility as an astronomer.

Tebbutt, however, was in a stronger position as a contender for the Sydney Observatory directorship in the face of Scott's premature retirement (see Orchiston 1998c). By 1862 Tebbutt had more than a decade's experience in conducting a wide variety of astronomical observations—albeit with very modest instruments—and he also had an excellent track record of reporting these observations in the Sydney newspapers and of forewarning members of the general public about up-coming astronomical objects and events of possible interest. Clearly his discovery and subsequent monitoring of what proved to be the Great Comet of 1861 also brought him considerable publicity (see Orchiston 1998b, c for details), and the fact that he had effectively taught himself the mathematics required to compute the orbit of this impressive object and earlier comets he had observed showed he possessed the requisite mathematical prowess required of a professional astronomer. Yet Tebbutt made a conscious decision to achieve an international reputation as an independent (i.e. amateur) astronomer, and he went on to achieve just this. Thus, within twenty years of refusing the Sydney Observatory post he had succeeded in satisfying attributes (3) to (7) and (9) in Table 9, and attribute (10) came a decade later, so had Tebbutt been offered a professional position in astronomy in 1892 his column would have featured a full complement of ticks, comparable to the records displayed in this Table by Innes and Nangle, and to a slightly lesser degree by Merfield.

Timing therefore played a crucial role in determining the potential for an Australian-based amateur astronomer to become an ATP, for by the 1890s this transition was no mere formality, even given a distinguished international record of research and publication and strong support from other leading Australian astronomers, as both Innes and Merfield discovered. In each case their quest to become an ATP took many years, and involved considerable frustration, and in Merfield's case what he perceived to be a succession of broken promises. Both astronomers also accepted considerable reductions in their respective incomes by accepting posts in professional observatories. But they were willing to make these financial sacrifices in exchange for the opportunity to work full time in astronomy.

Nangle was in a somewhat different position to Innes and Merfield in that he never hankered to achieve a professional position in astronomy, and probably he did not suffer financially in making the transition. All along he seemed happy to pursue his astronomical interests as an amateur, effectively using his telescope for a variety of observations, publishing these in the *Journal of the British Astronomical Association* (which was the appropriate journal for his kind of astronomy), and effectively promoting astronomy as a leading member of the New South Wales Branch of the British Astronomical Association. But with Cooke's unexpected resignation and financial and political challenges to the fore the Government needed as much an astute entrepreneur as an accomplished astronomer for the Directorship if Sydney Observatory was to survive, and through his highly successful and innovative role as Superintendent of Technical Education for the State of New South Wales Nangle had shown himself to be precisely that type of man. Besides, he also had intimate knowledge of the New South Wales Public Service and extensive political contacts. So in the case of Nangle's appointment, non-astronomical considerations also were important factors.

6 Concluding Remarks

The 'amateur-turned-professional' (ATP) was a distinctive feature of nineteenth century and early twentieth century international astronomy, and in an era where positional astronomy still reigned supreme Australia also had its fair share of ATPs. Two of the most prominent of these were Robert Innes and Charles Merfield, both of whom resided in Sydney and were very active in observational and computational astronomy. Both published prolifically in leading international astronomical journals in their respective quests to work in professional astronomy. Ultimately, both men were successful in achieving their dreams, but in each case it took much longer and proved far more challenging than they could have imagined. And for both, becoming an ATP also involved considerable financial sacrifice.

But while the case of Innes and Merfield may mirror those of other distinguished overseas amateur astronomers, some of their Australian colleagues found it much easier to become ATPs. Thus Robert Ellery and Edward White both gained employment at the newly-founded Williamstown Observatory—Ellery as Superintendent and ultimately Director—yet at the time neither could boast an international reputation as an astronomer. One who could was John Tebbutt, but in 1862 he turned down the offer to replace Scott as Director of Sydney Observatory, while much later, in 1925, the distinguished Sydney amateur astronomer, James Nangle, accepted this post, but as much because of his political and managerial acumen as his astronomical record.

These examples demonstrate that no hard and fast rule can be applied to the ATP syndrome. Each case must be examined on its own merits, and it was not always necessary for an amateur astronomer to have an impressive observatory, a strong track record of research with publications in leading professional journals, or to have played a key role in the formation and/or development of new astronomical groups and societies in order to travel down the ATP continuum. Sometimes, timing, the presence or absence of other contenders for a new position, and an element of luck could also be critical factors.

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