PAUL MURDIN

Rock Legends

THE ASTEROIDS AND THEIR DISCOVERERS

Springer

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Fig. 1.1 *Chelyabinsk bolide. The trail of smoky dust left by the Chelyabinsk bolide as it passed over the city and exploded (Illustration by Nikita Plekhanov. Used with permission)*

Chapter 1

My Asteroid, My Book

ARRESTED DEVELOPMENT OR CHIP OFF THE OLD BLOCK?

Orbiting somewhere in the space between the planets Mars and Jupiter there is a big rock on which there is the name of this writer, Paul Murdin, (128562) Murdin.[1] The rock is called "(128562) Murdin." It is the 128,562nd asteroid in the census of confirmed asteroids. (An asteroid's number in the list is placed in parentheses before its name.) It was discovered on August 10, 2004, by the Lowell Observatory Near-Earth Object Search (LONEOS) at the Anderson Mesa Station in Arizona. When it was discovered and its orbit was first determined, it was given an earlier, provisional catalog number: 2004 PM90. The designation has my initials in it, which is why this particular asteroid was chosen for me. An asteroid was seen near the expected places in the orbit of 2008 PM90 during the next season for being able to view it, so it was safe to assume that it was my asteroid seen again. In fact, my asteroid has been seen and measured over 100 times since discovery. This means that its orbit is well determined. Because its orbit is well known, my asteroid can be tracked indefinitely by any astronomers who become interested in it. They will not be able with an Earth-based telescope to see its surface—it will be just a point of light like most other asteroids—so it will be impossible to recognize its features. But because it is in the right place at the right time, it can be recognized indefinitely into the future. Thus, it has become recognized as a permanent entry on our census of the Solar System. That is how it has been given its accepted status and not only re-numbered but also named as asteroid (128562) Murdin.

The Jet Propulsion Laboratory in Pasadena, California, keeps a Small-Body Database that lists and shows the orbits of minor planets and comets, and other data. You can visit the database at http://ssd.jpl.nasa.gov/sbdb.cgi. The International Astronomical Union sponsors the Minor Planet Center in Cambridge, Massachusetts, with pages of data on minor planets at http://www.minorplanetcenter.org/iau/mpc.html.

Asteroids are minor planets. Within our Solar System there are eight planets recognized as such by astronomers, namely Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune, all of them large, solid and gaseous bodies orbiting the Sun. There are also innumerable, considerably smaller, solid, icy bodies orbiting the Sun; these include asteroids, which are icy rocks, and comets, which are dirty lumps of ice. The modern, technical name for all these objects is "small Solar System bodies." The early, still common and more elegant, but now informal, name for them is "minor planet," which I often use in this book.

Some minor planets jaywalk across the orderly, almost circular flow of the normal traffic of planets in the Solar System. Accidents happen, and sometimes a planet and a minor planet collide. The collision could be a small bump or a devastating crash.

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[1] Where possible, the number and name of any asteroid that is named after a person will follow that person's name. See the JPL Small Body Database, referred to above, for further biographical details about the person, such as dates of birth and death.

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_1

The smallest collisions between minor planets and Earth are called "meteors." If a very small minor planet (less than pea-sized) collides with Earth, it burns up in the atmosphere, causing a streak of light. Its dust drifts unidentifiably to the ground, adding a hidden cosmic zest to the carrots that grow in the garden. At the present time about 40,000 m. tons of meteorite dust fall on Earth each year, but of course it is spread thinly and hard to identify on the ground. High-flying aircraft, exposing sticky material to the air like flypaper, can catch meteor dust. A lot of it is ground up bits of asteroids; some of it is dirt loosened from the ice of comets when they melted.

If a larger asteroid (pea- to pebble-sized) collides with Earth, it will make a very bright meteor (a "fireball"). A boulder-sized asteroid (called a "bolide") may break up as it traverses the atmosphere and fracture into many pieces that run parallel as they streak through the sky.

The most dramatic bolide of recent times was the meteor that entered the atmosphere at a shallow angle over Alaska, streaked across the sky in a 30 s journey, and disintegrated over the city of Chelyabinsk near the Ural Mountains in central Russia on February 14, 2013. It was recorded by many Russians who had video cameras mounted on their cars (as a measure to record road incidents). Leaving a white trail in the sky (Fig. 1.1), the Chelyabinsk bolide seemed as bright as the Sun as it exploded at an altitude of about 35 km (20 miles). It carried an explosive power equivalent to ten times the atomic bombs of the Second World War. The boom of the explosion broke windows in numerous buildings and knocked people over; flying glass and other debris injured about 900 people. The asteroid that became the meteor was probably about 17 m (55 ft) in size with a mass of 10,000 m. tons. The event was of a size that occurs once per century on average. There was no warning of this event, because the asteroid was too small to be detectable at a distance large enough to be able to see it coming before it arrived.

Another well-recorded bolide of recent times was the Peekskill bolide, which flew eastwards across Kentucky, North Carolina, Maryland and New Jersey at 8 o'clock in the evening on October 9, 1992. It was witnessed by many Americans, some of them watching football games with video cameras in their hands, and at least 16 video records are known. The ill-fated space shuttle *Columbia* took on the appearance of a bolide when it disintegrated on re-entry in 2003.

Some pieces of a bolide may fall to the ground. What might then be found is typically a stony or metallic lump of rock called a "meteorite." Pieces of the Russian bolide were collected from the ice-covered ground and from a lake at the end of the trajectory of the largest piece, which had a mass of 654 kg (1442 lb). The Peekskill bolide ended up as a 12.4-kg (27-lb) meteorite that plunged through the trunk of a red Malibu coupe car, one of the few cars whose value has been increased by dented bodywork.

Between 18,000 and 84,000 meteorites bigger than 10 g (one third of an ounce) fall on to the surface of Earth each year. Most sink to the bottom of the ocean, hide in vegetation or become mixed into the litter of rocks on the ground and are never found. Meteorites are very easy to spot when they land on an ice-field. That is why most of the meteorites that have been collected have been picked up in Antarctica. The largest known intact meteorite was found, buried, by a farmer ploughing his land on the Hoba West farm in Namibia. The Hoba meteorite is shaped like a flat slab, 3 × 3 × 1 m in size (9 × 9 × 3 ft), and its mass is more than 60 m. tons. It fell perhaps 80,000 years ago. It still lies where it fell, exposed in a crater. The crater is however not a meteor crater, excavated by the fall. It is an amphitheater that has been dug around the meteorite, the better to display it to tourists and school parties.

If an even larger minor planet collides with Earth, one larger than say 50–100 m (150–300 ft) in diameter or more, it will puncture a fiery hole right through the atmosphere and, if it impacts on the ground, it will do so with such force that it makes a crater. There are a few hundred meteor craters on Earth; it is hard to be precise about the number because the weather and other erosion processes work over geological time to make craters hard to recognize. The Barringer meteor crater near Flagstaff in Arizona is 1.2 km (4000 ft) in diameter and was the result of a recent strike, only about 50,000 years ago, of an asteroid of that size. The plain around the crater is littered with fragments of the asteroid that made it; many fragments have been collected, and there are fewer now than there used to be.

If the minor planet is smaller (10–100 m in size, 30–300 ft), or made of rather weakly bound rock (perhaps bits of solid rock, frozen together with a lot of ice), it might disintegrate in the atmosphere, but in doing so it might cause an airburst with enough power to cause local damage. A minor planet (or comet) about 30–40 m (100 ft) in diameter created an airburst over the Tunguska River in Siberia in 1908 that stripped the branches off all the trees below, and toppled many, for a radius of 4 km (3 miles). The toppled trees are still visible today. The Tunguska bolide caused damage in the forest out to a distance of more than 30 km (20 miles), fully evident when the first scientific investigation of the impact was made in 1927 by the Russian mineralogist and meteoriticist Leonid Kulik, (2794) Kulik.

An asteroid of about the same size as the Tunguska minor planet passed close to Earth on February 14, 2013, coincidentally on the same day as the Chelyabinsk bolide fell to Earth. 2012 DA14 had been discovered almost exactly a year earlier from an observatory in Granada, Spain, and, traveling northwards, passed 27,700 km (17,200 miles) above the surface of Earth near Indonesia, the closest recorded approach for an object so big. Its trajectory took it inside the orbits of the geostationary artificial communications and meteorological satellites that provide continuous coverage over regions of Earth. Had it impacted Earth over an inhabited area, it would almost undoubtedly have caused casualties.

If an asteroid is very large, kilometers or miles in size, say, the crater that it would make on collision with Earth would be of considerable size; impact craters made on Earth by minor planets this size range up to 300 km (200 miles) in diameter, including the famous Chicxulub Crater in Yucatán, Mexico. This crater, the third largest meteor crater known on Earth, is 170 km (110 miles) or more in diameter and was created by an asteroid 10 km (6 miles) in diameter. The impact energy of such an asteroid would be equivalent to the simultaneous explosion of many, many times the world's entire nuclear arsenal. An impact like this could destroy an entire region, including the living things in it. Its effects would include vast clouds of dust that would spread over the world, causing serious climate change. This could result in the mass extinction of whole species. This happened when the Chicxulub asteroid struck 64 million years ago and helped make the dinosaurs extinct. If the asteroid plunged into the ocean, it would create a tsunami that would destroy the coastline of the surrounding continents.

An asteroid orbiting round and round the Sun in space that comes as close to Earth as one third of the distance between Earth and the Sun is called a Near-Earth Asteroid (NEA, or NEO, the O for "Object"). An asteroid that ever comes as close of 5 % of that distance, and is greater than 140 m across (460 ft), is called a Potentially Hazardous Asteroid (PHA). It is pretty certain that if an asteroid of 140 m diameter strikes Earth, it will reach the ground in one piece and make a crater. If an asteroid larger than this impacts Earth, to call it a "hazard" is scientific understatement.

I would not like to have my name on an asteroid that could wipe out the human race, however distant the prospect. Fortunately, I can take unalloyed pleasure in my modest association with my own large rock. It is certain that my asteroid is not a near-Earth asteroid, nor is it a potentially hazardous asteroid (PHA).

I did not discover this asteroid, nor have I ever worked on finding out about it. I am associated with this particular asteroid only because people kindly offered to name an asteroid after me, in recognition of my work in astronomy over the last 50 years, both research and administration; and because astronomers like their colleagues to write books such as this one that reach out and try to help people understand what astronomy is about. The asteroid has my name on it, but, given its orbit, I am not worried that this bullet will ever be fired at me, or those who come after me.

I don't know precisely how large my asteroid is, but it is pretty average. What can be said with some certainty is how bright it is. In the catalogs it says that, placed a standard distance from the Sun, such that it is illuminated in a certain way, and viewed from a standard distance in a certain orientation, it is like a star of magnitude 15.6. Imagine that the asteroid replaces Earth in its orbit and we are viewing the asteroid from the surface of the Sun. It would look like a star of magnitude 15.6. However, this is all a bit misleading. The problem is not only that nobody can stand on the surface of the Sun but also that the asteroid never puts itself in the standard conditions.

My asteroid is always further from the Sun than it is from Earth. In practice it never gets brighter, as seen from Earth, than magnitude 18.3. That is quite faint. I have only seen my asteroid in a picture taken by someone else, but in principle I could see it myself only if I looked through a hefty telescope with a lens or mirror with a diameter more than 40 in. (100 cm, say) (Fig. 1.2).

Asteroids generate no light for themselves; they reflect sunlight. The bigger an asteroid is the more sunlight it reflects and the brighter it appears, so there is a relationship between magnitude and surface area. From this relationship, I can estimate the size of my asteroid, but I need to know how effective it is in reflecting sunlight. If it is covered with white ice and reflects 80 % of the light that falls on it, it is small. If it is black like coal and reflects 4 %, it is larger. My asteroid is a stony composition and reflects quite a large fraction of the sunlight that falls on it, perhaps 20 %. If it were spherical, it would be perhaps 1.8 km (1.1 miles) in diameter.

The area of my asteroid is perhaps 10 sq. km (4 sq. miles), as large as one or two European countries—Gibraltar and Monaco. Few countries and territories (none at all?) are regular shapes. Likewise it is almost certain that my asteroid is not spherical; it is likely to be an irregular, potato-like, rocky shape. And it is more like a mountain than a country—or both, as in a volcanic island, such as Pitcairn Island (area 5 sq. km, 2 sq. miles). I like the thought of these comparisons. In one of my less modest, and completely unjustified, fantasies, I like to put myself on a par with those kings and queens, dukes and duchesses, presidents and explorers who have countries and territories named after them—Victoria, the Falkland Islands, Louisiana, Virginia, Alberta, Bolivia, Rhodesia, Washington, the Cook Islands…

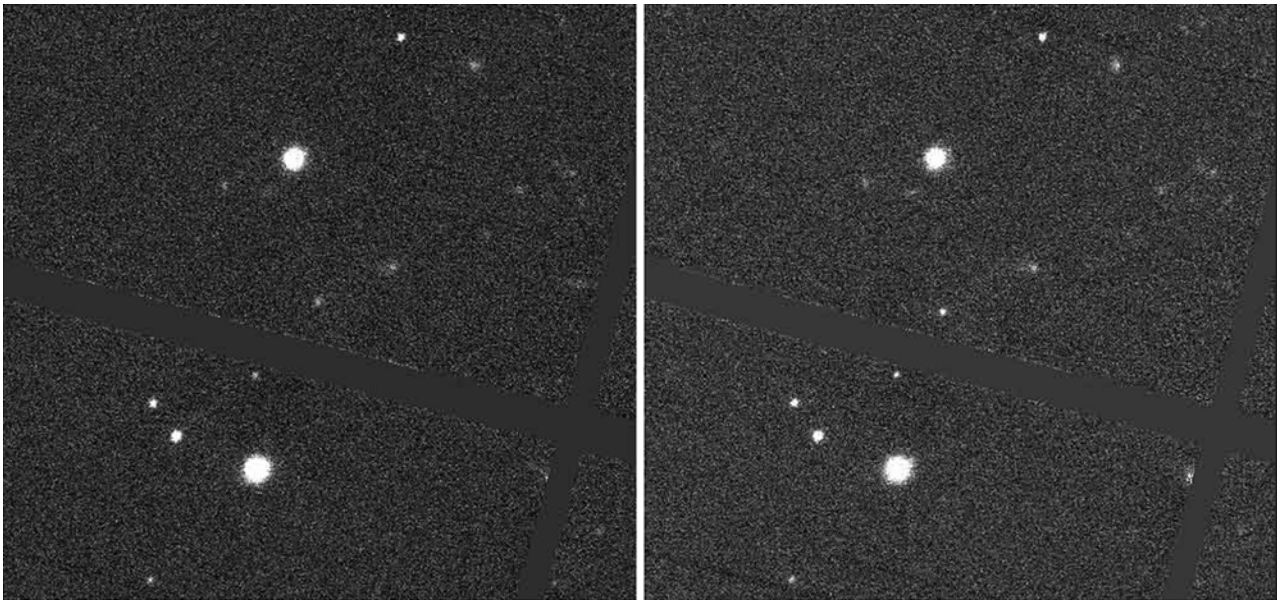

Fig. 1.2 Two views of asteroid (128562) Murdin moving among the stars. The asteroid is the central "star" that has moved a little bit down and to the left in the right-hand shot. Alan Fitzsimmons took these two pictures with the Pan-STARRS telescope on Hawaii. (Picture by courtesy of Alan Fitzsimmons, QUB)

I float off into a reverie, inspired perhaps by stories of living on a tropical desert island. I could settle there, for the peace and quiet. Maybe my asteroid has valuable minerals that I could mine and become rich, just as Ben Gunn dug up wealth from Treasure Island in Robert Louis Stevenson's story. Maybe, if I really controlled my asteroid, I could create a spacecraft docking station and charge the space agencies to moor there. I wouldn't have to live there to do this, but if I did, maybe I could establish an interplanetary service station.

I wake up. Life here on Earth is good and would have to become very bad indeed to make it better to live on a dry, dusty, sterile, airless asteroid, its surface exposed to the glare of the Sun, deadly cosmic rays, and the impact of other asteroids. On my asteroid I would have to be careful not to move too impulsively, in case I leapt off the asteroid by mistake, escaped its weak gravity and went drifting off, untethered, into space. Marooned on a desert island, like Ben Gunn, I would find it difficult to get away. Marooned on my asteroid, I imagine myself escaping too easily!

I come back with a bump from my reverie, returning to Earth and scientific reality.

I do not think that my asteroid is a very scenic place. It is made of a stony rock (silicate minerals, akin to quartz or the material of which a typical sandy beach is made), which reflects sunlight with characteristics that give it a classification of "S-type." S-type asteroids comprise 17 % of the asteroid population in the Main Belt of asteroids between Mars and Jupiter at distances of 1.5 and 5.2 times the distance of Earth from the Sun, so my asteroid is not a rare kind. My asteroid has an average distance from the Sun of 2.77 × the Earth-Sun distance, so if I lived there I would see a smaller, weaker Sun. Its orbit is quite elliptical, and its distance from the Sun changes over the 1689 days of its orbit by ±12 %. I would notice how the Sun gets larger and smaller, and the temperature would be rather seasonal. The average temperature of the surface is –70 °C (–100 °F), with a maximum temperature a balmy minus –20 °C.

Minor planets are a mixed bunch. Some are old bits of material leftover from the formation of the planets. The planets formed from a disc-like nebula of gas and dust that formed around the newly born Sun. The dust in the solar nebula stuck together and built up into bigger and bigger lumps. Jupiter, the giant planet on the outer edge of the Main Belt, grew so large that it had an inhibiting effect on this process. It kept stirring up any material that was close, and stopped the material from gathering into really big lumps. So Jupiter inhibited the formation of a single planet in the Main Belt, but this region is still populated by the small lumps. These asteroids are planets that, like Peter Pan, never grew up. Herded and jostled together in a confined region of space for billions of years some of these asteroids have collided and broken into pieces. These fragments made further small asteroids.

S-type asteroids can be either of these two sorts. Perhaps my asteroid is a small planet with arrested development. Or maybe it is a descendant of such a planet, a chip off the old block.

If asteroids are scraps and broken bits, why do astronomers think they are important enough to study? They were not always well-regarded. Astronomers once regarded them as the "vermin of the skies." But astronomers have completely changed their attitudes. Asteroids are now thought of as key to the early history of the Solar System. But how do you read history from rubble?

If there are no reliable documents, as is the case for much of the distant past, historians turn to archaeology. What, for example, was the history of the Trojans? We can read Homer's *Iliad* about the siege of the city of Troy, but the *Iliad* is a heroic poem, not a factual account to be relied on. For the history, we'd do better to read the account by Heinrich Schliemann, a wealthy German businessman and archaeologist, about his excavations of the city.

The excavation site was almost ideal: orderly, undisturbed and layered. The palace and the religious precincts of the city sat at the summit of a hill, and the sprawl of commercial and residential buildings below show the political hierarchy of the site, from the governors to the governed. Walls and gates delineate zones of the city inhabited by the social and occupational classes of the civilization that built the city—villas, commercial premises and tenements. The walls of the royal precincts were used by later peasants to make farm buildings offsite, but the foundation stones are still there, showing in map form how the civil buildings were laid out and how government functioned. The more recent buildings are layered over the earliest simple houses and encampments that show the development of the city over time.

Rubbish heaps are the opposite of orderly, but they, too, were rewarding places in Troy for the archaeologists to investigate and reveal the way of life of the Trojans. They contained abandoned building material, shards of pottery, bones and other food waste, broken household items, keys no longer needed, worn clothing, irreparable shoes and a few lost items of jewelry and coins. Some discarded items had been brought from distant regions and showed how the people of Troy interacted (by trade) with other peoples across the eastern Mediterranean.

The rubbish heaps contained everyday material that was simultaneously archaeological treasure. They revealed the history of the city and the way of life of its people, even if the evidence was all mixed up.

So, likewise, some astronomers study the major planets of the Solar System to see what they might reveal about its origins and history. The eight major planets—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune—are the orderly and massive governing features of the Solar System. They delineate its architecture, its functioning under the rule of gravity.

However, an increasing number of astronomers study the majority of the bodies of the Solar System, the minor planets. The major planets herd them together so that they congregate in permitted zones. There are other zones into which minor planets venture only seldom and briefly.

The minor planets constitute both the governed masses of the Solar System and the discarded items from its construction and use. The minor planets are small planets, comets, asteroids and meteoroids. They are planets that never grew up, solid icy fragments. They are broken rocks from the insides of planets that collided and split up. They are rocky bits of planets that separated because they were made to spin too fast. Among them are occasional transitional items, rare, revealing objects that show features that link one kind of item with another. In one case, the minor planet Sedna might be a planet that has strayed into our Solar System from another planetary system far away. These are the astronomical treasures in the zones where the minor planets have collected.

Just as archaeologists can attempt to find out about the history of a civilization by studying its rubbish, so astronomers can attempt to find out about the history of the planets by studying the small bits of left-over building material and broken bits that have accumulated in three zones of the Solar System: the Main Belt of asteroids (between Mars and Jupiter), the Kuiper Belt of trans-Neptunian objects (TNOs) (beyond Neptune) and the Oort Cloud of comets (on the periphery of the Solar System). These are the rubbish pits of the Solar System, their contents taken there and abandoned, after planet-building or world-shattering events that took place early in the history of our planetary system.

This view of the importance of the minor planets has emerged in the past few decades, and has altered the trajectories of spacecraft. NASA's policy for space missions to the outer planets is that, even if the primary target of the mission is a major planet such as Jupiter, the mission planners must consider whether the spacecraft will fly by minor planets on the way. If it is feasible and does not jeopardize the mission, they will divert the spacecraft to study them.

Astronomers and space mission designers think that asteroids are important. So does the Swedish Royal Academy. In 2012, it awarded the Kavli Prize for Astrophysics to the three pioneer discoverers of minor planets that orbit in the regions beyond Neptune, in the Kuiper Belt, Dave Jewitt, Jane Luu and Mike Brown. The Kavli Prize is the astrophysics equivalent of the Nobel Prize for Physics.

So, the primary scientific motivation for investigating the minor planets is to find out what they are and how they reveal the processes of the early history of the Solar System. By contrast, astronomers of earlier generations were interested in the orbits of minor planets as an exercise in mathematics. The mathematics is formidable. A century ago, it was a very complex calculation to predict the future orbits of asteroids. It was so notoriously difficult that in 1914-15, the author Arthur Conan Doyle used it as a marker for the intellectual prowess of Professor James Moriarty, the master criminal and arch-enemy of the private detective, Sherlock Holmes. As well as being "the greatest schemer of all time, the organizer of every deviltry, the controlling brain of the underworld," Moriarty is also described as the "celebrated author of *The Dynamics of an Asteroid*, a book which ascends to such rarefied heights of pure mathematics that it is said that there was no man in the scientific press capable of criticizing it."

The original mathematical problem was complicated but limited. Astronomers wanted simply to be able to follow an asteroid over a working lifetime, or perhaps into the next century. This limited problem has now been solved to almost arbitrary accuracy through the power of modern computers and mathematical techniques. But astronomers widened their ambition and tried to track the orbits of asteroids into the indefinite future or back to the almost unimaginable past. The idea here was to find out from where asteroids originated and to see to where they will evolve, to write the early history of the Solar System, and show how it will develop. Astronomers came up against new difficulties in the mathematics, known by the name of "chaos." These difficulties are not just technical, they are fundamental, and no amount of extra knowledge will enable mathematicians to circumvent them. They have to learn to deal with the fundamental limitations that chaos imposes.

Chaos is the same property of mathematical systems that makes it difficult to predict the weather more than a short time in advance. Chaos in celestial calculations arises from the shifting backdrop of intermittent interactions between the major and minor planets, and the phenomenon of chaos was first recognized here. The minor planets form a laboratory for the study of chaos in the Solar System.

I'm interested in astronomy, but I am also interested in astronomers. Asteroids were first discovered in the early years of the nineteenth century. The astronomers who worked to find them did so against the backdrop of political and social turmoil. The French Revolution of the last decade of the eighteenth century had destabilized Europe, and was followed by two decades of war and continuing political strife across the entire continent, when the nations so furiously raged together. While soldiers died in battle and seamen drowned, while families starved, while kings and queens were deposed and executed or, the luckier ones, reinstated, while constitutions were torn up and re-written, while royal courts were being torn down and parliaments erected, astronomers looked outwards to the stars. They communicated and collaborated across frontiers, sometimes mocked in cartoons for having their gaze on irrelevant details up in the heavens while being indifferent to great human events around them. The same remains true today, though in less stressful times. Astronomers stand shoulder to shoulder looking up to the stars, while political leaders stand eyeball to eyeball, staring each other down.

Asteroids bring astronomers together in a widely drawn community. Professional astronomers travel to telescopes, perhaps between continents. There they meet their colleagues. Although each astronomer is focused on the work that he or she is there to carry out, they are, for the duration of their stay on the mountain, a member of a community, almost like a monastery, united by unusual working hours and common mealtimes. It is inevitable that the astronomers talk and create relationships. Amateur astronomers support themselves on a more modest scale of equipment and travel, but just as strongly in their social interactions, within societies, internet groups and working teams. The observation of minor planets is within the scale of effort that amateur astronomers can bring to bear, with plenty of modest telescopes, cameras, computer systems and software available at affordable prices and capable of measuring the positions of many minor planets or their brightness.

In the early nineteenth century, most asteroids were discovered by eye, by non-professional astronomers. In recent decades, well-financed, professionally staffed, computer-assisted searches with quite large telescopes have produced by far the majority of asteroid discoveries, although asteroid discoveries are still made by amateurs, especially those who have upped their game from stargazing to systematic searches. So the swing of the pendulum for amateur astronomers, too, has been away from finding asteroids towards studying the asteroids themselves. There are huge numbers of minor planets to observe, and some amateurs happen upon a significant one and make a notable advance.

In one example, in 2008 the British amateur astronomer Richard Miles used the Faulkes Telescope South at Siding Spring Observatory, Australia, set up for the benefit of school students and amateurs, to discover that asteroid 2008 HJ rotates every 42 s, the fastest known rotation period for an asteroid. Asteroid 2008 HJ was discovered on April 25 but predicted to be visible for only a few days as it approached near to Earth, coming within 2.8 lunar-distances. On April 29 at its closest approach, it was moving so fast (45 km/s relative to Earth), that Miles had to reposition the telescope to continually keep it in view. Miles made very short exposures—less than one minute long. The telescope accurately tracked the stars so their images were circular but, even with exposures a few seconds long, the images of the asteroid were trailed by the asteroid's motion. Miles immediately noticed that there was a change in brightness along the trail, caused by the oblong-shaped asteroid turning, repeatedly presenting its wide and narrow sides in succession towards Earth and reflecting more or less sunlight (Fig. 1.3). A period search confirmed it to be a superfast rotator, having a rotation period of just 42.67 (±0.04) s, making it the shortest known rotation period of any natural object in our Solar System. The position and brightness of asteroids evolve in time, so an amateur astronomer can adopt a minor planet for study, follow it, elucidate its properties and make it his or hers.

Like professional astronomers, amateurs create social occasions on which to meet, perhaps physically through astronomical societies, or perhaps virtually through internet social media, like Yahoo's Minor Planet Mailing List (MPML). This list boasts nearly 2000 active members, posting typically 100–200 messages per month. Both professional and amateur astronomers focus minor planet observations through the IAU's Minor Planet Center, whose website provides aids to observers (including ways to check whether a minor planet that you think you have discovered has actually been seen before). It encourages people to observe minor planets

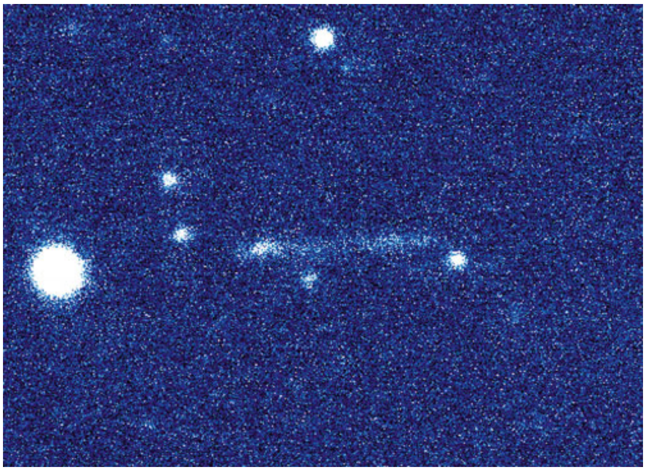

Fig. 1.3 At its closest approach to Earth asteroid 2008 HJ was moving at 1000 mph and made a trail among the stars in this time exposure of about 40 s. In that time it made one revolution and changed in brightness by one cycle of its rotation, reaching maximum brightness near one end (Image by Richard Miles. Used with permission)

whose orbits and positions are especially in need of improvement, vacuums up the observing data and mediates the orderly progression of the science. It lists over 2000 observing sites worldwide that have at one time or another made observations of asteroids, most of them in recent decades.

At the same time that astronomers manifest this selfless behavior in engaging with their science, they engage with each other in a revealingly human way. "Science" is a system of thought that develops under objective and dispassionate rules. "Science" is also a human activity that shows all the features common to emotional and irrational human behavior. In the study of asteroids this shows particularly distinctly in the manner in which astronomers name their discoveries, because the name of an asteroid has no scientific significance whatsoever. A name is a subjective human invention that helps scientists to remember what they are talking about so that they can discuss the science. A numerical designation is more useful as a label for a database or a spreadsheet in a computer file, used to correlate the asteroid's properties. But a name is easier to remember, and usually easy to pronounce.

A name is the product of the imagination and the names of asteroids have taken on an enormous human significance, for the discoverer, for his or her colleagues and for the wider community. So I follow the history of naming asteroids in this book in parallel with the history of their discovery and the scientific significance of the discoveries.

The act of discovery of a planet is in itself regarded as an achievement. We can all admire the single-mindedness and the persistence of astronomers who put themselves in the position to find a planet or a comet, or devote themselves to a long search. In times when planets were big and seldom discovered, the discoveries attracted international fame and national money. Galileo Galilei, William Herschel, Giuseppe Piazzi, Urbain Le Verrier, Clyde Tombaugh—all these astronomers, as I shall tell, came to the attention of kings, dukes and presidents, increased their scientific reputation, and got jobs and increases in salary as a result of their discoveries. Others were overlooked and their careers fizzled out.

Discoveries of planets nowadays attract the attention not only of an astronomer's peers, family and friends, but also, sometimes, the media and the social networks. There are no or few objective rules about the norms of behavior at this time, so there are plenty of opportunities for these scientists to show irrational human behavior, including erudition, wit and humor as well as gender bias, nationalism, self-interest and possessiveness, just like everyone else. "Science" means the activity that scientists carry out as well as what they find. Here, then, are the stories about the asteroid hunters, told alongside the knowledge they have gathered about their prey—stories about both the rocks themselves and the rock legends.

Fig. 2.1 Two meteorites. Peter Jenniskens arrives to collect meteorites that fell from the asteroid 2008 HJ on to the Nubian Desert (NASA)

Chapter 2

When the Stars Fell Down

2008 TC3: THE ASTEROID THAT FELL TO EARTH

It is hard to determine from afar what minor planets are made of. But there has been one case in which a minor planet has been tracked in space, and was witnessed as a fireball as it hit Earth. Later, bits of meteorites have been recovered from its impact area and analyzed. That was the asteroid known as 2008 TC3 that fell to Earth on October 6–7, 2008.

2008 TC3 was discovered at 06:39 GMT on October 6, 2008, by Richard Kowalski, (7392) Kowalski, who was that night carrying out work for the Catalina Sky Survey with its 1.5-m (60-in.) telescope at Mount Lemmon, near Tucson, Arizona. Although targeted at larger asteroids, the Catalina Sky Survey also identifies smaller asteroids that approach near to Earth. To react quickly enough to nearby asteroids, astronomers have formed themselves into a loose organization of internet-based networks and mailing lists known as Spaceguard, to make observations so that the object's orbit can be calculated. In the 19 h following the discovery of 2008 TC3, 27 amateur and professional astronomers made over 1000 observations of it. Its orbit was quickly calculated by the University of Pisa and the Jet Propulsion Laboratory's Sentry system, which was created exactly for the purpose of tracking asteroids that might well collide with Earth. Within an hour of receiving the data, JPL predicted that the asteroid would enter Earth's atmosphere above northern Sudan around 02:46 GMT on October 7.

One key observation was made 16 h after its discovery and just 3 h before it entered Earth's shadow, disappeared from view and was destroyed. By chance astronomer Alan Fitzsimmons, (4985) Fitzsimmons, and his colleagues of Queen's University in Belfast, specialists in the study of asteroids, had been scheduled to use the 4.2-m William Herschel Telescope on La Palma in the Canary Islands—but one night too late. He telephoned Gavin Ramsay, who had been scheduled to use the telescope for the crucial period but to study binary stars. Exploiting the community spirit that exists among astronomers, Fitzsimmons explained the importance of an immediate observation of 2008 TC3. Ramsay was willing to give up that night and use the following night instead. Stuck in Belfast because of his teaching commitments, Fitzsimmons had sent his more junior team, Ph.D. student Sam Duddy and postdoctoral fellow Henry Hsieh, (17857) Hsieh, to La Palma. Fitzsimmons had to follow the work sitting on the sofa at home, marking exam papers while monitoring his laptop computer link to the telescope.

The astronomers moved the telescope to the right place, the position predicted for the asteroid for a few minutes' ahead of the time, expecting that after any necessary fine adjustments the telescope would be in the predicted place at the moment the asteroid arrived there. To their consternation they could not see the asteroid at all. The telescope's TV camera showed the star field where the telescope was pointing, but there were no new "stars"—no asteroid.

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Worried thoughts chased through their mind. Had they positioned the telescope incorrectly? Had something gone wrong with the orbital calculations? Had something gone astray as the positional data was transmitted to La Palma? Just as they were about to panic, their attention was caught by something moving onto the edge of the TV picture. The asteroid was venturing into the field of view of the telescope. It was the first time they had ever seen an asteroid moving so fast that they could see the motion just by looking. Usually the asteroids that they observe are millions of kilometers away; this one was thousands. Being so much closer, the asteroid was whizzing across the sky, just as, to someone lying on his or her back in the grass, a bee would fly quickly across their field of view while a jet aircraft, high up and a long way away, would seem to dawdle.

The observing team obtained a spectrum of 2008 TC3 that showed the asteroid was a type known as an F-type. The meaning of this classification was later established for the first time by ground study, when fragments of the asteroid were recovered from the Nubian Desert in the Sudan.

JENNISKENS: FINDING THE ALMAHATA SITTA METEORITES

The impact point of 2008 TC3 on Earth was established by the calculations of its orbit and refined through the testimony of eyewitnesses who saw the asteroid fall as a bolide or fireball. The pilot and co-pilot of KLM flight 592 flying over Chad saw a sudden yellow and red brightening of the sky about 1500 km (1000 miles) to the northeast over the Sudan. Bystanders in the city of Wadi Halfa described a rocket-like fireball that ended abruptly. Sensors aboard secret US government satellites monitoring for rocket launches and other possibly hostile activity first detected the fireball at 02:45 GMT as the asteroid entered the atmosphere at 65 km altitude (210,000 ft). (The US military had been warned about the imminent impact, in case they had misinterpreted the explosion.)

The fireball pulsed twice in brightness as it broke into pieces at 37 km (121,000 ft) and then faded away. Abdel Moniem Magzoub, the attendant at a railway station on the north-south railway line between Wadi Halfa and Khartoum, near where the asteroid fell, was awoken by the bright light of the first explosion, sat up, witnessed the fireball continue and saw the second, weaker, final explosion. A short time afterwards, he heard the explosions, the delay being the time for the sound to travel to the railway station. A European meteorological satellite, Meteosat, monitoring cloud- and dust-cover and temperature over Africa, saw the explosions and the cloud of hot meteorite dust that resulted from the break-up. As dawn broke over Wadi Halfa later that morning, a lingering wind-blown dust trail was visible in the sky, lit from below the horizon by the rising Sun.

An asteroid became a meteor. Did the meteor become meteorites? The only way to answer that was to find out if there were any meteorites strewn in the field below the bolide's trail. The search area was defined by combining the eyewitness accounts with orbit calculations from the Jet Propulsion Laboratory, and adding new calculations of the possible trajectory of the meteor as it curved and tumbled through the air. The search area was 28 sq. km (11 sq. miles) in extent, a long box aligned along the asteroid's roughly east-west trajectory. That is a large area to search for pieces of rock, but the search was facilitated by the fact that the Nubian Desert consists of rocky plains, interspersed with hills, rocky outcrops and sandy river valleys, relatively easy to traverse. The ground is light colored, with little vegetation in which the darker meteorites could hide.

The man who set out to find the meteorites was Peter Jenniskens, (42981) Jenniskens, a meteor astronomer with the SETI Institute in Mountain View, California. In December, 2008, Jenniskens joined the Sudanese environmentalist Muawia Shaddad of the University of Khartoum to carry out the search. Jenniskens traveled to the search area for 18 h in a bus from Khartoum with 45 students and staff from the university. The group lined up, 20 m (20 yards) between each person, in a row a kilometer (three quarters of a mile) long, and systematically swept the terrain. The participants walked 18 km (11 miles) each day for the 3-day search. The first meteorite was found by a student, Mohammed Alameen, 2 h into the search on December 6, 2008. It was a small, black stone which stood out on the light sand. It was found simply resting on the surface, with no crater, not even a depression. What happens to a small meteorite is that in the atmosphere it slows down, impeded by the air, eventually falling vertically at a moderate speed, with little drama.

Few people have actually seen a meteorite fall. One of the best documented early falls occurred near the village of Wold Newton near Scarborough in England. A pillar marks the spot where in 1795 a 17-year old ploughman, John Shipley, saw and heard a 25-kg (55-lb) meteorite impact on the ground 8 m (26 ft) away and was showered by earth from the 50-cm (1.6-ft) deep crater that it made. Shipley escaped without injury from this unexpected event but suddenly died in 1829. The headstone at his grave in the cemetery of the village church near to the fall draws a moral from the parallels between the sudden end to his life and his earlier narrow escape:

Erected
TO THE MEMORY OF JOHN SHIPLEY
WHO DEPARTED THIS LIFE
MAY 17TH 1829
AGED 51 YEARS

All you that do behold my stone
O: think how quickly I was gone:
death does not always warning give
therefore be careful how you live.

A much smaller meteorite fell in Glatton, Cambridgeshire in the United Kingdom on May 5, 1991, about 20 m (60 ft) from Mr. Arthur Pettifor, who was working in his back garden. He heard a whining noise and looked up to see the branches of conifers in a hedge disturbed by something falling through them. Beneath the conifers he found a single crusted stone weighing about 0.75 kg (1.5 lb). The stone had made a shallow depression, only about 2 cm (1 in.) deep. The stone was warm but not hot when first picked up.

The asteroid 2008 TC3 was about 4 m (13 ft) in size and had a mass of, probably, 80 m. tons. Evidently friction with the air on its passage through the atmosphere had dispersed much of it as dust, and the final fireball explosions had shattered what remained into small pieces, which fell gently.

The fragment found by Mohammed Alameen was logged, then wrapped in aluminum foil to prevent contamination from handling and secured. Further fragments were found in the next days, increasing in size along the track from small pebbles to egg-size pieces (the larger pieces of an exploding meteorite travel further). Jenniskens himself found some of the pieces and described the experience: “For a moment you realize that you are the first person to lay eyes on these rocks from space, laying there in the sand much the same as the day they fell on the ground,” he said. Every find brought back that euphoric sense of discovery (Fig. 2.1).

The team found 250 fragments over those 3 days, strewn along 29 km (18 miles) of the meteor track, and the number doubled in further searches, adding to a total of 10 kg (22 lb). The meteorites are known collectively as the Almahata Sitta meteorite fall. Meteorites are named from the nearest place, and the name is Arabic for “Station Six,” the train station, on the approach to which the largest fragments fell.

Asteroids are the leftovers from the formation of the terrestrial planets—Mercury, Venus, Earth and Mars. Some are, as it were, the off-cuts from the raw material that built up larger planets, and some are fragments and chips from collisions between planets. Most of the asteroids that we know have been jumbled together in the Main Belt, having been formed in different zones of the Solar System, condensing from material that had been partially separated into different compositions. From that varied start, the asteroids experienced different histories, interacting one with another, moving and separating into different orbits. The larger asteroids “differentiated”: that is to say, as they were warmed by heat liberated in their interior by radioactivity, the minerals of which they were made plasticized, flowed, and separated into different zones in the body of the asteroid. If such an asteroid is shattered by a collision, its fragments vary in composition.

As a result of all this, asteroids are incredibly diverse. We can only view most asteroids from afar, visit rather few asteroids with robot spacecraft, retrieve small samples from an even smaller number (just one so far) and examine some bits of asteroids of unknown provenance that fell to Earth as meteorites. It is hard to make sense of it all. 2008 TC3 and the

Almahata Sitta meteorites are important because they are firmly linked, but we do not yet really know what to make of them. The meteorites are of a rare type known as ureilites, and 2008 TC3 was an F-class asteroid, which comprise only 1 % of the asteroid population. Astronomers are struggling to understand how these facts fit into the jigsaw-puzzle picture that will knit together asteroids and meteorites, mineral compositions and colors, orbits and distributions, shapes and sizes, and ultimately show how all the different kinds of minor planets originated.

There is one certainty in the conclusions that we might draw from the incident when 2008 TC3 fell. The asteroid revealed whether we could cope with a somewhat larger, death-dealing asteroid on an approach path. It showed that most of us would only be passive, impotent bystanders, listening to reports of what had already happened. Some of us would be more or less knowledgeable about what was about to happen—some astronomers, a few mathematicians, some whose jobs include surveillance of the world for peaceful and for military purposes, and, in the final seconds, some spectators who were simply in the right (or wrong) place at the right (or wrong) time. Most of us would be going about our everyday business, not knowing what is happening. At the present time, none of us could do anything effective about the situation; perhaps ignorance would be best. It is likely that we would have to react to problems rather than anticipate them, because disaster-planning for an asteroid strike is in a rudimentary state.

I know this because, when I worked at the British National Space Centre, I commissioned a report on the hazards associated with asteroid impact and witnessed the government response. The report's authors, responsible public figures, produced a careful, reasoned assessment of the risks. I had thought that the Home Office, the government department in the UK responsible for public safety, would respond by using the report as the basis for the production of a plan of what it would do, nuanced, realistic and proportionate. It could have analyzed the potential hazards according to the size of the asteroid. Few defensive measures are currently available to divert a very large asteroid on a collision course with Earth, although we might get warning far in advance. Mitigation after impact would have to be very wide-ranging and long-lasting, so specific measures may be inappropriate. In any case, the risk that a very large asteroid will impact Earth during the lifetime of people alive today is now known to be small, since most large asteroids have been found by recent surveys, and their orbits are well-enough determined to say that none of the big ones are likely to collide with Earth soon. At the other extreme of the size range, small asteroids such as 2008 TC3, can be seen only when close and arrive quickly, but these are generally harmless. Between the two sizes, however, the risk is real; there are numerous asteroids known to constitute a hazard. The damage they might cause will vary according to the height of the fall, and whether the asteroid falls onto ground or into the sea. Notice of the potential impact will vary too, from hours to years, depending on how far away the asteroid can be detected and from which direction it approaches. These factors indicate what could be done as mitigation in each combination of circumstances. For example, is a tsunami likely? On which coasts? Is it practical to evacuate the vulnerable coasts, or would this cause more casualties than the tsunami? If the parameters of the impact were analyzed, a disaster response plan could be drawn up, and filed, to be taken out and used as and when necessary.

In fact, the Home Office washed its hands of the report, and said only that it would rely on the local emergency services to act appropriately. It decided to do nothing at all. The plan, such as it was, was not much more sophisticated than a decision that, if an asteroid plunged onto British soil, the Home Office would send a bobby around on a bicycle.

55P/TEMPEL–TUTTLE: SOURCE OF THE LEONIDS

The impact of an asteroid with Earth is potentially momentous but, in miniature, beautiful. I have stood under a night sky, awestruck, gazing up at showers of meteors zipping through the air some tens of kilo meters (many thousands of feet) above me, miniscule versions of a death-dealing asteroid impact. Likewise, I have stood on an island on the edge of Victoria Falls, dizzy from the noise and motion, watching the Zambezi River thundering over the sheer drop meters from my feet, falling 100 m down into rapids hidden by the spray. And I have stood in the radiant heat, close to a creaking stream of red-hot lava flowing from the volcano, Kilauea, down into the steaming sea near Kalapana on the Big Island of Hawaii. All these streams were beautiful and awe-inspiring natural sights, the more exciting because of the proximity of danger, even death.

On a normal night there might be half a dozen sporadic meteors per hour. They streak through the sky in random directions. But at certain times of the year there are showers of meteors, anything up to tens of thousands of meteors per hour, that all appear to come from the same point in the sky. The meteors of a shower have a common origin, a single meteoroid stream through the Solar System—small grains of dust, up to pebble-sized stones, moving together on the same orbit. There are lots of these streams crisscrossing the Solar System, and meteor showers arise from those streams that happen to intersect Earth's orbit. Earth passes through the river of tiny asteroids. The intersection of the orbit of Earth and the orbit of the meteoroid, each passing at high speed, causes the dust and stones to streak into Earth's atmosphere. The meteoroid compresses the air, which heats up, just as air squashed in a bicycle pump gets hot. The meteoroid itself heats. Atoms of air (nitrogen, oxygen and the like) and atoms from the solid material of the meteoroid (sodium, in particular) are damaged, some of their electrons splitting off. As the electrons recombine into their parent atoms they emit light, which shows as a meteor trail.

Since the meteoroids travel in parallel tracks along their orbit, the meteors appear to radiate from the same point, just as, through the phenomenon of perspective, parallel railway tracks radiate from a point on the horizon. The point in the sky from which the meteors of a shower seem to originate is called the radiant. It lies in some constellation or other and that constellation gives the shower its name, such as the Leonids, which radiate from the constellation Leo, and the Geminids, which radiate from Gemini.

Each meteor stream remains more or less stationary in the Solar System. This means that, if Earth's orbit intersects one, it passes through the stream, taking a few hours or days to pass through at the same time each year, on the same date.

The Leonids can be the most dramatic meteor shower. They recur reliably, every year, between November 15 and 20, but the shower is more dramatic some years than others, because, while the Leonid meteoroids litter the entirety of their orbital track, there is a dense clump of meteoroids orbiting in a cloud, and, most years, Earth misses the cloud. The cloud is in the vicinity of Earth once per orbital period of 33 years. The Leonid meteor shower of November 1833 was quite spectacular, peaking at 1000 meteors per minute. It was best seen from North America and was recorded by Native Americans. The Sioux tribes keep a calendar by naming each year after a notable event, and 1833/34 was called "stars all falling down year," adding: "They feared the Great Spirit had lost control over his creation."

The same shower was witnessed by President Abraham Lincoln, (3153) Lincoln. According to the American essayist Walt Whitman, Lincoln was asked by a White House guest whether the Union would survive the ongoing Civil War. He replied:

> *When I was a young man in Illinois, I boarded for a time with a Deacon of the Presbyterian church. One night [in 1833] I was roused from my sleep by a rap at the door, & I heard the Deacon's voice exclaiming "Arise, Abraham, the day of judgment has come!" I sprang from my bed & rushed to the window, and saw the stars falling in great showers! But looking back of them in the heavens I saw all the grand old constellations with which I was so well acquainted, fixed and true in their places. Gentlemen, the world did not come to an end then, nor will the Union now.*

The same meteor shower inspired the 1934 jazz standard "Stars Fell on Alabama."

Analyzing this shower, two Yale University scientists, Denison Olmsted and Alexander Catlin Twining identified the radiant and explained it as the orbital path of the meteoroid stream. Later, Hubert Newton listed historical records of the shower back to AD 902 and calculated the orbital period of the meteoroids at 33 years.

The connection between the Leonids and a comet came a generation later with the discovery of Comet 55P/Tempel-Tuttle. This comet is the 55th that was found to be periodic (hence the "55P" in its designation) and was co-discovered by two astronomers, after whose names it is called. Wilhelm Tempel, (3808) Tempel, was an amateur astronomer who devoted his time and his earnings as a lithographer to his study of astronomy, during the course of which, as I will tell later, he discovered a number of asteroids and other celestial novelties. He discovered the comet late in 1865.

Within a month the comet was independently discovered by Horace Parnell Tuttle, (5036) Tuttle. Tuttle was an assistant astronomer at Harvard College Observatory, with a colorful career. He started work, unpaid, at Harvard in 1857. In his first year there, aged 20, he found four comets, an achievement for which he was awarded the Lalande Prize by the French Academy of Sciences. When the American Civil War started in 1861, Tuttle joined the Union Army, then within a year transferred to the Navy as a paymaster. He served on *USS Catskill* and was engaged in the capture of the British blockade runner *Deer* as it carried Confederate supplies into Charleston harbor, but he continued to hunt for and observe comets, sweeping the sky with his telescope when he could, from the decks of his ships.

After the war, Tuttle returned to Harvard and discovered Comet 55P/Tempel-Tuttle. His career crashed ten years later, in 1875. In the relative calm after the Civil War, after the military urgency, there was time for the Navy to audit its account book, and Tuttle's were found to be wanting. In particular, he had illegally cashed a large Navy check, falsely claiming that most of the money had been stolen by others. He was court martialed and convicted of embezzlement and "scandalous conduct tending to the destruction of good morals." He was dishonorably discharged from the Navy. Despite this, he was taken back into government service with the US Geographical and Geological Survey, helping to establish the boundary between Wyoming and Dakota, and then into the US Naval Observatory, from where he found one last comet in 1888. Altogether he discovered eight comets and two asteroids, (66) Maja and (73) Klytia. Penniless, he died in 1893.

Comet 55P/Tempel-Tuttle was seen briefly in 1865-66, long enough for the general features of its orbit to be measured but not long enough for an accurate orbit to be calculated. Hence the comet was lost and missed on two returns in 1899 and 1932. It was recovered in 1965, with help given by the discovery that the comet had been previously seen in close approaches to Earth in 1366 and 1699. This enabled Joachim Schubart (b. 1928; (1911) Schubart), of the Astronomisches Rechen-Institut in Heidelberg, to predict its return in 1965.

In 1867, the Italian astronomer Giovanni Schiaparelli, (4062) Schiaparelli, realized that the orbit of Comet 55P/Tempel-Tuttle, computed after the comet's apparition of 1865, matched the orbits of the Leonid meteors. The icy body of the comet followed the same path as the tiny bits of dust that made the meteors. The comet was the parent body of the Leonids.

Comets are essentially "dirty snowballs." They are made of bits of dust held together by ice. In the heat of the Sun, the ice vaporizes. The comet releases the dust in a tail, which litters the path of the comet with small meteoroids, which continue in orbits parallel to the orbit of the comet. The dust particles become meteors when, on falling to Earth, they become incandescent by friction with the air, as outlined above.

PHAETHON: DEAD SOURCE OF THE GEMINIDS

The Geminids are another meteor shower, usually visible around December 13–14, with about 150 meteors per hour. The shower suddenly appeared in 1862, and its origin was unknown until 1983. In that year an asteroid, provisionally designated 1983 TB, was discovered by British astronomers Simon Green, (9831) Simongreen, and John Davies, (9064) Johndavies, who were searching data from the infrared sensitive telescope on the Infra-Red Astronomy Satellite, IRAS.

Green was a Ph.D. student and Davies was a post-doctoral fellow, both of them working with the data stream that came from IRAS to the scientists through the Rutherford-Appleton Laboratory ground station. In each 100-min orbit, IRAS scanned the sky in a strip, using detectors that followed one another in succession in the same scan, seconds apart. Large enough signals were automatically extracted from the data as possible stars and galaxies. There was always the possibility that some glitch in the electronics or software had created spurious signals, so only signals seen twice in succession at the same place seconds apart were regarded as possibly real celestial sources. Indeed, the scans made during consecutive orbits of the satellite were made to overlap by 50 %, and only if there were signals at the same place, both seconds apart and orbits apart, was the celestial source regarded as confirmed to be real.

At each stage of processing, the signals that were detected but rejected were listed, and Green's and Davies's job was to search the rejected signals for sources that were actually real but moving in a consistent trajectory, displaced by seconds and then by 100 min. Sources moving too fast were space junk (bits of broken spacecraft and rockets orbiting Earth), but sources moving at the right rate could be asteroids or comets, warmed by the Sun so they give out infrared radiation. The job to find them had to be done as soon as the data came in, so that they could be followed up in other investigations.

Almost every day, one of Green and Davies sat in a temporary cabin at the ground station, sifting through long lists of computer printout. The pair of astronomers were under strong pressure to ensure that an object was real by getting someone on a list of pre-arranged collaborators who all had access to ground-based telescopes to confirm it before communicating about it to the world at large. The pressure was particularly strong about the first object they found, because no one could be sure about the processes that they had built up for the analysis. It turned out to be Comet IRAS-Araki-Alcock, a real comet, so the techniques had worked, and everyone was relieved.

Phaethon was the first rapidly moving asteroid that they found and confirmed. They were themselves convinced there were many more before this in data that were not convincing enough for other people to believe. As it happened, Phaethon was moving in the same direction that IRAS advanced its scan strip, so the asteroid got hit on a number of consecutive orbits, so it was a pretty good detection, even without the ground-based confirmation. When Green first saw Phaethon, he was determined not to lose it, so he immediately telephoned the first observatory westwards that was under nighttime skies. It was the Palomar Schmidt Telescope, and Charles Kowal was observing. He took down the coordinates and went straight to the right spot to find it.

When the discovery was published, Harvard astronomer Fred Whipple, (1940) Whipple, noticed that the orbit of the asteroid was virtually the same as the orbits of Geminid meteors. Their parent body had been discovered—not a comet but an asteroid that has never shown any strong signs of being a comet. For example, it has never had a tail, not even a small one. Some of Phaethon's properties are more consistent with it being a rocky body, but in 2009 it increased in brightness as it passed the point in its orbit near to the Sun. Maybe it is an asteroid with more ice than usual, or a comet with more rock than usual, perhaps a transitional object mid-way between the two kinds of objects. Or maybe it is a comet that has been past the Sun so often that nearly all the ice has vaporized. Or maybe it is an asteroid that is responding to its extreme orbit: perhaps it experiences such intense heat at its nearest approach to the Sun that its surface cracks, releasing rock and dust particles, similar to but much more extreme than, the freeze-thaw action on rocks on Earth, which, as I write in a cold winter, is cracking and flaking scallops of brick off the wall in my garden.

The beauty of a meteor shower distracts us from the implicit danger. The shower reveals that Earth passes through a path of meteoroids littered along an orbit. The litter of meteoroids has been dropped by a minor planet or comet, which orbits somewhere within the meteoroids and which, like the meteoroids, passes close to Earth. Just as wrappers dropped by cars make a path of litter that is wider than the road, the meteoroids form a thick cloud, within which the minor planet or comet tracks, a small lump within a thick tube of dust. Phaethon passes close to Earth, in the middle of a tube of Geminids, but major impact is not inevitable. The minor planet is certainly potentially hazardous. It would certainly constitute a danger if, at 5 km (3 miles) in diameter, Phaethon were to strike Earth. The same is true for Comet 55P/Tempel-Tuttle.

Phaethon not only passes close to Earth, it also passes very close to the Sun, within 0.140 times the distance of Earth from the Sun. One of Green's colleagues at Leicester University, Nick Eaton, came up with the name for the asteroid, based on the facts about its orbit. In Greek mythology, Phaethon's father, Helios (the Greek equivalent of the Roman sun god Apollo), offered to give his son anything he should ask. Phaethon asked to drive the chariot on which Helios carried the Sun in its course across the sky from day to day. Helios was reluctant to let Phaethon do this, because of the danger—the chariot was hot and its horses exhaled flames—but he had to keep his promise. Phaethon was unable to control the horses, and the chariot careened out of control, moving too high so that Earth grew cold, then too close to Earth so that it burned, creating deserts, drying lakes and rivers, charring Africans black. The mythological trajectory of the chariot seemed to fit the extraordinary orbit of the asteroid and to make the name apt.

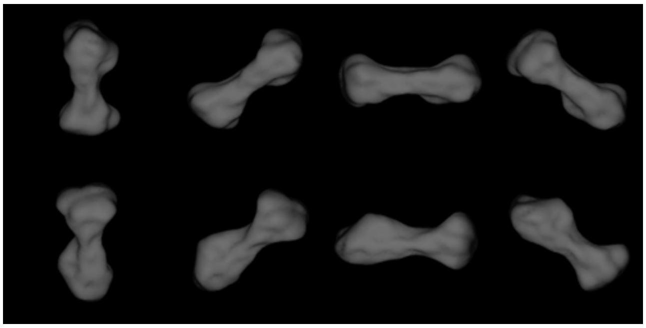

Fig. 3.1 Radar images of (216) Kleopatra show its rotation, its dog-bone shape and its size, comparable to the size of the state of New Jersey or Wales. Inside its curious shape, Kleopatra is a porous arrangement of solid metal fragments and loose metallic rubble. (Image courtesy of Steve Ostro, JPL, Arecibo Telescope)

Chapter 3

Finding Asteroids by Eye

TEMPEL: SWEEPING UP NEW STARS

Most of the known minor planets orbit the Sun in the gap between the planets Mars and Jupiter. This zone of the Solar System is known as the Main Belt of asteroids. There are some minor planets that are known in the distant, dark region of the Solar System beyond the planet Neptune. The name that best describes these minor planets, without prejudice to their nature, is trans-Neptunian objects, or TNOs. The zone that they inhabit is known as the Kuiper Belt.

Orbiting among and across these planets and asteroids are the comets. Comets are solid, like asteroids, but not rocky. Comets are made of ice mixed with dust. When a comet approaches the Sun and its surface is warmed, the ice becomes gaseous and releases solid bits of dust, creating a thin atmosphere that it drags along (called a *coma,* which means "hair"); this is the fuzzy patch that is the first distinctive look of a comet. As the comet gets nearer to the warmth of the Sun and melts further it leaves a tail of dust, which reflects a lot of sunlight and may be readily visible to the naked eye. This is the iconic look of a comet.

Comets thus look very different from asteroids, and have been named, treated and studied as quite separate objects. But there is a continuum between comets and asteroids. Both are ice mixed with solids—asteroids are icy rocks, and comets are dusty ice. Comets and asteroids are in some ways fundamentally similar. Indeed, some asteroids have incipient tails and look a bit like icy comets, and some comets are dead and look like rocky asteroids.

How minor is a minor planet? The scientific terminology is tedious but carefully graded. A few minor planets are large and have a strong enough force of gravity to settle down into a near-spherical shape (or slightly flattened if rotating fast). These are called "dwarf planets." Typically, minor planets are dwarf planets if they are more than about 500 km (300 miles) in diameter, but the status of being a dwarf planet also depends on the composition of the minor planet as well as its rotation speed. The largest minor planet in the Main Belt is the dwarf planet Ceres, which is near-spherical and almost 1000 km (600 miles) in diameter. There are two more minor planets in the Main Belt at around 500 km (300 miles); they come close to being dwarf planets but probably do not quite make it. The largest minor planets in the Kuiper Belt are Eris and Pluto, both of them just over 2300 km (1450 miles) in diameter, Eris probably slightly the larger. There are more than a dozen other minor planets known in the Kuiper Belt that are over 500 km (300 miles) in diameter. These are probably all dwarf planets, or close to deserving that label. It is difficult to find minor planets that are far from the Sun, beyond Neptune; these are dimly lit by the Sun and are made faint by their distance from Earth. There might be hundreds more dwarf planets out there.

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If a minor planet in the Main Belt is over, say, 1 m (3.5 ft) in size, it is called an "asteroid." If it is smaller, it is called a "meteoroid." You can hug a meteoroid, but you might fear an asteroid. (The boundary is arbitrary and some astronomers quote 10 m (35 ft) as the division.) In either case, apart from those few asteroids that are dwarf planets and therefore spherical, asteroids and meteoroids are irregular in shape. The larger asteroids might be generally rounded, in the shape of a potato; the smaller asteroids and the meteoroids might be quite angular, like the Rock of Gibraltar.

It is relatively easy to identify a comet when you see one, and many amateur astronomers take great pleasure in trying to find new ones. They sweep the sky with powerful binoculars or wide-angle telescopes, looking for a fuzzy patch of light, the coma or the incipient tail of a comet as it approaches the Sun. There are some other astronomical objects that look a bit like comets, especially in small telescopes, such as galaxies, nebulae (gas clouds) and distant star clusters, but if an astronomer finds a fuzzy patch he or she can look on a chart to see if a galaxy, nebula or star cluster is in that position. If not, the fuzzy patch might be a comet. The proof is to look at the same place an hour or a day later and to see if the fuzzy patch has moved. If so, it must be a comet, because galaxies, nebulae and star clusters remain fixed in space.

It is more difficult to spot an asteroid. They have no obvious tails and do not look fuzzy. They look just like stars. The original way of discovering asteroids was for an astronomer to sweep over the sky by eye, looking through a telescope, comparing the stars with a star chart. From time to time, the astronomer would see a star that had suddenly popped up, apparently out of nowhere. It would be a "new" star. The "new" star seen by the astronomer could be, rather prosaically, a star that had, for some reason, been left off the charts. In some cases it could be an old star that had suddenly brightened and become more visible—in modern astronomical parlance, a *nova*. This term is the Latin word for "new," part of the original phrase *nova stella*, "new star." It would be very interesting indeed and worth studying. But the new star would also be worth studying if, when the astronomer returned to view the same area of sky again an hour or a day later, the "new" star was still there but had shifted its position. It could be a comet, but, if it had no coma or tail, it could well be a new planet, or an asteroid.

Stars don't appear to move; planets do. Although the night sky of stars wheels overhead as Earth turns underneath in its daily rotation, the constellations remain the same. The relative positions of the stars that make the patterns of the constellations are fixed. With no or weak optical aid, planets look like stars and can disturb the pattern of a constellation so much that at first glance the constellation looks unfamiliar. But planets change their positions among the stars. The very word *planet* means "wandering star," as opposed to "fixed star." A fixed star is a star which (as we now know) is so far away that changes in its position due to its motion are imperceptible, except with the most accurate of measurements. Planets can readily be seen to move.

Movement was the key element of the first definition in the history of science that separates the concept of a “planet” from a “star,” as well as the first in this book. The property is founded in the external behavior of planets and stars, their positions and motions.

Planets are also distinguished from stars, and indeed comets, by their appearance, which is based on an intrinsic property: structure. But of course the appearance of something depends on how far away it is and how you look at it—with the naked eye or a powerful telescope—so it is not a fundamental property. Appearance is a useful diagnostic but, as someone may remark about someone else who looks disreputable but is really a nice person, “You can’t judge by appearances.” The appearance of something does not get to the heart of the matter. It took centuries of scientific advance to provoke a crisis in the years around the turn of the millennium in which the definition of “planet” focused most directly on the properties of planets themselves. There is an official resolution from the International Astronomical Union on this definition, but the scientific debate is not yet concluded.

Obviously the method of finding new planets by looking for new stars depends on having reliable charts of the old stars. One astronomer, Wilhelm Tempel, recounted in 1860 that he almost gave up at the outset of a program in which he planned to search for minor planets. Trying to use the star charts produced by the French astronomer Jean Chacornac, (1622) Chacornac, Tempel grew angry because so many stars were missing. This made the search for a new planet very frustrating. Tempel repeatedly saw stars that were apparently “new” but remained stationary when he looked at them a second time and were obviously not planets. He added that he was so disgusted that he almost lost the will to search for new planets. He temporarily changed his mind and went on to discover five. But after a number of years he stopped searching for them, not because the star charts that he was working from were incomplete, but because he had acquired a telescope that was too good. It showed many more stars than those on the best, improved star charts, confusing the identification of new stars. By contrast, the better the telescope, the easier to identify comets from their appearance. Tempel went on to discover nineteen comets in total.

PALISANA: FINDING MINOR PLANETS

The astronomer most successful at discovering asteroids by eye was Johann Palisa, (914) Palisana, born in Silesia, Austria (now in Czechia). He discovered 122 minor planets. As the young director of the Austrian Naval Observatory in Pola (now Pula), Palisa discovered his first asteroid in 1874 with a modest 6-in. (150-mm) refracting telescope. (A refracting telescope, or refractor, is one that has a lens to gather the light.) He named the new planet after his homeland, (136) Austria. Over the next 6 years, he discovered 27 more minor planets in the same way. He took a demotion in 1880 to be an assistant at the newly inaugurated Vienna Observatory so that he could use its 27-in. (69-cm) refractor, then and for the next 5 years the largest refracting telescope in the world. In routine use, the *Großer Refraktor*, as the Vienna telescope was called, took two assistants to operate it and its rotating dome, while the astronomer made observations at the eyepiece. But Palisa would send his assistants to bed at midnight, and observe on his own until the Sun rose. He must have been racing around during the night, putting down his charts, notebook and pen, leaving the eyepiece, operating the mechanisms to move the telescope and dome, and returning to the eyepiece to look and note down what he saw. He discovered 94 more minor planets with this telescope and a smaller 12-in. (30-cm) one.

Palisa developed a good working relationship with the German astronomer Maximilian ("Max") Wolf, who discovered hundreds of minor planets at his observatory in Heidelberg. Palisa followed up many of Wolf's discoveries, carefully measuring their positions in order to determine good-quality orbits. Wolf and Palisa together created 210 star charts to help their searches. The Wolf-Palisa star charts were based on photographs made at Heidelberg that were turned into maps in Vienna by superimposing grids of precise coordinates. Because they were photographic charts, they were complete in so far as the stars that they represented—no stars left off by mistake, as with Chacornac's. So they were ideal for discovering asteroids, which is why Palisa and Wolf had made the effort to produce them. The grids helped with measuring the positions of the asteroids that the two astronomers found.

Retaining the right to observe at the Vienna Observatory after he had retired, Palisa discovered six further confirmed asteroids, the last, (1073) Gellivara, in 1923 at the age of 75. He discovered his very last asteroid in 1926, but lost it and died before he could search for and find it again, so it was unconfirmed. It was rediscovered in 1930 by Karl Reinmuth, (1111) Reinmuthia, and named by the mathematician Bror Ansgar Asplind, (958) Asplinda, who calculated the orbits of the two asteroids and found that they were in fact one and the same. Asplind named it (1152) Pawona, the name being a portmanteau word of the names of Palisa and Wolf to commemorate the cooperation between the two men.

Palisa was memorialized in the name not only of asteroids (1152) Pawona and (914) Palisana, chosen by Asplind and Wolf respectively, but also asteroids (902) Probitas (probity), (975) Perseverantia (perseverance), and (996) Hilaritas (contentment), in recognition of his sterling qualities. Up to that time there were not many virtues represented in the pantheon of asteroid names. On the whole the names of the asteroids tended more to be associated with mythological personages who had vices more obvious in their characters. There is however an asteroid (494) Virtus, discovered in 1902 by Max Wolf, named for the Roman personification of virtue, a goddess dressed in a white linen robe. The name was suggested to Wolf in 1905 by the then General Secretary of the Société Astronomique de France, Camille Flammarion, with the comment that by an oversight the astronomers had neglected up to then to place Virtue in the skies and that, if it disappeared from Earth, it would be nice to be able to find it in the heavens.

The most notable asteroids discovered by Palisa are the strangely-shaped (216) Kleopatra, and (243) Ida, with its moonlet.

KLEOPATRA: RUBBLE PILE

(216) Kleopatra, named with German spelling after Cleopatra VII, the most famous queen of ancient Egypt, is a long, thin asteroid, shaped like a dog's bone. The first indications that the asteroid had this strange shape came from a discovery by David Tholen, (3255) Tholen, while he was still a student. He found that Kleopatra's light was changing regularly by a large amount—the largest amount of any asteroid in the Main Belt.

Every 2 h 42 min, Kleopatra's brightness dips to a minimum and then climbs to a maximum. These changes are due to the rotation of the asteroid with a period of 5 h 23 min. When its light is at a minimum, its elongated shape is pointing to Earth, and when it is at a maximum, the asteroid is broadside on half a rotation later. Completing its rotation, it presents the other end towards us, and then its other side. As it presents alternately a small area and then a large area towards us, it reflects a small amount of sunlight and then a large amount. Kleopatra is a relatively large asteroid, measuring 217 × 94 × 81 km (134 × 58 × 50 miles), so the side-on area is nearly 20,000 sq. km (7700 sq. miles) and its end-on area less than 10,000 (3800). This is the reason why its light changes by about a factor of two.

Kleopatra is one of the most elongated asteroids. (1620) Geographos is the most elongated, but it is much smaller, measuring 5.1 × 1.8 km (3.2 × 1.1 miles). Because Kleopatra is so large, it is possible—just—to see the elongated shape from Earth with ground-based telescopes. Astronomers succeeded in doing this, using special image-sharpening techniques with the 3.6-m (140-in.) telescope of the European Southern Observatory in Chile and the 10-m (390-in.) telescope of the Keck Observatory in Hawaii. The Hubble Space Telescope has a clear view of space from above Earth's atmosphere (but no image-sharpening capability), and it showed the same. But none of these images were sharp enough to show whether the asteroid was a single, elongated shape or two near-spherical asteroids in orbit around each other, nearly touching.

The bone-shape of Kleopatra was revealed in 2000 (Fig. 3.1) by a team led by radar astronomer Steven J. Ostro, (3169) Ostro. He bounced radar signals off the asteroid, using the largest single dish radio telescope in the world, the 300-m (980-ft) Arecibo radio telescope in Puerto Rico. Kleopatra was, at the time, 171 million km (106 million miles) from Earth, and the radar signals took about a quarter of an hour to make the return journey. Distortions in the returned signal, produced by the rotation of the asteroid, were used to construct a computer model of the shape of the asteroid, and to measure its size. The amount of signal reflected by the asteroid indicated that a lot of it was metallic rock. Calculations showed that Kleopatra is rotating so fast that the two swollen ends of the elongated, dog-bone shape are on the verge of splitting apart, due to centrifugal force.

Kleopatra is similar to Comet 67P/Churyumov-Gerasimenko, the comet that was visited by the Rosetta space probe in 2015. This, too, is a dumbbell shape (Fig. 3.2), revealed as the probe approached, carrying its lander Philae. The discovery of the irregular shape of 67P complicated the life of the controllers whose job was to land Philae on the comet. They accomplished the landing, so far as controlling the lander on to the comet's surface, but the very irregular shape meant that it fell over, which greatly reduced its data-gathering capacity.

Fig. 3.2 Comet 67P/Churyumov-Gerasimenko. In March 2015, ESA's Rosetta spacecraft was only 84 km (50 miles) from the nucleus of the comet, with a good view of its two-lobed dumbbell shape (ESA/Rosetta/Navcam)

Kleopatra had further surprises in store for astronomers. In 2008, Franck Marchis, (6639) Marchis, and colleagues, using the 10-m Keck Telescope on Mauna Kea in Hawaii, obtained pictures of the asteroid of amazing sharpness, considering the images were made from the ground by a telescope looking through the distorting effects of Earth's atmosphere. Marchis and his team used a camera working with Adaptive Optics controlled by a laser guide-star. What this means is that starlight passing through the camera optics is divided up by little mirrors into many independently directed beams, each beam individually controlled by wobbling the mirrors to counter the wobbles of the column of air through which the beam is looking. The wobbles are measured in the same camera by looking simultaneously at an artificial star generated by a sodium wavelength laser that illuminates a spot high in the atmosphere at an altitude of 100 km (60 miles). The light from the artificial star follows almost the same path as the light from the star that the telescope is studying, and corrections to the image gathered from the artificial star are applied to the real star. The result is to create a camera that could in principle from London see two New Yorkers walking side by side.

The team used the camera to image, not a star, but the asteroid Kleopatra, and found two moonlets orbiting the asteroid (Fig. 3.3), about 5 km (3 miles) and 3 km (2 miles) in diameter, respectively, orbiting with periods of 2.32 and 1.24 days. These have been named Alexhelios and Cleoselene, after two of the children that Cleopatra had with the Roman general Mark Antony: her eldest son Alexander Helios and his twin sister Cleopatra Selene II. These moons were very important in providing the information (periods, distances) from which the mass and therefore the density of Kleopatra can be estimated.

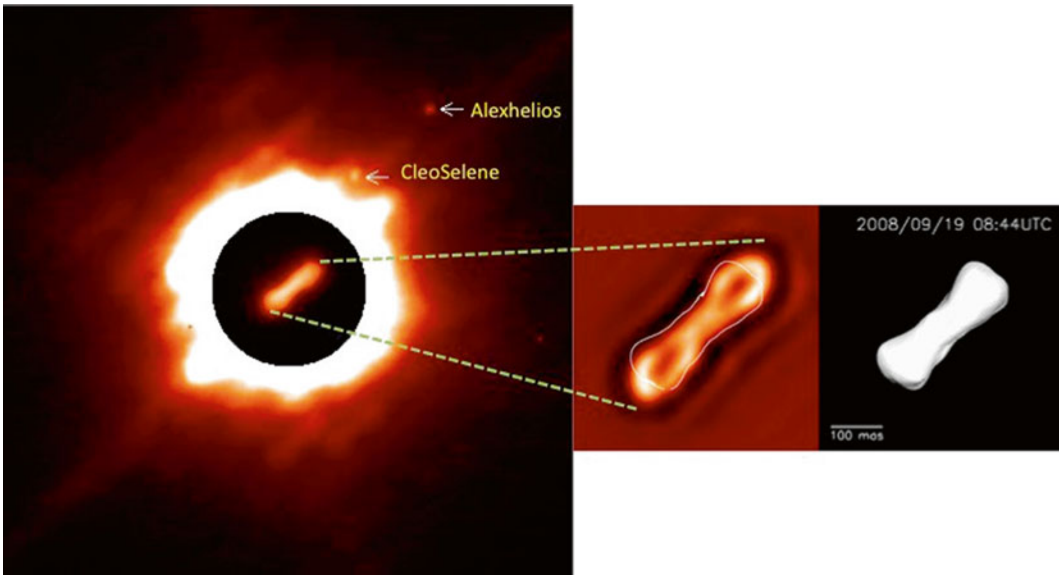

Fig. 3.3 Kleopatra and its two moons. A composite image (left) is necessary to show both the elongated dog-bone shape in the bright center of this image, taken by the W. M. Keck II telescope and its adaptive optics, and its faint moons, Alexhelios (the most distant) and Cleoselene. The shape of the asteroid obtained in this image from a ground-based telescope agrees with the radar-based model (right) (WMKT and Marchis)

It turns out that Kleopatra is full of holes. Perhaps a third of the space inside the "dog bone" is empty, the corners where its component rocks do not fit well together. This kind of structure for asteroids is called the "rubble-pile" model, which was originated by Arizona planetary scientists William K. Hartmann and Donald R. Davis. According to this theory, some asteroids, like Kleopatra, are a rather loose collection of bits and pieces of rock that have accumulated together, perhaps re-accumulating after earlier being broken up by a collision with another asteroid. The energy required to break up an asteroid is a lot less than the energy needed to scatter the pieces separately into space, so after a modest collision that breaks the asteroids into fragments, the pieces would re-assemble themselves by gravity in a loose collection.

Putting together all this together, astronomers have been able to guess at the scenario in Kleopatra's history that caused its strange, double, rapidly rotating, and spongy shape. At some time in the past, another asteroid hit Kleopatra with an oblique, glancing collision, causing the asteroid to spin much faster, like a geographical globe stroked vigorously with a hand. The asteroid broke into two main parts and a lot of smaller bits, much of which gathered together again, but with two chips remaining in orbit as moonlets.

PIAZZIA: A NEW PLANET SWIMS INTO HIS KEN

The 1000th asteroid was discovered from the Heidelberg observatory by the German astronomer Karl Wilhelm Reinmuth in 1923. No differently from other people, astronomers have a special regard for those numbers in a sequence that end in zeroes. The occasion was celebrated by naming the 1000th asteroid (1000) Piazzia, after the astronomer Giuseppe Piazzi, (1000) Piazzia, the first discoverer of an asteroid, the man who can be said to have started this whole area of astronomy. In the same exercise, several of the asteroids around number 1000 were named after other people who played a major part in the story: (998) Bodea, (999) Zachia, (1001) Gaussia and (1001) Olbers. Piazzi wasn't looking for new planets; in the words of the poet John Keats, a new planet swam into his ken.

The new planet was discovered on January 1, 1801, the first day of the nineteenth century (properly reckoned), when the inhabitants of Palermo in Sicily were celebrating the New Year. Palermo was at that time a particularly prosperous, cosmopolitan city, many wealthy, foreign families and many courtiers from Naples having fled there to escape the ravages of the French Revolution and the turmoil across Europe that flowed from it. On New Year's Day, families had attended Church in the morning, returning home to create extensive meals, sitting down at the table at about 2 o'clock for a 3-h lunch. The evening carried on lazily in the family home with games—board games with the children, card games for small stakes with the men—visits to or from friends or family, lots of gossip, some more to eat (biscuits, sweet cakes and liquors). It was a day to stay indoors and relax. The weather even further disinclined Palermitanos to venture out of their homes because of the increasing cold as the sparkling, clear afternoon descended into night.

One man, Giuseppe Piazzi, a monk of the Theatine order, was not participating in the festivities that afternoon. Following his religious duties in the morning, his attention was focused on the work to come. Piazzi was an astronomer, and he was preparing for a night observing the stars with the telescope of the Palermo Observatory. The telescope was mounted at the top of a tower of the Royal Palace of Palermo, in an observatory building that he would open to the elements, the better to view the dark sky. The building would protect him from the wind and stop the telescope from shaking, but for the clearest view he would have to stand at the eyepiece of the telescope in the chill air. Frost in Palermo is almost unknown, and Sicilian blood is thin (though very red); Palermitanos feel the cold more than most Europeans.

Piazzi found his warmest, longest coat. He gathered up his special observing hat. It had no brim to get in the way as he put his eye close to the telescope. He very much needed this item of dress during the cold night, since his hairline had retreated to the side of his head, and the bald scalp of his high domed forehead was fully exposed. He took up his observing gloves; they had no fingertips, so that he could adjust the small brass fittings of the telescope's mechanisms, but they were warm nevertheless. He retrieved his warmest boots. It was a well-worn routine for Piazzi, business as usual. There was no suspicion in his mind, as he prepared for work that night, a night that he would make a momentous discovery. He was about to discover a "new planet," only the second planet to be discovered since antiquity.

Giuseppe Piazzi was the last but one of ten children (many of whom died in infancy) born to a wealthy family of Ponte, Valtellina, now in northern Italy but at that time a region much fought over and whose status varied, decade to decade, from a Swiss dependency to a French conquered territory. As would have been typical of the younger sons of such a family, he entered the Church, and at age 19 he became a monk of the Theatine Order in Milan. He learned and taught mathematics, but he also expressed unwelcomed theological opinions that alienated a succession of his employers, so that he moved often from one position to the next, through a number of Italian universities. In 1781, he was appointed as a professor of mathematics at the Royal Academy of Palermo, precursor to the University of Palermo, in the Bourbon kingdom of Naples. In 1787 he became a professor of astronomy and was given the task to establish an observatory in Palermo in spite of the fact that he had probably never even looked through a telescope before. He became the observatory's director, and when a second observatory was established in 1817, in Naples, the director of that, too, dividing his time between them.

At first Piazzi's employer, King Ferdinand of Sicily, took the view that the observatory should be virtual. If an actual observatory building were needed in order to house the astronomical instruments that the king had provided, it was to be procured using Piazzi's salary. Sicily was actually run at the time by an enlightened viceroy, who persuaded the king that a building was necessary and that he should support the project accordingly. The small budget that was grudgingly conceded meant that the building was correspondingly meager. To consult on what to do to build a telescope and fit out an observatory in order to carry out an observing program, Piazzi received permission from the viceroy to travel to France and England in 1787–1789, seeking advice from the director of the Paris Observatory, Jean-Dominique Cassini, (24101) Cassini, from the director of the Greenwich Observatory, the then Astronomer Royal, Nevil Maskelyne and from the King's Astronomer, William Herschel, (2000) Herschel.

Just a few years earlier, Hershel had discovered the planet Uranus, with a telescope that he had made himself. He had garnered a reputation not only for the clarity of the optics of the telescopes that he made but the systematic way that he had surveyed the sky, noting everything that he saw—double stars, clusters of stars, patchy clouds (or nebulae), comets, and the new planet. He systematically looked at everything in the sky to discern its nature. Herschel realized when he saw it that Uranus was a planet; unlike stars, which appear as sparkling points of light, Uranus showed a steady, shining disc—a small disc, but a disc nonetheless. Piazzi was impressed by Herschel's large telescopes, even though he fell from one of them that had been erected in the garden and broke his arm. But Piazzi had decided to concentrate on measuring the positions of stars, not on seeing what they were, so Herschel's expertise in optics was not primarily what he was seeking. He needed not optical precision but mechanical accuracy. Unlike many continental astronomers, Piazzi did not commission the telescope for his observatory from Herschel, but from the greatest instrument maker of his generation.

RAMSDEN: TARDY GENIUS

To measure the positions of stars, Piazzi needed his telescope to point accurately. It had to be mechanically robust, rigid and precision-made on smoothly rotating bearings. The wooden telescopes made by Herschel supported his mirrors and lenses well but would not serve Piazzi's needs. He commissioned a brass telescope from Jesse Ramsden, (8001) Ramsden. The asteroid named after Ramsden was discovered in 1986 by the Czech astronomer Antonin Mrkos, (1832) Mrkos, and christened in his honor, on the occasion of a conference in Palermo in 2001 to celebrate the bicentenary of Piazzi's discovery.

Ramsden was a hard-working genius. He lived simply and worked long hours. He had set up as a businessman, selling instruments on commission, but he ploughed the profits back into the business, paying his staff well, and developing new techniques and improvements to the instruments that he made. Ramsden was also notorious for failing to deliver his commissions on time. His most spectacularly late delivery was a telescope for Dunsink Observatory in Ireland, which took 23 years to make and was only completed after Ramsden's death. His clients piled abuse on Ramsden's head—"a shatter-pated fellow" was one comment, "arch liar" another from a client whose commission was never delivered, though he added grudging praise: "Protect me from that sublime living artist." The manufacture of Piazzi's telescope had its problems, and Ramsden twice suspended work on it. But Piazzi was still in London, nursing his broken arm, and able to put pressure on Ramsden in his workshop in Piccadilly, next to St James' Church, at the Sign of the Golden Spectacles. After 2 years' work, the telescope was completed in August 1789, on the very day first promised, but a year late. (On another occasion, Ramsden attended an event at Buckingham Palace, in response to an invitation from the king, at the right hour on the right day but also a year later than the invitation specified.)

Although there were minor blemishes, Piazzi ascribed the defects to the pressure that he had put on Ramsden and accepted the telescope. Overall, the telescope was Ramsden's greatest work. It was used as the background to a portrait of Ramsden by Robert Home in 1791, which hangs in the Royal Society of London, to which Ramsden had been elected in 1786. The telescope was shipped to Palermo via Naples. As the telescope was loaded onto the ship in the docks at London, a zealous excise officer, laboring under the suspicion that it was a piece of technology associated with the manufacture of textiles and metal-working, claimed duty on the telescope on the grounds that it was an English invention. Ramsden bent the truth and won an exemption from duty on the grounds that any innovations were due to Piazzi. The telescope was installed in the Royal Palace of Palermo and for that Piazzi commissioned the help of a young mechanic from Hannover named Drechsler, who had worked in England.

At first Piazzi was disappointed in the telescope; the cross-wires that defined the center of the field of the telescope were so thin they broke easily, so he was unable to get the accuracy for which he had hoped, and there were other teething problems. But following this commissioning period, Piazzi brought the telescope to the peak of its performance, the finest in the world at the time. His basic faith in Ramsden's work was demonstrated by the number of instruments for astronomical and meteorological work that he bought from Ramsden over the following years.

Piazzi began observing with the telescope in 1780. The telescope was a refracting telescope, with a lens 3 in. in diameter (7.5 cm) to gather the light. It was pivoted in a 5-ft (1.7-m) vertical brass circle, which itself was floor-mounted on a metal turntable. The direction in which the telescope was pointing was read on scales with microscopes and micrometers. Combined with the time of the observation, these measurements constituted the position of a star. The measurements were of supreme accuracy; the telescope was reckoned as the most accurate of its time. Coupled with the excellence of Palermo as a site for astronomy—it was the southernmost European observatory and its weather was more favorable to astronomical observing than others—Piazzi had the opportunity to make more accurate measurements of the positions of stars in greater numbers than before. His two star catalogs, the first published in 1803, contained the positions of 8000 stars, each of them measured much more than once.

CERES: THE FIRST ASTEROID

On January 1, 1801, Piazzi was tempted from his primary ambition to measure star positions by the chance discovery of the first asteroid, (1) Ceres. An allegorical portrait of Piazzi in Palermo shows him inspired by the muse of astronomy, Urania, who directs his attention to the sky where the goddess Ceres sits. Piazzi locates the position on a star chart unrolled on the table. Piazzi is stern. His cheeks are sunken, the dome of his forehead prominent below a receding hairline. He is expressionless, quite stony-faced. There is no hint of the pleasure that he must have felt in discovering the first "new planet" since Herschel discovered Uranus.

That evening, Piazzi had been inspired to measure a star in Taurus that had previously been noted by the French astronomer Abbé Nicolas Louis de Lacaille, (9135) Lacaille, when he spotted an uncataloged star nearby. He observed the star again on subsequent evenings and found that its position was changing. It must be a planet or possibly a comet, though Piazzi could see no tail. Piazzi told his own story:

> *…[O]n the evening of the 1st of January of the current year, together with several other stars, I sought for the 87th of the Catalogue of the Zodiacal stars of Mr la Caille. I then found it was preceded by another, which, according to my custom, I observed likewise, as it did not impede the principal observation. The light was a little faint, and of the colour of Jupiter, but similar to many others which generally are reckoned of the eighth magnitude. Therefore I had no doubt of its being any other than a fixed star.*

> *In the evening of the 2d I repeated my observations, and having found that it did not correspond either in time or in distance from the zenith with the former observation, I began to entertain some doubts of its accuracy. I conceived afterwards a great suspicion that it might be a new star.*
>
> *The evening of the third, my suspicion was converted into certainty, being assured it was not a fixed star. Nevertheless before I made it known, I waited 'till the evening of the 4th, when I had the satisfaction to see it had moved at the same rate as on the preceding days.*
>
> *From the fourth to the tenth the sky was cloudy. In the evening of the 10th it appeared to me in the Telescope, accompanied by four others, nearly of the same magnitude. In the uncertainty which was the new one, I observed them all, as exactly as possible, and having compared these observations with the others which I made in the evening of the 11th, by its motion I easily distinguished my star from the others.*

Although Piazzi persistently returned to examine the object of his discovery, he did not allow himself to be distracted from his main task:

> *Meanwhile however I greatly wished to see it out of the meridian, to examine and to contemplate it more at leisure. But with all my labour, and that of my assistant D. Niccola Cacciatore and [of] D. Niccola Carioti belonging to this Royal Chapel both enjoying a sharp sight, and very expert in the knowledge of the heavens, neither with the night Telescope, nor with another achromatic one of 4 inches aperture, was it possible to distinguish it from many others among which it was moving. I was therefore obliged to content myself with seeing it on the meridian, and for the short time of two minutes, that is to say the time it employed in traversing the field of the Telescope; other observations, which were making at the same time, not permitting the instrument to be moved from its position.*

He delegated continued observations to his assistant:

> *In the meantime, in order to render the observations more certain, while I was observing with the Circle, D. Niccola Carioti observed with the transit instrument. The sky was so hazy, and often cloudy, that the observations were interrupted 'till the 11th of February; when the star having approached so near the Sun, it was not possible to see it any longer at its passage over the meridian.*
>
> *I intended to search for it, out of it [the meridian], by means of the Azimuth; but having fallen ill on the thirteenth of February, I was not able to make any further observations. These, however, which have been made, though they are not at the necessary distance from one another in order to assure us of the true course which the star describes in the heavens, are, notwithstanding, sufficient in my opinion, to make us know the nature of the same, as one may collect from the results, which I have deduced from them.*

If the "star" was a new planet it would have a near-circular orbit. If it was a comet it would have an elongated orbit, in the form of a parabola. To distinguish the two possibilities, Piazzi tried to fit a circular and a parabolic orbit to the observations. He fitted a parabola to three of the observations to see if the orbit matched the remainder. It did not. He tried a second, different group of three observations. This orbit did not fit, either. He moved on then to calculate the circular orbit, and found a fit for an orbit that lay at a radius of 2.7 times the radius of Earth's orbit, between the orbits of Mars and Jupiter. The circular orbit fitted all the observations a great deal better than any parabola.

Piazzi was aware that the planets describe orbits that are actually ellipses, not circles. He had not observed the new object over enough of an arc of its orbit to be able to calculate the ellipse. He convinced himself that the object that he had discovered was indeed a true planet.

Then he started to doubt his discovery. The object was almost, but, he thought, not quite, covered by one of the wires of his telescope, so Piazzi estimated its size. It seemed to be larger than Earth. But in the nights that followed, it appeared that the object was diminishing in size and brightness and therefore must be moving away. Perhaps it was a comet after all. But the nights on which it diminished were not perfect:

> *As after the 23rd [of January] the star began sensibly to diminish in size and brightness, uncertain whether it was to be attributed to its rapid receding from the Earth, or rather to the state of the atmosphere, which became after that still more dark and hazy, I began to doubt of its nature, so as even to believe it was a comet and not a planet.*

Piazzi observed his new star over an interval of 41 days until it moved too near the Sun and could not be seen in the bright light of the evening sky. Before it disappeared, he wrote to his friend and colleague Barnaba Oriani, (4540) Oriani, of the Brera Observatory in Milan, still worried about the nature of his discovery. "I have announced this star as a comet," he wrote, "but since it is not accompanied by any nebulosity and, further, since its movement is so slow and rather uniform, it has occurred to me several times that it might be something better than a comet. But I have been careful not to advance this supposition to the public." Having milked his discovery and established his priority for it, through a number of private communications, Piazzi published his data about the "new star" later that year. The hope was that this would enable astronomers to recover the object after it had moved on in the sky.

GAUSSIA: PREDICTING AND RECOVERING THE NEW PLANET

When the area of sky that Piazzi's new object inhabited reappeared from behind the Sun, it could not be found. The German mathematician Carl Friedrich Gauss, (1001) Gaussia, was attracted to the difficult problem of predicting where the body might be by computing its orbit from the brief run of data that Piazzi had published. In his book *Theoria Motus Corporum Coelestium* (*Theory of the Motion of Celestial Bodies*) Gauss stressed the nature of the difficulties and the eventual success of his work:

> *Nowhere in the annals of astronomy do we meet so great an opportunity, and a greater one could hardly be imagined, for showing most strikingly, the value of this problem, than in this crisis and urgent necessity, when all hopes of discovering in the heavens this planetary atom, among innumerable small stars after a lapse of nearly a year, rested solely upon a sufficiently approximate knowledge of its orbit to be based on very few observations. Could I ever have found a more seasonable opportunity to test the practical value of my conceptions, than now in employing them for the determination of the*

> *orbit of the planet Ceres, which during these forty-one days had described an arc of only three degrees and after the lapse of a year must be looked for in a region of the heavens very remote from that where it was last seen? This first application of the method was made in the month of October, 1801, and the first clear night when the planet was sought for as directed by the numbers deduced from it, restored the fugitive to observation.*

How did Gauss do it? The mythology of astronomical history suggests that Gauss used a new statistical method, the "method of least squares," to deal with the observations of Ceres and fit the best possible orbit to them. It is perhaps true that Gauss was attracted to this topic as a result of his difficulties with the orbit of Ceres. So maybe Ceres inspired Gauss to invent the method. But he did not actually use the method to make his predictions of where to look to recover Ceres. What he did use was a method of fitting an elliptical orbit to the observations, not a circular one. Right from the start Gauss realized that the orbit could be an eccentric ellipse, as it proved to be. Its eccentricity was 0.08, meaning that its distance from the Sun varied by ±8% over an orbit. Up to then it was long and laborious to fit an eccentric orbit to observations of a planet's position; Gauss invented a quick way to do so, using three measurements of the planet. He applied the method that he had invented to different trios of measurements as a check on consistency.

In December 1801 Gauss wrote with predictions of where the new planet might be to Baron F. von Zach at the Gotha Observatory, who used them to recover the planet almost exactly where Gauss had calculated it to be. Zach looked for Ceres first on December 7, 1801, and saw four stars at the position that Gauss had indicated. Two weeks of cloud intervened, and when he looked again on a poor night, December 18, he saw that one star was missing. That must have been the planet, but it had moved so far that he could not immediately relocate it through the hazy cloud. It took him hours of searching on the next clear night, December 31, 1801, to recover Ceres. He found it after midnight, on New Year's Day, 1802, so it had been found again exactly one year after Piazzi had first seen it. In correspondence he told his colleague Barnaba Oriani the story of his frustration at the weather. That frustration often persists in the present day. Even when scheduled on telescopes situated on the best sites in the world, astronomers are sometimes kept from their work by opaque skies. Martin Ward, now professor at Durham University, but at that time a young post-doctoral fellow, was observed raging with his fists at the overcast sky above the Anglo-Australian Telescope in Coonabarabran, Australia, shouting "Go away!," his voice having no effect on the clouds but causing the kangaroos grazing around the observatory building to bound off into the bush in fright. In 1977, perhaps more subtly, Paul Wild encapsulated the gloom that besets astronomers when the sky remains overcast for weeks on end in the name of the asteroid that he had just discovered, (5708) Melancholia, one of the four humors or human temperaments.

After that protracted time of frustration, Zach expressed his feeling that Ceres had been toying with him, and his joy at the re-discovery:

> *After Dec. 7 I have not had a clear sky. That day I observed many unknown stars, that I have not found in any catalogue not even in the one in folio that Bode has recently published … On Dec. 16th there was a break in the clouds and I had observed many little stars of 4 or 5 magnitude … When No. 1 had to transit across the meridian it didn't come. Great joy! I thought I had caught this coquette Ceres but the joy lasted less than a minute since I didn't see either N. 2 or N. 3. It was a light haze that hid them from me. (Letter of December 18, 1801)*
>
> *I hasten to inform you, that I found [Ceres] on December 7 of last year. I had already published this observation in the January 1802 issue of my journal … without realizing then that it was the planet; but I suspected it was. On Decbr. 31, I verified the thing and my suspect star had changed its position, on January 11 I observed it for the third time (the weather here is terrible) and I had the certainty of my finding, that I have the pleasure to announce to you … Mr. Olbers has discovered the planet Ceres independently at Bremen, but later than me, on Jan. 2. I said independently since in truth he made the discovery as well as I did, since I had not sent him my observations, that I kept secret until after Jan.ry 11 when I was completely sure of my Discovery. … I hope that Piazzi, or you other Gentlemen Astronomers [taking advantage] of the beautiful Italian climate have found the planet before me. (Letter of January 14, 1802)*

As Zach noted, a German doctor and amateur astronomer, Wilhelm Olbers had begun to search for the new object, also using Gauss' predictions. He was luckier with the weather. He began his search on January 1, 1802, and saw Ceres, but he had to wait until the next night to confirm that it moved and really was a planet.

The recovery of Ceres, where Gauss had calculated it would be, proved that its orbit was that of a planet, moving between Mars and Jupiter. Zach was triumphant: "Finally the new primary planet of our Solar System has again been discovered and found, like a starfish on the beach."

PALLAS: A SECOND NEW PLANET

Wilhelm Olbers, (1002) Olbersia, was a prominent doctor in Bremen, but also a keen amateur astronomer. Bremen is an estuarine port city in northwest Germany between Denmark and the Netherlands, near to the North Sea. Its climate as winter gives way to spring is marked by cloud, cold and damp. It is not the ideal place or time in which to practice astronomy. But in 1802, March was the time at which Ceres was visible again, and its position had to be repeatedly and accurately observed in order to nail down its orbit so that it could be followed indefinitely. It had been lost but then found; a number of astronomers were determined that it should not be lost again. Olbers was one of them.

Olbers was born in Bremen. At the age of 15 he was sent to school in Göttingen to study medicine. He also studied mathematics in order to further his interests in astronomy, and devised a method of calculating the orbits of comets while sitting at the sick bed of a fellow student. He kept his interest in comets throughout the rest of his life, and argued that their tails were not attached to comets' heads like flags attached to a mast but were trails of material left behind the comet, repelled by a force from the Sun, as they proved to be. He drew his conclusions from observations that he had made with his telescope from an upper room in his house, from where he discovered six new comets. It was well known of him that he was able to survive on just 4 h sleep a day, leaving time for both his busy professional life as a doctor and his passion as an astronomer.

Olbers wrote an influential article, still important and the subject of much discussion in modern times, on what is now known as "Olbers' paradox." This is the question of why the night sky is dark. If the universe is populated throughout with stars and is infinite, then every line of sight outwards from Earth ends on the surface of a star, and the sky should be bright everywhere like from the brightness of the Sun. Obviously it is not. One reason is that the universe is populated by galaxies, not stars, but neither is it true that the night sky is as bright as a galaxy. The paradox assumes that the universe is not infinite, because it started at some time in the past (we now call the moment of origin the Big Bang), so lines of sight do not extend infinitely far. Olbers justifies the accolade of being called the "greatest" of amateur astronomers.

On March 28, 1802, Olbers was making repeated observations of stars in Virgo that surrounded the then position of Ceres, so that he could determine the position of the new planet more precisely. He saw a seventh magnitude star (just below the brightness limit of stars that can be seen by the naked eye). Olbers was absolutely sure that the "star" was not there at the time of earlier observations in January. He measured its position and continued to follow the star over a period of 2 h. Even in that short time he could see that it had moved; certainly it moved substantially over the next couple of days.

Was the new "star" another new planet? Or a comet? "What shall I think of this new star?" Olbers wrote to Johann Bode on March 30. "Is it a strange comet or a new planet? I do not dare judge it yet. It is certain that it does not resemble a comet in the telescope; no trace of nebulosity or atmosphere around it can be seen." Bode dismissed the discovery. "I consider it a very distant comet, maybe to be found beyond Ceres orbit." Bode thought that now that Ceres had been found there could not be another planet in a similar orbit. Using "Pallas" for the new planet, which was then becoming the accepted name, he commented in a letter to William Herschel: "I hold myself still convinced that Ceres is the eighth primary planet of our Solar System and that Pallas is an exceptional planet—or comet—in her neighbourhood." But Carl Gauss settled the question with his calculation of the orbit of Pallas, which was very similar to Ceres. Similar orbit, similar appearance, similar kind of astronomical object: two new planets.

Olbers immediately latched on to the name Pallas for his new planet: (2) Pallas is its modern designation. He wrote to Baron von Zach about it. Zach was able to confirm Olbers' planet on April 4, and wrote to Piazzi:

> *The star of Dr. Olbers, that I have had the honour to announce to you [on 5 April], is actually a primary Planet that revolves around the sun on a highly inclined orbit. … It exists then between Mars & Ceres; & undoubtedly many more planets of this kind must exist in the various spaces among the Planets; … It is to you, Eminent Confrère, that we owe all these discoveries, without your Ceres, no Pallas. Without Pallas no future discoveries by any of us. What a new field!* (Letter of April 8, 1802)

Within weeks of his discovery, Olbers had an explanation for why there were two planets in the same orbit. The idea originated from a friend, the lawyer, politician and astronomer Baron Ferdinand von Ende (1760–1817), who suggested that the two small planets had earlier been one bigger one. Olbers fleshed out the idea in a letter to William Herschel on May 17, 1802:

> *How might it be if Ceres and Pallas were just a pair of fragments, or portions of a once greater planet which at one time occupied its proper place between Mars and Jupiter, and was in size more analogous to the other planets, and perhaps millions of years ago, had, either through the impact of a comet, or from an internal explosion, burst into pieces?*

The Russian meteor scientist Yevgeny Leonidovich Krinov, (2887) Krinov, followed by comet specialist Sergei Orloff, suggested that the disrupted planet should be named Phaethon (or Phaeton or Phaëton), after the son of the sun god Helios. As already laid out in Greek mythology, Phaethon was permitted by his father Helios, the sun god, to drive the chariot in which Helios carried the Sun in its course across the sky from daybreak to the day's end. The chariot careened out of control, and Zeus, the father of the gods and of men, averted a disaster by throwing a thunderbolt at the chariot, exploding it. It plunged into the river Eridanos, and Phaethon drowned. The idea that the asteroids all originate from the same larger planet turned out to be a gross oversimplification of the truth, so the name Phaethon for this imaginary creature fell out of use and is now used as the name of one particular asteroid, number 3200.

The name of Pallas, however, thrived in its use for the chemical element palladium. In July 1802, the chemist William Wollaston for the first time isolated palladium, from the residues left in chemical experiments with platinum. His claim that he had found a new element, number 46 in the Periodic Table, ran immediately into trouble.

The announcement in 1803 of his discovery of the new metal had not been done in the usual scholarly manner, in front of his peers in the Royal Society. It is not known why he did what he did, which was to advertise it for sale as a potentially valuable novelty. One reason might be that he could thus retrospectively demonstrate the date of his discovery, if the competition disputed his priority (the French chemists Hippolyte-Victor Collet-Descotils, Antoine François, comte de Fourcroy and Louis Nicolas Vauquelin were pursuing research along similar lines), without having to carry out further work that he would like to complete on the metal's properties. Another was that his experiments on the handling of platinum were potentially valuable intellectual property, and he did not want to expose the details.

The way that he announced the new element was to print a handbill that he posted in the window of a mineralogical shop in Soho in London and place an advertisement in the press. The announcement was couched in chemical jargon that had been common but which already, by that time, read as quaintly old-fashioned:

PALLADIUM;
OR,
NEW SILVER,
HAS these Properties amongst others that shew it to be
A NEW NOBLE METAL.

1. IT dissolves in pure Spirit of Nitre, and makes a dark red solution.
2. Green Vitriol throws it down in the state of a regulus from this solution, as it always does Gold from Aqua Regia.
3. IF you evaporate the solution you get a red calx that dissolves in Spirit of Salt or other acids.
4. IT is thrown down by quicksilver and by all the metals but Gold, Platina, and Silver.
5. ITS Specific Gravity by hammering was only 11.3, but by flatting as much as 11.8.
6. IN a common fire the face of it tarnishes a little and turns blue, but comes bright again, like other noble metals on being stronger heated.
7. THE greatest heat of a blacksmith's fire would hardly melt it;
8. BUT if you touch it while hot with a small bit of Sulphur it runs as easily as Zinc.

IT IS SOLD ONLY BY
MR. FORSTER, at No. 26, GERRARD STREET, SOHO,
LONDON.
In Samples of Five Shillings, Half a Guinea, & One Guinea each.

Another chemist, Richard Chenevix, bought one of the samples and, finding against his expectations that it was indeed a new metal, bought the remainder for 15 guineas and experimented on it to find its properties. He reported to the Royal Society on the "pretended new metal":

> *On the 19th of April I learned, by a printed notice sent to Mr. Knox, that a substance, which was announced as a new metal, was to be sold at Mr. Forster's, in Gerrard-Street. The mode adopted to make known a discovery of so much importance, without the name of any creditable person except the vender, appeared to me unusual in science, and was not calculated to inspire confidence. It was therefore with a view to detect what I conceived to be an imposition, that I procured a specimen, and undertook some experiments to learn its properties and nature.*

> *I had not proceeded very far, when I perceived that the effects produced by this substance, upon the various tests, were such as could not be referred, in toto, to any of the known metallic substances. I immediately returned to Mr. Forster, and became possessed of the whole quantity which had been left in his hands for sale. I could not obtain any information as to its natural state, or any trace that might lead to a probable conjecture.*

Though he agreed that it was a new metal, he concluded from his experiments that it was not an element but an alloy of mercury and platinum:

> *… [W]e learn that palladium is not, as was shamefully announced, a new simple metal, but an alloy of platina; and that the substance which can thus mask the most characteristic properties of that metal, while it loses the greater number of its own, is mercury.*

The new metal was bogus, Chenevix suggested, and he scorned the language of the handbill. It was written by someone who was uneducated, someone like "a hair dresser at Islington," and its "chemical language and phrases sound like Alchemy."

Chenevix's paper sparked off a number of experiments by chemists in France, Germany and England on the potential alloy of mercury and platinum, which to his great mortification failed to repeat his initial results. Someone anonymously added interest to the dispute by offering a reward of £20 for anyone who could, in front of three disinterested chemists who would stand as judges, make palladium from platinum and mercury. It was presumably Wollaston himself who made the offer of the reward, but he spiced his offer with mystery by making it without identifying that he was its source. No one claimed the reward.

Over the next couple of years, Chenevix worried further at the problem, remaining unconvinced that palladium was an element. Wollaston kept silent about his role in the discovery. Not until 1805 did Wollaston reveal that he was the initiator of the handbill and the discoverer of palladium, and indeed, of another element, rhodium:

> [*A*] *proportional quantity of platina … was purchased by me a few years since, with the design of rendering it malleable for the different purposes to which it is adapted. That object has now been attained, and during the solution of it, various unforeseen appearances occurred, some of which led to the discovery of palladium; but there were other circumstances which could not be accounted for by the existence of that metal alone. On this, and other accounts, I endeavoured to reserve to myself a deliberate examination of these difficulties which the subsequent discovery of a second new metal, that I have called rhodium.*

Wollaston explained that he had "published a concise delineation of its character" in the handbill, and "reserved to myself an opportunity of examining more at leisure many anomalous phenomena, that had occurred to me in the analysis of platina, which I was at a loss to explain, until I had learned to distinguish those peculiarities, that I afterwards found to arise from the presence of rhodium."

Although the dispute between Wollaston and Chenevix had been scientifically bitter, Wollaston showed no personal rancor to his fellow chemist and entertained him several times at the Royal Society Dining Club.

In 1801 Wollaston concluded the experiments that convinced him that the residue was a new element, and he referred to it in his notebooks as "C," short for "ceresium," after the asteroid Ceres that had just been discovered. However, the name of the new planet being taken for cerium by the time he announced the new element a year later, he announced it as palladium: "I … subsequently obtained another metal, to which I gave the name Palladium, from the planet that had been discovered nearly at the same time by Dr. Olbers."

It is not known specifically why Wollaston chose to name his new element after the asteroid. He was, concurrently with his experiments on palladium, working on the refractive properties of transparent minerals; in the course of this work he discovered dark lines in the spectrum of the Sun. So he had an interest in astronomy, as did Wollaston's father, the Rev. Francis Wollaston. He was the rector of Chislehurst. Perhaps it is a lay person's prejudice to suggest that this job gave him the leisure on most weekdays to indulge his enthusiasm in astronomy, but he certainly had a private observatory. It seems likely that, with his knowledge of the current developments in astronomy, Wollaston felt that the new planets were symbolic of what was then a modern era in the expansion of scientific knowledge and appropriated that symbolism into his discovery of the new element.

So, too, did the Swedish biologist and chemist Jöns Jacob Berzelius, (13109) Berzelius, who discovered the rare earth cerium. It was he who in 1811 invented the one- or two-letter notation for the chemical elements (H for hydrogen, He for helium, and so on). His patron was Wilhelm Hisinger, a chemist and a wealthy mine owner, who provided him with specimens of unusual ore from his mines and gave him a tungsten ore known as the "heavy stone of Bastnäs." In 1803 he crushed fragments of the ore into water and electrolyzed the solution, identifying a new element, which he named cerium after the then recent discovery of Ceres. It is element 58 in the Periodic Table.

In 1789 the German chemist Martin Klaproth discovered a new element in pitchblende ore. He proposed to call his element uranium after the planet then recently discovered by William Herschel. Since the Periodic Table of the Elements had not yet been formulated by Dmitri Mendeleev, (2769) Mendeleev, Klaproth did not realize that uranium was positioned at the end of the tabular list of the elements and was the last element (number 92), just as Uranus was the last planet. Elements 93 and 94 were made artificially in 1940 and named neptunium and plutonium after the two planets that had also been discovered since 1789. The element neptunium was created by Edwin M. McMillan and Philip Abelson at the Berkeley Laboratory of the University of California by neutron irradiation of uranium. Plutonium was created by Glenn T. Seaborg, McMillan, Joseph W.

Kennedy, and Arthur C. Wahl at the same laboratory by irradiating uranium with deuterons. The work was carried out under conditions of wartime secrecy to produce fissionable material for the Hiroshima and Nagasaki atomic bombs and revealed only in 1948. In his autobiography Seaborg explained how his group chose the euphonious name for plutonium, and the scatological pun of its chemical abbreviation:

> *It was so difficult to make, from such rare materials, that we thought it would be the heaviest element ever formed. So we considered names like extremium and ultimium. Fortunately, we were spared the inevitable embarrassment that one courts when proclaiming a discovery to be the ultimate in any field by deciding to follow the nomenclatural precedents of the two prior elements… Conveniently for us, the final planet, Pluto, had been discovered in 1930. We briefly considered the form plutium, but plutonium seemed more euphonious. Each element has a one- or two-letter abbreviation. Following the standard rules, this symbol should be Pl, but we chose Pu instead. We thought our little joke might come under criticism, but it was hardly noticed.*

Just as in the case of asteroids, having discovered a number of elements, Seaborg was honored by having an element named after him: seaborgium. As in the naming of asteroids, the name was controversial. The element had been discovered by a Berkeley/Livermore team of chemists and physicists, who proposed the name, but the International Union of Pure and Applied Chemistry rejected this name, adopting a rule that no element can be named after a living person. They recommended that element 106 should be named rutherfordium. This was disputed, since there had been a precedent in the naming of einsteinium while Albert Einstein was alive. In 1997, the name seaborgium was recognized by the IUPAC. The elements named after scientists are, in order, 96 curium, 99 einsteinium, 100 fermium, 101 mendelevium, 102 nobelium, 103 lawrencium, 104 rutherfordium, 106 seaborgium, 107 bohrium, 109 meitnerium and 111 roentgenium; this was a much more exclusive group than asteroids. All save two of the same scientists have asteroids named after them: (7000) Curie, (2001) Einstein, (8103) Fermi, (2769) Mendeleev, (6032) Nobel, (4856) Seaborg, (3948) Bohr, (6999) Meitner, and (6401) Roentgen. (4969) Lawrence and (1249) Rutherfordia look as if they might complete the list, but asteroid Lawrence is named after an asteroid hunter, and Rutherfordia after the town of Rutherford, New Jersey.

Peter Simon Pallas was a German natural scientist, who in 1772 came into possession of a large metallic stone from the city of Krasnoyarsk. It proved to be from a previously unknown class of stony-iron meteorites, which were named Pallasites after him. They therefore had nothing to do with the asteroid Pallas.

The Palladium in ancient Greek mythology was a wooden statue of the goddess Pallas Athene. It was maintained in the citadel of Troy, and the city was believed safe from capture as long as the idol was there. Only after it was stolen did Troy fall to the besieging Achaian Greeks. It was taken eventually to Rome. The statue was said to have fallen from heaven, but since it is made of wood, its meteoric origin is implausible.

What is this to do with the theatre? The name of the ancient Greek Palladium was borrowed for the Palladium Theatre, built in Argyll Street, London, in 1910 by the circus manager Charles Hengler and subsequently used for a number of theatres throughout the world. Hengler had operated his Grand Cirque in Argyll St since 1871. He was under the mistaken impression that the original Palladium in Troy was a building for entertainment and spectacle, like the Roman Colosseum.

KEATS: LIKE SOME WATCHER OF THE SKIES

John Keats, (4110) Keats, was one of England's most renowned Romantic poets. He was an unruly child, but as he became a teenager he became more studious and stood out at the small school that he attended in Middlesex, reading voraciously and winning a succession of school prizes. In 1811 he was given a copy of *Introduction to Astronomy* by John Bonnycastle, a mathematics teacher and prolific author. This book, in the form of "a series of letters from a Preceptor to his Pupil," was first published in 1786 and had a number of editions, of which Keats was given the sixth, published in 1803. The book sets out to be of interest to general readers through the inclusion of numerous extracts from poems, including a number from *Paradise Lost*. In the final letter of the book, entitled "Of the New Planets and Other Discoveries," Bonnycastle describes the discovery of Uranus by "Dr. Herschel" in 1781, and of Ceres by "M. Piazzi" in 1801, and briefly mentions what must at the time of writing been the very recent discovery of Pallas by "Dr. Olbers" in 1802.

In October 1816, having left school, Keats was staying with long-time friend Charles Cowden Clarke (1787-1877). Clarke was the son of one of Keats' teachers, and he himself took part in educating Keats, introducing him to literature. He showed Keats a free translation of the Greek poet Homer by the Elizabethan playwright George Chapman. Keats "discovered" an energetic style of English literature that caught his imagination, and the next morning, Clarke found a sonnet by Keats on his breakfast-table, "On First Looking into Chapman's Homer." It was Keats' first work of significance, and in it he compares his experience with astronomical and geographical explorers.

> *Much have I travell'd in the realms of gold,*
> *And many goodly states and kingdoms seen;*
> *Round many western islands have I been*
> *Which bards in fealty to Apollo hold.*
> *Oft of one wide expanse had I been told*
> *That deep-browed Homer ruled as his demesne;*
> *Yet did I never breathe its pure serene*
> *Till I heard Chapman speak out loud and bold:*

Then felt I like some watcher of the skies
When a new planet swims into his ken;
Or like stout Cortez when with eagle eyes
He star'd at the Pacific—and all his men
Look'd at each other with a wild surmise –
Silent, upon a peak in Darien.

Unlike Cortez and the Pacific Ocean, Keats did not make specific who and what he had in mind as the watcher of the skies and the new planet. Usually the event referred to is identified as the discovery of Uranus by William Herschel. However, that event took place 35 years before Keats wrote the sonnet, more than 10 years before Keats was born, and since then two further planets had been discovered. The discovery of Ceres and Pallas occurred in the years more immediately preceding the composition of the poem. Given the general nature of the astronomical simile, by contrast to the specific nature of the second simile, it seems more likely that Keats had in mind all three discoveries of new planets, including those of the minor planets Ceres and Pallas.

The French *gastronome*, Jean Anthelme Brillat-Savarin, author of *The Physiology of Taste,* had both an appreciation of astronomy, among many interests, but a more down-to-Earth view of what constituted human joy than Keats: "The discovery of a new dish does more for the happiness of the human race than the discovery of a star."

Fig. 4.1 Taken with NASA's Galileo spacecraft at its closest approach of 10,000 km (6500 miles) in 1993, this mosaicked image shows the asteroid Ida and its small moon, Dactyl, in enhanced color, whose variations indicate differences in the physical state and composition of the asteroid's surface soil (or "regolith") (NASA/JPL)

Chapter 4

Finding and Investigating Asteroids Using Technology

PHOTOGRAPHICA: AUTOMATION

Piazzi found the first asteroid by eye, by spotting a “new star.” This method remained the norm for 90 years. But in the mid-1850s, the newly invented technology of photography began to be applied to astronomy, though at first only to the brightest of astronomical targets. But photographic materials became progressively more sensitive, able to detect fainter stars. Astronomers became able to use the new technology to find minor planets. They did not look for new stars, comparing new photographs with old star charts; they looked for moving stars. This characteristic of asteroids is symbolized in the name of the asteroid (1891) Gondola, discovered in 1969 by the Swiss astronomer Paul Wild, which he selected as a beautiful sounding word, well suited to an object moving smoothly and silently across the sky.

The new technique was to make two exposures separated by an hour or two, and look for a star that occupied a different place in the two pictures. This method to find asteroids was brought to its peak of efficiency by the German astronomer Maximilian (“Max”) Wolf, (827) Wolfiana and (1217) Maximiliana. He discovered the first asteroid found in this way, (323) Brucia, in 1891, the first of the 248 asteroids that he discovered. The total score for Wolf and the staff of the observatory, including his successors, was the discovery of over 800 asteroids.

Wolf would, in the long nights of the wintertime, work at the telescope from, say, 5 p.m. to 2 a.m. He balanced on a step ladder to view the eyepiece of the telescope to keep it tracking correctly during the time exposure, smoking Virginia cigars, one of which he could make last a whole night. After perhaps five hours sleep, he rose to develop the exposed photographs. He laboriously examined each pair of pictures, side by side, section by section through a magnifying glass. If he found any possible asteroid (the record was to find 25 asteroids in one area, 12 of them new), he would send its position to collaborators in Vienna and Rome, so that its position could be re-measured accurately, and so that its orbit could be calculated.

Wolf wrote that he had never had the pleasure of seeing one of his asteroids except on a photograph. He paid tribute to his preferred technique in the name he gave to (443) Photographica, which he discovered in 1899. Many of the asteroids that he discovered are named after characters in opera, so we can infer that he enjoyed music. He would have enjoyed working in observatories in the modern era, when it is common for astronomers to fill the observing dome with loud music from a stereo system. It is not clear that this would have compensated for the fact that, nowadays, he would have been forbidden to smoke near a telescope.

A special machine was invented to help the process of finding a moving asteroid, called a “stereo comparator.” The two pictures were mounted in the machine and viewed through a microscope as if a three-dimensional pair. The shift of position of the asteroid made it look as if it was in front

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_4

of the rest of the stars; it leaped to attention, springing out of the star field. Wolf used a stereo comparator made and offered to him by Carl Pulfrich, a German physicist with the Carl Zeiss Company in Jena. He named the first asteroid that he found by this instrument (566) Stereoskopia, a minor planet that he had previously overlooked on photographic plates that he had taken earlier.

Another efficient technique to find moving stars, effective in the later discovery of what was acclaimed at the time as the ninth planet Pluto, was to use a "blink comparator." Like the stereo comparator, it was a machine to view two pictures, but rather than looking at both at the same time through different eyes to simulate a single 3D view, the operator flips a mirror back and forth to alternate the view of each picture in quick succession. A minor planet looks like a moving star that flies back and forth from one place to the other.

Asteroids were often discovered by serendipity as astronomers made a photographic time-exposure on, say, a faint galaxy and found trails where a minor planet had been recorded, drifting through the stationary stars in the background of its orbit. Astronomers often regarded these trails as blemishes in the photograph of the primary target, and usually discarded the observation, since any follow-up would delay their primary study. So many minor planets turned up in this way that the Austrian astronomer Edmund Weiss called them "the vermin of the skies." In a paper arguing against the same negative attitude, the amateur astronomer the Rev. Joel Metcalf, who himself discovered 41 asteroids, wrote:

> *Formerly the discovery of a new member of the Solar System was applauded as a contribution to knowledge. Lately it has been considered almost a crime. It is like the birth of a child in an already too large family; to keep track of it and bring it up properly is too much of a strain on the family exchequer.*

We can see that the idea that asteroids are somehow inferior has persisted to the present day in the public outrage that Pluto was in some way being demoted, when astronomers recognised in 2006 that it was not a planet in the same sense that the eight main planets are, but a particularly large minor planet. (This tale is told later in this book.)

LONEOS, CATALINA, SPACEWATCH, NEAT AND LINEAR: STARING AT THE SKY FOR ASTEROIDS

The modern technique to discover minor planets is similar to the methods invented by Wolf, replacing electronic CCD detectors for photography and substituting computers for comparators in the examination of the images. Searches for asteroids with this technology began to produce results on an industrial scale, when, in 1998, concerned at the threat of an impact on Earth by near-Earth asteroids (NEAs), the US Congress issued a mandate to NASA requiring it to discover 90 % of the NEAs with diameters greater than 1 km and catalog them.

A number of observatories took on the task, including the birth of the program called the Lowell Observatory Near-Earth-Object Search, directed by Ed Bowell, (2246) Bowell. The LONEOS project, (12574) LONEOS, discovered 19,052 asteroids (678 of them NEOs), including the one with this author's name (thank you, Ed). Other NASA-funded NEA discovery programs include the Catalina Sky Survey, run from the Lunar and Planetary Laboratory of the University of Arizona, (83360) Catalina); Spacewatch, run from Steward Observatory of the University of Arizona, (4255) Spacewatch; Near-Earth Asteroid Tracking, run from the NASA/Jet Propulsion Laboratory, (64070) NEAT; and the Lincoln Near-Earth Asteroid Research program, (118401) LINEAR.

LINEAR is run from MIT's Lincoln Laboratory, and is the most productive asteroid discovery program ever, with 135,000 discoveries. LINEAR uses the "step-stare" technique. A telescope located near White Sands, New Mexico, images the sky, building up a mosaic with a stepped array of brief exposures with a CCD recorder, repeating the mosaic after an hour or two. Computers are used to compare the exposures for "stars" that shift from one exposure to the next. Electronic blemishes produce a number of false alarms, so a third confirmatory mosaic is needed.

The technically most advanced system to discover asteroids (among other scientific projects) is Pan-STARRS (Panoramic Survey Telescope and Rapid Response System). It finds asteroids as part of an amazing project to seek out and study anything in the sky that changes. If it all proceeds as planned, Pan-STARRS will be a set of, ultimately, four 1.8-m telescopes. The first, PS1, began work in 2010 on the island of Maui in Hawaii. Construction of the second, PS2, began before PS1 was finished, but the project to complete it has been drawn out by funding issues. It is planned, ideally, that the telescopes will be coordinated to point to the same area of sky 3 degrees square, but operational factors might force them to be used in an independent but coordinated fashion. Each telescope feeds a CCD camera. Each camera contains an array of 64×64 CCDs, each CCD containing approximately 600×600 pixels, roughly the capacity of a CCD in a consumer camera, for a total of 1,400,000,000 pixels. The reason for this unusual configuration is that CCDs and computers are now relatively cheap, but large mirrors remain relatively expensive, so this is the best performance for a given cost—four smallish telescopes with gigantic cameras.

The extraordinary data-gathering capability of Pan-STARRS makes it possible to survey the sky over Hawaii about three times every month. The aim is to pick out variable stars, comets and asteroids—anything in the sky that is transient. However it is impractical to store all the data that the telescopes produce; the data has to be analyzed and condensed immediately. Each image, exposed in about 30 s and read out in about the same time, is added to a master image, built up week by week to produce the deepest possible image of that part of the sky. Secondly, each image is subtracted from an earlier master image, highlighting parts of the sky that have changed, like asteroids. Thirdly, data about the position and brightness of every star or other image that has been recorded is archived. All these steps must be completed while the next exposure is being obtained, in about 1 min, otherwise the project will inexorably fall behind, with data gathered faster than it can be used, discovering things too late.

This project uses money from the US Air Force and techniques developed by USAF to make a catalog of Earth's orbiting satellites as a defense and surveillance measure. At first, the civilian project contained features that would not permit it to record information that was defense-sensitive, such as properties of defense-related space satellites, but this restriction has, since then, been relaxed.

The NASA program in its entirety is geared to find near Earth asteroids but finds asteroids of all kinds. Because of it, the rate of discovery of asteroids took off in the early years of the twenty-first century. Prior to 1999 there were 10,000 numbered asteroids known, that is, asteroids whose orbits had been well determined. This was the result of 198 years of asteroid discovery. In just 2 years more the number had doubled, due to the new surveys. Currently between 20,000 and 30,000 numbered asteroids are being added to the lists each year.

By 2015, 12,745 NEAs had been found, with sizes ranging upwards from 1 m. It is estimated that there are almost 1000 NEAs with a diameter over 1 km (0.6 miles), with perhaps fewer than 100 yet to be discovered, so the mission given to NASA by the US Congress has been fulfilled, but it would be nice to find the missing ones in case they pay a surprise visit! The original mission is regarded now, however, as a first step. Calculations suggest that asteroids over about 1 km in diameter would devastate a continent. Asteroids 100 m (120 yards) in diameter or more would cause an impact that would have serious regional consequences, devastating everything within a radius say of 10 km (6 miles). Such an impact in an urban area would be catastrophic. So the limit of 1 km is conservative so far as the protection of Earth from celestial disasters is concerned (though it fairly represented an achievable search limit at the time). There are estimated to be about 4700 potentially hazardous asteroids of 100 m (330 ft) or more in diameter, of which perhaps only a quarter are known. It is difficult to see an asteroid this size at a distance. If we aimed to catalog all asteroids, not just those whose orbits take them as close to Earth as PHAs, there are perhaps 200,000 NEAs of 100 m in size.

About 400 NEAs of all sizes are listed by the Sentry System of the Jet Propulsion Laboratory, (78577) JPL, on a website, http://neo.jpl.nasa.gov/risk/, which is kept up to date on a daily basis. Most of the entries are probably less than 50 m in diameter (less than 200 ft). They have been flagged and put on the Sentinel list because it is possible that they could perhaps collide with Earth within a century, based on currently available observations. Their orbits are not precisely enough known to be certain about this. By far most will be removed from the list as their orbit becomes better known and it will be proved that they will miss Earth. The point of the exercise is to see if any of them turn out for sure to be on a trajectory for a collision with Earth, and then to see what can be done about this.

There are plenty of books that discuss this issue, some in depth and some with a degree of sensationalism, so we are not going to do that here.

In 2002 a group of American astronauts and physicists, Rusty Schweickart, Clark Chapman, Piet Hut, and Ed Lu established the B612 Foundation, (46610) Besixdouze, to help protect Earth from asteroid impacts. Their first goal was to be able to alter the orbit of an incoming hazardous asteroid to deflect it from its path. As a step to this, the foundation is developing a space-borne infrared telescope, which will orbit near the planet Venus, and, facing away from the dazzle of the Sun, will be able to view asteroids approaching near to Earth, no matter from which side. This is the Sentinel program, and its aim is find and catalog 90 % of NEOs with diameters larger than 140 m (150 yards).

All these asteroid discovery programs are memorialized as asteroid names. The names are obvious except for the name of asteroid (46610) Besixdouze, where the linkages in the name and numbers are intriguing. In Antoine de Saint-Exupéry's eponymous story, the Little Prince has his home on an asteroid, B612, which (in the story) was discovered by a Turkish astronomer, although this discovery was not widely known. The asteroid has (in the story) two active volcanoes and a rose growing on it. (46610) Besixdouze is the counterpart of this fictional asteroid. The name in French translates as B612—"B-six-twelve"—and in hexadecimal notation, 6-12, translates to the asteroid's number, 46,610, in decimal notation.

Altogether, over 300,000 minor planets, mainly asteroids in the Main Belt, have been found and designated in serial order with a catalog number, such as 128562. Of these, 17,000 have been named. There are another 250,000 asteroids with provisional designations, like 2008 TC3; it needs more work to be able to calculate a definitive orbit for each of these, well enough that they can be recovered indefinitely.

IDA: AN ASTEROID WITH A MOON

In 200 years, astronomers progressed from viewing asteroids as moving points of light to seeing them as little worlds, by using sophisticated radar and optical telescopes based on or near Earth, but ultimately by sending spacecraft to rendezvous with them for a close look. The asteroid (243) Ida was investigated as a serendipitous target by the Galileo space probe on its way to Jupiter in 1993. A serendipitous target is one that turns up by accident in a program. The Galileo program was planned with an orbit and launch time that suited the flight to Jupiter, and then it turned out by chance that Ida was on the way. More science for not much more effort—NASA scientists like this idea!

Ida is a modestly sized asteroid compared to Kleopatra, measuring 56 × 24 × 21 km (35 × 15 × 13 miles). Images taken by Galileo as it passed by showed that Ida has a moonlet, the first confirmed discovery of an asteroid with a satellite. Ida is quite irregular, but its tiny moon (Fig. 4.1) is remarkably spherical, with a mean diameter of 1.4 km (0.87 miles). The moon was named Dactyl. In Greek mythology, Mount Ida was a sacred mountain in Phrygia in Anatolia (today the western part of Turkey). It was the home of the ten Dactyls (the word means "fingers"), who were small, blacksmithing daemons.

Ida is heavily cratered, with the craters named after caverns and grottos on Earth and other geographical areas named after the Galileo project participants, the discoverer of Ida and places associated with him. Craters on the moon Dactyl are given individual names of the dactyls themselves.

It is estimated that about 15 % of the small asteroids of the Main Belt may have moons, but a smaller percentage of the larger ones. About 250 binary asteroids are actually known, of which about 20 are triple (or more). Most were discovered by radar observations, seen to be double in the radar images (Fig. 4.2), or with the moon standing out from the radar signal reflected from the asteroid by virtue of its different frequency characteristics. (The reflected radar signal is altered in frequency by the rotation and revolution of the moon, which are different from the similar characteristics of the asteroid.) A few binary asteroids have been discovered to be double by direct imaging from Earth or by a telescope on a satellite, like the Hubble Space Telescope. Some have been found to be double by the shape of their light curve; the way that the brightness of the asteroid changes with time can reveal times when the moon obscures or is obscured by the asteroid. A few have been detected by seeing a double drop in brightness when an asteroid passes in front of ("occults") a star. Until the advent of portable telescopes, it was rare for such an event to happen at the site of an observatory with a large telescope and the right equipment. Anything found on such an occasion remained unconfirmed—and there was always the uncertainty that the double drop might have been some atmospheric glitch. In fact the first occasions when an asteroid was suspected to have a moon were during stellar occultations, observed in the 1970s. These results were regarded with skepticism. Nowadays several portable telescopes can be deployed in the right area to see the occultation and the detection equipment has improved, so there are more examples of binaries detected in this way. Finally, there is some evidence for the existence of a few dozen binary asteroids that, although widely separated, follow almost exactly the same orbit in space. When extrapolated back their orbits intersect, so it seems that on some occasion they were in the same place at the same time. Up to then they were probably a true pair, but then something happened to disrupt this. What was it? In fact, what makes binary asteroids in the first place?

The first theory of the origin of binary asteroids was that the moons were formed through collisions between asteroids, with some bits knocked off the parent body but not scattered, free, into space. These moons were "chips off the old block." This seems to have been the origin of some of the moons of the large asteroids such as Kleopatra, but the theory did not account for the larger fraction of small asteroids that have moons. Other ideas include the possibility that two asteroids were jostled together in the hurly-burly in the crowded early Solar System, and have fused together.

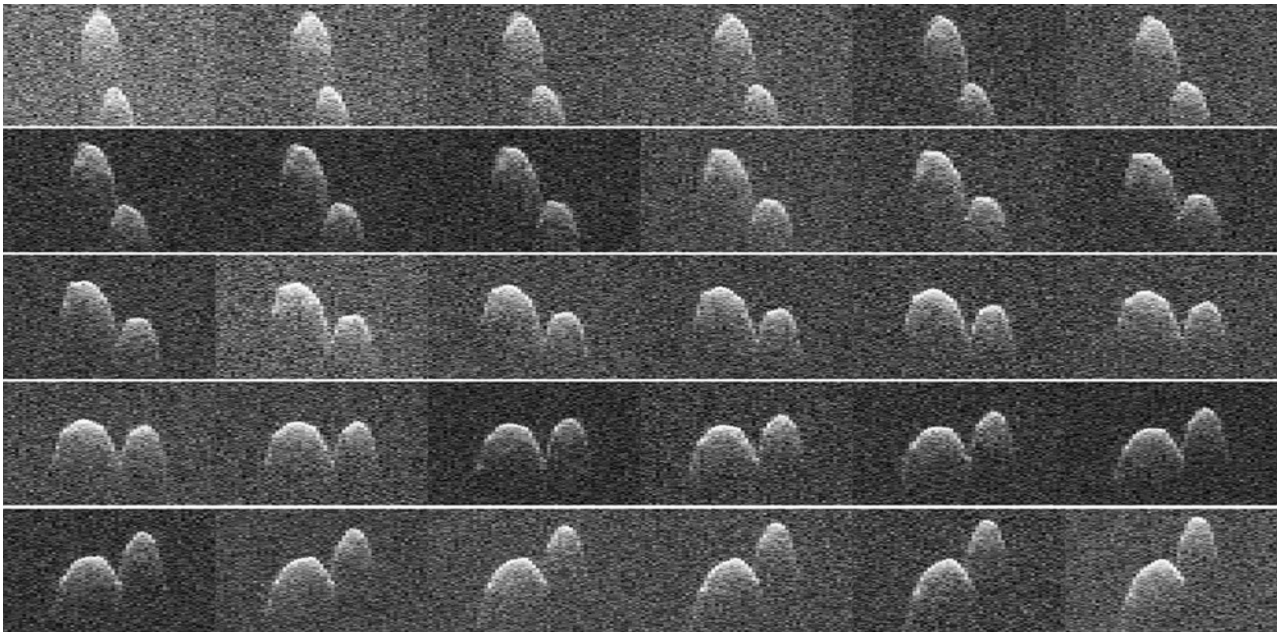

Fig. 4.2 Asteroid (85989). These radar images of a nameless but carefully cataloged asteroid, (85989) = 1999 JD6, were collected in 2015. The asteroid is revealed as, in fact, a pair of asteroids that touch. They may have fused together, like Comet 67P/Churyumov-Gerasimenko. Asteroid 1999 JD6 rotates as shown here in the sequence of images with a period of 7 h 39 min (NASA/JPL-Caltech/GSSR)

An interesting theory about the origins of double asteroids starts with the concept of asteroids as loose collections of rocky material in "rubble piles," as mentioned earlier. Material at the equator might not be well bound, but might lie loose at the surface. If a fast-rotating asteroid—they tend to be the smaller ones, and the ones that orbit in the inner part of the Solar System—is made to rotate even faster, beyond a certain critical value, the material can be flung by centrifugal force off the equator, into a ring of debris, which gathers together to make a moon. But how can an asteroid be made to rotate faster?

YORP: GETTING FASTER BY THE BRUSH OF A FEATHER

The first hint that small asteroids rotate quite fast came from looking at the statistics of their rotation periods, as revealed by their changes of brightness. In general, the smaller asteroids rotate faster than the larger ones. Most asteroids rotate with a period between 4 and 10 h. If an asteroid rotates faster than once every 2.2 h, loose bits will fly off. Asteroids larger than about 0.5 km in size (say, 2000 ft) rotate at this speed or less. These may have been pushed up to this speed, and then if any have been pushed over it they have disintegrated. They must be loose rubble piles, rocks on the equator simply sitting there, not cemented down, held only by the weak gravity of the small asteroid.

A few of the very smallest asteroids rotate as fast as 1000 revolutions per day. The record is held by 2008 HJ, a very dense asteroid, some 12 m × 24 m (40 × 80 ft) in size. It made a close approach to Earth in 2008, and was seen to revolve once every 42.7 s. This discovery was made by amateur astronomer Richard Miles (Fig. 4.3), using the Faulkes Telescope South, a telescope in Australia that is remotely controlled from the UK and is made available for short periods at a time for use by school students and amateurs. The previous record was held by the asteroid 2000 DO8, which rotates half as fast, once every 78 s. Superfast rotators like these must be strong, monolithic pieces of rock. So many small, monolithic asteroids rotate faster than the critical value of one rotation every 2.2 h that it seems that there is indeed something that speeds them up.

The process that speeds the rotation of asteroids is called the YORP effect. It is a gentle touch on an asteroid, like the brush of a feather as it falls down your cheek. Although its force is almost imperceptible, the YORP effect has millions of years in which to work and inexorably changes an asteroid's rotation.

The YORP effect is named after the initials of the scientists, Yarkovsky and Radzievskii, who thought of various aspects of it, as elaborated by O'Keefe and Paddack. They were all working independently over a period of a century, their work's significance for the problem of the rotation of asteroids realized by NASA scientist David P. Rubincam in 1998 in an article "Does sunlight change the spin of small asteroids?"

The ideas that combined into the YORP effect are the following. The Russian-Polish engineer Ivan Yarkovsky, (35334) Yarkovsky, realized that radiation leaving from a body warmed by the Sun produces a backward push ("radiation pressure"), and applied this to the motion of planets. He published a privately printed pamphlet on this topic in 1901, but his work had little impact outside Russia. It was kept barely alive in the West by the Estonian astronomer Ernst Öpik, (2099) Opik, an émigré to Armagh in Northern Ireland. In 1954 the Soviet astronomer V. V. Radzievskii applied the idea to the rotation of blotchy meteoroids by asserting that black patches absorb more sunlight than white patches, so there could be an asymmetry in the backward push that changes the asteroid's spin. American planetologist John O'Keefe, (6585) O'Keefe, and NASA's aerospace engineer Stephen Paddack, 5191) Paddack, who were also interested in why meteoroids and asteroids spin, realized that the shape of the asteroids was very important in the working of the effect. Not only did Paddack make theoretical calculations, he carried out experiments, getting an assistant to drop irregular stones into a swimming pool while he watched them spin from below the water, turned by the push of water on bumps on their surface.

Asteroids are typically irregular in shape; there are hills or mountains on the surface. Sunlight shines on the surface, which warms up, absorbing sunlight, and cools, re-emitting heat radiation. As radiation leaves the surface of the asteroid, traveling directly away from the surface, it imparts a little push back on the asteroid. If the surface is spherical, the push will be through the center of the asteroid, but if the surface is irregular because of the mountains, the backward push will be oblique. If the distribution of mountains over the surface of the asteroid is asymmetric and the asteroid has something of a windmill or propeller shape, the push will tend to turn the asteroid. The effect can be amplified by differences in color over the surface, the blotchiness of the asteroid.

The net rotational push, or torque, will either slowly increase or decrease the asteroid's rotation speed. Over a few million years, a small asteroid could spin up to the point where surface material flies off its equatorial region. Alternatively the braking effect could slow it down to a standstill and make it spin the other way. The slowest known rotating asteroid is a 30-km (20-mile)-sized example, (288) Glauke, which rotates once every 50 days.

Although the YORP effect is small, astronomers have observed a small number (three!) of asteroids whose rotation is indeed getting faster and faster. The first was (54509) YORP, which, according to an international Anglo-American team of astronomers, is speeding up at the rate of about one millisecond per year. Its name commemorates the effect that has brought it to its present condition of rotating once in 12 min. It is thought that it will eventually reach a speed of one rotation every 20 s.

Additionally to changing the speed of rotation of the asteroid, the YORP effect causes its rotational axis to twist. In general the spin of an asteroid will not be at right angles to sunlight and the accidental windmill shape will not be aligned with either direction, so the asteroid is likely to twist as it changes speed, for much the same reasons that a spinning bicycle wheel held by its axle will twist when the axle is tilted. A slowly rotating asteroid increases its rotation speed while tipping over more and more. Eventually the asteroid tips over so far that it starts to slow down, either reversing its spin or spinning so slowly that it tumbles, instead of spinning around one of its axes of symmetry. (4179) Toutatis does this.

TOUTATIS: THE SKY MIGHT FALL

(4179) Toutatis was seen first in 1934, lost and re-discovered in 1989. The asteroid is named after a god, the protector of the Gauls. His name is found in inscriptions across France and Britain up to the Roman period and is invoked frequently ("By Toutatis!") by Vitalstatistix, the chieftain of the tribe to which the warrior, Asterix, and his friend Obelix belong in the cartoon books *Les Aventures d'Asterix* by Albert Uderzo and René Goscinny. Vitalstatistix' only fear is that one day the sky might fall onto his head.

Vitalstatistix's fear might have been proved prudent. The reason for the asteroid's name is that it has an eccentric orbit that crosses the orbit of

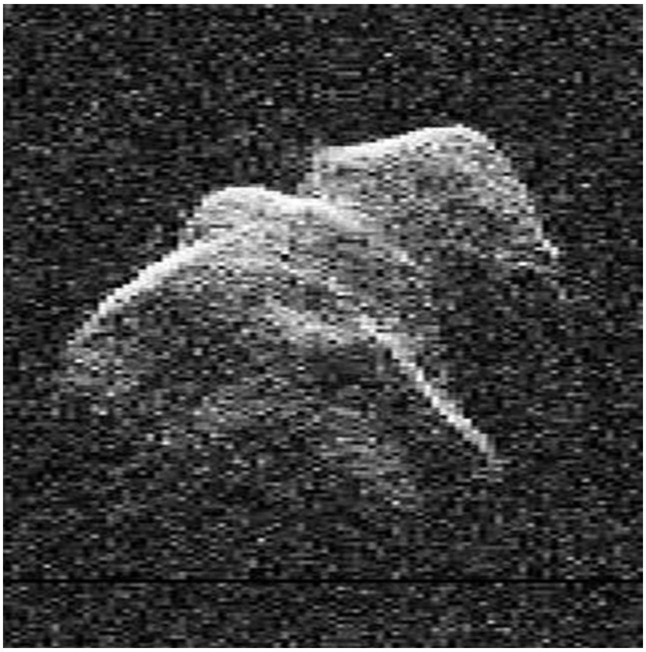

Fig. 4.3 Asteroid Toutatis was imaged by radar techniques in 1996 (Steve Ostro, JPL, Arecibo Telescope)

Earth; in fact, its orbit is nearly in the plane of Earth's orbit, and the asteroid thus makes numerous approaches near to Earth. At present Toutatis can come as close as 2.5 times the distance of the Moon. Its orbit is strongly affected by the terrestrial planets and is chaotic. It is likely to be ejected from the Solar System within 100,000 years, but it might collide with Earth first. Earth is safe from this eventuality for at least 600 years, so Vitalstatistix himself would in fact have nothing to fear from this asteroid, but Gauls of the future might justifiably be apprehensive.

Because the asteroid comes so close to Earth it has been possible to make images of its surface through radar studies (Fig. 4.3), in the same way as of Kleopatra. The shape found by radar was confirmed in December, 2012 when the Chinese space probe Chang'e 2 flew by Toutatis, but the closer look showed lots of surface detail, too (Fig. 4.4). Like Kleopatra the asteroid is long and thin: 4.6 by 2.4 by 1.9 km. (2.9 by 1.5 by 1.2 miles). It has a very complex rotation and tumbles through space, turning "head over heels." The strange shape, the extraordinary rotation and perhaps also the extreme orbit suggest that this asteroid may have been struck in the past by another large asteroid.

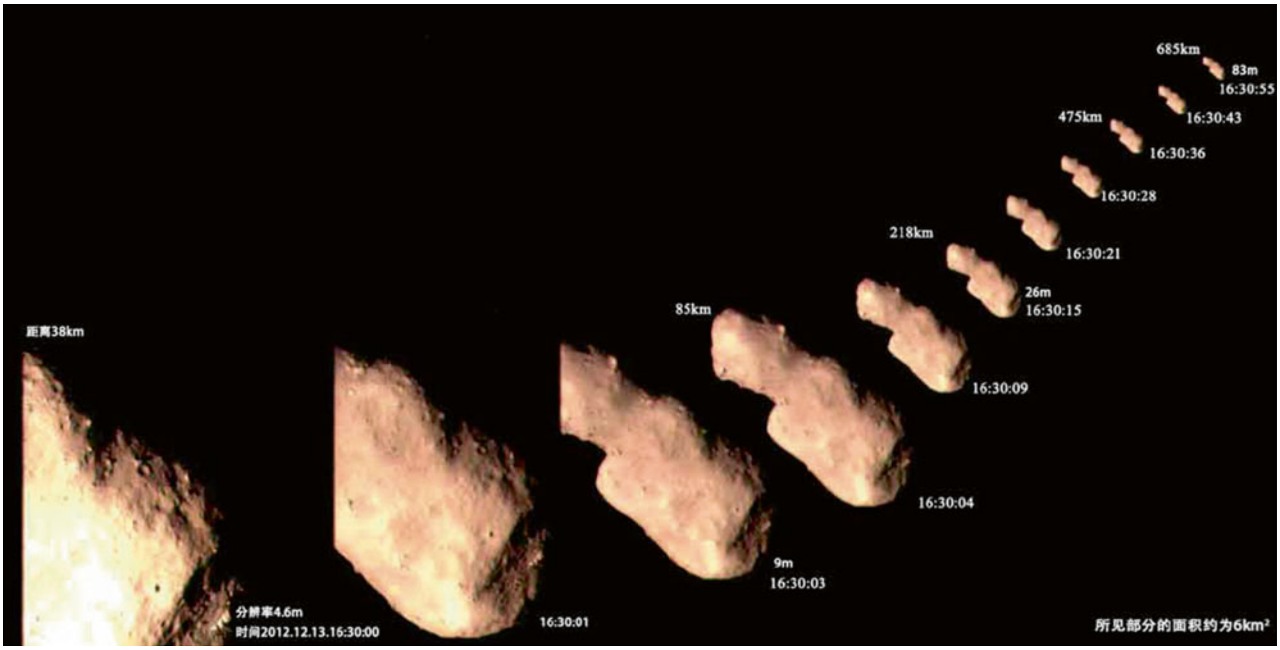

Fig. 4.4 During the closest flyby of Chang'e 2 to Toutatis the spacecraft took a sequence of photos at distances of 40–700 km, some occluded (straight edge on the left of some images) by the spacecraft's solar panels (Chinese Academy of Science, Chang'e 2 spacecraft)

ITOKAWA: THE FALCON'S DUSTY PERCH

The asteroid (25143) Itokawa was selected as the target of the first attempted sample return mission to an asteroid. A sample return mission is a space mission that attempts to recover samples of the object of the mission into the spacecraft and return them to Earth for analysis. The final missions of the Apollo program, Apollo 11–17, were sample return missions to and from the Moon. (25143) Itokawa was the target of Japan's Hayabusa mission. Hayabusa means "Peregrine Falcon." The spacecraft reached the asteroid in September 2005 and maneuvered into orbit alongside it. Itokawa is a small asteroid, roughly ellipsoidal in shape, only 600 m long and 250 m wide (2000 ft × 800 ft), not massive. Its gravity was too weak to hold the spacecraft in orbit like a satellite. The weak gravity was one reason why the asteroid was chosen as a target for the sample return mission—it would be easy for the spacecraft to re-launch itself back to Earth so it would need to carry the minimum of fuel for the return journey.

The spacecraft carried out remote observations of the asteroid for a month and then in November 2005 attempted to land a small spacecraft called Minerva. The descent was fraught with difficulties. There were technical problems, which caused the spacecraft to make fruitless approaches, but there was a serious last-minute problem on the last descent that proved almost fatal. The asteroid proved to be remarkably rocky, and the spacecraft software thought in the descent that it was landing too near an obstacle. It entered a defensive configuration, which meant that the sample-return mechanism failed properly to activate and could not collect material in the manner intended. However, the controllers surmised that the thrust rockets that controlled the descent might have blown dust up into the open collector horn as the spacecraft touched down. So the controllers decided to continue with the mission. The return capsule was sealed and sent home. The return trip was equally fraught with incident, but heroic efforts by the controllers eventually brought the capsule back to Earth in June 2010. As anticipated, the spacecraft disintegrated like an asteroid or fireball on re-entry into the atmosphere, but the capsule survived intact and was recovered at the Woomera range in Australia. The capsule proved to contain over 1000 tiny grains of material from the asteroid.

The images from Itokawa were a surprise (Fig. 4.5). It has a two-fold shape, two potato-like pieces fused together end-to-end, with an angle between them. Light measurements made by Stephen Lowry and his collaborators at the University of Kent showed that the asteroid is rotating, and its period, just over 12 h, is increasing at the rate of 0.045 s per year. Theoretical interpretation of this result in terms of the YORP effect suggests that the two parts of the asteroid have different densities—the larger part has a density of 1.75 g per cc, the smaller part 2.85 g per cc. It seems that the asteroid is two separate bodies that have fused together.

The small asteroid is littered almost everywhere with rocks, from big boulders to pebbles, and there are few craters. Those craters that do exist are small. Any meteorites that have impacted on have buried themselves in loose material, or the craters been backfilled by the mobility of small stones and dust on the surface. The density of the asteroid is low and indicates that the asteroid is a loose agglomeration of rocks with large spaces where the rocks do not fit well together. Itokawa is, and looks like, a rubble pile. Its gravity is so weak that the rocks and ores of which it is made have not consolidated. It is representative of a small planetesimal in the very early history of the Solar System that might have grown into a planet if it had accumulated more material. The naming convention for Itokawa is that surface features are to be named after places and features associated with astronautics and planetary sciences.

The dust on Itokawa has a similar composition to meteorite dust. Dust from asteroid collisions permeates the Solar System, created as one rocky surface grinds against another throughout its orbital plane, the "ecliptic." Interplanetary dust is the medium that reflects sunlight in the phenomenon known as the zodiacal light, a cone of light that shines up from the horizon after sunset, its axis along the line of the ecliptic. In the first hour of a moonless sky, far from artificial lights, the zodiacal light shines like a broad searchlight beam along the zodiacal constellations. The dust falls on Earth, grain by grain, and shows at night as each flies, incandescent, through the air as a meteor. The meteors do not radiate from a single point on a given date of the year as in a meteor shower but streak at random times in random directions; these are so-called "sporadic" meteors. The dust originates from a number of sources, including melted comets and crumbled asteroids.

Fig. 4.5 Images of Itokawa from the Japanese Space Agency's spacecraft Hayabusa show a very rough surface studded with boulders. It has few craters, and the surface must be very young, littered with an abundance of dusty soil that has recently fallen and covered the asteroid. (Image ©JAXA)

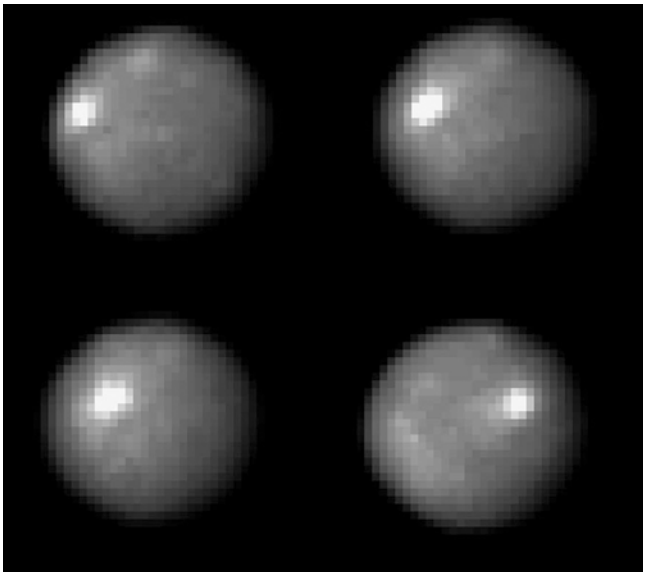

Fig. 5.1 The Hubble Space Telescope took these images of the asteroid Ceres in 2003 over a 2-h and 20-min span, the time it takes the asteroid to complete one quarter of a rotation. One day on Ceres lasts 9 h. The bright spot that appears in each image was clarified by the close-up inspection of the Dawn spacecraft, but its origin remains much of a mystery. The pixellation of the images is due to the small size of Ceres as seen at such a great distance, even with the most powerful astronomical telescope that is operational. (NASA, ESA, J. Parker (Southwest Research Institute), P. Thomas (Cornell University), and L. McFadden (University of Maryland, College Park))

Chapter 5

Naming and Possessing

ANTARCTICA: COMMON HERITAGE OF MANKIND

As related earlier (Chap. 2), the asteroid 2008 TC3 was seen for less than 24 h while it traversed just a tiny fraction of its orbit, and, since it was destroyed when it impacted Earth, there was never any question of tracking it and recovering it in later orbits. It will forever remain identified with its provisional designation (the year of discovery, two letters and figures). It will never be dignified by a permanent number, still less a name.

As of October 2015, there are over a million provisional designations representing the discovery of 700,000 asteroids. More than half of them have been observed on enough occasions that they have had their orbits well determined. They can be followed indefinitely. These asteroids have been entered into a catalog of 450,000 permanently designated asteroids, with a number. Nearly 20,000 of these have been given names by the discoverer, or someone he or she gives that opportunity to, or, if no one has bothered for 10 years, by any third party, subject to a ratification process that will be described later. Names are now optional for asteroids, but all of them eventually get a number in what is now long list that grows even longer with time. The number is thus largely correlated with the date of discovery and the date at which the orbit was determined, but not exactly. Even if an asteroid gets a name, it is the practice, in referring to it, to give the number as well, positioned in parentheses before the name, like "(128562) Murdin."

To name something is, in some way, a measure of control and possession. Explorers proclaimed the name of the land that they discovered, and took possession of it for their rulers. Houses are often named by owners. Whether the names are accepted is up to the community, which might use the names that are given. If the ownership of a territory is disputed the name is disputed, too. A map that refers to a disputed territory by one name or the other might provoke heated discussion. Airlines that provide maps in in-flight magazines to show the routes that they fly often add a disclaimer to the effect that the names of geographical areas have no political significance; they deny that the names which they might use for disputed territory imply some particular view of its ownership.

What of celestial objects? No one can be said to own a celestial object. In the twentieth century this principle is enshrined in the Outer Space Treaty, originally of 1967, created through the United Nations and signed by over 100 nations. The view is that the celestial bodies, like Antarctica, are the common heritage of all mankind. In less high-flown language, Article II of the treaty says that "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." As this principle has developed over the past 400 years, since the discovery of the satellites of Jupiter, so, too, has the idea that the naming of celestial objects should be an activity guided internationally. Nowadays this function is

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_5

taken by the International Astronomical Union, who enforce the ideal, expressed through the naming of asteroid (2404) Antarctica.

Whatever the formalities, it remains true that some individuals have a personal relationship with some asteroids. Earlier, I referred to (128562) Murdin as "my" asteroid, though I could never really lay claim to it. The then Astronomer Royal, George Airy wrote of a deeply emotional reason why he, in some way, "possessed" asteroid (18) Melpomene. The asteroid was discovered in 1852 by J. R. Hind in London and named by Airy at Hind's invitation. Airy wrote, in a letter to the Cape astronomer David Gill:

> *I look upon her as my planet for the following reason which you will not find in books. On 1839 June 24, I lost my noble boy Arthur. On 1852 June 24 (just 13 years later), I lost my dear daughter Elizabeth. And, while feeling that day of sorrow, I learnt that on that day a planet was discovered which I was requested to name. So I fixed on the name of the Muse of Sadness.*

In the early history of asteroids, in the nineteenth century, when asteroids were first discovered, they were referred to with the discoverer's name—"Hind's new planet," and similarly. In this the practice echoed the convention for comets; the comet is usually referred to by the name of the discoverer, for example, "Kirch's Comet of 1680," discovered by the German astronomer Gottfried Kirch, the first discovery of a comet with a telescope. Usually the discoverer is the astronomer who first saw it. However, the discoverer was defined by Max Wolf in 1859, in line with precedent, as "not the one who first saw or observed [the asteroid] but the one who first realised it as a new object." So mathematicians who calculated the orbits of two comets or asteroids and realized that the two appearances are one and the same object are counted as discoverers. Edmond Halley's discovery that comets seen every 74 years were successive appearances of the same comet was the reason why Halley's Comet was named for him.

GALILEA: THE MEDICEAN STARS

Galileo Galilei, (697) Galilea, was the first astronomer to discover new worlds—not planets or asteroids, but the four main satellites of Jupiter. He discovered them in 1610, and the asteroid (697) Galilea was named to celebrate the tercentenary of this, his historic first use of a telescope for astronomy. The main planets were known to antiquity, and the name of the person that christened them, if there was one such person, is lost to history. Galileo was the first astronomer to choose a name by which to refer to another world. He was consequently also the first astronomer to run into controversy on this topic.

It has proved to be a tricky issue when an astronomer wants to name something after a living or recently deceased historical figure, especially an actual or potential sponsor. Galileo wanted to call the satellites of Jupiter the "Cosiman stars" or the "Medicean stars." He had been the mathematics tutor to the young Cosimo de' Medici, who became Cosimo II, Grand

Duke of Tuscany in 1609. Galileo went so far as to explain in his book *The Starry Messenger* how Cosimo had, in some way, inspired the discovery:

> *Therefore, since I was evidently influenced by divine inspiration to serve Your Highness and to receive from so close the rays of Your incredible clemency and kindness, is it any wonder that my soul was so inflamed that by day and night it reflected on almost nothing else than how I, most desirous of Your glory (since I am not only by desire but also by origin and nature under Your dominion), might show how very grateful I am towards You. And hence, since under Your auspices, Most serene Cosimo, I discovered these stars unknown to all previous astronomers, I decided by the highest right to adorn them with the very august name of Your family.*

The Medicis hesitated over accepting the offer, following the publication of the book, presumably not confident about the implications. Galileo piled on the pressure; others might want to take up the offer of naming rights, he wrote in May 1610:

> *…whenever possible, please make sure that your most serene highness would not delay the flight of fame by taking an ambiguous stand about what he has seen many times himself—something that fortune reserved to him and denied to everybody else.*

It worked, and the possibility that Galileo was playing for came to fruition. In July 1610 Galileo was awarded a contract for life to work at the Medici's court. He was awarded a very large salary. But Galileo could not control the reaction of astronomers in other countries to his proposed names. Scientists are supposed to be cool and objective, but they can be as jealous, dog-in-the-manger or nationalistic as anyone else, and scientists outside Galileo's circle, especially outside Italy, did not accept that a celestial object should be possessed, in any sense, by Cosimo de' Medici. The name of the "Medicean stars" did not catch on, and the satellites names became Io, Europa, Ganymede and Callisto after mythological lovers of Jupiter. These names had been put forward by the German astronomer, Simon Marius, (7984) Marius, following a casual suggestion by Johannes Kepler, (1134) Kepler, when they met at a fair.

Galileo was not pleased with the rejection of his proposed name, still less was he pleased that names proposed by a rival were coming into favor. Galileo had no time for Simon Marius. The man had been implicated earlier by a case of blatant plagiarism when one of his pupils, Baldessar Capra, published under his own name a book on an astronomical instrument that had been written by Galileo. Moreover, Marius claimed, without proof, to have observed Jupiter's satellites before Galileo. Gaileo could not have expressed his views on these incidents more clearly:

> *May I be pardoned this if, against my nature, my habit, and my present intentions—I show resentment and cry out, perhaps with too much bitterness, about a thing which I have kept to myself these many years. I speak of Simon Marius of Gunzenhausen; he it was in Padua, where I resided at the time, who set forth in Latin the use of the said compass of mine and, appropriating it to himself, had one of his pupils print this under his name. Forthwith, perhaps to escape punishment, he departed immediately for his*

> *native land, leaving his pupil in the lurch as the saying goes; and against the latter, in the absence of Simon Marius, I was obliged to proceed in the manner which is set forth in the defence which I then wrote and published. Four years after the publication of my* Sidereal Messenger, *this same fellow, desiring as usual to ornament himself with the labours of others, did not blush to make himself the author of the things I had discovered and printed in that work. Publishing under the title of* The Jovian World, *he had the temerity to claim that he had observed the Medicean planets which revolve about Jupiter before I had done so. But because it rarely happens that truth allows herself to be suppressed by falsehood, you may see how he himself, through his carelessness and lack of understanding, gives me in that very work of his the means of convicting him by irrefutable testimony and revealing unmistakably his error, showing not only that he did not observe the said stars before me but even that he did not certainly see them until two years afterwards; and I say moreover that it may be affirmed very probably that he never observed them at all.*

Galileo steadfastly refused to accept Marius' names for the satellites of Jupiter. In his notebooks he called them simply I, II, III and IV, while using the name "Medicean stars" in formal writings.

URANUS AND NEPTUNE: STICKING TO MYTHOLOGY

William Herschel, (2000) Herschel, had a similar problem after discovering the new planet Uranus in 1781. He wanted to call it "Georgium Sidus" ("George's star"), in honor of the British King George III. After the discovery, the king had summoned Herschel to his palace and offered him the position of the Royal Astronomer, including an annual allowance of £200 per year. Herschel greeted with enthusiasm the suggestion of a courtier that he should show appropriate gratitude. The name of "Georgium Sidus" that Herschel offered was used for a short time in England; it was used as the name of the planet in the British *Nautical Almanac* even up to 1850, but it was never used on the continent of Europe, where Uranus was at first referred to as "Herschel's planet." The world of astronomers gradually came to accept the proposal of the Prussian astronomer Johann Bode in 1783 that "we had better stick to mythology" with the name Uranus. "Georgium Sidus" became obsolete.

There was controversy, too, over the name of the planet Neptune. It was first seen in 1846 by the German astronomer, Johann Galle, (2097) Galle, of the Berlin Observatory, on the basis of a prediction of its position by the French mathematician Urbain Le Verrier, (1997) Leverrier, who was therefore regarded as the discoverer of the planet. Le Verrier proposed the name Neptune for the planet that he had discovered theoretically, but then tried to name the planet "Le Verrier," after himself. This name was supported from within France, and French astronomers went back to the name "Herschel's planet" for Uranus in order to bolster the case. But the name "Le Verrier's planet" was not accepted outside of France, and the name Neptune became internationally accepted.

CERES FERDINANDEA: FERDINAND'S CERES

Acting to name his new planet, Giuseppe Piazzi in Palermo only partly learned the lessons from history. In May 1801, Piazzi named the planet Ceres Ferdinandea, after Ceres, the goddess of agriculture (her name gives us words like "cereal"). Piazzi was following the ancient tradition of naming planets after Roman deities. He was also acknowledging his support by his adopted country, since Ceres is the patron goddess of Sicily. This would have been accepted. Where he went too far was that he added also the name of his earthly supporter, King Ferdinand III of Sicily. The king was also simultaneously King Ferdinand IV of Naples, the kingdom of Naples being the southern half of the boot of Italy. In a complicated career, reflecting the chaotic political situation in Europe arising from the republican reforms of the French Revolution and then Napoleonic expansionism, Ferdinand had fled in 1798 to Sicily from Naples, transported there by the English Admiral Horatio Nelson. He returned to Naples in 1799 and took back control in a bloodbath of reprisals against the Roman Republicans. He fled again to Sicily in 1806 when Napoleon Bonaparte's brother, Joseph Bonaparte, took control of Naples, but, when Napoleon fell, he confusingly gained a third title in 1816 when he became King Ferdinand I of the new and united Kingdom of the Two Sicilies.

As with the name that Herschel gave to Uranus, "Georgium Sidus," Piazzi's choice of name for his new planet set off a firecracker of a squabble that hopped about Europe. The German astronomer Johann Bode could not stomach the name of a foreign king on a celestial body and wrote to a colleague Baron Franz Xaver von Zach:

> *I would like to suggest the name Juno (Hera, in Greek) … We must remain with mythology for the sake of analogy and to avoid flattery, and because the planets found over Jupiter carry the name of his ancestors and those standing closer to the Sun the names of his spouse and children.*

Writing a letter behind Bode's back to an Italian colleague, Zach took some glee in the ridicule that had been heaped by French astronomers on Bode with an insulting pun on his name for his presumption to christen the new planet, "for it belongs to two fine Italians and not to a heavy German like Baudet" (in French, "baudet" means "donkey" or "ass").

Further suggestions for the name were reported in Zach's journal of astronomy, the *Monatliche Correspondenz (Monthly Correspondence),* the world's first astronomical journal: Vulkan, Cupido and Titan. Barnaba Oriani of the Brera Observatory in Milan alerted Piazzi to the situation in Germany: "I must tell you that the name Hera or Juno has been given universally by all of Germany, for which it will be very difficult now to rename it Ceres."

Piazzi was unimpressed, in fact icily angry, replying: "If the Germans think they have the right to name somebody else's discoveries they can keep calling the new star the way they want, for we will always call it Ceres. I will be very glad if you and your colleagues will do the same."

None other than Napoleon Bonaparte joined in the naming frenzy. Bonaparte, who had a keen interest in science, would have liked the new planet to be called "Junon" (French for Juno). The French astronomer Jérôme de Lalande, (9136) Lalande, wanted to call it "Piazzi," scorning kings and the gods with a zeal which had been intensified, perhaps, by the then recent events of the French Revolution: "The pagan deities are no longer interesting; and adulation pleases only the person who is the object of it." But Bode gave in, and wrote to Piazzi: "I accept with much pleasure the name Ceres Ferdinandea. You discovered it in Taurus, and it has been found again in Virgo, the Ceres of ancient times. These two constellations are the symbol of Agriculture. The chance is very singular."

The double-barreled name did not persist. Zach at first said that he would continue to call it Ceres "while begging Mr. Piazzi to dispense with 'Ferdinandea,' which is a bit long." Piazzi stuck to his guns:

> *Being the first in the discovery of this new planet, I thought to have the full right to name it in the most convenient way to me, like something I own. Thankful to my master, thankful to the Sicilian nation, willing to maintain a certain coherence with the other planetary names, it looked right to me to name it Ceres Ferdinandea. I will always use the name Ceres Ferdinandea, nor by giving it another name will I suffer to be reproached for ingratitude towards Sicily and its King, who with so much zeal, protects the sciences and arts, arrived at this discovery. It is not adulation, but tribute, right and fair homage.*

The christening of the new planet was materially rewarding to Giuseppe Piazzi, just as the christening of the Medicean stars had been to Galileo. "King Ferdinand increased his salary by 1200 francs in consequence of the discovery of the new planet and the homage he rendered to his majesty by naming it in his writings Ceres Ferdinandea."

You can bring a horse to water, but you cannot make him drink; you can give a new planet a name, but you cannot make astronomers use it.[1] Astronomers accepted Piazzi's right to name his planet Ceres, but within a year the suffix *Ferdinandea* had dropped out of use. It is not known what King Ferdinand thought of this, but perhaps he would have been mollified by the naming of the Isola Ferdinandea, a submerged volcanic island 30 km (19 miles) south of Sicily, between Italy and the Tunisian coast, which was named for his family.

The same sequence of events occurred in the naming of asteroid (10) Hygiea. It was discovered by Annibale de Gasparis, (4279) De Gasparis, in 1849, working at the Naples Observatory in Italy. With his director, Ernesto Capocci, de Gasparis named the asteroid Igea Borbonica ("Bourbon Hygieia"). Hygieia (or Hygiea) was the Greek goddess of health, daughter of Asclepius. Borbonica was added in honor of the Bourbon ruling family of the Kingdom of the Two Sicilies, which included Naples. By 1852, as John Russell Hind wrote, "it is universally termed Hygeia, the unnecessary appendage 'Borbonica' being dropped." John Herschel offered a sop to de Gasparis to offset against this disappointment by suggesting that it would

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[1] One could say the same about present-day commercial schemes that purport to sell to members of the public the right to name a star. Such names are never used by astronomers, even though the selling company enters the name in a ledger. These schemes effectively sell a worthless certificate.

be appropriate to give the name Parthenope to a future asteroid discovery, Parthenope being the original name for the ninth century BC colony that became known as Napoli in the sixth century BC De Gasparis was encouraged to continued his efforts to "realise a Parthenope in the heavens," which were crowned by the discovery in 1850 of (11) Parthenope, the second of his nine asteroids.

Ceres is the largest asteroid, an icy, rocky planet some 950 km (590 miles) in diameter. Because it is large, it has a strong force of gravity that has inexorably pulled the asteroid into a nearly spherical shape. Also because it is large, its outer layers have been able to act like a thick blanket that has kept in the heat generated in the planet's interior, from radioactive decay of the elements within, including radioactive material that was generated by a supernova that polluted the solar nebula just before the birth of the Sun. This has plasticized or even fluidized the body of the planet, and the heavier material has sunk to the bottom, with the lighter material floating to the surface. As a result, Ceres has "differentiated" into a rocky inner core, rich in metallic ores, and an icy outer mantle. Ceres is what a "rubble-pile" asteroid spontaneously turns into if the pile grows large enough. In fact, if Ceres had been allowed to develop by accreting more of the asteroids around it, it would have become *the* Earth-like planet between Mars and Jupiter. The strong gravitational pull of Jupiter, so close to Ceres, stirred up the asteroids and inhibited this process.

Using Earth-based telescopes (on the ground, or in space like the Hubble Space Telescope), it was known before close inspection by the Dawn spacecraft, starting in 2015, that the surface of Ceres is covered with icy, watery minerals such as carbonates and clays. The best pictures taken by the Hubble Space Telescope showed it as an almost uniform sphere, with one bright spot (Fig. 5.1). It rotates rapidly once every 9 h, which has made Ceres slightly flattened at the poles.

The Dawn spacecraft arrived at Ceres in March 2015 and entered into orbit around it. Pictures (Fig. 5.2) show a world with surface features superficially like our Moon (Fig. 5.3). It has a large number of craters, which on the whole have lower walls and shallower floors (Fig. 5.4). Presumably this is to do with the strength of the surface minerals, which are icy. There are some interesting bright spots, some of which appear to become hazier from time to time (Fig. 5.5). These may be places where there is outgassing from below the surface, with brighter minerals deposited nearby. Ceres has a tenuous atmosphere of water vapor, and there are localized areas where gaseous water is more abundant than elsewhere. This asteroid is still remarkably active.

Ceres is one of the few large asteroids that have survived, apparently relatively unscathed as a small planet, from the time of the origin of the major planets 4.6 billion years ago. It seems likely that there were at one time a number of similar asteroids that were fragmented into bits when they collided. The resulting rocks are made of iron and other heavy metals if they came from the central core, or of stone if they came from the outer mantle. This is the distinction between iron meteorites and stony meteorites, the two main kinds. Iron meteorites are dense and surprisingly heavy for their size; an iron meteorite the size of a tennis ball is very weighty. The surface of iron meteorites is often covered with dents like thumbprints, or thin, stretched flow marks, where their surface has become molten as they traversed the atmosphere. They are dark and easy to spot in a rocky, sandy desert. Meteorite hunters can collect iron meteorites by looking down as they sail in a hang glider over a desert plain, like the Nullabor in Australia, or the Karoo in South Africa. Stony meteorites are the most common type, and were once part of the outer crust of an asteroid. They are much like any other stony rock and are much more difficult to find. Sometimes, when they are freshly fallen, stony meteorites have a black crust as a result of the heat generated when they burned during their flight to Earth through the air.

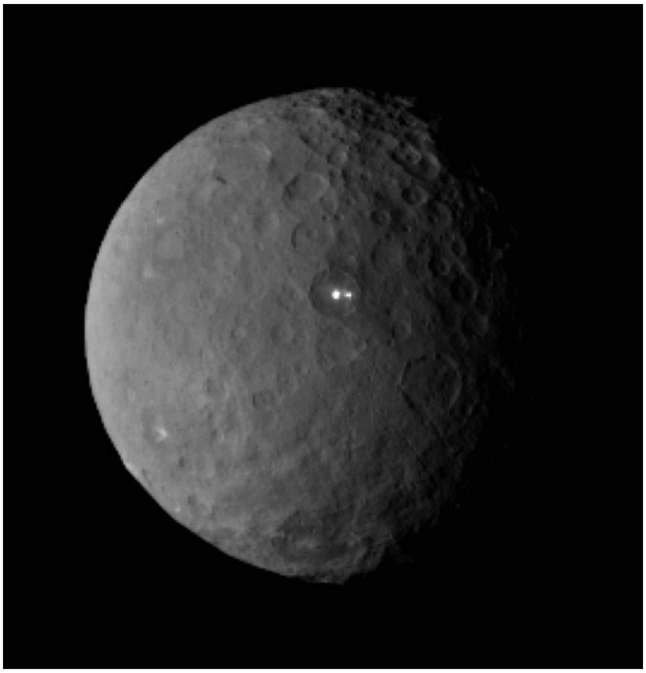


Fig. 5.2 This image of the hemisphere of Ceres was taken by the Dawn spacecraft on its approach in February 2015. Generally Moon-like, Ceres is covered in craters, in one of which lies the bright spot, here shown to be double (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

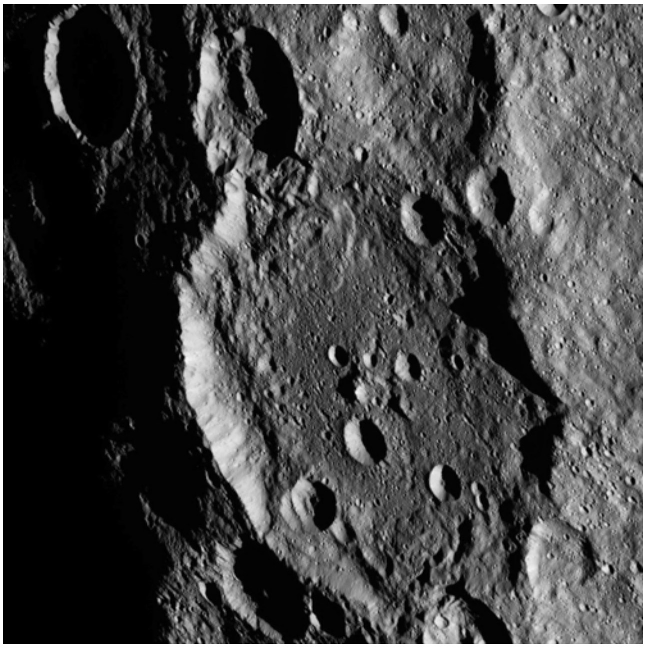


Fig. 5.3 This image might be of craters on our own Moon, but in fact it was taken by the Dawn spacecraft 1470 km (915 miles) above the southern hemisphere of Ceres. A number of more recent, sharper contoured, smaller craters and rills litter the inside of an old, large, eroded crater (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

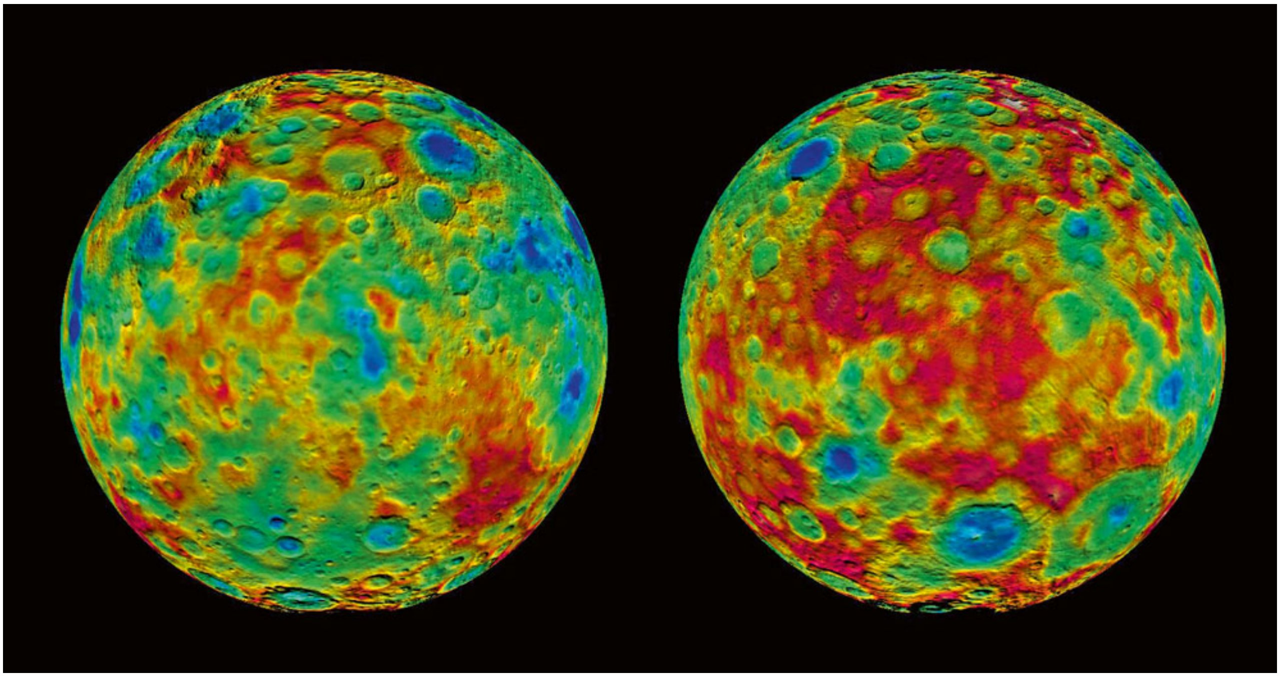
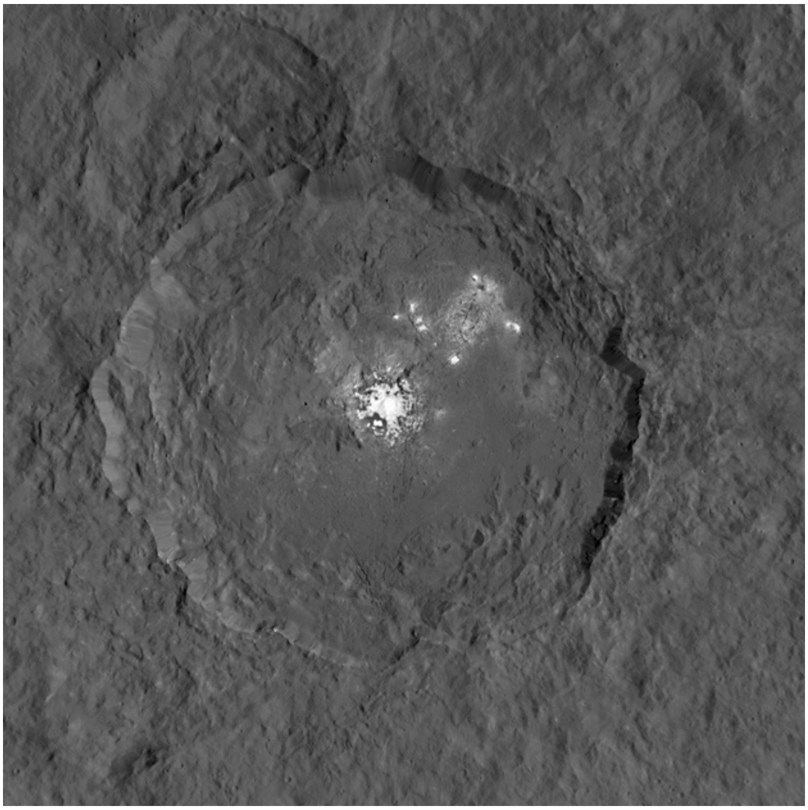


Fig. 5.4 Color-coded maps of Ceres show the relief of the asteroid, ranging from 7.5 km (5 miles) below the mean level of the surface in indigo to the same above the surface in white. The well-known bright spots in the center of Ceres' northern hemisphere (right hand image) are color-coded in the same green elevation of the crater floor in which they sit (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

Fig. 5.5 The crater known as Occator is distinguished by "Spot 5," in close up shown to be a collection of intriguing bright spots on its floor. These seem to be areas where white mineral salts have been deposited by outgassing vents. The crater itself is sometimes obscured by a haze, suggesting that outgassing is still happening (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)



PLANET X: PLUTO

The staff of the Lowell Observatory, founded by Percival Lowell, (1886) Lowell, agonized over the name of the planet Pluto when Clyde Tombaugh discovered it from that observatory in 1930. Lowell used his family's wealth to devote himself to astronomy. He moved in 1894 from Boston to the clear skies of Flagstaff, Arizona, where he founded the observatory to study the planet Mars, in the belief that he could find evidence that it was inhabited, such as surface features made by intelligent life. In 15 years' close study of Mars, he produced maps of the planet showing a network of "canals," apparently transporting water over the dry planet in an irrigation system. The canals proved to be spurious, over-interpreted detail, in which surface blotches had been joined up into the evidence sought of intelligent life on Mars. But eventually, Lowell found he could make little further progress, because the subject had become limited by the quality of the telescopes available to him. He turned to a search for a new planet beyond Neptune. That planet, the target of the investigation, was referred to as Planet X, where X signified the unknown object.

Lowell's search was modeled on the story of the discovery of Neptune. In the 1840s, the French mathematician Urbain Le Verrier succeeded in accounting for the way the planet Uranus was deviating from its predicted orbit by supposing that another planet, undiscovered, was pulling it off-course. He identified the area of the sky where he expected the new planet to lie, and then, lo and behold! When the Berlin astronomer Johann Gottfried Galle looked in that place he was immediately able to see that there was a "star" in that position, which was not on his star charts, and which by the next night had shifted in position. The "star" proved to be the eighth planet, Neptune.

By the end of the nineteenth century Neptune itself was suspected to be off-course, and this immediately raised the suspicion that a ninth planet existed outside the orbit of Neptune. A number of astronomers calculated where the new planet might be, including the Harvard astronomer William Pickering, (784) Pickeringia—the name referring both to William and his brother Edward. Lowell repeatedly photographed the sky to look for star-like images that moved and could be planets. Lowell measured 515 asteroids, but only one is recognized as his discovery, (793) Arizona, named after his adopted state. He found no Planet X.

Lowell died in 1916, and the direction of the observatory passed to Vesto Melvin Slipher, (1766) Slipher—the name referring both to Vesto and his brother Earl—who hired Clyde Tombaugh, (1604) Tombaugh, to take the search forward. Tombaugh was a self-educated farm boy from Kansas, one of a family of six, an amateur astronomer. He joined the staff of the observatory in a menial capacity but soon he was being given scientific tasks. At first Tombaugh simply took photographs for the search while Vesto Slipher and his brother, Earl, (1766) Slipher, searched them for the

Planet X, but Tombaugh produced pictures faster than they could cope. They became overloaded, and probably bored. They delegated the task of inspecting his pictures to Tombaugh himself.

In the course of his searches he observed 4000 asteroids, but only 15 were followed with sufficient diligence to be numbered and named, beginning with (2839) Annette in 1929. The asteroid named after him, (1604) Tombaugh, was one of his own discoveries, in 1931. At the age of 24, in February 1930, with the aid of a blink comparator, Clyde Tombaugh discovered what was interpreted as Planet X. It was identified at the time as the ninth planet of the Solar System. Tombaugh went on to study astronomy formally and became a college astronomy instructor. NASA has accorded him a rare honor in that some of his ashes are being carried on the New Horizons space probe that was launched in 2006 and arrived at Pluto in the middle of 2015.

The widow of Lowell Observatory's founder, Constance Lowell, suggested her own name, Constance, for the new planet. The staff of the observatory took a dim view of her suggestion, since she had been trying in vain to get her hands on the endowment that her husband had given to his foundation. They would have welcomed calling the planet Percival after their founder but were aware of the earlier reluctance to accept the name of a recent historical figure for Uranus and Neptune. The suggestion of the name Pluto came from Venetia Burney, (6235) Burney, an 11-year-old schoolgirl from Oxford. Over breakfast, as her grandfather read aloud about the new planet from the *Times* newspaper, she remarked that it was a cold, dark world like Hades and that Pluto, the god of the underworld, would be an appropriate name. This suggestion made its way via the grandfather, a librarian at the university's Bodleian Library, to the Oxford professor of astronomy, Herbert Hall Turner, (1186) Turnera, to Lowell Observatory. A factor that influenced the observatory to adopt this name was that Percival Lowell's initials were implied by the name, and became the symbol for the planet. Lowell was more overtly memorialized by the name of (1886) Lowell, discovered in 1949 at the Lowell Observatory in Flagstaff with the same 13-in. refracting (330 mm lens-type) telescope with which Pluto was discovered.

In 1930 the Walt Disney studio created a companion for their Minnie and Mickey Mouse cartoon characters. The dog was at first called Rover but became Pluto in 1931, within a few months of the discovery and christening of the planet. Walt Disney's family and colleagues believe, although there is no documentary proof, that Disney chose the name Pluto because of the sensation in the press about the astronomical discovery.

In 1978, astronomer James Christy, (129564) Christy, of the US Naval Observatory, saw that the image of Pluto on photographs that he had taken was elongated. The bulge rotated around the image over a 6-day period. Pluto's brightness varies slightly with the same period. It has a bright hemisphere and a dim hemisphere and alternately presents each to us as it rotates. All this suggested that the bulge in Pluto's image was a close moon, its revolution around Pluto locked to the planet's rotation. In the 1990s the orbit of the moon was edge-on to Earth, and astronomers witness a series of eclipses as the moon passes in front of and behind its parent. It was christened Charon. Charon was imaged by the Hubble Space Telescope, in an exploration intended to find satellites of Pluto to enable the New Horizons spacecraft to thread its way safely through the system in 2015. Four further small moons, 7–55 km in size (5–40 miles), were found. Charon is half Pluto's diameter, one-eighth its mass and the nearest to the parent planet. In order of distance from Pluto the four small moons are Styx, Nix, Kerberos, and Hydra.

In Greek mythology, Charon was the ferryman who took the dead across the River Styx to Hades, which in Roman mythology was ruled by Pluto; the name echoed the name of the discoverer's wife Charlene. Nix was the Greek goddess of darkness, mother of Charon, Hydra the nine-headed serpent who battled Hercules. Taken together their initials are the initials of the New Horizons spacecraft that visited the Pluto system in 2015. Kerberos was the dog that guards Hades; in English the name is usually rendered as Cerberus, but there is already an asteroid named in this form, (1865) Cerberus, so a more direct transliteration from the Greek was adopted as the name for Pluto's moon.

Kerberos is "odd man out" compared to the other three small satellites. It is much blacker. If these moons originated together (for example as fragments, or by-products, from a collision that created the Pluto-Charon double planet), they are presumably fragments that retained some of their different mineralogical identities.

The naming of Pluto itself had wriggled around the astronomical community's traditional reluctance to accept the name of a planet after a sponsor. But further developments raised questions, not about its name but what sort of object it was. The first indication that something was wrong was its orbit. It is tilted at a considerable angle to the orbits of all the rest of the planets, and it is a much more elongated ellipse than the orbit of any other planet. The orbit is so elliptical that, although Pluto is usually outside the orbit of Neptune, its orbit takes it inside the orbit of Neptune for a period of time. Pluto is only trans-Neptunian on average. The next oddity is Pluto's size. It is 2300 km (1400 miles) in diameter. This is not nearly as big as its neighbors, the gas giant planets Jupiter, Saturn, Uranus and Neptune, whose sizes range from 51,000 to 143,000 km (31,000–89,000 miles). Pluto is smaller than Mercury (4900 km, 3000 miles) and even smaller than the Moon (3400 km, 2200 miles). In fact it was because it is so small that it took a long time to find it. It intercepts and therefore reflects a small amount of sunlight and is very dim. Right from the start, Pluto stuck out as an anomaly among the rest of the planets. The anomaly was not resolved for 70 years.

IMAGO: GODS, ASTEROIDS AND NAMES IN PICTURES

In the history of geographical exploration, discoverers of lands and islands have taken the right to name them after members of their royal family and other nobility. The names have sometimes been the cause of vigorous argument, sometimes about claims of priority, sometimes about the politics of territorial control and exploitation. Some historical disputes are ongoing. The English name of the Falkland Islands in the South Atlantic, used in Britain, was derived from Anthony Cary, 5th Viscount of Falkland, sponsor of the first expedition recorded to have landed there in 1690. The Spanish name, used in Argentina, is Islas Malvinas, derived from the French name, Îles Malouines, given to the territory in 1764 by the first settlers, sailors from Saint-Malo in France. The dispute between the UK and Argentina is encapsulated in the name by which the territory is referred to in each country.

Other geographical names based on the names of people have been generally accepted, even if they commemorate the rule of a former colonial power. American examples are Virginia (named after Queen Elizabeth I, the Virgin Queen of England) and Louisiana (named after King Louis XIV of France). The generally accepted name has to be generally accepted by the potential user-community.

The first names for asteroids—(1) Ceres, (2) Pallas, (3) Juno, (4) Vesta, et cetera—were all based on classical Greek or Roman mythology, a principle strongly endorsed in a dogmatic article in the journal *Astronomische Nachrichten* (*Astronomical Notes*) in 1861 by Robert Luther, of the Bilk Observatory near Düsseldorf, who discovered 24 asteroids from there between 1852 and 1890: "As long as people believe it appropriate to give special names to celestial bodies like stars, comets, the moons of Saturn and Uranus and even for the mountains of the Moon, it seems also appropriate to adhere to names from classical mythology… Classical names are necessary, unclassical names are rejected." Others agreed that it would be best to avoid all names referring to living people or current events. Because the number of asteroids grew rather large, however, the list of potential names then widened out to other cultures, like Egyptian, Chinese or Babylonian names, but the rather dogmatic rejection of non-mythological names caused some controversy in the pages of the *Astronomische Nachrichten*, the discussion of which was terminated abruptly by the editor, the German astronomer Christian August Friedrich Peters: "I do not like this controversy, which being of no scientific importance will not be discussed further in this journal."

The rule that asteroid names had to be mythological was so firmly entrenched in 1868 that the pugnacious German-American astronomer, Christian Heinrich Friedrich Peters, (100007) Peters, was able to needle a pious colleague through its use. Peters discovered 48 asteroids while working at Hamilton College in Clinton, New York, and named one of them

(102) Miriam, after the sister of Moses, the Hebrew prophet. The rule implied that she was mythological, not a real figure, with implications about the literal truth of the Bible. According to US astronomer Edward Holden, (872) Holda: "The name of the asteroid Miriam was chosen in defiance of a rule, and of malice aforethought; so that the discoverer could tell a theological professor, whom he thought to be too pious, that Miriam also was a 'mythological personage'."

Astronomers who are well-read have continued to find less well-known mythological characters in classical literature, like (12238) Actor (the father of Cteatos and Eurytos, two Greek warriors who beat Nestor in the chariot race). The pool of names widened out to non-classical cultures, like (2174) Asmodeus (the Babylonian demon of lust, excessive behavior). In recent years, astronomers have found names from cultures whose significance has been previously overlooked.

A group of three mythological characters from the creation myth of the Luiseño native-American people, who live in the area surrounding Mt. Palomar in California, were used to name three asteroids discovered by one of the Mt. Palomar Observatory's scientists. The asteroids were discovered from 1987 to 1991 by Jean Mueller, (4031) Mueller. She is now the senior operator of the 200-in. Hale Telescope, but at the time was using the 48-in. Samuel Oschin Telescope. They were named (12711) Tukmit, which means Father Sky, (11500) Tomaiyowit, which means Earth Mother, and (9162) Kwiila, or Black Oak, one of the first peoples descended from Father Sky and Earth Mother. All three are near-Earth asteroids.

The names of the minor planets in the Kuiper Belt reflect their nature as faint objects on the dark, cold fringes of the Solar System. They are appropriately given mythological names associated with the Underworld (such as (90482) Orcus) or with creation (such as (50000) Quaoar).

Orcus was one of the gods of the Underworld in Etruscan mythology, who later merged with Dis Pater, the Roman Pluto. (90482) Orcus has a moon, Vanth, the winged Etruscan psychopomp (a creature who guides the souls of the dead to the Underworld). Another similar minor planet is (28978) Ixion. In Greek mythology, Ixion was an evildoer, a son of Ares, who murdered his father-in-law in a feud over an unpaid bride-price, betraying him at a feast and pushing him into a fire.

(50000) Quaoar (pronounced Kwa-war) is named after the creator god of the Tongva native American people of the area of California around Los Angeles. Quaoar has a moon, Weywot, a name chosen by the Tongva. Weywot is the sky god, son of Quaoar.

(2989) Imago was discovered 1976 by Paul Wild and is named with the Latin word for image, which may refer to a full appearance, a mental picture, a vision or a dream. In modern computer language we might use "icon" or "avatar." The first few asteroids were represented not only with names and numbers but also with images, so that the position of the asteroid could be plotted on a chart or used as shorthand in a notebook, just

Table 5.1 Symbols of the sun, moon and planets

Name	Symbol	Symbol represents
Sun	☉	Sun
Mercury	☿	Mercury's winged helmet and caduceus
Venus	♀	Venus' hand mirror
Earth	⊕	Terrestrial globe with equator and a meridian
Mars	♂	Mars' shield and spear
Jupiter	♃	Jupiter's thunderbolt,
Saturn	♄	Saturn's scythe
Uranus	♅	A globe surmounted by the letter H, for Herschel
Neptune	♆	Neptune's trident
Pluto	♇	PL monogram for Pluto and Percival Lowell
Moon	☾	Crescent Moon

like the major planets (Table 5.1). After the first 15 asteroids had been discovered the symbols (Table 5.2) had become too numerous and were considered too complex to draw or remember, although the tradition to invent a symbol dragged on for a few more years, even if the symbols were never used.

The change to a simple numerical system was made by Johann Encke, (9134) Encke, in 1851 in the *Berliner Astronomisches Jahrbuch*, and it was picked up enthusiastically by astronomers. The American editor of the *Astronomical Journal*, Benjamin Gould approved:

> *As the number of known asteroids increases, the disadvantages of a symbolic notation analogous to that hitherto in use increase much more rapidly even than the difficulty of selecting appropriate names from the classic mythology. Not only are many of the symbols proposed inefficient in suggesting the name of which they are intended to be an abbreviation; but some of them require for their delineation more artistic accomplishment than an astronomer is necessarily or generally endowed with… To remedy this evil, and not to lose the unquestionable advantage connected with a system of symbols easily remembered and readily drawn, it has been agreed upon by several astronomers in Germany, France, England, and America, to propose for adoption a more simple system for the group in question, consisting of a circle containing the number of the asteroid in the chronological order of its discovery.*

As a result, when an asteroid is now plotted on a chart, it is as the number in a circle.

Table 5.2 Symbols of the minor planets

Name	Symbol	Symbol represents
1. Ceres		A handle-down sickle
2. Pallas		A spear
3. Juno		A scepter topped with a star
4. Vesta		An altar with fire on it
5. Astraea		An anchor
6. Hebe		A wineglass
7. Iris		A rainbow with a star
8. Flora		A flower
9. Metis		An eye with a star above
10. Hygeia		A serpent with a star; the Rod of Asclepius
11. Pathenope		A fish with a star
12. Victoria		A star with a branch of laurel
13. Egeria		A buckler
14. Irene		A dove carrying an olive-branch in its mouth, with a star
15. Eunomia		A heart with a star on top
16. Psyche		A butterfly's wing and a star
17. Thetis		A dolphin and a star
18. Melpomene		A dagger over a star
19. Fortuna		A star over a wheel
26. Proserpina		A pomegranate with a star inside it
28. Bellona		Bellona's whip and spear
29. Amphitrite		A shell
35. Leukothea		An ancient lighthouse
37. Fides		A cross

VICTORIA: IMPERIAL OR MYTHOLOGICAL?

On September 13, 1850, John Russell Hind, (1897) Hind, working in the private observatory in London established by a wealthy wine-merchant-turned-astronomer, George Bishop, (2633) Bishop, discovered the twelfth asteroid. Queen Victoria was the reigning monarch in Britain at the time of the discovery, a very popular figure there, and Hind proposed to give the asteroid her name, but did not mention the connection. Instead, he wrote that "I have called the new planet Victoria for which I have devised as a symbol a star and laurel branch, emblematic of the Goddess of Victory." He later claimed that "the name Victoria was submitted for the approbation of astronomers on mythological grounds and not exclusively marking the country from which the discovery was made." The discovery of the asteroid was reported in the *Astronomical Journal*, edited in the United States by Benjamin Gould, but with a protest that "the nomenclature is at variance with established usage, and liable to the objections which have very properly led astronomers to reject the names 'Medicean stars', 'Georgium Sidus', …, and even those of the astronomers Herschel and Le Verrier." William Bond, (767) Bondia, the director of the Harvard Observatory, responded in the same journal that "Victoria was the daughter of Pallas and one of the attendants of Jupiter and therefore the name appears to fulfill the required conditions of a mythological nomenclature." Gould disputed whether Bond's mythology was correct, Pallas being a giant who had no children. He adopted the name Clio for the twelfth minor planet. This name had also been mentioned by Hind. Gould consistently used the name in his journal.

This argument turned into an Anglo-American or European-American spat. As pointed out by the editor of the British journal *Observatory* "Her Majesty's name is derived from the goddess." This enabled Hind to claim that his proposal was based on the name of the mythological personage, and had been accepted throughout Europe. The British Astronomer Royal expressed his unhappiness: "When I looked for Victoria in the index to Gould's Journal and expected at the least to find 'Victoria—see Clio' and found it not, I was very indignant." Hind weakened under the pressure and said that he would agree with the name Clio as a replacement, but Bond's opinion prevailed, and the name for (12) Victoria slipped through the objections.

There were no objections to (359) Georgia and (525) Adelaide, also named after British monarchs. In 1893, (359) Georgia became one of the 99 asteroids discovered by the French astronomer Auguste Charlois, (1510) Charlois, at Nice, and it was named at a meeting in 1902 of the German Astronomical Society, Astronomische Gesellschaft, in Göttingen. The name commemorates Georg August, later King George II, (359) Georgia, who founded the University of Göttingen in 1737. (525) Adelaide was originally discovered in 1904 by Max Wolf and named for Queen Adelaide, (525) Adelaide, consort of the British King William IV, for whom the capital of South Australia was also named. However, the present asteroid (525) Adelaide is not the original one. There was confusion between the original asteroid discovered in 1904 and a second asteroid, (1171) Rusthawelia, discovered in 1930. These were later shown to be the same asteroid. To minimize possible confusion, on the basis that more work had been done with Rusthawelia than with Adelaide, everything was consolidated under the name Rusthawelia, and the number and name for Adelaide were vacated for a time. The number and name (525) Adelaide were then given to a third asteroid discovered in 1908 by the American astronomer Rev. Joel Hastings Metcalf, (792) Metcalfia, from Taunton, Massachusetts.

Metcalf was a hard-working Unitarian minister, an optical designer and craftsman, and an amateur astronomer who discovered 41 asteroids, most of them from an observatory that he built himself in Taunton. He invented an interesting method of finding asteroids, the reverse of the normal method used in photography. He tracked his telescope at the expected speed of an asteroid through the background of stars so that stars appeared as streaks and the asteroid appeared as a star-like spot. The advantage of the method was that all the light of the asteroid was concentrated in one place, not smeared into a streak, so he was able to find fainter asteroids than other astronomers. At the time of his death he was making a 13-in. lens of his own design, which was completed later and used by Clyde Tombaugh for the discovery of Pluto.

"MAXIMILIANA": THE ILLEGAL EXERCISE OF ASTRONOMY

Once the precedent had been broken, some asteroids were given non-Classical names, based on historical personages or places, to the great consternation of the astronomical community. The first non-Classical name given to an asteroid was (45) Eugenia, named in 1857 by its discoverer the Franco-German astronomer Hermann Goldschmidt, observing from Paris. He used the name of Empress Eugénie de Montijo, (45) Eugenia, the wife of Napoleon III, the then emperor of the Second French Empire (from 1852). "(65) Maximiliana" was a similar case in which the name of a real person was used as an asteroid name. It was discovered by Ernst Wilhelm Tempel, (3808) Tempel, in 1861 from Marseilles Observatory.

Tempel was born in Saxony. His interest in astronomy was sparked by a schoolteacher, who also taught him drawing. He was apprenticed to a lithographer in Meissen, and worked as a lithographer himself all over Europe: Denmark, Germany, Italy and France. He offered his services as a lithographer to a number of observatories in those countries, and was allowed to use the telescopes in some. While living in Venice in 1858, Tempel bought his own telescope, a 4-in. (108 mm) refractor, made by Carl August Steinheil in the workshop of scientific instruments at the Bavarian Academy of Science in Munich. The telescope had a wooden tube, and Tempel mounted it in an altazimuth mounting made locally. "Altazimuth" means that the telescope pivoted up and down between two vertical pillars that rotated on a base. Tempel sat in a chair at the side of the mounting. In order to track a star field, he would have had to work the up-and-down and side-to-side motions simultaneously, while viewing through the eyepiece and making notes and drawing what he saw; it can't have been easy. The telescope cost 400 South German florins, not much less than the annual salary of an assistant at the nearby University of Padua at the time. Falling onto hard times, Tempel at one point in 1865 considered selling the telescope, and even drafted an advertisement for it, but in the end he managed to get by, and did not have to let go of his pride and joy.

It was 1859 when Tempel started using his telescope in Venice, observing from the Scala Lombard, the winding staircase of the Palazzo Contarini del Bovolo. He found it difficult to observe to his own satisfaction for long enough at night and earn his living during the day as a lithographer. He was offered a paid position in France by Benjamin Valz of the Marseilles Observatory and moved there in 1860, using the telescope from the terrace of the observatory building, searching for minor planets and comets, drawing nebulae. In 1861, Valz retired as director, succeeded by an interim director for a year, Charles Simon, for whom Tempel had little regard. He left his employment at the observatory and began work again as a lithographer, but continued his astronomical work from his home in Marseilles, setting up his telescope in the garden or the balcony, and peering out of the windows of his house. In 1871 he moved to Milan, and then to Florence, where he was an assistant at the Brera and Arcetri observatories, respectively.

Tempel discovered five asteroids, all from Marseilles, the first two from the observatory and then four from his home. The names of the first two were mired in controversy. From altruistic motives, Tempel allowed two of his supporters to name them. The name for (64) Angelina was put forward by Benjamin Valz. The name refers to another observatory in the mountains above Marseilles at Notre Dame des Anges. It belonged to Baron Franz Xaver von Zach, leader of a team of astronomers who searched for minor planets. The opportunity to name asteroid 65 was offered by Tempel to the maker of his telescope, Carl August von Steinheil. He chose Maximiliana, after Maximilian II the Holy Roman Emperor and king of Bavaria in the sixteenth century. This name for asteroid 65 did not stick. Sanford Gorton), the amateur astronomer and editor of the *Astronomical Register* (Britain's first journal for amateur astronomers), railed against all these names: "It really is much to be wished that planet-namers would be more discreet: we are already overburdened with names objectionable on the score of likeness of sound and orthography [like (76) Freia and (77) Frigga], and as exemplifications of human vanity, evidenced by the choice of Eugenia, Angelina and Maximiliana &c. Can popular opinion not be brought to bear to enforce adherence to the accepted rule of ancient female deities?"

Gorton was supported by the barrister, author and amateur astronomer, George F. Chambers in a letter 2 or 3 years later:

> *Sir,—To judge by some of the names applied of late years to some of the recently discovered minor planets, the discoverers are hard up for appropriate designations. Under these circumstances, I have drawn up the following list of names at present unappropriated, in the hope that they and others similar may be taken up before we are presented with any more barbarisms like Angelina, Maximiliana &c. Female classical names are undoubtedly the best but no complaint need be raised against reasonable geographical names, such as Parthenope.*

Trying to play the Hind defense, Tempel noted that with a minor spelling change Angelina could be renamed Angelia, a daughter of Hermes, the messenger of the gods. This suggestion never took off. The name of asteroid "(65) Maximiliana," on the other hand, was completely changed in 1861 to (65) Cybele.

In a twist to the story 60 years later, asteroid 1217, discovered in 1932 by the Belgian astronomer Eugène Delporte at the Belgian Royal Observatory, Uccle, was named Maximiliana, but this was in memory of Max Wolf of Heidelberg, a prolific discoverer of minor planets. Wolf discovered asteroid 1217 on the day before Delporte, but died a few months afterwards. Delporte took naming rights, and consulted Wolf's widow. She took the opportunity to memorialize her husband.

These events were the basis of a book made by the *avant garde* typographer and editor Ilia Zdanevic, known as Iliazd, and the surrealist painter Max Ernst. The book was published in 1964. It is entitled *65 Maximiliana, ou l'Exercice Illégal de l'Astronomie: L'Art de Voir de Guillaume Tempel* ("65 Maximiliana or the illegal exercise of astronomy: Wilhelm Tempel's art of seeing"; Paris, Imprimerie Union 1964). The book is a set of 30 folio sheets of images and typography, including a poem by Tempel, and was produced in an edition of only 75 copies. In 1966, Ernst and the German film director, Peter Schamoni, made a film derived from the book, *Die widerrechtliche Ausübung der Astronomie–Ein Film über Ernst Wilhelm Leberecht Tempel (1821–1889).*

Iliazd, an émigré to Paris from Georgia, and Ernst, an émigré from Germany to Paris, produced this book as homage to Tempel, a third émigré, "wandering through Europe with his telescope, looking for new planets and in vain for recognition… The refusal of astronomers to acknowledge Maximiliana as a name endows Tempel with an invisibility like that of his planet or an avant garde hero." Tempel is presented as an astronomer who persevered in his search for minor planets and comets in spite of the humiliating rejection of the name that was proposed for 65 Maximiliana and the lack of recognition of his work by his colleagues. Iliazd poured scorn on the discovery of the replacement asteroid, (1217) Maximiliana, which, by contrast with "(65) Maximiliana," was discovered by photography.

For the two artists, the astronomer Tempel was a fellow believer in the creative artist's credo of *l'art de voir*, "the art of seeing." What would Iliazd think of present-day industrial methods of finding asteroids by CCD cameras and computers?

(45) Eugenia is a triple asteroid; it has two moons, Petit-Prince (diameter 7 km, or 4 miles) and one known only with a serial number S/2004 (45) 1 (its diameter is 5 km, or 3 miles). The two moons orbit at 1165 and 610 km (725 and 380 miles) from Eugenia in almost-circular orbits.

The name of the moon Petit-Prince alludes to Empress Eugenia's son, the Prince Imperial, and to the children's story *The Little Prince* by Antoine de Saint-Exupéry, (2578) Saint-Exupéry. The author and aviation pioneer has his own asteroid, (2578) Saint-Exupéry, discovered by the Ukrainian astronomer Tamara M. Smirnova, (5540) Smirnova, in 1975.

HERA AND RAGAZZA: GODDESSES AND GIRLS

In contrast to the major planets, which all have male names (except for Venus, conventionally and stereotypically regarded as beautiful and female because of its pure, white brightness), the names given to asteroids started off female—goddesses such as (103) Hera (goddess of women), wives such as (253) Mathilde and girlfriends such as (1839) Ragazza (Italian for "girl"). There does not seem to have been a logical reason for this; the clue seems to be in the fact that, in the history of astronomy astronomers were almost exclusively male, especially those astronomers who worked telescopes. Women were thought to be too frail to endure long nights in frigid observatory domes, and could not, almost by definition, manhandle big telescopes. Women astronomers could be expected to keep records, inspect photographic evidence and make calculations. One concentrated example of this was at Harvard Observatory, where the director (between 1877 and 1919), Edward Pickering, established an office of women scientists to analyze data derived from thousands of photographs. The women were known as the "Harvard Computers," sometimes as "Pickering's Harem," a much less respectful term that denigrated Pickering's active attempts to open up the access by women to astronomy. One of the Harvard Computers was Anna Winlock. Her father, Joseph Winlock preceded Pickering as the observatory's director and died leaving a widow and five dependent children, including Anna. To support the family, she took on the job offered by Pickering, along with a number of other women who tolerated the very low pay with which the work was rewarded (25 cents per hour, or about $500 per year, full time). Among her achievements was her work on Eros, the first near-Earth asteroid. Discovered in 1898, the asteroid had left its images, pre-discovery, on photographs taken at Harvard Observatory between 1893 and 1896. Winlock measured them and used this data to calculate the asteroid's orbit, providing the basis by which it could be found and its orbit re-observed and refined when it next became visible in 1903, so it could be always be identified in the future.

The first woman to discover an asteroid appears to have been Margaret Harwood, (7040) Harwood. Educated at Radcliffe College, the women's college of Harvard University, Miss Harwood (as she was always called) first worked as one of the Harvard Computers, but sensed that her career would remain plateaued at a low level if she stayed in that job. She joined the Maria Mitchell Observatory in Nantucket, where she was appointed as its first director in 1916 at a salary of $1200 per year. Studying variable stars on photographs, a technique that relies on making repeated exposures of the same place, Miss Harwood kept an eye open for moving stars, which were likely to be asteroids. In 1917 she discovered asteroid (886) Washingtonia. Credit for the discovery is, however, assigned to George Peters of the US Naval Observatory in Washington DC, who found it 4 days later but was quick off the mark in communicating his results to the astronomical press and naming it, even before it was proved as a new discovery (the convention was that the discoverer and therefore the person with the right to name the asteroid was "not the one who first saw or observed it but the one who first realized it as a new object"). Moreover, it appears that Miss Harwood was inhibited from pressing her claim to priority after the senior people around her advised her that it was inappropriate that a woman should be thrust into the limelight with such a claim, and squashed it. Miss Harwood selflessly sent her photographs to Peters to incorporate in his analysis of the asteroid's orbit, a fact that was mentioned by Peters only at the end of an article in 1919. She would have wished to name her asteroid "Nantucket" after her island home and location of her observatory. Her frustrated ambition to see an asteroid named in this way was realized 40 years later with the naming of asteroid (7041) Nantucket, which is preceded in the list of numbered asteroids by (7040) Harwood, named after her, belatedly, to recognize her achievements.

In a social climate in which women were discouraged, or, it seems, even forbidden to discover asteroids, it is not unlikely that the male discoverers of asteroids were being patronizing in christening asteroids with female names, in the same way that men used to refer to ships and hurricanes, and other things they regarded as less than completely predictable, with female names. "There is reason to ask the discoverers not to deviate from the rule of choosing female names: so far this rule has only once been offended—and for a good reason—with 433 Eros," wrote Julius Bauschinger in 1899, not saying what the reason was that was in his mind. Eros is, of course, the god of love, the equivalent of the Roman god Cupid; it is manifest from many representations of this figure that he is male. But Bauschinger had overlooked the asteroid (342) Endymion, discovered by Max Wolf in 1892, 6 years earlier than Eros. This minor planet was named for another male figure, a beautiful young shepherd who enchanted Selene, so that she visited every night to gaze upon him, sleeping. (334) Chicago was the first name with a non-feminine appearance, but was named for the city, where an astronomical conference was being held in association with the Columbian Exposition of 1893 that commemorated the 400th anniversary of Columbus's discovery of America.

Within 100 years, two or three hundred asteroids had been discovered, and the list of names that were both available and well-enough known to astronomers became very short. From about 1880, straightforward female names became increasingly common, to the snobbish consternation of some astronomers: "[M]any of them, at least, read like the Christian names in a girls' school," wrote the West Point-trained American astronomer Edward Holden, (872) Holda, the first director of the Lick Observatory in 1896.

Sometimes the names were suggested by the names of acquaintances of the discoverer, the asteroids discreetly named without identifying the person concerned. (283) Emma, (284) Amelia, (285) Regina, (289) Nenetta, (294) Felicia, (295) Theresia, (297) Cäcilia, (302) Clarissa and (303) Josefina are examples of these "living, not ancient goddesses," whose undocumented association with their asteroid is now lost. For some asteroids, especially the more recent asteroids, the association is known. In 1906 the German astronomer August Kopff, (1631) Kopff, working in Heidelberg as an assistant to Max Wolf, discovered (596) Scheila, the name of an English student at the same university as the discoverer, (607) Jenny and (608) Adolfine, the two given names of a friend of the discoverer, who had recently become engaged to be married. (614) Pia has the name of the wife of the Bavarian selenographer[2] Johann Nepomuk Krieger, but her name was given to his observatory in Trieste and the asteroid, which Krieger discovered, was named for the observatory and thus only indirectly for her.

The first man to have an asteroid named after him was the scientist and explorer Baron Alexander von Humboldt, (54) Alexandra. The reason for the name was not concealed by the French mathematician Abbé Moignot, the person given that responsibility by its discoverer in 1858, the painter and amateur astronomer Herman Goldschmidt. But the origin of the name was only briefly noted in a passing comment; the asteroid's name was feminized to Alexandra, and it was intended also to refer to Alexandra, daughter of Priamus, so the significance of the male origin of the christening passed over the heads of most astronomers.

BETTINA AND ALBERT: RAISING FUNDS, REWARDING PATRONS

It is not possible now to openly buy the right to name a minor planet. This rule was implemented for asteroids after an early scandal about (250) Bettina. In the astronomical magazine *Observatory* in 1885, there appeared the following announcement: "Herr Palisa, being desirous to raise funds for his intended expedition to observe the Total Solar Eclipse of August 1886, will sell the right of naming the minor planet No. 244 for £50."

£50 was a considerable sum in 1885, about the annual salary of a laborer or bank clerk, or the annual rent of a family house in suburban London. The offer was not taken up immediately for asteroid 244 (which was named Sita, wife of the Hindu god Rama, regarded as an ideal of womanhood), and Palisa did not travel to the eclipse. But when Palisa discovered further asteroids the naming rights for number 250 were successfully sold. In the same magazine for 1886 the name was announced: "Minor planet No. 250 has been named 'Bettina' by Baron Albert de Rothschild." Bettina Caroline de Rothschild, (250) Bettina, was the young wife of the Austrian banker Albert Salomon von Rothschild, (719) Albert. Bettina died 6 years later at the age of 34. Rothschild was, incidentally, a talented chess player and a sponsor of the Vienna chess tournaments, as well as various musical charities. He continued to sponsor Palisa's astronomical work and was himself posthumously recognized through the name that Palisa gave to one of his later discoveries, (719) Albert.

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[2] A selenographer is a mapper of the Moon.

(719) Albert has a very eccentric orbit, and dips well inside the orbit of Mars and of Bettina approaching the orbit of Earth. But it does not cross Earth's orbit. By definition it is thus a member of the group of Amor asteroids, named after the prototype (1221) Amor. Another member of the group is (433) Eros. Eros is the Greek god of love, and Amor is the Roman version of the same god, also known as Cupid. Neither is at the present time a potentially hazardous asteroid for Earth, although both are for Mars. The orbit of Albert is mathematically chaotic, which means that, as a result of the large tugs of the planets whose orbits it crosses and approaches (Jupiter, Mars and Earth), the orbit is subject to large and random alterations. It will become an Earth-crosser and be potentially hazardous. Eventually, it will either be ejected from the Solar System or will become a Sun-grazer, most probably within the next 5 million years.

Albert and Bettina, the husband and wife, were said to be very much in love. It is a shame that, while Bettina, the asteroid, will almost eternally orbit the Solar System, stable in her near-circular orbit, Albert, the asteroid, more erratic, ranges further. For a century, in fact, Albert went missing altogether. Its orbit was not very well determined, and it was lost a few days after its discovery. It was finally recovered in 2000 by the Spacewatch project, and recognized by Gareth Williams, associate director of the Minor Planet Center, an astronomer who, in an attempt to recover Albert, had learned its orbit by heart so that should he ever find an asteroid with the same orbit he would recognize it. Because of the chaotic orbit, Albert the asteroid will eventually stray even further, perhaps leaving Bettina altogether at some time in what is in astronomical terms the near future.

A number of patrons have been rewarded with the names of asteroids. Catherine Wolfe Bruce, (323) Brucia, heiress of a typefounder, was a philanthropist who had donated $10,000 for the construction of the telescope at the Heidelberg-Königstuhl State Observatory above Heidelberg, Germany, used by Max Wolf to discover asteroids, among other astronomical work. The telescope was known as the "Bruce double astrograph." The first asteroid discovered by Wolf with this telescope was named (323) Brucia, to commemorate the donor. (904) Rockefellia commemorates John D. Rockefeller, (904) Rockefellia, the founder of the Rockefeller Foundation. (1037) Davidweilla likewise commemorates Michel David-Weill, (1037) Davidweilla, a benefactor of the Sorbonne University, Paris. (1728) Goethe Link is named for Dr. Goethe Link, (1728) Goethe Link, a surgeon and amateur astronomer from Indianapolis, Indiana, donor of the Goethe Link Observatory.

EROS: A ST. VALENTINE'S DAY ENCOUNTER

The minor planet (433) Eros was discovered independently in 1898 by Gustav Witt at Berlin, and, on the same night, by Auguste Charlois, (1510) Charlois, at Nice. When its orbit was calculated, it was immediately recognized as the astronomical sensation of the year because it comes close to Earth. Up to that point all minor planets lay comfortably in the Main Belt, orbiting completely within the gap between Jupiter and Mars. The mean distance of Earth from the Sun is called one astronomical unit (AU). The mean distance of Eros from the Sun is 1.458 AU, considerably less than the mean distance of Mars at 1.52 AU. Its orbit is quite elliptical and it crosses the orbit of Mars. Such asteroids are known as Mars-crossers, with Eros the first that was recognized. Its closest approach to the Sun is 1.133 AU, with its closest approach to Earth at 0.149 AU, so it is also a NEA. Its orbit is likely to evolve quickly with time because of the repeated influence of Mars at each crossing, and it will, sooner or later, become an Earth-crossing asteroid, with the consequent risk that it will impact Earth. It is 34 × 11 × 11 km in size, and if it does impact Earth it will produce a crater that will rival the scale of the Chicxulub Crater, the impact that, it is thought by astronomers, caused the extinction of the dinosaurs. There is a 5 % chance that Eros will impact Earth in the next 100 million years.

Eros was visited and examined for nearly a year in 2000–2001 by a space probe, the Near Earth Asteroid Rendezvous–Shoemaker (NEAR-Shoemaker, or just NEAR). Gene Shoemaker, (2074) Shoemaker, was a geologist who worked on the Barringer Crater in Arizona. The crater was first recognized as a meteor crater by mining engineer Daniel Moreau Barringer, (3693) Barringer, who unsuccessfully searched for the potentially highly profitable mass of iron and nickel that he envisaged to be buried below the crater. Shoemaker definitively showed that it was indeed a meteor crater by identifying mineral structures that were only produced by intense heat and pressure, such as are produced by a nuclear bomb explosion or meteor impact. He studied impact craters all over the world, and was killed in a road accident while driving to study a remote meteor crater in Australia. With NASA's flair for public relations, the flight controllers ensured that the NEAR-Shoemaker space probe would meet and join up with Eros by entering orbit around the asteroid on February 14, 2000, St. Valentine's Day. At the end of its mission, the spacecraft was lowered to the surface of the asteroid, touching down on February 12, 2001. The impact was on the scale of a terrestrial fender-bender car crash—the asteroid is small and its gravity is weak. An astronaut who landed on the surface would weigh 1 oz there. If his or her exploration of the surface of the asteroid was too exuberant and the astronaut leaped about excitedly, he or she could end up in orbit.

During its descent, NEAR transmitted pictures in real time before it impacted at about 4 mph, sufficient to crush the instruments mounted on the lowest parts of the spacecraft but not to damage what was inside. Its last picture transmitted prior to touchdown was obtained from a range of 120 m (390 ft) and was truncated in transmission by the impact (Fig. 5.6), but the spacecraft continued transmitting other scientific data for days after its landing, until its mission was declared to be over. Eros was the first asteroid touched by a human—at least by a machine that had been made by a human, the second being (25143) Itokawa.

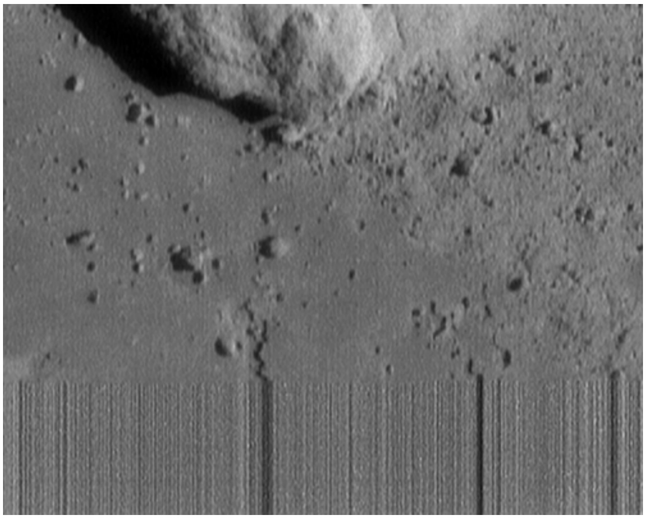

Fig. 5.6 The surface of Eros. The NEAR spacecraft survived its landing on Eros, but the transmission of its last picture to Earth was interrupted. The image was taken 130 m above the surface and spans 6 m across. Rocks as small as a human hand are visible (NEAR Project, JHU APL, NASA)

Eros is a curious shape, like a curved potato, a tongue or a slipper (Fig. 5.7). Its surface is covered with craters caused by the impact of other smaller asteroids and meteoroids. Apart from one crater, Shoemaker, named after the geologist, the craters are named after various lovers, such as Casanova and Heathcliff; planetologists have had more fun naming these craters than the craters on (253) Mathilde, which are named after the coal fields of the world. The surface of Eros is littered with rocks that have been ejected from these craters. They range from castle-sized boulders to small pebbles. The smallest pebbles imaged by NEAR in the picture sent from its last transmission from just above the surface were just millimeters in size. There are fewer small craters than expected, so something has been happening to cover them up. Eros is completely without an atmosphere, which means the process is not weathering by wind or rain; one thought is that the asteroid shakes when struck by other asteroids and meteoroids, causing landslips on the slopes of hills that bury craters in the valleys below and topple the walls of small craters so that they fill up. In some cases the finer powdery material has separated from the rocks and has flowed into a hollow to make a flat-surfaced area looking like a dry pond. One particular strike about 1 billion years ago produced most of the rocks on the surface, maybe the “ponds” and one of the larger craters, the one named after Shoemaker.

Eros has been important in the history of astronomy. Its orbit was accurately tracked by observatories worldwide on two occasions, in 1900–1901 and 1930–1931, when it passed near to Earth. Measurements made from different locations on the surface of Earth squint at the asteroid at different angles, so it was possible to measure the size of its orbit very accurately. This made it possible to determine the scale of the Solar System more accurately than ever before. The output of the two programs was the Earth-Sun distance, the astronomical unit (AU) as measured in meters. The value determined from the 1930 approach of Eros lasted until 1968, when it was superseded by a value based on radar measurements that determined the distances of the nearer planets and hence the modern value of the AU.

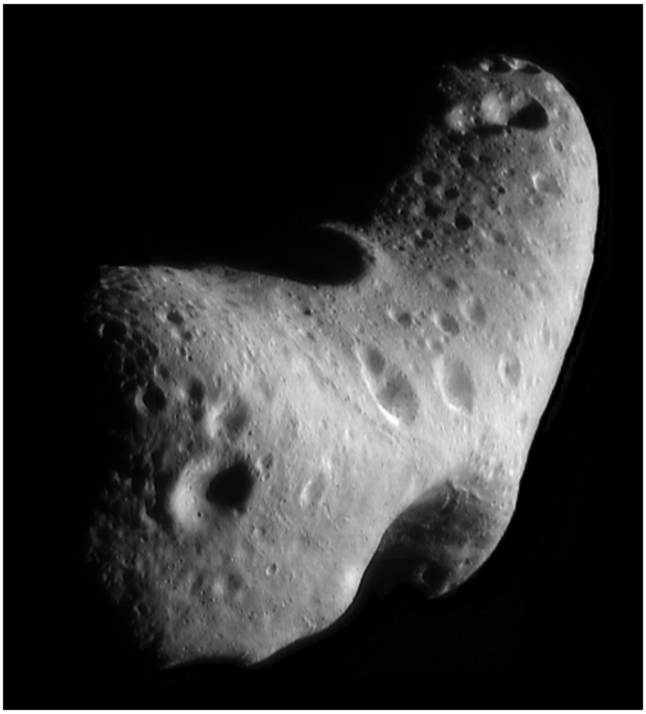

Fig. 5.7 Eros' northern hemisphere. In size comparable to the asteroid that created the Chicxulub crater on Earth and caused the extinction of the dinosaurs, Eros is an irregular shape, like a peanut. Viewed by the NEAR-Shoemaker spacecraft in February 2000 from an orbital altitude of about 200 km (120 miles), the image shows the craters Psyche above and Himeros below. The smaller crater in the foreground is Narcissus. The naming convention is that craters on Eros are called after famous lovers (NEAR Project/JHU/APL/NASA)

UTOPIA: COMMEMORATING PLACES

Some discoverers have chosen names for their asteroids derived from, say, the observatory from whence they were discovered, or a place dear to the discoverer's heart, or to everyone's, such as (1282) Utopia. To start with, discoverers chose feminine or feminine-sounding names, such as (136) Austria, (232) Russia, (301) Bavaria, (371) Bohemia, (589) Croatia, and (1197) Rhodesia. (327) Columbia is named for Christopher Columbus (1451–1506; (327) Columbia), but the name is also the personification of the United States. Some place-names have been feminized, such as (1132) Hollandia, (1351) Uzbekistania and (3512) Eriepa (that's Erie, PA). (20) Massalia, called after Latin name of the French city of Marseilles, was the first asteroid to be given a non-mythological name. It was discovered in 1852 by Annibale de Gasparis and independently a day later by Jean Chacornac at Marseilles. It was named by Benjamin Valz, the director of the Marseilles Observatory, unaware of the discovery in Naples by de Gasparis, who did not make an issue of his priority.

A recent group of names commemorates places that were strongly affected by the earthquake of March 11, 2011, off Honshu Island, Japan, which caused great loss of life and destruction. The list was adopted at a conference on asteroids held in Japan in 2012: (23649) Tohoku, (14701) Aizu, (19534) Miyagi, (19691) Iwate, (19701) Aomori, (19713) Ibaraki, (19731) Tochigi, (20613) Chibaken, (21966) Hamadori, (22719) Nakadori, (22745) Rikuzentakata, (22885) Sakaemura, and (22914) Tsunanmachi.

(21) Lutetia was the first asteroid to be discovered by an amateur astronomer. It was found in 1852 by a German painter, Hermann Goldschmidt, (1614) Goldschmidt, in Paris, the first of 14 minor planets that he found. Searching for a diversion with which to overcome chronic depression, he had been fired with enthusiasm for astronomy only a few years earlier by attending a lecture given by Urbain Le Verrier on a forthcoming solar eclipse. He sold two portraits and used the proceeds to buy a 5-cm (2-in.) telescope, describing this as the happiest event of his life. He observed the sky by peering out of the windows of his *atelier* and the garret bedroom of his apartment on the sixth floor above the Café Procope in Rue de l'Ancienne Comédie in the Latin Quarter, the oldest restaurant still operating in the city. Goldschmidt contacted the Paris Observatory, which confirmed his discovery. The scientific director there, François Arago, (1005) Arago), was a showman, a politician and a fixer as well as an astronomer (and secretary of the Académie des Sciences); he was the man who got Léon Foucault, (5668)

Foucault, to suspend his pendulum from the dome of the Parthenon to demonstrate to the citizens of Paris the rotation of Earth, and who arranged for the photography pioneer Louis Daguerre, (3256) Daguerre, to share his invention of the daguerreotype with the French people. Arago suggested the name Lutetia for Goldschmidt's asteroid, the Latin name of the Gallic city that evolved into the modern city of Paris.

Lutetia rotates in a little over 8 h. On its way to Comet 67P/Churyumov-Gerasimenko, the Rosetta spacecraft flew by Lutetia on July 10, 2010, approaching within 3200 km. The ground controllers monitored the spacecraft's orbit very accurately as it approached Lutetia, and were not only able to determine the volume of the asteroid from the images that it transmitted back (Fig. 5.8) to Earth but also the mass of the asteroid, which they calculated from the deflection of the spacecraft's orbit caused by Lutetia's gravity. The asteroid is a rather irregular shape, on average about 100 km in diameter (121 km × 101 km × 75 km). Pictures of its surface show that Lutetia is heavily cratered, with the larger craters being softly rounded. The most recent large crater is a 21-km diameter crater cluster, close to the north pole. Some of the splash of material ejected from the impacts has fallen back to the surface, and the surrounding areas are partially covered by smashed-up, dusty, smooth material. In fact, the asteroid's surface is deeply covered with dust, with which the crater walls are covered. Erosion of the walls and other rocks on the surface by the impact of a rain of small meteoroids may be another source of the dust, as well as "asteroid-quakes" and tremors caused by the impact of the larger meteoroids. Surface features on Lutetia are named for cities and regions of the Roman Empire contemporary with the Roman occupation of Lutetia.

Lutetia has a rather high density and must be made of dense rock, concentrated with metals. It is not therefore a "rubble-pile" asteroid. It is a solid, battered, surviving protoplanet from the early history of the Solar System, bashed to its present, irregular shape by repeated impacts. Indeed, its surface characteristics show similarities with a certain kind of meteorite called enstatite chondrites, which were the original material of the Solar System from which Earth formed. Lutetia is thus one of a small number of asteroids that formed near Earth in the densely populated inner Solar System. It has been scattered to its present orbit in the Main Belt of asteroids by interaction with Jupiter. It is a planetary fossil whose subsurface rock represents the original geology of the nascent Earth.

JUEWA: STAR OF CHINA'S FORTUNE

Asteroid (139) Juewa was found in 1874 by James C. Watson, (729) Watsonia, during a trip to China, and was named to commemorate that event.

Brought up in rural Canada in a poverty stricken family, Watson was a child prodigy, self-taught at first but later enrolled as a student at the University of Michigan at the age of 15. He had a prodigious memory,

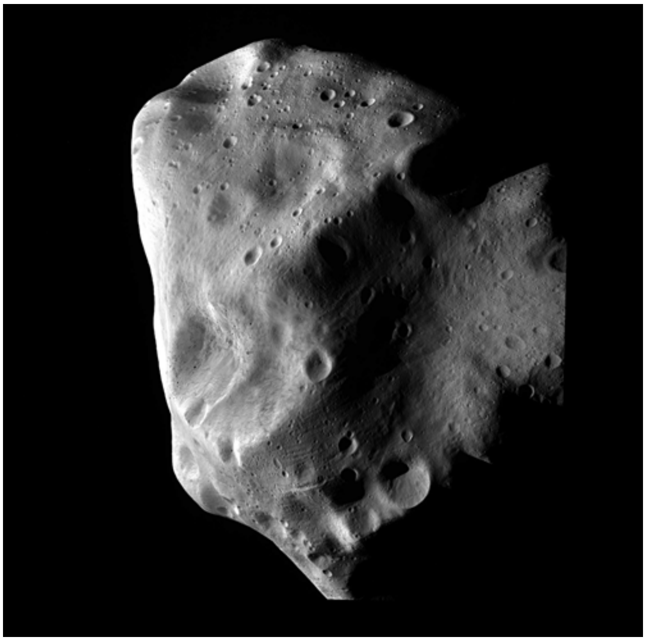

Fig. 5.8 In July 2010, ESA's Rosetta spacecraft flew past the asteroid Lutetia and obtained this image at closest approach. Its surface is largely covered in smooth dust, comparable to the dusty surface of the Moon, ground from the surface by numerous micrometeorite impacts (©ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

assimilating the classical languages with ease, and a facility for computation. Unlike the other students in his year he responded well to the astronomy lectures given in broken English to a dwindling class by the director of the observatory, Francis Brünnow. Watson was extraordinarily vain. His notebooks are repeatedly signed with his own name, sometimes repeatedly on the same page, and once with the post-nominal and imagined description "Astronomer Royal." A draft description of a telescope that he planned as a student starts off with a dream of fame: "The Hon. James C. Watson is one of the greatest astronomers that this country has ever produced, to whom immeasured devotion to science owes some of its greatest blessings. Astronomy under his patronage has reached a summit rarely obtained."

When Watson graduated in 1858 he was appointed as Assistant Astronomer at the Detroit Observatory under the direction of Brünnow, and succeeded him as the director when Brünnow resigned, having supported the loser of a battle in which the university's board of trustees forced out its president. Watson made several international trips to observe eclipses and the transit of Venus in 1874, during which he visited Peking (as Beijing, the capital of China, was then called). Watson colorfully described the discovery of a minor planet in his record of his *Observation of the Transit of Venus*:

> *On the night of the 10th October, while observing in the constellation Pisces, with the 5-inch equatorial, I came across a star of the 11th magnitude in a region of the heavens with which I was very familiar, and where I had not hitherto seen any such star. Subsequent observations the same night by means of a micrometer, extemporized for the purpose, showed that the star was slowly retrograding* [going backwards in the sky], *and that it was a new member of the group of planets between Mars and Jupiter. The discovery was duly announced to astronomers in other lands, and it became also speedily known in Peking. Some mandarins of high rank came to our station to see the stranger with their own eyes, and upon observing the change of configuration with neighboring stars on two successive nights, they gave free expression to their astonishment and delight. This being the first planet discovered in China, I requested Prince Kung, regent of the Empire, to give it a suitable name. In due time, a mandarin of high rank brought to me the document containing the name by which the planet should be known, coupled with a request—communicated verbally—that I would not publish the name in China until the astronomical board had communicated to the Emperor an account of the discovery and the name which had been given to the planet. This request was of course promptly acceded to; and I afterwards learned upon inquiry that if the knowledge had come to the Emperor otherwise than through the astronomical board, organized specially for his guidance in celestial matters, some of the ministers would have been disgraced.*

The name that had been chosen was Juewa, or more fully, Jue-wa-sing, which means the "Star of China's Fortune."

Watson went on to discover a total of 22 asteroids and became an important figure in American astronomy, moving on to become director of the observatory at the University of Wisconsin in Madison. He was an entrepreneur in his spare time and made a considerable fortune. He died early, aged 42, and left $18,000 to the National Academy of Science for the "care" of the Watson asteroids, namely the publication of tables of the asteroids that he had discovered. The amount of $18,000 in that year would buy the equivalent of $2.5 million worth of labor today. Watson left nothing to his widow. Astronomers honored him by naming the asteroid (729) Watsonia; his widow left nothing that said what she thought of him, but one may guess that she would not have been flattering.

Juewa is one of the most slowly rotating asteroids, with a period of 42 h. It is not known why large asteroids such as Juewa rotate so slowly. The slowest rotating asteroid 162058 (1997 AE12) has the extraordinarily long period of 1880 h (78.3 days). Astronomers expect that impacts between asteroids over time will cause the fragments to spin more quickly, and have not identified the process that does the reverse. Processes that have been suggested include the idea that slow rotators are extinct comet nuclei that were slowed by gas jets that sprayed from the surface of the comet. Another idea is that they have been binary asteroids in which a moonlet has slowed down the rotation of the main asteroid by raising tides, just as Earth's Moon has slowed the rotation of Earth, and then something has happened to the moonlet to drive it away.

VULCAN: MINOR PLANETS THAT WEREN'T THERE

Watson falsely claimed to have discovered two minor planets that became visible near the Sun during the total eclipse of 1878, which he identified with Vulcan, a hypothetical planet thought to orbit between Mercury and the Sun.

The story of Vulcan really starts with the story of Neptune, discovered by Urbain Le Verrier through its effect on Uranus, pulling that planet off its calculated course. The planet Mercury had also been troublesome, like Uranus. The discrepancies between its real and calculated positions were apparent in predictions of when it would pass across the face of the Sun. It was a day late transiting across the Sun in 1707, several hours off in 1753, and 53 min off in 1786. Le Verrier tackled the problem and improved the situation with "A New Determination of the Orbit and Perturbations of Mercury" published in 1843. He turned to the problem of Uranus, resulting in the discovery of Neptune in 1846. He lost some prestige and worldwide critical acclaim, though, as a result of errors in his prediction of the transit of Mercury of 1848.

In 1859, in the wake of his success in predicting the existence of Neptune, he thought of a reason why the orbit of Mercury was wrongly calculated. Perhaps, just as Uranus was being perturbed by a planet that was unseen, Mercury was being perturbed by a planet, or possibly a group of planetoids, orbiting inside Mercury. However, although the planet outside Uranus had not been discovered up to then, in the gloom of the outer Solar System, the planet inside Mercury was unseen, he suggested, not because of the lack of light but because of the bright glare of the Sun. How could it be found? From time to time, this planet or planets would pass across the Sun as Mercury does, but no one had yet noticed. Astronomers, he instructed, should look more carefully.

When Le Verrier published this theory, an amateur astronomer, a country doctor, Edmond Lescarbault, living in Orgères, south of Paris, informed him that earlier in the year he had already observed a spot transiting the Sun over a period of 4.5 h. Le Verrier traveled to Orgères to interrogate the doctor, was satisfied that the observation was genuine and named the planet Vulcan. Le Verrier had apparently discounted the reduction of credibility that accrued to the doctor's story when he revealed that, although he had made notes about his observation by writing with a crayon on a wooden tablet that he also used to make notes about his patients, he had shaved off the surface of the tablet with a plane in order to re-use it. Le Verrier sponsored Lescarbault in his appointment as a *chevalier* of the *Legion d'Honneur*, a title that was later taken away. Astronomers collected a number of apparent observations of Vulcan, patches on the Sun that had been thought at the time to have been sunspots. Le Verrier used them to formulate Vulcan's orbit. It was a disappointment when the next transit of Vulcan predicted by Le Verrier to occur in 1860 failed to materialize.

Lescarbault's story having got out, the Chamberlain of the City of London, Benjamin Scott, claimed that he, too, had seen a transit of Vulcan long before Lescarbault, in 1847. (Scott was a Fellow of the Royal Astronomical Society for 30 years, but his obituary mentions no astronomical activity. He must have had a rather casual interest in astronomy.) The circumstances of Scott's observation did not fit Le Verrier's orbit of Vulcan; perhaps there were two intra-Mercurial planets? The situation was confused by a number of further sightings that Le Verrier systematized in 1876. They could not, when considered all together, be explained by one planet; perhaps there were indeed a number of Vulcans? The search widened and gathered up an enthusiastic amateur community eager to find a new planet; *Scientific American* received so many claimed sightings in 1876 that it had to call a close to the correspondence, which was taking up too much space in its columns.

Another transit that Le Verrier predicted for March 22, 1877, also failed to appear and damaged confidence in the whole idea of Vulcan. Astronomers began to think that all those transits were misidentified sunspots. The French astronomer Jules Janssen laid down a series of suggestions for Vulcan hunters, rather pointedly including the instruction to learn how to tell a sunspot from an object above the Sun's surface. Le Verrier died later that year, on the exact anniversary of the discovery of Neptune. In Europe, interest in Vulcan ebbed away. But a total solar eclipse visible in North America from Alaska to Texas on July 29, 1878, revived interest in the United States. Could Vulcan be seen, not by the shadow of its transit across the Sun but in the way that planets are usually seen, by reflected sunlight while the Sun's direct light was shaded by the Moon?

First reports of the search for the new planet were negative. But there were two positive reports, one from James Watson viewing the eclipse from Rawlins, Wyoming, and one from Lewis Swift, (5035) Swift, from Denver, Colorado. Both astronomers claimed to have seen new stars in the vicinity of the Sun. Watson claimed that his new star had a disc, but no tail, so it was not a comet. It was "ruddy." It looked like a star of the 4th magnitude, which enabled astronomers to estimate its size to be about 600 km (400 miles). It was roughly the size of a large asteroid, and its gravitational effect would be too small to account for the discrepancies in the orbit of Mercury. Watson then claimed that perhaps he had also seen a second new star. His account was tainted by changes he made to the position of the first star. Swift also said that he had noted a second new star, but his account was also tainted by discrepancies between his accounts. Watson's and Swift's reports of the positions of the new stars could not be reconciled, and it seemed there were at least three asteroids, even four. Other skilled astronomers had, however, noted nothing untoward as they viewed the eclipse.

The American astronomer Christian Peters, (100007) Peters, made a blistering attack on Watson's and Swift's reports. Peters was well-educated and a linguist as well as a talented astronomer, but he was a brawler in matters of argument. Simon Newcomb, (855) Newcombia, who got on Peters' wrong side, candidly summed up the man in his autobiography, *The Reminiscences of an Astronomer*: "Of his personality it may be said that it was extremely agreeable so long as no important differences arose."

Peters was a man with a colorful history. He had been born and educated in Germany, and worked with Carl Gauss on the orbits of asteroids. He took up with a young geologist, Sartorius von Waltershausen, and traveled with him on an expedition to Sicily to explore Mount Etna. As a result, he was offered a position in the Geodetic Survey of Sicily. He used telescopes at the observatory of Capodimonte, Naples, to observe sunspots, also discovering a faint comet in 1846. At that time, Sicily was on the verge of revolt against Piazzi's patron, King Ferdinand and his son. King Ferdinand had scrapped the constitution and established a police state. Peters sided with the rebels and eventually was forced to flee to Turkey, where in Constantinople he became scientific adviser to Reshid Pasha, Grand Vizier of Sultan Abdul-Mejid II. The sultan and the grand vizier had plans to establish an observatory around a recently acquired telescope and wanted Peters to direct it. However, according to a newspaper, "Reshid Pasha's power and protection were not sufficient to overcome the antagonistic influences within the palace, nor could astronomical science, which would not stoop to rule the planets, prevail against the astrologers." The plans came to nothing, shelved on the outbreak of the Crimean War in 1854.

Peters fled from Turkey to America, and gave a talk at a meeting of the American Association for the Advancement of Science on his sunspot observations. As a result of the publicity surrounding this he was given a job in the US Coast Survey in Washington, DC. The director of longitude, Benjamin Gould, became scientific adviser of the Dudley Observatory in Albany, New York, and arranged a job there for Peters. It was a poisoned chalice. Gould was the chairman of a scientific council that had been appointed by the Board of Trustees of the Dudley Observatory to give life to the moribund scientific program. Gould did this with ambitious and therefore expensive plans for its scientific equipment and staffing. He came into conflict with the Board of Trustees not only over the expense of the scientific work but also the public role for the observatory, which the trustees thought was important to attract esteem and sponsorship but which interfered with the scientific work. As Simon Newcomb wrote, this "grew into a contest between the director and the trustees, exceeding in bitterness any I have ever known in the world of learning and even of politics." Eventually Gould was ejected from the observatory by "hired ruffians."

In 1857, Peters discovered a comet that he proposed to name Olcott after a trustee, and he should have been able to stay Gould's and the trustees favor, but he was caught in the middle of the feud and could not stay in everybody's good graces. In 1858 a colleague at the Dudley Observatory discovered an asteroid. Mrs. Blandina Dudley was the founder of the observatory and widow of Charles E. Dudley, a former US senator and wealthy banker. She was asked to name the asteroid and chose (55) Pandora,[3] after the first mortal woman, as suggested in Greek mythology. Pandora was given great gifts of beauty, eloquence, etc., by the gods, but also a box that she was not supposed to open. Curious, she did open it and all the evils of the world escaped to afflict the human race. It was the myth that gave rise to the expression "to open Pandora's box," meaning to take an action that produces a number of unforeseen and undesirable consequences. It was a myth not without relevance to the state of affairs at the observatory.

Peters turned his back on all this, and moved from Albany to Hamilton College, in Clinton, New York (near Utica), where he observed sunspots and discovered 48 asteroids. He made observations intended to generate a series of star charts to help with the discovery of new stars. He had not put conflict behind him, though, and had at one point to sue to get his past year's salary paid; less creditably, he was sued himself by a scientific assistant whose work he refused to credit with co-authorship of his publication. He died in 1890, still working. According to the American psychiatrist,

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[3] Pandora is also the name that was given, confusingly, to a small satellite of Saturn discovered in 1980.

amateur astronomer, historian and author William Sheehan, (16037) Sheehan, “Peters was found lying, a half-burned cigar at his fingertips, on the doorstep of the building where he lodged; observing cap on his head, he had fallen in the line of duty, on the way to the observatory the night before.”

Early in his time at Clinton, Peters became an enemy of James Watson, who in 1868 famously discovered six asteroids in 1 year, rivaling Peters’ record, and who set out, like Peters, to make star charts to facilitate asteroid discovery. On the basis of his experience in observing sunspots, Peters discounted the reported observations of Vulcan, an opinion diametrically opposed to Watson’s, who was a supporter of Le Verrier, having received the Frenchman’s praise for his theoretical work. Peters refused to join in the search for intra-Mercurial planets, saying that he would “not go on a wild goose chase after Le Verrier's mythical birds.” When it came time to comment on Watson’s and Swift’s claims of the discovery of Vulcan at the eclipse of 1878, Peters was scathing, as Joseph Ashbrook noted, “a strange blend of sharp insight and utter tactlessness.” Watson and Swift responded, with anguish but in vain. No intra-Mercurial asteroids were confirmed during subsequent eclipses.

Vulcan has been looked for and not found, so astronomers have concluded that it does not exist; the theoretical reason for Vulcan to exist has also ceased to exist. The discrepancies in Mercury’s motion were explained by Albert Einstein, (2001) Einstein. Newton’s theory of gravitation, which had been used by Le Verrier and everyone before him to analyze the orbit of Mercury, has proved not to be the last word on how gravity works. In 1915, Einstein produced a revision of Newton’s theory, which he published as the General Theory of Relativity. The extra details in Einstein’s theory accounted for the discrepancies that had been identified in Mercury’s orbit when compared to Newton’s theory. The fact that the General Theory of Relativity did explain these discrepancies played a significant part in boosting Einstein’s confidence enough to encourage him to make his theory public. Einstein himself was honored with the name of an asteroid, (2001) Einstein, discovered in 1973 by the Swiss astronomer Paul Wild. Wild took pride that, although Einstein was born in Germany and did most of his later work in the United States, he created his inspired scientific theories while working in the Swiss Patent Office in Berne, the same city from which Wild discovered the minor planet named for him.

UNIVERSITAS: COMMEMORATING UNIVERSITIES

Academia and observatories are commemorated in a good share of the names of asteroids. (905) Universitas looks as if it commemorates universities in general but was intended by its discoverer, Arnold Schwassmann, to commemorate the University of Hamburg in Germany. Academic institutions that are overtly commemorated in the name of asteroids include (226) Weringia (named for Währing, the part of Vienna in which the university observatory is located), (1465) Autonoma (Universidad Autonoma de El Salvador), and (736) Harvard, (1312) Vassar, and (1420) Radcliffe, all in the United States. (391795) Univofutah is obvious. Some university names have been feminized, such as (325) Heidelberga (discovered at Heidelberg observatory), (508) Princetonia (named after Princeton University), (516) Amherstia (Amherst University) and (620) Drakonia (Drake University). (694) Ekard is a disguised university name (Drake backwards). (740) Cantabia also commemorates Harvard, which is located in Cambridge, Mass., whose Latin form is Cantabrigia, but (2531) Cambridge celebrates both Harvard University in the United States and Cambridge University in the UK.

URANIA: ASTRONOMERS IN SPACE

All the muses of Greek mythology are represented by asteroids: (18) Melpomene (the Muse of Tragedy), (84) Klio (History), (27) Euterpe (Music), (23) Thalia (Comedy), (81) Terpsichore (Choral Dance and Song), (62) Erato (Lyric Poetry), (33) Polyhymnia (Singing and Rhetoric), (22) Kalliope (Heroic Poetry) and (30) Urania (Astronomy). Astronomers have been inspired by their muse to name lots of asteroids after other astronomers.

By convention no discoverer should name an asteroid after him- or herself, although others may do so. Asteroid (1604) Tombaugh, discovered by Clyde Tombaugh, also the discoverer of the more famous dwarf planet Pluto, was named by the Lowell Observatory on the occasion of a symposium on Pluto, held in 1980 on the fiftieth anniversary of its discovery. In modern times, one asteroid poignantly named after its discoverer is (96747) Crespodasilva. Lucy D'Escoffier Crespo da Silva discovered the asteroid in 1999 as an MIT undergraduate, observing light curves of minor planets for a project. A year later she committed suicide; after this tragedy she was memorialized by the naming of her asteroid.

Notable astronomers whose names have been given to asteroids, although their connection with the study of asteroids is or was not strong, include Caroline Lucretia Herschel, (281) Lucretia, Simon Newcomb, (855) Newcombia, Edwin Hubble, (2069) Hubble, Patrick Moore (2602) Moore, Martin Rees, (4587) Rees, and Charles Messier, (7359) Messier. (768) Struveana was named after an entire family of astronomers: Otto Wilhelm von Struve, (2227) Otto Struve, Friedrich Georg Wilhelm von Struve and Karl Hermann Struve, but later Otto Struve got an asteroid of his own.

Isaac Newton, (8000) Isaac Newton, appears to have had two asteroids named after him, (662) Newtonia, and (8000) Isaac Newton, as well as after his famous book, (2653) Principia. (8000) Isaac Newton was certainly

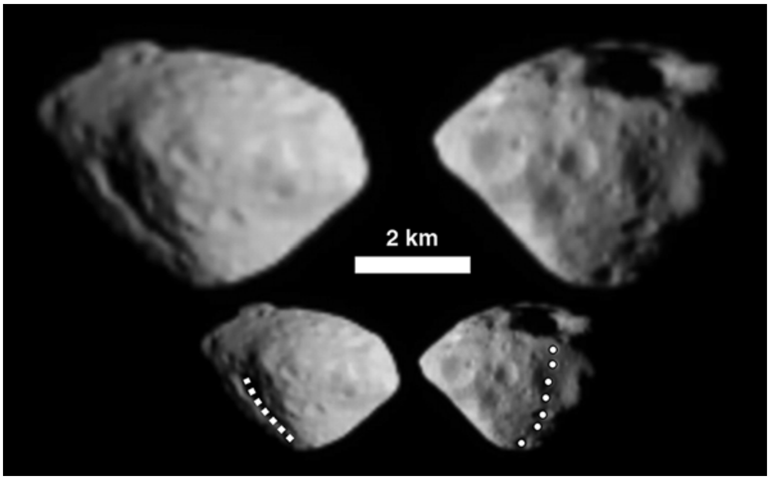

Fig. 5.9 Asteroid (2867) Steins. The images were taken by the Rosetta spacecraft during the flyby of September 5, 2008. The dashed lines indicate geological features (©ESA 2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

named after the physicist, but the formal reason for the name of (662) Newtonia, which was discovered in 1908, is that it is named for the city of Newton, Massachusetts. However, the originator of the name, Princeton astronomer Zaccheus Daniel, could not make his mind up whether to honor Isaac Newton or the American meteoricist Hubert Anson Newton (1830–1896), and in the end plumped for both and neither.

The Franco-American astronomer Dorothea Klumpke is celebrated in two asteroids, (339) Dorothea and (1040) Klumpkea. French astronomer Camille Flammarion, (107) Camilla and (1021) Flammario, also has two asteroids specifically named after him, more if you include (141) Lumen, the title of one of his novels, (605) Juvisia, named for the city of Juvisy-sur-Orge where he lived, and (87) Sylvia and (355) Gabriella, his first and second wives. (25143) Itokawa was discovered by the LINEAR asteroid search program and named after Hideo Itokawa, (25143) Itokawa, the Japanese rocket scientist known in Japan as Dr. Rocket.

Asteroid (2867) Šteins is a small asteroid named after a little-known Soviet/Latvian astronomer of modest achievement. Both man and asteroid sprung into the limelight when, in 2008, the asteroid happened to lie close to the path of the Rosetta spacecraft on its way to Comet 67P/Churyumov-Gerasimenko, and was imaged by the cameras on board. Kārlis Šteins, (2867) Steins, was known locally as a teacher, and in 1936 he calculated the orbit of, and named, asteroid (1284) Latvia; this is the first minor planet to bear a Latvia-related name. An irregular, roughly diamond shape, Steins is 6.7 × 5.8 × 4.5 km in dimension and rotates in 6 h. It seems likely that it is a fragment of a larger body that broke up through a big impact, and acquired its shape when it began to rotate faster due to the YORP effect and loose material migrated to its equator. However, the interior is thought to be a rubble pile and, because it will rotate faster and faster, the asteroid will eventually break up, spinning loose material off into space (Fig. 5.9).

Among the (many) astronomers who do not have an asteroid named after them is Gustav Stracke of the Berlin Rechen-Institut. He had specifically asked that no planet should be named after him. However, in 1932 Karl Reinmuth named eight of the minor planets that he had discovered after plants and flowers whose initials in numerical sequence spell

"G. Stracke": (1227) Geranium, (1228) Scabiosa, (1229) Tilia, (1230) Riceia, (1231) Auricula, (1232) Cortusa, (1233) Kobresia, (1234) Elyna. The same trick was used to honor the former director of the Minor Planet Center, Brian Marsden, (1877) Marsden, in a series of asteroids named after artists and writers in 1977: (5694) Berényi, (5695) Remillieux, (5696) Ibsen, (5697) Arrhenius, (5698) Nolde, (5699) Munch. The proposers of the name noted that they did not have a long enough list of discoveries to spell out his name in full.

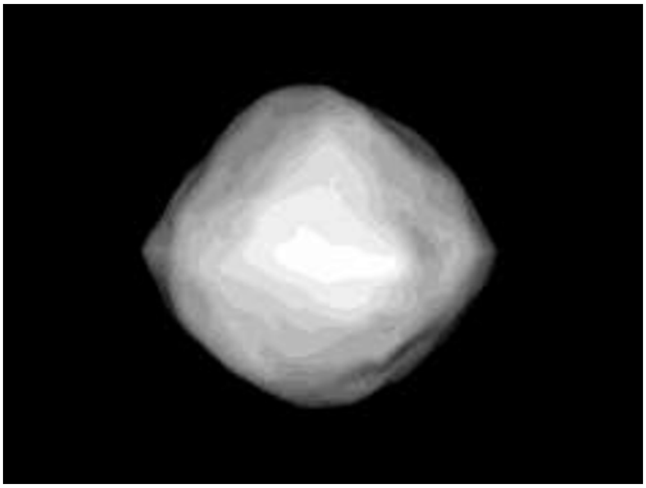

Fig. 6.1 Bennu. This computer-generated image of asteroid 1999 RQ36 was derived from radar data acquired by the Arecibo Observatory in Puerto Rico. The image is intended to help plan the OSIRIS-Rex mission, culminating in the return to Earth for laboratory analysis in 2023 of some of the surface material. The pixellation and coarse contouring represent the shape of the asteroid as precisely as the calculations were made from the radar data. (NASA/NSF/Cornell/Nolan)

Chapter 6

The Catalog and the Names It Inspires

MPC: IN CHARGE, WITH A COMPUTER

When asteroids were first discovered in ones and twos, their designations were decided by individuals, and discussed by writing letters or by publishing opinions in astronomical journals. In disputes a consensus emerged by an undefined process. As the number of asteroids grew, there was a need for some sort of systematization, and German astronomers stepped into the breach, particularly those of the Astronomisches Rechen-Institut (Astronomical Calculation Institute), originally in Berlin, now in Heidelberg. The editorial practices of publications like the *Zirkulare des Rechen-Institut*, the *Berliner Astronomische Jahrbuch*, and the *Astronomische Nachrichten* (*Astronomical Notes*, published since 1821) set the standards to define names, numbers and orbits, and even settled some disputes over the priority of discovery. After the Second World War, this role was given to the Minor Planet Center (MPC), located at first in Cincinnati, Ohio, now at the Smithsonian Astrophysical Observatory in Cambridge, MA, and funded by NASA.

So far as the names are concerned, in the modern era not quite anything goes. There is no gender discrimination for or against feminine names but—maybe this sounds familiar to modern ears—there is a committee in charge, with rules and a computer. The names of asteroids are decided by the Committee on Small Body Nomenclature (CSBN) of the International Astronomical Union (IAU). Founded in the 1970s as the Working Group for Small Body Nomenclature, this had three members, but it has grown to a committee of 15 professional astronomers with research interests in asteroids, comets and moons, who, it could be said, are an oversight body for the MPC.

One of the main aims of this administrative structure is to avoid confusion. Historically, a number of asteroids have been discovered, numbered, named, and then lost. One case of a lost asteroid was (330) Adalberta, discovered March 18, 1892, by Max Wolf. Ninety years later, in 1982, it was found that some stars had been misidentified as observations of a minor planet, and the asteroid never existed. The same name and number (330) Adalberta was then reused for an asteroid discovered by Max Wolf on February 2, 1910. A few asteroids have been discovered and then unknowingly re-discovered and named a second time.

About half of the asteroids that are discovered are lost. This looks alarmingly inefficient, but is only natural. There are more of the small, faint asteroids than of the large, bright ones, so most asteroids that are discovered are near the limit of visibility of the telescope. Half of them are getting closer to Earth and getting brighter, but half are receding and getting fainter. These drop below the limit of visibility of the telescope so they are viewed for only a short time, perhaps not long enough to determine their orbit accurately enough so they can be recovered when they get bright enough again. They may be re-discovered later but might or might not be linked with the earlier discovery.

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_6

The MPC's modern computer database was built to control duplication and confusion, but asteroids do not carry any identification markings that can be seen by telescopes based on Earth, and the vast majority can be identified only from their orbit. Control of the situation is possible only by combining the observations of the positions of an asteroid on a number of occasions and determining its orbit accurately, without any ambiguities. This is usually enough to distinguish a given asteroid from any other. It is a labor-intensive task that has to be done carefully. As a matter of acknowledging the debt astronomers owe to the office that carries out the task, asteroid (4999) MPC honors the Minor Planet Center.

The method of identification is sequential over a period of years. When first discovered, an asteroid is given a provisional designation derived from the date of discovery. The first group of characters is the year of discovery, followed by a second group of characters, two letters, the first of which defines the half-month period of the year in which it was discovered (A to Y, with I not used and no need for Z). The second letter is given in sequence (again, I not used). If there are more than 25 minor planets discovered in that 15-day period, the designation is recycled and a number is appended to signify how many times. Asteroid (128562) Murdin had a provisional designation of 2004 PM90. This means that it was discovered in 2004, with the letter P meaning that its discovery was between August 1 and 15. The first 25 discovered in that period were designated A, B, C … Z, the next 25 A1, B1, C1 … Z, and so on. M90 means that my asteroid was the $25 \times 90 + 12$th reported to the MPC in that period, i.e., the 2262nd.

When the orbit of an asteroid becomes so well determined that its position can be reliably predicted far into the future (typically this means after it has been observed for 4 or more years), the asteroid's provisional designation is upgraded to a permanent one. The permanent designation of an asteroid is a catalog number, issued sequentially, which acts as a label with which to access its orbital characteristics.

The Minor Planet Center is also responsible for keeping track of comets. Most comets are seen very infrequently, perhaps only once, so their orbits are often not well determined. These comets do not get past the provisional naming stage, akin to the asteroid-naming convention. Comets are routinely designated for their year (and now, like asteroids, the date) of discovery and their discoverer (or discoverers, if there were more than one). Like the minor planets, comets are given designations based on the year and half-month of discovery, with the half-month indicated by letters (A to Y, with I omitted and no need for Z), and with a numeral (1, 2, 3, etc.) in sequence. The designation of a comet is preceded by the characters "C/" indicating "comet." So, for example, three comets discovered in the first half of January 2020 would be designated C/2020 A1, C/2020 A2, and C/2020 A3.

To flag up a comet that appears over and over again and might have different designations, the characters "P/" are prefixed to the designation if the comet has an orbital period under 30 years. After a "periodic" comet has been observed to return to its closest point to the Sun on two occasions, it is given a catalog number in sequence. There are currently (in 2015) just over 300 periodic comets cataloged. The number precedes the designation. The list starts: 1P/1682 Q1 (Halley), 2P/1818 W1 (Encke) …, and goes on through 67P/Churyumov-Gerasimenko to end (in 2015) at 316P/LONEOS-Christensen. The characters D/ are prefixed to the designation if the comet was periodic and no longer exists or has disappeared, as in the third on the list 3D/1826 D1 (Biela), a comet that broke up and disintegrated.

If necessary, the prefix A/ precedes a designation that has been given to what was thought at the time to be a comet but is now thought to be an asteroid, perhaps a comet that has become extinct and indeed is now an asteroid.

There are some historical exceptions. Occasionally a very bright comet (usually one near the Sun) suddenly became visible to many observers worldwide nearly simultaneously as a naked-eye object, so it was discovered by nobody in particular. Such comets may have a "generic" name, like the Great September Comet of 1882, or the Eclipse Comet of 1948, as well as a designation. Some comets have been named, not after the person who first saw them but after the person who computed their orbit and showed that several comets thought to be distinct are one and the same. Halley's Comet is the most famous example of this.

Asteroids are not named after their discoverers, but the discoverer of an asteroid has the right to suggest a name to the Committee on Small Body Nomenclature, through a short citation. The discoverer can ask someone else to suggest a name, or simply decline to arrange for a name, as some prolific discoverers have done, either to make the opportunity available to others or simply because they are daunted by the task of making up so many names.

The CSBN has developed a code for the suitability of proposed names. To avoid confusion, the name must not be too similar to an existing name, especially of something else similar in the Solar System. Before this rule was monitored, some asteroids were named for identical personages, except for spelling differences: (43) Ariadne, (1225) Ariane; (699) Hela, (1370) Hella; (140) Siwa, (1170) Siva; (1071) Brita, (1219) Britta; (207) Hedda, (673) Edda; (1175) Margo, (1434) Margot; (579) Sidonia, (1106) Cydonia; (1357) Khama, (1387) Kama. Three were given the same name as planetary moons: (85) Io, (106) Dione, and (593) Titania. Nowadays names of gods and goddesses are reserved for important asteroids.

Then there are matters of taste. The name cannot be completely random letters; it must be pronounceable (in some language). The name must be inoffensive. Furthermore, to avoid trouble and with history in mind, the IAU, as an inclusive, international organization wary of political controversy, now fights shy of the names of individuals or events principally known for political or military activities until 100 years after the death of the individual or the occurrence of the event.

This policy has waxed and waned over the years. It has thus been correspondingly applied with greater or lesser vigor, and in the context of the citation; a citation for a name that stresses the political importance of the person or event intended to be honored might not be convincing to the IAU committee on minor planet names, but a citation on behalf of the same individual that stressed other qualities could be successful. (185) Eunike was discovered in 1878 by C. H. F. Peters and named after the signing of the treaty that ended the Russo-Turkish War of 1877–1878, as a result of which Russia made considerable territorial gains. The name translates as "Happy Victory," more a happy victory for the Russians than for the Turks. Among politically controversial christenings, (852) Wladilena is named with the first syllables of the name of Vladimir Ilyich Lenin, (852) Wladilena. Josip Broz Tito, (1550) Tito, and Karl Marx, (2807) Karl Marx, are as prominent and as politically controversial. These asteroids were christened before the ban on politically motivated names was implemented. Later, the Argentinian astronomer Manuel Itzigsohn, (1596) Itzigsohn, was allowed to memorialize his hero Eva ("Evita") Peron, (1588) Evita, with a group of names, including not only the affectionate diminutive form of her given name but various soubriquets: (1588) Evita, (1581) Abanderada ("a woman who carries the flag"), (1582) Martir ("martyr"), (1588) Descamisada ("shirtless woman [worker]," the symbol of trade unions), and (1589) Fanatica ("a woman devoted to a cause"). The tragedy of Eva Peron's early death was mirrored in the tragedy of Itzigsohn's daughter, Matilde Itzigsohn de García, who disappeared in the last year of his life, 1977, presumed kidnapped and killed by Argentinian death squads.

There were historically also attempts to give comets individual names, commemorating people. In 1857, a comet discovered by C. F. H. Peters of Dudley Observatory was named by him the Olcott Comet after a "very beloved and esteemed, distinguished citizen," one of the observatory's trustees. Another comet was revealed at the solar eclipse of 1882, discovered in Egypt in the presence of the Khedive Tewfik Pasha. Khedive is an Ottoman title, roughly viceroy or governor. There was an attempt to name the comet as Comet Tewfik. The comet was seen only the once and then disappeared, so it would not have been a very auspicious christening for the Khedive. However, neither Comet Tewfik nor Comet Olcott were accepted as names.

The IAU does accept that asteroids may be named after suitable organizations. Some of them designated by initials are (3654) AAS (American Astronomical Society), (8900) AAVSO (American Association of Variable Star Observers), (2848) ASP (Astronomical Society of the Pacific), (5000) IAU (International Astronomical Union), as well as (4999) MPC (both the journal *Minor Planet Circulars* and Minor Planet Center). To avoid being associated with advertising, the IAU does not allow names of a commercial nature to be given to asteroids, although (2138) Swissair (the former airline) slipped around this prohibition, named after its discovery on April 17, 1968, by Swiss astronomer Paul Wild at the Zimmerwald Observatory near Berne, Switzerland, partly because its provisional name was 1968 HB and HB is the international designation of Swiss aircraft, and partly because he liked the airline.

The IAU agonized over (8080) Intel, discovered in 1987 at the Centre de Recherches en Géodynamique et Astrométrie (CERGA) in Caussols, France, and let it pass because the name matched the number, and because the Intel 8080 microprocessor was the ancestor of a series of microprocessor chips that were fundamental to the "Personal Computer revolution" and did much to advance astronomy at amateur and professional observatories worldwide. There was no angst over naming asteroid (9000) HAL after the name and model number of the rebellious computer, Hal 9000, in the book and film *2001*: *A Space Odyssey* by Arthur C. Clarke. Other computer-based names are asteroid (3568) ASCII (American Standard Code for Information Interchange, the character-encoding scheme used in computers) and (1625) The NORC, the Naval Ordnance Research Calculator in Virginia, made by IBM, at the time (the late 1950s) the most powerful computer. There is something inhuman about (7767) Tomatic, "named in honor of A. U. Tomatic (b. 1997), a collaborator at the Minor Planet Center. An ardent computer of orbits and distributor of observational data of minor planets and comets, Tomatic is a godchild of the MPC astronomers B. G. Marsden and G. V. Williams. Tomatic takes a lot of the drudgery out of keeping up to date and coordinated the lists of data about the million minor planets.

(3728) IRAS, (9995) Alouette, (9996) ANS, (9997) COBE and (9998) ISO, are all named after space satellites, and there are plenty of observatory names.

Although the names of asteroids may not be sold, the names of a number of asteroids have been won in contests such as the Discovery Channel's Young Scientist Challenge and the Intel International Science and Engineering Fair; high school and technical school teachers also feature in such naming awards. (Although the naming opportunities are offered as prizes they still have to go through the IAU's approval process!). NASA offered the opportunity to name the asteroid 101955 (=1999 RQ36) as a prize to encourage citizen participation in its space mission, to be launched in 2016, called with the cumbersome name "Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx)," which will return samples from the primitive surface of this near-Earth asteroid. The winner was Michael Puzio, a third-grade student from North Carolina, whose choice of name, Bennu, for asteroid 101955 refers to an Egyptian mythological bird, whose heron-like outline the silhouette of the satellite resembled, with its deployed instrument arm.

The asteroid has been imaged by radar technology (Fig. 6.1) and is roughly spherical with a diameter of 0.5 km (0.3 mile). Images purporting to be from an Indian Space Agency space probe that flew past the asteroid and viewed artificial pyramid structures are hoaxes. Bennu was chosen as the target for the OSIRIS-Rex mission because it comes near to Earth (so it is readily accessible), it is relatively large and slowly rotating (which minimizes the difficulty that a spacecraft will have to land on it), and, from remote analysis of its light, is composed of material from the early Solar System (and therefore of considerable interest).

ANNEFRANK: PRACTICE FOR STARDUST

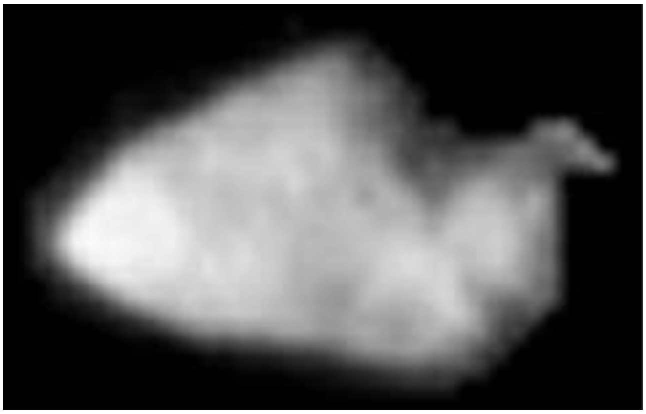

Fig. 6.2 Asteroid Annefrank is an irregularly shaped, cratered body shown in this image taken by the Stardust spacecraft during the flyby of the asteroid in November 2002. It is a blurry picture, even after digital processing, but the view is roughly equivalent to taking a picture of Manhatten Island from from the distance of London. (NASA/JPL)

There are some technical limitations which the MPC imposes on the names, based on computer technology or other practical requirements. The name must be 16 characters or less in length. It should be one word, so if a discoverer wants to name his or her asteroid with somebody's full name, the names are run together, like (5535) Annefrank. This rule is not followed by asteroid names created before the rule was enforced.

Anne Frank, (5535) Annefrank, was a Jewish girl who was hidden with her family in an attic in Amsterdam during the Second World War, but who was captured by the Nazis and died in a concentration camp. Her story is known through the preservation of her diary. Her asteroid, discovered in 1942 by Karl Reinmuth and named in 1995, is not very remarkable, except that in November 2002 it was fortuitously positioned near the trajectory of the spacecraft Stardust on its way to its main target of Comet Wild 2. It was thus used to practice the observational techniques that were to be used later (Fig. 6.2). The images of it that were obtained were rather poor resolution compared with others images of asteroids, because the asteroid is small and Stardust came no closer than 3000 km (2000 miles). Annefrank is an irregular, angular asteroid, 6.6 × 5.0 × 3.4 km in size (4.1 × 3.1 × 2.1 miles). Its surface is cratered and littered with boulders.

HESTIA: FRIENDS AND RELATIONS

After the long battles of the nineteenth century, the IAU has accepted that asteroids can be named after living people. One of the first was asteroid (42) Isis, which looks as if it is named after a goddess, but it was also (in 1856) named after Elizabeth Isis Pogson, (42) Isis, daughter of the discoverer, astronomer Norman Robert Pogson, (1830) Pogson. Elizabeth Isis was herself named after the River Isis, the name given to the River Thames as it flows through Oxford. It looks as if this is something to do with Isis the ancient Egyptian goddess, but the word is simply part of Tamesis, the Latin name for the Thames, recorded by Roman invaders from the Celtic name for the river, Tamesas, whose meaning is disputed but which is the reason why the modern name for the river is pronounced "Temms." Elizabeth Isis became her father's assistant and was in 1886 nominated to membership of the Royal Astronomical Society (RAS), but was refused admission on discriminatory grounds of gender; the naming of asteroids was discriminatory in the reverse sense. The spurious legal reason for her not to be accepted as a member of the RAS was that the founding Charter of the Society referred to members solely with male pronouns. This impediment was removed and the first women members were admitted to the RAS in 1915. Elizabeth was successfully nominated in 1920.

Around the same time, asteroid (46) Hestia was discovered by Pogson, who offered the opportunity to name the asteroid to the amateur astronomer, Admiral W. H. Smyth. Smyth was pensioned off in the mid-1800s as a lieutenant from the Royal Navy and rose only through the passage of the years to the rank of admiral. It was a title of which he was perhaps overproud but, with the pension that came with it, he had the time and the resources to indulge his hobby of astronomy. He had erected an observatory at his home in Bedford, using its telescope to compile his famous book, *A Cycle of Celestial Objects*, still in print and still used by amateur astronomers. Upon completion of the research for the book, Smyth donated the telescope to Dr. John Lee, an antiquary, lawyer, dilettante and politician, who had inherited a large country house, Hartwell House, between Bedford and Oxford. Lee and Smyth not only used the telescope themselves, they gathered a small circle of enthusiastic observers into a science society centered around the house, including Norman Pogson.

Pogson had been employed as an assistant at the Radcliffe Observatory in Oxford, but his salary was modest, not enough to support his family (£120 per year to support a wife and a large number of children, eventually 11 of them), and he fell out with his director Manuel Johnson. Johnson was an astronomer of modest achievements in cataloging stars, although a popular and respected figure at Oxford University, especially in high Church circles. The reasons for the disagreements between Johnson and Pogson are not known, although there is evidence that Pogson was not a tactful person. Pogson was also not university educated and thus could never become an integral figure in the scientific circle at Oxford or any other university at that time.

Pogson attempted to court richer, private observatory owners, including Dr. Lee. While using Smyth's telescope in Lee's observatory at Hartwell House in 1857, he found asteroid Hestia. Pogson wrote that Smyth "obligingly complied with my request to stand God-father to this first offspring of his former telescope." Smyth recommended Pogson to Lee, and he was appointed in 1859 to direct the Hartwell House observatory at an increased salary of £220 per annum with a house and garden provided in the grounds of the stately home.

In Greek mythology, Hestia was the virgin goddess of the hearth, domesticity and the family. It seems that Hestia could be deemed to be the patron goddess of many of the discoverers of asteroids, because there are plenty of asteroids named after family and friends. A few examples are (87) Sylvia (a wife), (153) Hilda (a daughter), (154) Bertha (a sister), (1280) Baillauda (named after a son, but also the family name of the discoverer himself, Benjamin Baillaud), (3044) Saltykov (a grandfather), (10588) Adamcrandall (a stepson), (12848) Agostino (a father), and (19524) Acaciacoleman (a granddaughter). (960) Birgit is named after a daughter of Swedish astronomer and orbit calculator Bror Ansgar Asplind; the name was passed on to the U.S.S. *Birgit*, an Artemis-class attack cargo ship of the Second World War. (1838) Ursa was discovered in 1971 by the Swiss astronomer Paul Wild and named for his wife, Ursula, their son, Urs, and for the bears of Berne.

Gene Shoemaker, (2074) Shoemaker, and Carolyn Shoemaker, (4446) Carolyn, assiduously searched for comets and asteroids in the early 1900s using telescopes at the Mount Palomar Observatory. They were honored themselves by having asteroids named after them, and they have named asteroids after several members of their family (Fig. 6.3). Their asteroidal family-tree extends to mothers-, sons- and daughters-in-law, uncles and aunts, and grandchildren.

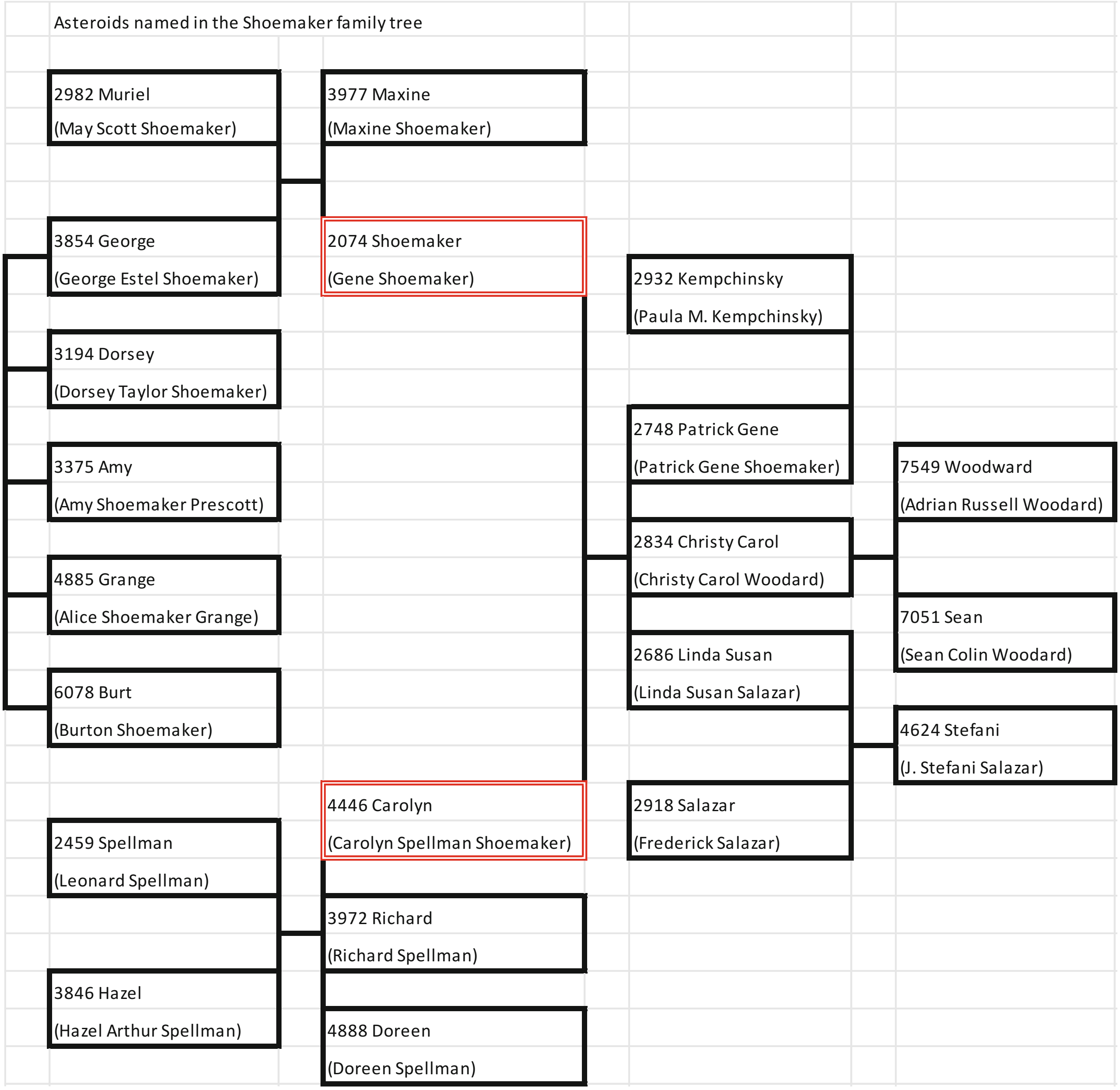

Fig. 6.3 The Shoemaker family tree contains a score of people who have had asteroids named for them, because of the many asteroids that the Shoemakers have discovered

MATHILDE: COAL BLACK

A distinguished asteroid named after a female relation is (253) Mathilde, which was found in 1885 by Johann Palisa, at the newly completed Vienna Observatory. The orbit of the asteroid was calculated by V. A. Lebeuf, of the same observatory, and named after Mathilde Palmyre Leowy, (253) Mathilde, the wife of Moritz Leowy, the vice director of the Paris Observatory, a former boss of Palisa's in the late 1800s. Do we infer simple friendship in the christening, or look for an underlying story such as sycophancy, or romance? Whatever the motives, Mathilde would undoubtedly have been pleased by the gesture; she would perhaps less pleased by the unromantic decision by the IAU to name craters on Mathilde after coalfields.

Mathilde is a slowly rotating (rotation period 17.4 days), black, rocky asteroid, 50 km (30 miles) in diameter. It is potato shaped, somewhat ellipsoidal (Fig. 6.4). It was appropriately placed for a visit by the NEAR-Shoemaker spacecraft in June 1997, on its way to its main target, asteroid 433 Eros. Mathilde is a C-type asteroid, the most common kind; three quarters of the asteroids are this type. Their spectra are similar to the spectra of meteorites called carbonaceous chondrites. These meteorites are made of light rocks, with compositions close to the composition of the material of the solar nebula from which the terrestrial planets formed, except that the very lightest materials (hydrogen, helium and some volatile ices) have been driven off by the warmth of the Sun. They contain water-bearing minerals and carbon compounds. The carbon compounds create tarry substances in the rock, which is the reason why Mathilde is as black as coal.

Mathilde has several large craters, the largest being 30 km in diameter. Because of Mathilde's black color, the convention is to name Mathilde's craters after the coal fields of the world. Given that Mathilde is only 50 km in diameter, the largest impacts and the huge excavations they caused must have come close to disrupting the asteroid. Although the density of carbonaceous chondrites is low, the average density of Mathilde is lower, by half, so half the volume inside the asteroid's surface is empty. This may be the reason why Mathilde did not break up when hit by other asteroids and meteoroids; the energy of the impactor was absorbed in shuffling around the rocks of which it is made, much as a stunt artist uses loosely packed, empty cardboard boxes to absorb the energy of a fall. If ever it becomes necessary to attempt to break up a similar asteroid that is heading for a collision with Earth, this resistance to impacts will have to be borne in mind. It might be very difficult to disrupt such an asteroid to render it into small enough pieces to burn up in the atmosphere.

Fig. 6.4 An image of asteroid Mathilde was constructed in a mosaic of four images acquired from a distance of 2400 km (1500 miles) by the NEAR spacecraft in June 1997. The face of the asteroid shown is about 59 by 47 km (36 by 29 miles) across. The large, deeply shadowed crater is more than 10 km (6 miles) deep. The angular shape of the upper left limb of the asteroid is the rim of another large crater viewed edge-on (NASA/NEAR)

JAMES BOND AND TRIPAXEPTALIS: HEROES AND CURIOSITIES

Many asteroids are named after people celebrated for achievements outside astronomy, reflecting the kind of interests you would expect well-educated, young, mostly male astronomers to have. Asteroids named after people who invented or discovered things include the inventor of the saxophone (Adolphe Sax, (3534) Sax, the discoverer of the law of floating bodies, Archimedes, (3600) Archimedes, and the inventor of the World Wide Web (particle physicist Tim Berners-Lee, (13926) Berners-Lee. Artists and musicians celebrated in this way include Ludwig van Beethoven, (1815) Beethoven, William Shakespeare, (2985) Shakespeare, Michelangelo di Lodovico Buonarroti Simoni, (3001) Michelangelo, and Rembrandt Harmenszoon van Rijn, (4511) Rembrandt.

A number of asteroids are “rock stars” in two senses of the phrase. The four Beatles make a consecutive run: John Lennon, (4147) Lennon; Paul McCartney, (4148) McCartney; George Harrison, (4149) Harrison; and Ringo Starr, (4150) Starr. Brian Wilson, (18125) Brianwilson, (19367), Pink Floyd, and (19383) Rolling Stones are further examples from modern popular music. (3834) Zappafrank was named for the American composer Frank Zappa, (3834) Zappafrank, after a naming campaign organized by fans through the World Wide Web; the curious backwards construction of the name was intended to avoid confusion with other asteroids, including (2813) Zappalà (named after the Italian astronomer and asteroid hunter Vincenzo Zappalà,(2813) Zappalà, and a number of names beginning with ‘Frank.’ These were (982) Franklina, (1925) Franklin-Adams (both named for English amateur astronomer John Franklin-Adams, (982) Franklina and (1925) Franklin-Adams, who created the first comprehensive all-sky photographic celestial atlas, (2824) Franke (named for an American biophysicist) and (2845) Franklinken (named for the American astronomer-popularizer Kenneth Linn Franklin.

Another consecutive run of asteroids include (9617) Grahamchapman, (9618) Johncleese, (9619) Terrygilliam, (9620) Ericidle, (9621) Michaelpalin, and (9622) Terryjones, as well as (13681) Monty Python, (19535) Rowanatkinson, (18610) Arthurdent, and (17826) Normanwisdom, all of whom represent British comedy. Arthur Dent, of course, is the anti-hero of the book by Douglas Adams, (25924) Douglasadams, *The Hitchhiker’s Guide to the Galaxy*. The preliminary designation of Adams’ asteroid, 2001 DA42, contains both his initials and the answer to life, the Universe and everything. A consecutive run of asteroids representing American comedy is (30439) Moe, (30440) Larry and (30441) Curly, who made movies as the Three Stooges.

The movie world is well represented with the names indicating the shift of taste in movie actors over time: (4238) Audrey (Audrey Hepburn), (6377) Cagney (James Cagney), (6546) Kaye (Danny Kaye), (8353) Megryan, (9341) Gracekelly, (9342) Carygrant, (12818) Tomhanks, (12820) Robinwilliams, (13070) Seanconnery, (15131) Alanalda, (17744) Jodiefoster and (19578) Kirkdouglas. Sports fans were responsible for (17493) Wildcat (after the University of Arizona's athletics teams), (3767) DiMaggio (the baseball hitter) and (8217) Dominichašek (an ice hockey goaltender).

Although animals themselves are acceptable as names (one notable group is (9937) Triceratops, (9941) Iguanodon, (9949) Brontosaurus, (9951) Tyrannosaurus and (9954) Brachiosaurus), since 1971 the IAU has shown a reluctance to trivialize the subject of asteroid research by discouraging the giving of the names of pet animals to asteroids. The first pet names that were used were (482) Petrina and (483) Seppina, named after the pet dogs of the astronomer who discovered them from Heidelberg Observatory in 1902, Max Wolf. (The members of Wolf's household figure prominently in the names for his asteroids, but the reasons behind most of them have been lost. One name of this kind that is documented is (468) Lina, named after his housemaid.) Another pet dog gave its name to (2474) Ruby, the asteroid discovered in 1979 by the dog's owner, the Czech astronomer Zdeňka Vávrová, (3364) Zdenka. The reference to the pet in *Alice in Wonderland*, asteroid (6042) Cheshirecat, tests the boundaries of the IAU's rule.

These pet names did not cause an incident, but in 1971 an asteroid was named (2309) Mr. Spock. This was not, as it at first sight appears, a name commemorating the fictional Vulcan first officer on the Starship Enterprise in the film series of *Star Trek*. If this had been the case, it would probably have been acceptable. Mr. Spock was the name given to a pet cat who was also "imperturbable, logical, intelligent, and had pointed ears," according to the asteroid's discoverer and pet-owner James B. Gibson, (2742) Gibson, an astronomer then at the Yale-Columbia Station at El Leoncito, Argentina. Gibson was making a point about the unsuitability and triviality of many names that have been given to asteroids in recent years, especially those named after people who had contributed nothing to astronomy, less, he thought than his cat, who had accompanied him on some of his moves from observatory to observatory and given him and his wife companionship, from Connecticut through South Africa to Argentina. In this he was echoing the views of Brian Marsden, (1877) Marsden, Director of the Minor Planet Center: "I just like to see imaginative names. Most of the names submitted are terribly boring." Astronomer Tom Gehrels, (1777) Gehrels, did not see the joke about Mr. Spock. At the IAU meeting in 1985 in New Delhi he complained bitterly, and the IAU issued guidance discouraging the naming of asteroids after pets.

Of course, being a Vulcan, Spock is not Mr. Spock's real name, which is Xtmprsqzntwlfb, according to Dorothy Fontana, the "Star Trek" script editor. She has explained: 'Of course, the formal Vulcan language is not written with English letters. As in Hebrew, Arabic, Chinese and so on, the phonetic rendering has nothing to do with the written language.' Mr. Spock's real name written in Latin characters is realistically reckoned as unpronounceable, and according to one of the other IAU rules, it would be ineligible as the name of an asteroid.

Astronomers are scientists, and scientists like numbers. So some asteroids' names are based on their numerical designations and catalog numbers, such as (24680) Alleven and (13579) Allodd. Subtler connections with their numbering are provided by asteroids (9007) James Bond and (8380) Tooting. Bond is the fictional Agent 007 in Ian Fleming's thrillers. Tooting is a suburb of London, whose postcode is SW17; the designation of the asteroid before its orbit had been defined was 1992 SW17. It was discovered in September 1992, by Henry E. Holt, (4435) Holt, at Palomar Observatory, and émigré Englishman Brian Marsden of the Minor Planet Center recognized the post code and suggested the name. The name of (9669) Symmetria was also suggested by its permanent number, which is both palindromic (reads the same when reversed) and is the same when each pair of digits is rotated by a half turn. (3142) Kilopi has a designation number that is 1000 times "pi," the mathematical ratio of the circumference of a circle to its diameter. Perhaps the name most like a cryptic crossword clue is (2037) Tripaxeptalis, christened by Paul Wild. Its number, 2037, factors as 3×679 and also 7×291. To decipher the clue you need to know the names of asteroid (679) Pax and (291) Alice.

Paul Wild, (1941) Wild, was a Swiss astronomer. (His name is pronounced "VildtW, and he is not to be confused with J. Paul Wild, the Australian radio-astronomer and solar physicist.) As a young man he worked on galaxies and supernovae at the California Institute of Technology, but as time passed his interests returned to the Solar System. He was director of the Astronomical Institute of the University of Bern, Switzerland, from 1980 until 1991, working at the Zimmerwald Observatory and discovering a number of comets, 49 supernovae and 94 asteroids. One of his comet discoveries, 1978 XI, P/WILD 2, was also known as 81P/Wild and was visited by the Stardust mission. The spacecraft flew through the comet's tail, collecting samples of the dust on sticky gel, and returning it to Earth for laboratory analysis. Wild was renowned for his subtle play with the numbers and names of his asteroids. He named (6475) Refugium, which he discovered in 1987, with the Latin word for a refuge. Such a facility might have come from examining the prime factors of $6475 = 5 \times 7 \times 37$ and looking at those numbers for the corresponding asteroid names: (5) Astraea, justice; (7) Iris, the rainbow; and (37) Fides, faith and honesty.

Another mathematical curiosity is (6765) Fibonacci. The most important work of the twelfth-century Italian mathematician Leonardo Fibonacci was to introduce Arabic numerals into Europe to replace Roman numerals, but he is most often remembered for "Fibonacci numbers." In his book *Liber Abaci*, Fibonacci posed the question of how the population of rabbits would grow. He assumed that a pair of rabbits can mate at the age of 1 month, when the female will produce another pair of rabbits. His rabbits were assumed not to die, and every pair was supposed to produce a new pair every month. How many pairs will there be after a given period of time? The answer for the population at the end of every month is known as the Fibonacci sequence, in which the first number is 1, with each subsequent number the sum of the previous two. The sequence runs as follows: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597, 2584, 4181, 6765… Asteroid 6765 thus has a Fibonacci number and is appropriately named for the mathematician.

(2029) Binomi is named after a non-existent mathematician, the purported inventor of the binomial theorem. The asteroid was discovered in 1969 by Paul Wild and is five ahead of (2034) Bernoulli, a dynasty of genuine mathematicians, including Daniel, who co-founded hydrodynamics. According to Wild, a student, on being asked when Binomi lived, suggested that he had been a contemporary of Newton, a response that became notorious around the university. A few years later another student, on being asked when Bernoulli lived, immediately answered: "I'm not going to fall into the trap; it is well known that the man never existed!"

(20461) Dioretsa is a name that looks like the name of an obscure female, mythological character, but which refers to the asteroid's defining characteristics. The name is the word 'asteroid' spelled backwards, because the asteroid orbits backwards against the mainstream of the rotation of the Solar System (anticlockwise as seen from the North Pole). The name of (3200) Phaethon also refers to its orbit.

MYRIOSTOS: KILO-ASTEROIDS

The name of (513) Centesima commemorates the 100th planet discovery by Max Wolf in 1903. Perhaps it was this name that kicked off the tradition of naming the 1000th, 2000th, and so on up to 10,000th asteroid with a special celebration (Table 6.1). With the sky-rocketing numbers of minor planets that modern techniques have discovered, minor planet number inflation set in, and the celebrations were reduced in frequency to every 5000, then every 10,000 minor planets, then every 50,000 and in the future perhaps every 100,000.

It had originally been proposed that the number 10000 should be given to Pluto, on the grounds that Pluto was the first known member of the "Trans-Neptunian Belt" or "Kuiper Belt." A vote gathered overwhelming support for this proposition, and the Small Bodies Names Committee was in favor, but in 1999 the Committee "…had a rather sudden change of heart following agitation by a group of planetary astronomers, mainly located in the United States [the American Astronomical Society's Division for Planetary Sciences]. Acting on this sudden decision, the International Astronomical Union Secretariat announced on Feb. 3 that the Small Bodies Names Committee had 'decided against assigning any Minor Planet number to Pluto'…" In the next chapter, we see how the IAU executed a complete U-turn, and termed Pluto a special sort of body called a dwarf planet, and designated it with a number, 134340.

Table 6.1 Kilo-asteroids

(1000) Piazzia was named after Giuseppe Piazzi, the astronomer who discovered the first asteroid
(2000) Herschel was named after William Herschel, discoverer of the first telescopic major planet
(3000) Leonardo was named for Leonardo da Vinci (1452–1519), the Italian painter and Renaissance man
(4000) Hipparchus was named for the greatest astronomer of ancient times
(5000) IAU was named after a vote by astronomers with an interest in asteroids and comets for the International Astronomical Union, the international association of professional astronomers
(6000) United Nations (=1987 UN), named also by vote and proposed for this asteroid on the basis of the letters UN of the provisional designation
(7000) Curie was named in memory of Marie Curie, the only person to receive Nobel prizes for both physics (1903) and chemistry (1911), and for her husband Pierre Curie, who shared the Nobel prize for physics with her and Henri Becquerel
(8000) Isaac Newton was named for Isaac Newton, hailed by some as the greatest universal genius of all time
(9000) Hal was named for the computer HAL 9000 in Arthur C. Clarke's novel; it "serves to this day, more than three decades later, as an icon for artificial intelligence and a beacon that has motivated an incalculable number of careers in computing, computer science, electrical engineering and space exploration"
(10000) Myriostos. "The Greek word for ten-thousandth, Myriostos honors all the astronomers, past and present, from all around the world, professional and amateur, observer and orbit computer, who participated, over an interval of 198 years, in the achievement of accumulating 10,000 minor planets with orbit determinations of the highest quality"
(15000) CCD. "A charge-coupled device, a two-dimensional array of light-sensitive microelectronic semiconductor capacitors, is used as an imaging detector. With its high sensitivity and stability, the CCD has almost completely replaced the photographic emulsion and photomultiplier as the detector of choice in quantitative scientific work"
(20000) Varuna. "Varuna is one of the oldest of the Vedic deities, the maker and upholder of heaven and earth. As such he is king of gods and men and the universe, and he has unlimited knowledge"
(25000) Astrometria. "Utilized in star cataloguing that brought the discovery of (1) Ceres, then for two centuries by means of micrometry and photography, astrometry with CCD cameras began flourishing vigorously in the 1990s, through all-sky surveys and in the hands of dedicated amateurs, now doubling minor-planet numberings in less than 2 years"
(50000) Quaoar. "Quaoar is the great force of creation in the diverse myths of the Tongva, the indigenous people of the Los Angeles basin. Quaoar has no form or gender and dances and sings Weywot, Sky Father, into existence. Together, they create Chehooit, Earth Mother, and the trio bring Tamit, Grandfather Sun, to life"
(60000) Miminko. "Miminko is a Czech word that expresses the unique stage of innocence at the beginning of human life"
(100000) Astronautica. "This minor planet is being named Astronautica to recognize the 50th anniversary of the start of the Space Age, inaugurated by the launching of the first artificial earth satellite on October 4, 1957. The name is associated with this significant number, as space is defined to begin at an altitude of 100,000 m above Earth's surface"

HERSCHEL: THE WORD "ASTEROID"

Immediately after the first asteroids, Ceres and Pallas, had been discovered, the question arose of their nature. Ceres was a "moving star," so it was Piazzi's immediate reaction to call it a "planet," although he realized that that was a bold conclusion. Although he could scarcely believe it, he wanted it to be true. The first indications from the details of its orbit tended to confirm the designation of "planet"—its orbit was very similar to other planets and it fitted among them. Olbers took the same view about Pallas, but Bode took some extra convincing. The fact that two planets moved in nearly the same orbit was new and un-planet-like.

William Herschel took a track that started to home in on a third feature of planets—not on what a planet does or the company it keeps but what it is. This was a natural line for him to take. He thought in a way that was consistent with the optical quality of his telescopes and his method of using them, looking at anything in the sky to discover its nature. He laid the foundation for the discussion of 2003 by the International Astronomical Union about whether Pluto was a planet or not. His foundational achievements in planetary science, especially his discovery of Uranus (which he saw immediately to be non-stellar, thanks to the optical quality of his telescope), were commemorated with the name of asteroid (2000) Herschel.

When Herschel examined Ceres and Pallas with his large telescope, he could see no discs. The planets must be small; Herschel estimated that the diameter of Ceres was 162 miles (258 km), of Pallas 80 miles (130 km). These measurements were a factor of four or five too little, but nonetheless the new planets were indeed unusually small.

In 1802, in a paper read to the Royal Society of London, Herschel tried to classify Ceres and Pallas. Were they really planets? Herschel listed the properties of the seven major planets known to him, Mercury to Uranus:

1. They are celestial bodies, of a very considerable size.
2. They move in not very excentric [sic] ellipses round the sun.
3. The planes of their orbits do not deviate many degrees from the plane of the earth's orbit.
4. Their motion is direct [anti-clockwise as seen from the north pole].
5. They may have satellites, or rings.
6. They have an atmosphere of considerable extent, which however bears hardly any sensible proportion to their diameters.
7. Their orbits are at certain considerable distance from each other.

Herschel concluded that Ceres and Pallas, failing to meet any of these criteria save for the fourth, were not planets. Perhaps they were comets? Herschel listed the properties of comets:

1. They are celestial bodies, generally of a very small size, though how far this may be limited is yet unknown.
2. They move in very excentric ellipses, or apparently parabolic arcs, round the sun.
3. The planes of their motion admit to the greatest variety in their situation.
4. The direction of their motion also is totally undetermined.
5. They have atmospheres of very great extent, which shew themselves in various forms of tails, coma, haziness, &c.

Ceres and Pallas failed the second and the last criteria, and did not show the typical characteristics of the third and fourth, so they were not comets. Herschel concluded that Ceres and Pallas were members of a new class of object, and gave the new objects a new name:

> *Since, therefore, neither the appellation of planets, nor that of comets, can with any propriety of language be given to these two stars, we ought to distinguish them by a new name, denoting a species of celestial bodies hitherto unknown to us … they resemble small stars so much as hardly to be distinguished from them, even by very good*

> *telescopes. It is owing to this very circumstance, that they have been so long concealed from our view. From this, their asteroidical appearance, if I may use that expression, therefore, I shall take my name, and call them Asteroids; reserving to myself, however, the liberty of changing that name, if another, more expressive to their nature, should occur. These bodies will hold a middle rank, between the two species that were known before; so that planets, asteroids, and comets, will in future comprehend all the primary celestial bodies that either remain with, or only occasionally visit, our Solar System.*

On May 22, 1802, William Herschel wrote to Piazzi on this subject, proposing the term asteroid, since these small planets are comingled with the stars. Ceres was not worthy of the name planet since it did not occupy the space between Mars and Jupiter "with the proper dignity." Herschel envisioned a hierarchy of planets, asteroids and comets. He put the positive spin on his proposal, to make it more palatable to Piazzi:

> *Moreover, if we were to call* [Ceres] *a planet, it would not fill the intermediate space between Mars and Jupiter with the proper dignity required for that station. Whereas, in the rank of Asteroids it stands first, and on account of the novelty of the discovery reflects double honour on the present age as well as on Mr. Piazzi who discovered it. I hope you will see the above classification in its proper light, as so far from undervaluing your eminent discovery it places it, in my opinion, in a more exalted station. To be the first who made us acquainted with a new species of primary heavenly bodies is certainly more meritorious than merely to add what, if it were called planet, must stand in a very inferior situation of smallness.*

Piazzi was not entirely impressed with this ranking scheme. He scribbled a note on Herschel's letter: "Soon we shall also be seeing counts, dukes and marquesses in the sky!"

Some astronomers liked the new term; some did not. Wilhelm Olbers, the discoverer of Pallas, concurred with Herschel: "I agree with you, honoured Sir, in your sagacious suggestion that Ceres and Pallas differ from the true planets in several respects, and the name asteroid seems to me to fit these bodies very well."

Karl Friedrich Gauss disagreed, however, writing to Olbers: "Mr. Herschel also gave me information on his "Asteroids." What surprises me is (1) that he doesn't announce it as being a modest proposal, but rather says simply "I call them," and (2) that his reason in Ceres' case consists in that it now "is out of the zodiac." That shows a very biased and, it seems to me, unphilosophical outlook.

Pierre Laplace was in the "no" camp: "As to the name that you have given to these stars, I can't yet see sufficient reason to discard the name 'planet.'"

Piazzi had an alternative in mind, replying to Herschel's letter: "As for the description, can we not call the small planets 'planetoids'? Because, I confess to you, the name "asteroids" seems to me more appropriate for small stars?"

Herschel was forcefully criticized by some for what appeared to be an attempt to belittle Piazzi's discovery, and by an ill-natured, anonymous editor of *The Edinburgh Review* for complicating the composition of the Solar System by inventing an unnecessary category with "a new and uncouth name." The critic is thought to have been Henry Peter Brougham, a Scottish lawyer who eventually rose to office in the national government, reaching the rank of lord chancellor. A precocious young man with broad interests, including natural sciences, he was elected a Fellow of the Royal Society at the age of 25. He was a very active writer for *The Edinburgh Review*, with an iconoclastic, lively, controversial and sometimes abusive style. He wrote about science, often writing satirical and sometimes wrong-headed reviews of significant work. One scientist who had reason to be angry about his treatment was Thomas Young, whose pioneering work on the wave nature of light was dismissed; this contributed to the fact that few of Young's books were sold and were little read.

The Edinburgh Review alleged that Herschel had devised the word "asteroid" so that the discoveries of Piazzi and Olbers might be kept on a lower level than his own discovery of Uranus. We can see the same reaction to the re-classification of Pluto from a planet to a dwarf planet in 2006: the change of classification was called a downgrading, and a number of people were offended. So far as the allegation of bad faith made about Herschel, many scientists would have been much offended at this contemptible insult, but Herschel merely remarked that he had incurred "the illiberal criticism of *The Edinburgh Review*," and that the discovery of the Asteroids "added more to the ornament of our system than the discovery of another planet could have done."

Herschel's suggestion of the word "asteroid" was picked up rapidly in the United States, and was always used in the US Naval Observatory, and the US *Nautical Almanac,* but did not catch on very quickly in other countries, even Britain where the word originated, and even by William Herschel's astronomer-son, John Herschel, who ignored the word until 1849 and even then used it sparingly.

Europeans on the whole preferred the phrase "minor planet." According to the *Oxford English Dictionary,* it was first recorded in use in Britain by the astronomer Stephen Groombridge, (5657) Groombridge, in 1823 and picked up by the British *Nautical Almanac* in its volume for 1845, published in 1841. In 1854, by which time there were 33 asteroids, the phrase *kleine Planeten* started to be used in the *Astronomische Nachrichten*. In 1866 Paris Observatory astronomers started to use the phrase *petites planetes*, at first allowing the first four asteroids their names without any classification. The International Astronomical Union, founded in 1919 and dominated for most of the twentieth century by European members, institutionalized the phrase "minor planets" by establishing a study group called "Commission 20 on the Positions & Motions of Minor Planets" and an institute to keep track of them, the Minor Planet Center. It was only with the beginning of the space exploration of the Solar System, led by NASA, and the consequent explosion of data about and interest in asteroids, that the term "asteroid," as was mentioned had been commonly used in the United States, became commonly used by Europeans in parallel with the phrase "minor planet."

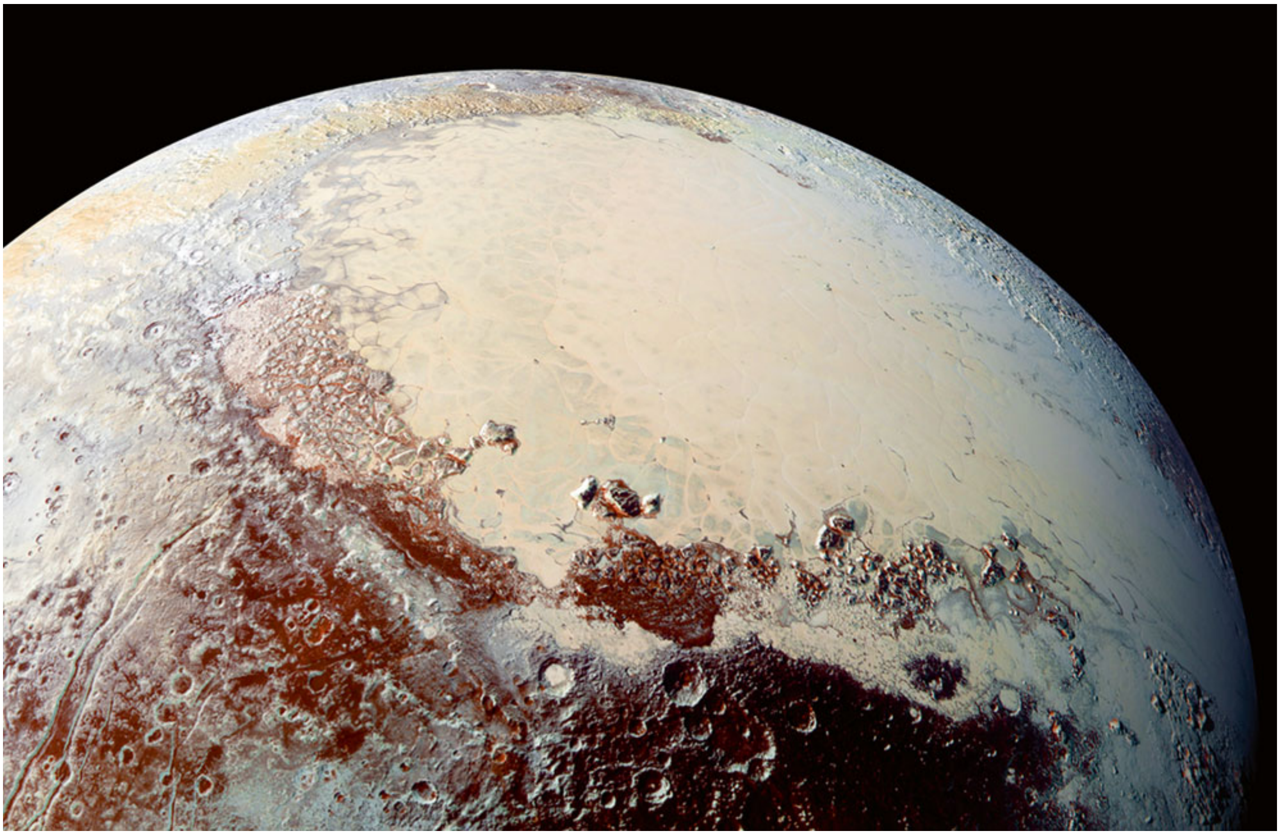

Fig. 7.1 Pluto seen by the New Horizons spacecraft. The bright expanse is the western lobe of Sputnik Planum, covered in nitrogen, carbon monoxide and methane ices (NASA/JHUAPL/SwRI)

Chapter 7

At the Edge of the Solar System

OORT: THE FINAL FRONTIER?

Comets must have formed and remained at low temperatures. That is why they still have a high content of solid but volatile substances such as water and carbon monoxide. They must therefore have been made in the outer regions of the nebula disc that formed around the newborn Sun, and which produced the Solar System. The outer regions of this zone are far from the warmth of the Sun, so comets that formed there remained icy.

Some comets are orbiting very far away, perhaps still in the place that they formed. Others may have formed somewhere further in towards the Sun, but still cold, say somewhere near Uranus and Neptune, and have been disturbed by the movements of the planets and ejected outwards, beyond Neptune to where they are now. Many comets would have been kicked out of the Solar System entirely. But those that just failed to break free now orbit in a cloud around the fringes of the Solar System called the Oort Cloud, after the Dutch astronomer who first suggested it, Jan Hendrik Oort, (161) Oort.

Oort inferred the existence of the Oort Cloud, the source of the long-period comets, by looking at how far away comets come from and the way their orbits are oriented. Some comets have long, thin orbits. They appear, as if from nowhere, getting close enough to see as they track in through the outermost planets. They must have originated from somewhere further away than that, and eventually they swing around the Sun and go back there. Their periods are very long; in fact many have such long periods that astronomers have seen them only once in centuries. This again indicates how far away they live. Their orbits point out from the Sun in all directions so the region where they live must be spherical, centered on the Sun. Oort's vision was that there was a swarm of slowly moving, cold comets in a far-flung cloud on the perimeter of the Solar System. If a comet was disturbed from its orbit there by the passing of a star or a massive cloud of gas in its journey around the Milky Way Galaxy, past the Sun, the comet would plunge down directly towards the Sun on a long, thin, highly elongated elliptical orbit, oriented at a direction inwards from the spherical cloud.

The Oort Cloud is hypothetical. It has never been seen.

Other comets have short periods (less than or about 30 years) and only ever come from directions that lie in the plane of the Solar System. They come from somewhere nearer than the Oort Cloud, a disc-like zone that extends outwards from the orbit of Neptune. They come from the Kuiper Belt, and a thicker zone that surrounds it called the scattered disc. How did the comets get there? Some comets from the Oort Cloud could be perturbed on their infall and become members of the Kuiper Belt. The minor planet 2008 KV42 is a trans-Neptunian object (TNO) moving around the Sun backwards in an orbit that is almost perpendicular to the orbits of the planets. Its odd inclination and backwards motion suggests that it made a transition from the Oort Cloud to become a TNO on its way

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_7

to being a comet. Other comets might have found their way directly into the Kuiper Belt and the scattered disc from closer in, moved there from interactions with the major planets of the Solar System, and are hanging about there like sullen teenagers with nothing to do, waiting around before they fall in towards the Sun, on their way back home.

1992 QB1: THE FIRST CUBEWANO

The Kuiper Belt is the zone of the minor planets that orbit beyond Neptune. It was an idea before its existence was verified. The US astronomer Frederick Leonard was the first to mention the idea in a publication in 1930 for amateur astronomers. It was little read and overlooked completely by professional astronomers. Leonard's idea was simply that there was no reason why the Solar System ended at Pluto, and there might be similar planet-like bodies further away.

Irish amateur astronomer Kenneth Edgeworth, (3487) Edgeworth, laid out the idea clearly in papers that he wrote in the late 1940s, again largely overlooked by the professionals. He put some meat on the bare bones of Leonard's idea by pointing out that any bodies this far from the Sun would be moving in their orbits very slowly and would be widely spaced. They would not have had many opportunities to agglomerate into planets, so they would be small as well as cold.

American professional astronomer Gerard Kuiper, (1776) Kuiper, was the first person to put forward the idea of the Kuiper Belt in a way that was noticed, at a symposium in 1951. Hence, perhaps not entirely justly, it is his name that is attached to it. His line of reasoning was similar to Edgeworth's, but he added that Pluto would have perturbed any small bodies in that zone and flung them out of the Solar System. The discoverer of the first recognized member of the Kuiper Belt, David Jewitt, (6434) Jewitt, has pointed out that "the name is unfortunate, in that Kuiper … anti-predicted the belt by specifically asserting that the region where we found objects would be empty." Some people recognize the injustice to Edgeworth by calling this region the Edgeworth-Kuiper Belt. But like the Titius-Bode Law, the better known astronomer through whose activities the concept became known got his name on it rather than the originator of the concept. Minor planets or comets in the Kuiper Belt are called Kuiper Belt objects (KBO's), or TNO's, without prejudice as to what their nature might be—rocky, like asteroids, or icy, like comets.

The basic argument of all these astronomers was simple and similar: there is no reason why the Solar System should end abruptly at Neptune and Pluto, so what lies beyond? The idea has good foundation in the modern theory about the way the Solar System was formed.

When the Sun condensed out of its parent gas cloud, it became surrounded by a rotating disc-like structure, called the solar nebula. The nebula extended well beyond the distance of Neptune. Planets started to form in the dense inner regions. The dust grains in the nebula jostled and collided and stuck together, building up into big lumps. As the lumps orbited through the nebula, they created turbulent wakes that brought dust together in eddies. Eventually, the lumps grew into such a size—planetesimals—that they attracted smaller lumps to infall. The planetesimals grew by accretion to become large planets.

Large planets could not form beyond Neptune, because everything moves so slowly out there that collisions in which smaller bodies stuck together to grow to bigger ones were very infrequent. There was time only for small planetesimals to grow there, in the trans-Neptunian region. Because it is so cold, planetesimals in those distant regions are ice-rich minor planets, or they are comets. Because these regions are so far from the Sun, sunlight is weak. Because the trans-Neptunian regions are far from Earth, the weak sunlight, reflected in small quantities from the small planetesimals, is difficult to see. All the reasons work together to explain why no TNO's were known in 1987, except for Pluto, just beyond Neptune, with a status that was not properly recognized.

In 1987, David Jewitt of the University of Hawaii increasingly asked himself why the outer Solar System was so empty. Does the Solar System really stop at Neptune and Pluto? With astronomer Jane Luu, (5430) Luu, he set out on a search for things out there, using the same technique used by Wolf to find asteroids and Tombaugh to find Pluto, of repeated imaging of an area of sky to find moving "stars." In the electronics era, however, they used electronic techniques—CCD imagers instead of photography. And to find the moving stars they switched the images rapidly from one to another on a computer monitor, not in an optical-mechanical machine like a blink comparator.

The distinctive characteristic that they were looking for was that the moving stars were to be slow moving; indeed their project was called the Slow Moving Objects (SMO) survey. Why was this important? Because the minor planets they were looking for are very far away and orbiting slowly around the Sun, and their apparent motion is primarily due to Earth orbiting the Sun, overtaking them on an inside track.

It was an unpopular project. An astronomer gets access to a telescope by making a proposal to the institution that operates the telescope, saying what he or she will do. The proposal is judged by fellow astronomers—how feasible is it to make the observations that are proposed and how important would the outcome be? The proposals judged the best get assigned some time to use the telescope, typically a few nights, or a few nights at regular intervals throughout a season. Jewitt and Luu found it hard to get access to national telescopes, such as ones run by NASA, because their project was judged to have a low chance of success. Anyway, what would be the importance of a few solid bits and pieces so far away?

But then Jewitt and Luu were able to use a new CCD camera on the University of Hawaii's 2.2-m (86-in.) telescope on Mauna Kea. They had put together the ingredients for success: a more sensitive CCD, a camera able to search a larger area, and a telescope on a clearer site, to which, as University of Hawaii astronomers, they had good rights of access and could follow their instinct for what they considered to be significant. Even to access this telescope they had to resort to subterfuge to carry out their SMO survey. In Jewitt's autobiography, written as he accepted the Kavli Prize for astrophysics in 2012 (awarded jointly to Jewitt, Luu and Michael Brown), he confesses that "under false but necessary pretences, I obtained time for other projects and then used it for the survey. Similarly, NASA rejected my proposals to fund the work, so I diverted money allocated for other purposes to maintain the SMO survey, possibly illegally. This went on for years."

The subterfuge paid off. In August, 1992, after a 5 year search using successively more powerful CCD cameras, they found the first member of the Kuiper Belt. Jewitt writes that when people ask about a career in astronomy, he says that for him "Astronomy is an obsession, not a career. And they ask how best to do research in astronomy, as though I am some sort of an expert. But I am not. Everything I do, no matter how simple, feels to me like a new thing for which I am unprepared and which I know I will get wrong many times before I get it right. 'Success is the ability to go from one failure to another with no loss of enthusiasm', Churchill brilliantly observed."

The first Kuiper Belt object was cataloged like a minor planet as 1992 QB1. Its orbit is well known, and it has a number, (15760), but it has never been given a name, although Jewitt and Luu gave it a nickname, "Smiley," after the fictitious British spymaster George Smiley in John Le Carré's spy novels. It is always referred to as "QB1," and objects like it are called Cubewanos. They orbit in near-circular orbits in the same plane as the orbits of the major planets. QB1, however, is not planet-sized; it is asteroid-sized at about 160 km (100 miles) diameter and is likely an embryo planet that never grew up—a planetesimal, in other words. Over 1500 Kuiper Belt objects are known as of 2015, all of them smaller than our Moon. They are a varied lot of minor planets, with colors more diverse even than the Main Belt asteroids. They must have come from many different places and have had varied histories.

ORCUS AND IXION: PLUTINOS

About a quarter of the TNOs discovered by Jewitt and Luu, and others, have the same special relationship with Neptune as Pluto, unable to break away even if they wanted to! Pluto orbits in the 2:3 resonance with the planet Neptune. What that means is that it makes two revolutions around the Sun in exactly the time that Neptune makes three. If Pluto strays from this by getting a bit ahead or a bit behind, it gets pulled back into line, so it has gotten locked up in the resonance. It has been joined by other TNOs, which all have the same relationship with Neptune. Pluto is thus the prototype of a group of TNOs called “plutinos.” (28978) Ixion is one, and there are many others.

(90482) Orcus is also a plutino, but it orbits in the opposite sense to Pluto; this means that Pluto is closest to the Sun at the time that Orcus is furthest, and vice versa. (90482) Orcus is the anti-Pluto. It has a small moon, Vanth.

Others TNOs occupy different resonances with respect to the orbit of Neptune. As well as the common group of 2:3 resonant objects, there are some in the 2:5, 3:5, 4:7 and 1:2 resonances. The latter have been called “twotinos.”

The University of Arizona theorist Renu Malhotra, (6698) Malhotra, has studied the origin of the plutinos and the other resonant TNOs. She has shown that the most likely reason there are so many is that Neptune has migrated outwards from its birthplace. As Neptune pushes out and gets into resonance with a TNO, it gathers it up, herding the TNO along as it migrates out further. Eventually it has gathered up a horde of resonant TNOs. This is one of the central features of the so-called Nice simulation of the early history of the planets, which we outline later.

Plutinos are thus TNOs that have been herded together like a flock of sheep by Neptune and remain controlled by it; by contrast, some other TNOs have broken free from the flock and now roam free everywhere. They have been randomized by Neptune. At some time these TNOs passed close to Neptune. Its gravitational effects pumped up the eccentricity of their orbits to large values, so that their orbits have become inclined to the orbit of Neptune by some tens of degrees. They are called “scattered Kuiper Belt objects.” Their fate is not a good one. They will be progressively loosened from the attraction of the Sun and leak away further into space as time goes on, eventually becoming interstellar asteroids or comets.

The origins and histories of the KBOs are very varied, one of the reasons why they are such a motley collection of objects. The variety shows now in the structure of the Kuiper Belt. It is thick, more like a doughnut than the sheet of paper that could represent the inner part of the Solar System inside Neptune. The thick part is populated with the scattered KBOs. The shape of the Kuiper Belt shows that it is a rough-and-tumble neighborhood. It has experienced a violent past, some of its members flung into wide-ranging orbits. Even now some are still leaving the neighborhood, banished from the Solar System entirely. It also has a violent present, with its members sometimes falling into the Solar System, and showing up as comets, progressively melting in the heat of the Sun.

QUAOAR: OBJECT X

Since 2001, several TNOs much larger than QB1 have been discovered in the distant reaches of the Kuiper Belt, including some that are as large as or larger than Pluto. The largest of all have been discovered by a team led by

Michael Brown, (11714) Mikebrown, of CalTech. His search was deliberately targeted at the big TNOs, with the aim of discovering what at the time would have been the tenth planet, after what was then reckoned the ninth, Pluto. His work was in one sense counter-productive in that what he succeeded in doing was not to add more planets to the list; he removed one planet, Pluto, from the list. In another more important sense, of course, his work was highly successful in that it brought about a new understanding of the Solar System.

Brown's main scientific motivation in looking for big things was to be able to study their nature. Because the largest TNOs reflect the most sunlight they are the brightest TNOs. The brighter something is the easier it is to use telescopes to analyze what it is made of. Of course, even the brightest TNOs are distant, so they are never very bright, and would have to be examined with very large telescopes. But CalTech operates a number of telescopes, including big telescopes on Mount Palomar in California and the Keck Telescopes on Mauna Kea in Hawaii, which are among the very biggest in the world, as well as being located on a site renowned for the astronomical quality of its sky. If he found the tenth planet with the telescopes on Mount Palomar, he could follow it up in detail on Mauna Kea.

The usual characteristic of a population is that big things are rarer than small things. So you have to search a large area to find them. CCD cameras record a small area, because CCDs are small. But they are sensitive. Jewitt and Luu's survey for TNOs was a long search over a relatively small total area of sky for faint minor planets, brilliantly successfully. Brown at first took a different tack, to search a relatively large area, even if not as sensitively, for the very largest, rarest objects.

Starting in 1997, Brown used very large photographic plates—thin glass sheets, 14-in. square, coated with sensitive photographic emulsion. He used them as the detectors in a telescope on Mt. Palomar that had been designed and built to image a large area of the sky. The photographs were then scanned into digital form and compared for moving stars by computer software. His search covered an area of sky oriented along the zodiac where the orbits of the other large planets are concentrated, but because photography is not as sensitive as CCDs, it was low sensitivity. He and his team spent the first 3 years completing the search and not finding what he was looking for. The largest TNOs were too small and/or too far away to be recorded by this old detector technology.

In 2000, Brown and Chad Trujillo, (12101) Trujillo, a young colleague whom Brown had recruited into the CalTech team for the purpose, started to repeat the search using a new type of CCD detector that could see stars or planets that were two or three times fainter than could be seen on the photographic plates. It could not image as large an area of sky on a 14-in. photographic plate, but developments in CCD technology meant that it was larger, more sensitive and quicker than the CCD detectors available earlier in 1997, and so in combination better than photography. They repeated what they had done before by photography. The new technique meant that they were able to search the same area as before in a few months rather than 3 years. But they still found nothing. They decided to widen the search area outside the immediate area of the zodiac. This paid off. Trujillo made his first discovery of a large TNO in January 2002. Minor planet (55565) 2002 AW197 (so far, it has no name) proved to be about 700 km (450 miles) in diameter, so it was not as large as Pluto, about one third its diameter.

However, in June 2002 Trujillo walked into Brown's office and announced "We've just found something that is bigger than Pluto." It was elating news, but, exciting though the news was, it proved not to be 100 % true. Trujillo and Brown referred to the new object at first as Object X, mimicking the Lowell Observatory search for Planet X. When examined closely with the Hubble Space Telescope and the Keck telescopes, Object X turned out to be highly reflective, so it was smaller than they had first estimated, about 1200 km (750 miles) in diameter, about half the diameter of Pluto. They searched out some old photographs of the sky and found Object X on two pictures taken in 1983. This helped tie down the orbit, which is near-circular and is tilted by 8°, a large angle compared to the other planets, but not as much as Pluto at 17°. Pluto orbits the Sun with a period of 246 years, Object X with a period of 288 years. Continuing the tradition of naming objects in the Kuiper Belt after creation deities, but moving to New World mythologies, Brown and Trujillo chose Quaoar (pronounced "Kwawar) as the name for minor planet (50000).

Brown was ignorant of the IAU procedure to name planets, and he did not seek any kind of approval for the name Quaoar; he just went ahead and called it that. Since he had followed the naming convention, the Committee on Small Body Nomenclature (CSBN) had no objections and approved the name retrospectively. Brown was relieved that he did not have to argue about the name with this body in the International Astronomical Union, and concluded that no one cared much about the procedure. When he found and named his next large TNO, he found that he was wrong.

The next large planet found by Brown and his team was (90377) Sedna. Brown was very pleased that it came even closer to challenging Pluto as the ninth largest planet, but Sedna was one of the agents of its own demise as a planet, taking Pluto with it.

SEDNA: EXOTIC AND EXCENTRIC

At the end of 2003, Brown had the opportunity to work with one of the first truly large-scale CCD cameras. He seized the chance. "The camera was, in many ways, an improvisation," he has written, in an autobiographical essay when he was awarded the Kavli Prize in 2012. "It used large numbers of cast-away detectors to assemble itself into what was, for most of a decade, the largest—and possibly most difficult to work with—digital camera in the world. But this quick start paid off. By using the

[48-in., 1.2-m, Samuel Oschin] telescope nearly every single night for 8 years, we covered nearly the entire sky and found nearly every bright object in the Kuiper Belt there was to find."

Brown's technique was to take pairs of pictures with the camera and compare them to star-like images, moving at the expected speed of distant TNOs. The problem with the detectors in the camera was that they had large numbers of defective areas that fooled the software into thinking irregularities generated in the camera were moving stars. Each candidate moving star had to be looked at, and there were tens of thousands, too many to cope with. Brown figured out how to blank off everything from the worst-affected areas. He would not be searching the whole of the area that was imaged, but he would have the software reliably search 90 % of the area. This reduced the number of candidates to about 100, a feasible number to inspect individually by eye. The CalTech Wide-Area Survey observed a strip of an area of the sky that could be seen from California, about half the sky aligned along the zodiac, where most minor planets orbit.

In the very first night, Brown found a TNO, but it was not very big. Several more routine new discoveries followed. But then, in November 2004, Brown spotted a new TNO that he could immediately see was very far away. This was obvious because it was moving so slowly between the exposures. The further away a planet is the slower it actually moves around the Sun, and moreover, the slower it seems to move as a result of the reflection of Earth's motion. It is the same reason that, although nearby trees flash past the train window as seen from a moving express train, a distant, slow, cargo train running on a parallel track seems to crawl. The new planet was 100 AU away—100 times as far from the Sun as Earth is. 100 AU is two and a half times the distance that Pluto is from the Sun. To be visible at that distance, the new object had to be big. The immediate suspicion was that this was the long-sought tenth planet.

As with Quaoar, Brown sought out and found some old pictures so that, with the extended time interval and arc of the orbit that would be covered, he could calculate the orbit. It was extraordinary. The planet takes 11,400 years to orbit once around the Sun, moving as far as 937 AU from the Sun, approaching as close as 76 AU, in a highly eccentric orbit, over ten times as long as it is broad. The orbit was almost comet-like.

It had taken some time for Brown to be able to establish the fundamental properties of the minor planet. In order to be able to refer properly to this important new planet when it was announced in his scientific paper, Brown named it before the usual time had passed to establish its orbit definitively. (Of course, with a period of 11,400 years, it will be some time before this task is complete.) His name for minor planet (90377) was Sedna, after the Inuit goddess of the sea, who lives at the bottom of the Arctic Ocean. Apart from the suitability of the name for a cold planet, Brown chose the name because it was pronounceable, learning the lesson from Quaoar, the only word in the English language with the letters 'uaoa' in sequence. But he jumped the gun again, and publicly announced the name which he had chosen before getting approval from the International Astronomical Union's Committee on Small Body Nomenclature (CSBN).

This stirred up a hornet's nest, not only at the IAU but in a sector of the astronomical community, principally the active amateur (and some professional) astronomers of the Yahoo internet forum, the Minor Planet Mailing List (MPML). They felt that Brown had bulldozed his way past the procedures, helped (as they saw it) by the arrogance and might of NASA. One of the people who had taken offence tried to forestall the name Sedna by proposing to name a routine asteroid by that name; if this was done, it would not have been possible to have a second body with the same name because of the confusion that would cause. This suggestion was rejected by the CSBN on the grounds that the name Sedna, as a goddess, should be reserved for an important minor planet. The secretary of the CSBN, its main administrator, Brian Marsden, came in for almost as much personal abuse from some members of the MPML as Mike Brown. One of the most uncompromising critics was the German amateur astronomer, Reiner Stoss, (7689) Reinerstoss, a talented and hardworking observer and discoverer of asteroids. The name of asteroid Reinerstoss rightly pays tribute to his scientific work, but the nomination did not mention diplomatic skills.

The issue was not only whether procedures had been followed in giving a name to a minor planet but also at what stage a discoverer should make public a discovery. On the one hand, the discoverer has an obligation to make the discovery public so that it can be investigated, confirmed and followed up by other scientists, for example to determine its orbit and other properties. On the other hand, the discoverer will want to be sure of his or her facts, so that the announcement will not be misleading or damaging to a reputation. This tension is all the more acute because of the general public interest and media attention that would result from the discovery of a large planet. Sedna has a diameter of 1000 km (600 miles) or so. The original estimate of 1800 km (1100 miles) was rather close to Pluto's diameter, and would certainly have generated public interest. The estimate was revised down when Brown and his team took time to examine the object with the Hubble Space Telescope and the Keck Telescope. Even if not as large as Pluto, Sedna is still a substantial body.

There has been an active debate about Sedna's origin. The exceptional fact about Sedna that stands out is its highly eccentric and highly inclined orbit. Two interesting possibilities are that Sedna might have been tugged into its current orbit by a passing star, possibly a star in the cluster in which the Sun was originally born. Another even more outlandish theory is that Sedna is an exotic planet, in the same sense that the word is used in botany and natural history, meaning that it did not originate from the neighborhood where it is found. For example the flocks of parrots that fly over southwest London are exotic, being an Australian species, escaped from an aviary. Likewise the rabbits that populate both Britain and Australia are exotic, having escaped from breeding colonies when brought in with the Norman and the British colonialists, respectively. Sedna may have been passed into our Solar System from another planetary system, lost by a passing star.

The discovery of Sedna raised the question of whether the tenth planet of the Solar System had been found, and this question was turned back to a discussion of what constituted a planet. In the debate over this issue, the status of Pluto was in question, as it had been for some years, but with an outcome that had been unresolved, or at least unarticulated. Members of the public took an interest in the issue, as did space scientists working on space missions to that world. The forum for the debate was the International Astronomical Union, which meets infrequently, with a debating and decision-making structure that is opaque. It all dragged on for far too long.

HAUMEA: THE DISPUTED PLANET

Brown had found Sedna because it moved, but it was far away so it moved slowly. It was so slow moving that its image in two successive pictures were close together. When the pictures were compared, the images only just made it through the software to be offered up by the computer as a candidate minor planet. Brown started to think that he had set the bar too high. Perhaps he could tweak the software with which he analyzed his pictures to make it possible to be more discriminating against unmoving stars but make it easier to identify slowly moving minor planets. Perhaps this would identify even more slowly moving minor planets than Sedna, which were even further away. The advantage that he now had was that he had the real data on which the software had to work, and he could fine-tune it to be as discriminating as it could be. He made the changes. Around Christmas 2004, he ran all of his old data through the new software. This threw up the brightest slow-moving minor planet he had seen.

Following his discovery up with the Keck Telescope on Mauna Kea and the Gemini Telescope in Chile, Brown and his team found that the minor planet varies in brightness with a period of 4 h. It is elongated, like Kleopatra, alternately presenting its small sides and its large sides towards us. Moreover it has two satellites, circling it with periods of 18 and 49 days. This makes it possible to determine the mass of the minor planet, and even, because the moons pass across the minor planet, the inner one in particular, its size. It is $2000 \times 1500 \times 1000$ km ($1200 \times 930 \times 620$ miles) in dimensions, or about 60 % of the diameter of Pluto. It is 30 % of Pluto's mass. Its satellites are 170 and 310 km (105 and 190 miles) in size, respectively.

The shape of the minor planet is very surprising, given how big it is. At that size astronomers would expect that the heat that was trapped from the time that it first formed and the inner heat from radioactivity, released over the planet's lifetime, would have plasticised its body so that it settled down into a spherical shape. Something must have happened recently to make it so misshapen.

The minor planet itself is icy rock; its moons are even icier. Moreover, as Brown's Ph.D. student Kris Barkume first realized, it is accompanied in its orbit by a family of about ten small, icy minor planets, the largest of them 250–350 km (150–220 miles) in size. It seems likely that the strange shape, the moons and the minor planet's family are the result of a recent glancing blow by another minor planet, which broke off icy fragments from Haumea's outermost layers.

The IAU's CSBN accepted the designation (136108) Haumea for the minor planet. Haumea is the Hawaiian goddess of childbirth and fertility, representing also the birth of the land as stony lava. Like Ceres, Haumea is the patron goddess of her volcanic home island. The larger of the two moons is called Hi'iaka, who was born from the mouth of Haumea and carried as an egg to Hawaii by her sister Pele, the goddess of fire, lightning and volcanoes. Hi'iaka danced the first hula and is the patron goddess of the island of Hawaii. The smaller moon is called Namaka, a water spirit, born from the body of Haumea, sister of Pele. When Pele sends her burning lava into the sea, Namaka cools the lava to become new land.

The discovery of Haumea was the subject of an ugly dispute over priority. While he made and organized further observations to elucidate its nature, Brown delayed publishing his identification of the minor planet from Christmas 2004 until July 2005, when he and his team published the abstract of a contribution they were going to make to a conference in Cambridge, England, in September. The object was identified in the abstract by a code number that the team had used, generated on the occasion when it was identified by the computer and never to that point used publicly. The same number had been used in observation logs filled out by Brown's team at telescopes when they observed the object in the first half of 2005. In July 2005, a student of the Spanish astronomer, José Luis Ortiz Moreno of the Instituto de Astrofísica de Andalucía, found Haumea in pictures that the Spanish team had made in March 2003. At the end of July, the Spanish team read Brown's abstract and wondered if this object was the same as the one they had found. They looked for the code number on the Internet and found the log of the California team's observations in Chile of the object. The log was publicly accessible at the website of the telescope, for the benefit of the users of the telescope. Recognizing the competition, the Spanish team immediately communicated with the Minor Planet Center. In their follow-up work they found images on old pictures. They arranged for Reiner Stoss to follow up their discovery so that the orbit could be as well determined as possible. They told the MPC about their additional work.

Ortiz and his team thus became the first group to announce the discovery of Haumea. Brown has accepted that this is so, but has also voiced suspicions about how much the Ortiz group used his team's observations in making the discovery. News media reported the dispute, with openly nationalistic views being expressed and, with repetition, becoming entrenched. Haumea is a Hawaiian deity; the Spanish astronomers counter-proposed that the minor planet should be given the name of an Iberian goddess.

The CSBN took a long time to come to a conclusion about who to credit with the discovery and what to call the minor planet. In fact it took 3 years. In September 2008, the IAU gave a diplomatically ambiguous resolution to its discussions, agreeing on Brown's proposed name of Haumea and listing the date and location of the discovery as March 7, 2003, at the Sierra Nevada Observatory, not CalTech; it did not state the name of the discoverer. "It's deliberately vague about the discoverer of the object," Brian Marsden was quoted in news reports as saying. "We don't want to cause an international incident."

No one was completely happy about the dispute and its outcome. The MPML Internet forum exploded with unconstrained ire, verbal abuse and paranoia about conspiracies. Marsden remarked that the controversy was the worst priority dispute since Simon Marius claimed the discovery of the satellites of Jupiter from Galileo Galilei and named them. Galileo is recognized as the discoverer of Jupiter's satellites, but Marius's names are used for them, a similarly ambiguous resolution of that dispute. Ortiz is reported as saying "I am not happy, I think the decision is unfortunate and sets a bad precedent." Brown remarked "I think this is as good a resolution as we'll get."

ERIS: THE TENTH PLANET AT LAST?

Within a few days of finding Haumea, Brown discovered, at last, a planet larger than Pluto. It was 120 AU away and three times brighter than Pluto would be at that distance. It had come to light almost 1.5 years after the data were obtained.

At first, Brown's team referred to the planet as "Xena," the quasi-mythological Warrior Princess in a TV drama series. They chose it because the name started with an X (echoing with Planet-X, the name by which Pluto was identified during its search at Lowell Observatory), and because the team wanted to name more minor planets in the Kuiper Belt after female deities. Brown had been criticized when he named Sedna without waiting for the official process to go through the IAU Committee on Minor Planet Names, and was keeping his informal choice private. He also wanted to keep it quiet until he had it nailed down, due to his growing conviction that it was larger than Pluto and therefore could be regarded as the tenth planet.

Brown's team imaged "Xena" with the Keck telescopes in Hawaii, using a camera able to adapt the shape of its lenses and mirrors to compensate for the blurriness of Earth's atmosphere (a technique described earlier). "Xena" has a moon. It orbits its parent planet in 16 days. Brown's team referred to the moon as "Gabrielle," the fighting companion of Xena, the Warrior Princess. The moon made it possible to calculate the mass of "Xena." It proved to be 1.27 times the mass of Pluto. It is 2330 km in diameter, a bit larger than Pluto. If its orbit and size make Pluto a planet, "Xena" is a planet, too.

In July 2005, Brown published an abstract of a talk that his team would be giving at the Cambridge astronomical meeting in September, also referring to the discovery of Haumea by a code number. Alerted by this, NASA officials wanted to know about it, so that they could release the information to the press. The officials were excited by the size, and by the possibility that the new object was the tenth planet. Then Ortiz released his own estimate that the earlier object, Haumea, was bigger than Pluto. The press reacted to this announcement with excitement, although Brown knew that Haumea was only 30 % of the mass of Pluto. It started to dawn on Brown that a retraction would have to follow. The press would be confused, and the credibility of Brown's announcement about "Xena," that it was indeed larger than Pluto, would look as if astronomers were repeatedly crying wolf. As the priority dispute about Haumea escalated, and Brown realized that his observation logs were compromised, he decided not to risk the same problem surfacing with "Xena." He called in the CalTech press office. In the course of a discussion about Haumea, Brown "inadvertently" let the core of the discovery of "Xena" slip prematurely to a reporter from the *New York Times*, with the "Xena" name.

It came time to consider the formal name to propose for "Xena." This object had to have a dignified name, standing on the same level as the other large planets. Brown considered Persephone, the wife of the god Pluto, but an asteroid with this name already exists: (399) Persephone. He got a colleague to correlate lists of asteroids and classical gods and goddesses to see which names had not been used. The list was short and the names were mostly obscure. But one stood out. Eris is the Greek goddess of strife and discord, reflecting the heated debate over the nature of this planet, Brown's earlier discoveries, and Pluto. "Xena" became (136199) Eris.

Eris is a dwarf planet. Its size has been accurately measured by watching it pass across a star, timing how long that took. On November 6, 2010, Eris occulted (hid) a faint star in the constellation Cetus. It was not easy to predict exactly from where on Earth the occultation would be visible, and 26 observing stations worldwide were tasked to follow Eris at the predicted time. Three telescopes in Chile, two at San Pedro de Atacama and one at La Silla saw the star wink off and on. Effectively these events define the shadow of Eris on Earth. The planet is very nearly spherical and its diameter is 2326 km (1445 miles).

After the name Eris had been accepted by the IAU, the moon was named Dysnomia, after the Greek goddess of lawlessness who was Eris's daughter; Brown chose the name to echo the name of his wife, Diane.

PLUTO: DWARF PLANET

While all these discoveries were going on, and astronomers gathered more information about the Trans-Neptunian objects (TNOs) and the Kuiper Belt, features of the ninth planet Pluto became clearer. It was no longer seen to be in an orbit that was uniquely different from the rest of the bodies. There were other objects like it in similar tilted, eccentric orbits, near and beyond Neptune. It dawned on astronomers gradually that Pluto was more like other TNOs than other planets. In a renovation in the year 2000, the Hayden Planetarium created an influential display with a model of the Solar System with the Sun and eight planets. Pluto was not represented in the model; it was described in a separate panel as a TNO, not as a planet.

The proposition that Pluto was not a planet caused a public backlash, particularly in the United States. It is not easy to articulate why the general public would have been so concerned about this scientific issue, and there must have been an emotional dimension. Was it that Pluto was the only planet that had been discovered by an American? Was it that it has a name that had come to have cuddly overtones, due to the Disney cartoon dog, Pluto? Was it sheer conservatism, especially by school students who had recently invested effort in learning the names of the nine planets through amusing mnemonics?[1]

No less intense was the reaction of some space scientists involved in the exploration of the far regions of the Solar System and Pluto. No one wanted the object of their effort apparently humiliated by being downgraded. How would it be explained to Congress investigating whether the US taxpayer's money had been spent wisely on a space mission whose object had diminished status? Scientists were concerned that although the New Horizons space mission to Pluto was already under way, the funding for it could be stopped. The scientific argument to continue was that Pluto was now not the smallest and least significant planet; it was the largest and most important of the Kuiper Belt objects. But of course, that meant embarking on a difficult conversation about a rather technical sounding issue in astronomy. The conversation would get off to a rough start by having to explain what those KBO thingies were.

For Mike Brown, the issue of whether Pluto is a planet came to a head when he had to talk about his own discoveries. Should he describe Quaoar, Sedna, Haumea and Eris as planets? To the people that he talked to, they were planets. They moved in orbits around the Sun, and thus fulfilled the classical definition of the word. Brown knew that asteroids do the same, but, following Herschel's line of argument in 1802, it had been accepted that they are not in themselves really like the main planets; comets also do the same and they are certainly not like the main planets. Likewise the main planets are not really like Quaoar, Sedna, Haumea and Eris. And if they were not planets, then nor was Pluto, in spite of 70 years' use of the English language in which Pluto had been described as one.

Normally in the history of science, a similar issue would not have had a clearly expressed decision articulated on a specific occasion. Like the discussion on the nature of the minor planets that were first discovered between Mars and Jupiter, the issue would have been discussed in individual scientific papers, as Herschel did for asteroids. Some astronomers would have expressed different shades of opinion, as Piazzi and Bode did, and other astronomers would have followed the terminology that they found most convincing. Respected leaders of the astronomical community would have provided their summary of the problem, perhaps in lectures, review articles or text-books. A consensus would have emerged. However, in the argument over Pluto, the issue became political, and the discussions found their way to the International Astronomical Union as a result of the union's position in the naming of minor planets. In the naming conventions, planets and minor planets (and indeed comets) are treated differently, so the IAU needed to come to a decision for practical reasons.

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[1] "My very elegant mother just served up nine pizzas" is the version often taught in British schools to help learn Mercury, Venus, Earth, Mars, Jupiter, Saturn, Neptune and Pluto in order. "Men very easily make jugs serve useful nocturnal purposes" less so.

No consensus emerged spontaneously, so the IAU set up a committee to recommend what to do. It was a large committee. In 2005, this committee put forward three properties that, in addition to the fact that it orbits the Sun, define a planet, but without making a choice. The informal conclusion would be that a planet is a planet if enough people say it is. The formal conclusion would be that a planet must be an object large enough to make itself spherical (unlike comets, or all asteroids but one). For this definition, size matters, and planets would all be over about 400 km (about 300 miles) in diameter, depending on what they are made of. The dynamical conclusion would be that the object must also be large enough to cause all other objects eventually to leave it alone in its orbit, either by absorbing them or ejecting them.

The first committee had analyzed the problem but had found it difficult to develop a consensus about which route to follow. Perhaps the larger a committee, the more difficult it finds it to make a decision on a finely balanced issue. A smaller, second committee was appointed to come to a conclusion. In 2006, the IAU proposed that:

> *A planet is a celestial body that (a) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (b) is in orbit around a star, and is neither a star nor a satellite of a planet.*

Pluto, Ceres and Eris would have been considered planets under this definition, possibly other bodies. Pluto's largest satellite Charon posed a problem, since it was not literally in orbit around Pluto. Both Pluto and Charon orbit around their common center of gravity, which, because Charon is massive and close to Pluto, lies inside Pluto's orbit. Pluto and Charon would be deemed as a double planet. There were other difficulties and further discussion took place intended to solve these.

The matter came to a head at the IAU General Assembly in Prague in August 2006. Unusually, this scientific matter was decided by a vote. In science, unlike in democratic politics, the majority does not have the last word on a subject. Science is decided by argument and the consensus as it changes over time. The Latin motto of the Royal Society of London expresses this. It is "Nullis in verba," which translates as "Words mean nothing." What counts is the science. The IAU's General Assembly lasts two weeks and there were several passionate debates in the main meetings and in specialist breakout groups, giving time for the temperature to rise. The proposal that was put rather autocratically to the first General Assembly by the IAU President Ron Eckers was seen as a take-it-or-leave-it ultimatum by some astronomers and was rejected. The proposal was reworked and put in stages to the General Assembly on the last day of the meeting. It passed by a large majority. I was one of the attendees who assented, and I have to admit that, in part, I was motivated by wanting to see an end to this process. It had been both protracted and with aspects that were intractable, but it needed to be resolved. We astronomers were in danger of looking even more foolish than we were, like medieval theologians arguing about the degrees of angels.

The IAU decided that planets and other bodies in the Solar System, except satellites, should be classified into three distinct categories in the following way:

> *A "planet" [the eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune] is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighborhood around its orbit.*

The classification is distinctive because it relies on three separate criteria, each of a different nature, to work in combination to form one definition. We can readily understand the first criterion, about a planet's orbit, because it is what we have always thought was the main property of a planet. The second criterion is about the structure of a planet—basically, that it is massive enough to settle down, balancing its internal structure under its own force of gravity, into a spherical world. This is also readily understandable because it is essentially the reason why planets look like we expect, although there might be some difficulties in calculating exactly what is going on. There is some difficulty in being sure that the planet is in hydrostatic equilibrium.

The significance of the last criterion is that at the end of the process that forms a planet, it will have "cleared the neighborhood" of its own orbital zone, either absorbing or ejecting other bodies of comparable size (other than its own satellites). Pluto has not done this, because it orbits in company with other "plutinos." This part of the definition of planet is rather unsatisfactory, because it relies on a theoretical hypothesis about the distant past. We might believe this is what happened, but the statement is not readily verifiable. The statement is even more uncertain than deciding whether a given planet-like body is really in hydrostatic equilibrium.

The second category of Solar System bodies consists of dwarf planets:

> *A "dwarf planet" is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite.*

The third category is "everything else":

> *All other objects [these currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies], except satellites, orbiting the Sun shall be referred to collectively as "small Solar System bodies."*

At the same time that it developed these criteria, the IAU noted that Pluto is a "dwarf planet" by the above definition and is recognized as the prototype of a new category of Trans-Neptunian objects, which it later termed "plutoids." Plutoids were defined as celestial bodies in orbit around the Sun at a distance greater than that of Neptune that have sufficient mass for their self-gravity to overcome rigid body forces so that they assume a hydrostatic equilibrium (near-spherical) shape, and that have not cleared the neighborhood around their orbit.

As a consequence of all this, the asteroid Ceres was recognized as a dwarf planet. Pluto was demoted from "planet" to a "dwarf planet," indeed a "plutoid." However, it joined an exclusive group of other dwarf planets in the Solar System: Ceres, Haumea, Eris and a fifth, discovered by Mike Brown's team, (136472) Makemake, shown by José Luis Ortiz, from observations made in 2012 as it blocked the light of a distant star, to be nearly spherical at 1430 km across in one direction and 1500 km in the other (890 × 930 miles). We just used the word "demoted" for the change that was made to Pluto. The word is emotional—how can there be a ranking order of status in natural objects? But no doubt it expresses how many thought, and certainly it was how the change was reported in the press. Pluto was assigned a minor planet designation, as (134340) Pluto.

Many astronomers remain unhappy at the process and this set of definitions. Their feelings are well summed up by Dave Jewitt and Jane Luu:

> *Unfortunately, in the "what is a planet" debate, the IAU trapped itself between the irreconcilable positions of the [American] public, which was overtly interested in having the IAU pronounce Pluto a planet, and of the astronomers, most of whom were more interested in clearing the air by reversing a seventy-six-year-old mistake. Worse, the IAU allowed its deliberations to drag on, mostly in secret, for years, so magnifying the impression that a weighty and complicated scientific issue was under study. They could have, and should have, declared that Pluto was first and foremost a big [Kuiper Belt Object], and that calling it a planet was an unhelpful and ultimately unjustifiable matter of public relations and planetary politics, not science. Instead, they waffled, struggling for years in a doomed quest to find a compromise that would keep all sides happy. While the IAU in the end reached the right decision (except for the unnecessary invention of the "dwarf planet" class), the public perception of the process, and of astronomers and astronomy, has been soiled. Millions of people now think of astronomers as having too much time on their hands, and as unable to articulate the most basic definitions or clear problems in a coherent way. Even the nature of science was muddied: do scientists really make progress democratically, by voting, as they did on the status of Pluto? Should we vote on the value of the gravitational constant? None of this is good for astronomy.*

The definition that has been adopted mixes the nature of planets with their orbital characteristics and their formation history. Some of, perhaps all of, the parts of the definition are arguable and are inherently uncertain. We could see this debate revived soon, as this topic returns to the traditional and well-tested methods by which science understands the natural world.

Meanwhile other allied topics in planetary science marched on. While the IAU was debating definitions and trying to arrange the planets into them in 2006, a spacecraft, New Horizons, was passing Mars, heading through the Main Belt of asteroids towards Jupiter and on towards Pluto. It made its closest approach to Pluto in July 2015 and flew on into the Kuiper Belt. On its flyby, it carried out a fully automated scientific exploration of Pluto with cameras and other measuring equipment, storing the data in on-board memories. When the pace of the data-gathering had slowed as the planet was left behind, the spacecraft turned its attention to the job of transmitting the data back to Earth. This process took a long time because the radio connection between New Horizons at Pluto and NASA's receiving stations on Earth is so weak. The distance is large, the radio transmitter on board the spacecraft has to be small and cannot be powerful, and the receiving antenna, although the largest that can be made, is nonetheless not as sensitive as everyone would like. The data is taking more than a year to download in its entirety.

Still, what New Horizons has already shown us was a complete surprise. The surface of Pluto is covered with water-ice and consists of a wide variety of terrains, from mountain ranges, cratered areas, dunes and smooth plains (Fig. 7.1). Areas on the equator have large craters, formed by asteroid impacts early in the history of the Solar System. But the largest smooth plain, Sputnik Planum, has no craters on it at all and must have been recently smoothed over, with craters that have been covered by whatever flowed over the surface. The plain is covered with dunes of ice crystals. Glaciers flow in the valleys in the mountains around the plains (Fig. 7.2). The colors of the surface features change from place to place, indicating a range of chemical composition—different organic compounds in the ice. This may be some sort of clue as to the origin of the different geological structures.

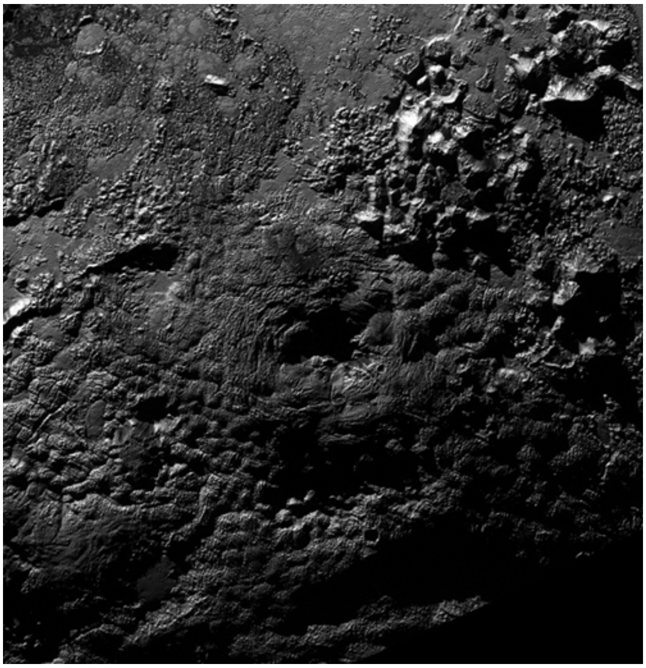
It is not known what has caused the development of Pluto's surface. There are signs that Pluto's major satellite, Charon, has a surface that is equally active, with a split where the surface has been torn apart (Fig. 7.3). Do these two distant Trans Neptunian Objects have tectonic forces? If so, where does the energy come from? The ice-volcanoes of Pluto are vents that run down into the source of the energy in its interior (Fig. 7.4).

Pluto has a tenuous nitrogen and methane atmosphere with a surface pressure at roughly 1/100,000 that of Earth's. To the casual eye, its sky looks black because its air is so thin, but there is a slightly blue ting to the faint residual light of its sky, its atmosphere layered with soot-like chemicals called tholins, created by the action of ultraviolet light from the Sun on the methane in the atmosphere. The chemicals filter down onto the ground and cover it in a hydrocarbon frost. As a world to live on, Pluto would be like a high mountainous plateau in an industrial, smoky Antarctica in midwinter.

Fig. 7.2 Mountains and icy plains on Pluto. A mosaic from the New Horizons spacecraft shows a strip 80 km (50 miles) wide, which moves (left to right) from the edge of "Badlands" northwest of Sputnik Planum, through the al-Idrisi mountains, across a "shoreline" and onto its icy plains, with strange pits and fragmented polygonal sections (NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)

Fig. 7.3 Charon. Pluto's largest moon, 1214 km (754 miles) in diameter, is a world of mountains, canyons and landslides. Its water-ice covered surface is divided at the equator by a striking geological fault line, creating a system of canyons that extends around the entire world. The color anomaly at Charon's north pole indicates that it is active, emitting gases that condense into the red stain (NASA/JHUAPL/SwRI)

Fig. 7.4 Ice Volcanoes on Pluto. Wright Mons is a mountain about 160 km wide (100 miles) and 4 km (13,000 ft) high. Its summit is a crater (center) approximately 56 km (35 miles) across. This mountain could be a cryovolcano, an eruption, not of magma as in a typical volcano on Earth, but of ices from beneath Pluto's surface (NASA/JHU/SW RI)



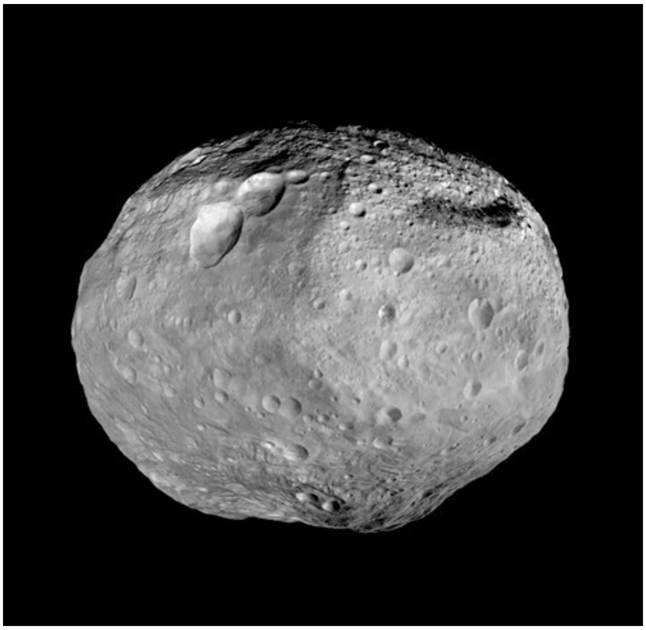


Fig. 8.1 A mosaic of images from the Dawn spacecraft shows Vesta in 2011–12. A mountain twice as high as Everest towers above the horizon at the south pole. Three craters overlap in the upper-left of the image (see Fig. 8.2) (NASA/JPL-Caltech/UCAL/MPS/DLR/IDA)

Chapter 8

Filling the Gap

KEPLER: MIND THE GAP!

The minor planets of the Kuiper Belt extended the Solar System outwards into space. But there had been an inner space in the Solar System, filled earlier. The first asteroids to be discovered, Ceres and Pallas, occupied a gap in the Solar System that had emerged when its structure first became clear, with the Sun in the center.

In 1543, in the very last days of his life, the Polish cleric Nicolaus Copernicus put forward his idea publicly in a book that the planets orbited the Sun, not Earth. It was an historic change in the way that we look at the universe, and like all great ideas it formed the basis of advances of knowledge on many fronts. It was particularly important for astronomers to have discovered the realistic structure of the Solar System. It became possible to map planetary orbits, to find out their exact shape and determine the distances of the planets from the Sun. As the detail of this map emerged Isaac Newton was able to develop the reason why the planets moved around the Sun, namely through the force of gravity.

The breakthrough in mapping the structure of the Solar System was made by the astronomer Johannes Kepler, (1134) Kepler, born in Tübingen in 1571 what is now Germany. Kepler was a curious mixture of a modern scientist and a medieval mystic. He learned astronomy from an early age, recalling in later life that he had been taken outside at the age of six to view the Great Comet of 1577. He studied theology at Tübinger Stift, a Lutheran seminary. As a student he had for taken a range of arts courses, and then philosophy and theology. He was inspired by one of his teachers, Michael Maestlin, (11771) Maestlin, to take up the sciences, astronomy, geometry and mathematics. But he was also attracted by the pseudo-science of astrology and cast horoscopes for credulous fellow students. He kept up this skill in later life, turning it to good advantage when he became the court astronomer in Prague, when, especially in times when his patron fell behind in paying his stipend, he cast horoscopes for the rich members of the court, including the Holy Roman Emperor himself. It was Maestlin who privately, outside his public lectures, introduced Kepler to the works of Copernicus, at a time when this was seen to be unsound theology. Kepler became a Copernican in his early 20s, committed to the view that it was the Sun at the center of the Solar System, not Earth.

Even before he had finished his studies in 1594, Kepler was invited to become a teacher of astronomy at a Protestant school in Graz in Austria. A great mathematician, Kepler was a poor lecturer, and the subject that he taught was not a popular one. He expected too much of his students, gabbled too much, and ventured down too many side streets away from the simple main road of the subject. His teaching was confused. Thus he attracted few students to his classes. But ideas incessantly bubbled up in his mind, and one summer's day in 1595 he had a brainwave about the

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_8

orbits of the planets. "There were three things in particular about which I persistently sought the reasons why they were such and not otherwise: the number, the size, and the motions of the orbits," he wrote in the Preface to his book *Mysterium Cosmographicum* (*The Cosmographic Mystery*), first published in 1596 with a second edition in 1621. In the book, he explained his brainwave, according to the title page of the book. It was "the Secret of the Universe: the Marvellous Proportion of the Celestial Spheres, and the True and Particular Causes of the Number, Magnitude, and Periodic Motions of the Heavens; Established by Means of the Five Regular Geometric Solids."

Thus, Kepler quite consciously set out to discover the plan of creation. On July 19, 1595, Kepler was preparing to teach a class in geometry. He drew a diagram on a blackboard of a large number of equilateral triangles within a circumscribed circle, which joined their corners. There was within all these triangles another circle inscribed within, touching the triangles' sides. He realized that the ratio of size of the two circles was the same as the ratio of the size of the orbits of Jupiter and Saturn. He wondered whether he could fit the orbits of all the planets with geometric figures—a triangle, a square, a pentagon, and so on. This did not work out. He tried the same thing with three-dimensional geometric solids, better representatives (he thought) of the planets as corporeal bodies. This idea proved to be more of a success.

Six planets were known to Kepler—Mercury, Venus, Earth, Mars, Jupiter and Saturn, and Kepler wondered why there were this number, rather than the seven planets that the ancients considered—Mercury, Venus, Moon, Sun, Mars, Jupiter and Saturn. Seven is a renowned mystical number; there are seven stars in the Plough or Big Dipper, seven stars in the Pleiades, seven days in Creation, seven deadly sins, seven wonders of the ancient world, seven colors in the spectrum, and so on. Astrologers and alchemists considered that the number seven was split into the spiritual three and the material four; the seven liberal arts were divided in the same way into the trivium and quadrivium of subjects, as taught in medieval universities (grammar, logic, and rhetoric and arithmetic, geometry, music and astronomy, respectively). Seven had a special place in the studies that Kepler would have made, but what was sacred about the number six?

Kepler found that he could fit simple, regular, geometric solids into the orbits of the planets, starting on the outside with a sixth solid sphere that represented the orbit of Saturn. He fitted a cube into the sphere, and within that fitted a second sphere that represented the orbit of Jupiter. Inside that sphere he fitted a tetrahedron, within which a sphere represented the orbit of Mars. Inside that sphere he fitted a dodecahedron (Earth), followed by an icosahedron (Venus), and, finally, the innermost sphere that represented the orbit of Mercury was fitted inside an octahedron.

These solids are known as the Platonic solids—regular solids whose faces are plane figures with equal sides: squares, equilateral triangle, etc. Mathematically, there are only five of them. Add a sphere and that makes

Table 8.1 Distances of the planets from the Sun

Planet	Distance from Sun (in terms where the distance of Earth from the Sun is 1.0)	Kepler's estimate from his geometric construction
Mercury	0.39	0.56
Venus	0.72	0.79
Earth	1.0	1.00
Mars	1.52	1.26
Jupiter	5.20	3.77
Saturn	9.54	6.54

six solids, which correspond to the six planets. The Platonic solids are called after the Greek philosopher, Plato, who wrote about them in his work of philosophy, *Timaeus*, but they were known long before him. They were especially important to Greek science because they became associated with what were thought to be the five elements from which everything was made: air, water, earth, fire and the ether. If the orbits of the planets were associated with the Platonic solids, it followed that celestial motions were directly connected with the elements.

With this geometric construction, Kepler estimated the distances of the planets from the Sun and found what he thought at first was an impressive fit. The planets orbited at distances from the Sun as shown in Table 8.1.

The goodness of the fit brought Kepler to tears. What had started out as an intellectual speculation had ended up at what seemed to hint at a profound truth. Planetary orbits, mathematical solids, universal elements—Kepler thought that he had discovered some fundamental, divinely inspired connection between mathematics, astronomy and the nature of the universe. He had glimpsed God's profound glory.

However, the geometric construction was not perfect. The agreement between the calculated and actual distances of the planets was not perfect. In fact, like many eureka moments that are viewed in the cold dawn after an evening's calculations, it was rather weak. It went a long way off track at the outer planets. Kepler was also struck by the gap between Jupiter and Mars, as well as the less striking gap between Venus and Mercury. Broadly speaking, the distances of each planet from the Sun were doubling up from one planet to the next, except that the distance to Jupiter was nearly a factor of four times that to Mars. Kepler wondered whether there were undiscovered planets there:

> *Between Jupiter and Mars I placed a new planet, and also another between Venus and Mercury, which were to be invisible on account of their tiny size, and I assigned periodic times to them. For I thought that in this way I should produce some agreement between the ratios, as the ratios between the pairs would be respectively reduced in the direction of the Sun and increased in the direction of the fixed stars… Yet the interposition of a single planet was not sufficient for the huge gap between Jupiter and Mars; for the ratio of Jupiter to the new planet remained greater than is the ratio of Saturn to Jupiter.*

Kepler had to reconcile the urge to populate the gap between Mars and Jupiter with further planets. Adding the sphere to the five Platonic solids brought the number to six, exactly the same as the sacred number of planets. To preserve this connection, Kepler thought that any extra planet had to be a lesser sort from the six major planets. This is why he suggested that the hypothetical new planet was small.

But Kepler rejected the thought that there were extra planets. If one extra, why not two? Or three? Or any other number? Kepler favored keeping his geometric construction, limiting the number of planets to 6, and the gap continued to pose a puzzle.

Kepler was also not satisfied with the completeness of the fit of the geometric construction shown in Table 8.1, and continued to seek further explanations, or laws, about planetary distances. Even in the book in which he proposed his geometrical construction he was thinking whether there was a relationship between the distances of the planets from the Sun and their orbital periods. In 1599 religious conflict was growing in Graz between Lutherans and Roman Catholics, and, a Lutheran, Kepler was preparing to leave Graz. He was invited to move to Prague by the Danish astronomer Tycho Brahe, and seized the opportunity, using Brahe's observations to show three foundational "laws" of planetary motion.

Brahe was a rich Danish nobleman who had the means to indulge in his eccentric interests. He kept a pet moose, which tragically died when, drunk, it fell down a flight of stairs. As a student he had lost most of his nose in a duel, and habitually wore a prosthetic one made of gold. More significantly, he devoted much of his energy to establishing his astronomical observatories, Uraniborg and Stjerneborg (both names meaning "Star City") on the Danish island of Hven. The enterprise was supported by the then king of Denmark, Frederick II, but when his successor Christian IV came to the throne in 1588, royal support began to dry up as Christian imposed an age of austerity in the national budget to compensate for Frederick's profligacy. Brahe's observing program began to run down and he looked for opportunity elsewhere. In 1597 Brahe moved to Prague to benefit from the patronage of Emperor Rudolf of the Holy Roman Empire, where he became imperial astronomer. Soon after Kepler had arrived, Brahe died in 1601 of retention of urine, having been too embarrassed to leave the table at a formal banquet and empty his bladder. Kepler inherited Brahe's papers and his measurements. Kepler pored over them, trying to understand better why God had made the Solar System as he had.

Isaac Newton addressed the same issues in letters exchanged with a classicist, Richard Bentley. In 1692 Bentley was appointed as the first Boyle Lecturer, whose duties were to give eight sermons about the relationship between Christianity and science. (This lecture series has continued, with gaps, to the present day.) In preparation for his lectures, which he entitled *A Confutation of Atheism,* Bentley studied Newton's view of the universe expressed through his physics, and asked him some hard questions. In reply Newton offered his explanation for the gap in the Solar System beyond Mars that Kepler had identified. In order to take care of his human creation, Newton said, God had separated Jupiter from the rest of the planets so that it would not disturb the motion of the Earth. Newton's letter survives in the library of Trinity College, Cambridge:

> *…the Planets of Iupiter & Saturn as they are rarer then the rest so they are vastly greater & contein a far greater quantity of matter & have many Satellites about them: which qualifications surely arose not from their being placed at so great a distance from the Sun but were rather the cause why the creater placed them at that great distance. ffor by their gravitating powers they disturb one anothers motions very sensibly as I find by some late Observations of Mr Flamsteed, & had they been placed much nearer to the Sun & to one another they would by the same powers have caused a considerable disturbance in the whole Systeme.*

The letter expresses, in Newton's own handwriting and spelling, his belief, held by few people today, that the universe has been constructed for human benefit.

As an astrologer as well as an astronomer, Kepler was inclined to numerological explanations within a religious framework; for example, he was convinced that the motions of the planets were connected to musical notes, and that the angels could hear "the music of the spheres." He tried a large number of calculations to find what was underlying the distances of the six planets. In 1618, Kepler had a flash of inspiration, which related the distance of each planet to the period of its orbit around the Sun. In what became known as Kepler's Third Law of Planetary Motion, he explained that "The square of the periodic times of each planet in orbit round the Sun are to each other as the cubes of the mean distances." Table 8.2 lists the periods and the distances; if Kepler's Law is exact then the ratio of the period-squared divided by distance-cubed should be the same for each planet—and it is.

Around the 1680s a number of people were able to explain the origin of Kepler's Third Law by supposing that the planets are attracted to the Sun by the force of gravity, provided that the force follows an inverse square law. Isaac Newton published the most comprehensive explanation in a book, known as the *Principia*, in which he set out his theory of gravity and dynamics. He successfully knitted together a large range of facts and laws that had seemed to that point arbitrary. The motion of the planets had inspired the discovery that everything in science was rational. The underlying idea was powerful. It was for example taken as one of the foundation stones of the French Enlightenment. We see the idea persisting in modern politics in the concept of "evidence-based policy."

Table 8.2 Kepler's third law

Planet	Period (P, year)	Average distance (R, AU)	P^2/R^3
Mercury	0.241	0.39	0.98
Venus	0.615	0.72	1.01
Earth	1.00	1.00	1.00
Mars	1.88	1.52	1.01
Jupiter	11.8	5.20	0.99
Saturn	29.5	9.54	1.00

TITIUS: ONE DEPARTURE FROM AN EXACT PROGRESSION

The Titius-Bode Law about the distances of the planets from the Sun is recognized as the discovery of Johann Daniel Titius, (1998) Titius. Titius was professor of physics at Wittemberg from 1756, and worked on thermometry and mineralogy, his work now all forgotten except for the law, or numerical rule, that he formulated. He was the translator into German of a work in French by the Swiss natural philosopher Charles Bonnet, published in 1764, called *Contemplation de la Nature*. The translation was rather free, and Titius inserted into the text several passages of his own, without, in the first edition, identifying them as such. In one passage about the Solar System, Bonnet says that "We know seventeen planets [and satellites] that enter into the composition of our Solar System; but we are not sure that there are no more", going on to anticipate more discoveries as telescopes improve. Titius then inserts what we now call the Titius-Bode Law:

> *For once pay attention to the width of the planets from each other and notice that they are distant from each other almost in proportion to their bodily heights increase. Given the distance from the Sun to Saturn as 100 units; then Mercury is distant 4 such units from the Sun, Venus 4 + 3 = 7 of the same, the Earth 4 + 6 = 10, Mars 4 + 12 = 16. But see, from Mars to Jupiter there comes forth a departure from this so exact progression. From Mars follows a place 4 + 24 = 28 such units, where at present neither a chief nor a neighbouring planet is to be seen. And shall the Builder have left this place empty? Never! Let us confidently wager that, without doubt, this place belongs to the as yet undiscovered satellites of Mars; let us add that perhaps Jupiter also still several around itself that until now not been seen with any glass. Above this, to us unrevealed, position arises Jupiter's domain of 4 + 48 = 52; and Saturn's at 4 + 96 = 100 units. What a praiseworthy relation!*

In this passage Titius speculates that there is a new planet between Mars and Jupiter, although he could not bring himself to call it a "chief planet," he predicted satellites of those planets, of which several had been discovered up to the time he was writing, in 1766. By the time of the fourth edition of the translation, Titius noted that the existence of a relationship and the gap had been pointed out earlier by Johann Lambert and Christian Freiherr von Wolf, although they did not give the relationship mathematical form.

BODEA: THE LAW USURPED

Titius published a second edition of his translation—with the new relation located in a footnote and signed—just as another astronomer, Johann Elert Bode, (998) Bodea, was sending to press the second edition of his introduction to astronomy, *Anleitung zur Kenntniss des gestirnten Himmels*, the first edition of which he had published in 1768 when he was only 19.

Bode had discovered the relationship as proposed by Titius and inserted it, unacknowledged, as a footnote in his text:

> *This last appears to follow from the entirely praiseworthy relation which the known six chief planets follow in their distances from the Sun. One calls the distance to Saturn 100, then Mercury is distant by 4 such units. Venus is 4 and 3 = 7. The Earth 4 and 6 = 10. Mars 4 and 12 = 16. But now comes a gap in this so orderly progression. From Mars out there follows a position of 4 and 24 = 28 parts, where up to now no planet is seen. Can one believe that the Creator of the universe has left this space empty? Certainly not. From here we come to the distance of Jupiter through 4 and 48 = 52, and finally Saturn's through 4 and 96 = 100 units.*

The parallels in the wording make it clear that Bode is following Titius, but he makes no admission of this, not even mentioning the man he was copying. However, it was Bode's promulgation of Titius' law that made it of interest to international astronomers and caused his name to be attached.

The modern form of the Titius-Bode law is formulated such that the distance from the Sun to Earth is 1.0 AU. In modern algebraic notation the Titius-Bode law is

$$a = 0.4 + 0.3 \times 2^n, \quad \text{for } n = -\infty, 0, 1, 2, 3\ldots$$

The law as constructed by Titius and Bode is given in Table 8.3.

Bode was pleased with the success of what came to be called Bode's Law, Titius being for a time forgotten. But Bode was profoundly disappointed that "no mention has ever appeared of this progression in the astronomical work of foreigners. Only German astronomers have mentioned it…" This changed in 1781 with the discovery by William Herschel of the planet Uranus, which proved by 1784 to be orbiting at a distance of 19.2 AU from the Sun. A new line could be added to the table (Table 8.4).

Table 8.3 Titius-Bode's law

Planet	n	2^n	0.3×2^n	$0.4 + 3 \times 2^n$	Compare
Mercury	$-\infty$	0	0	0.4	0.39
Venus	0	1	0.3	0.7	0.72
Earth	1	2	0.6	1.0	1.00
Mars	2	4	1.2	1.6	1.52
The gap	3	8	2.4	2.8	
Jupiter	4	16	4.8	5.2	5.20
Saturn	5	32	9.6	10.0	9.54

Table 8.4 Titius-Bode's law extended

Planet	n	2^n	0.3×2^n	$0.4 + 0.3 \times 2^n$	Compare
Mercury	$-\infty$	0	0	0.4	0.39
Venus	0	1	0.3	0.7	0.72
Earth	1	2	0.6	1.0	1.00
Mars	2	4	1.2	1.6	1.52
The gap	3	8	2.4	2.8	
Jupiter	4	16	4.8	5.2	5.20
Saturn	5	32	9.6	10.0	9.54
Uranus	6	64	19.2	19.6	19.2

This was remarkable: Bode's Law, which started as a numerological curiosity, had apparently proved to have predictive power. It is fitting that minor planet (998) Bodea is named after Johann Bode. But there was more to come.

ZACHIA: THE CELESTIAL POLICE

The man who set off a systematic search for the planets that filled the gap between Mars and Jupiter to overflowing was Baron (*Freiherr*) Franz Xaver von Zach, (999) Zachia. He was a doctor by training, being ennobled for his services at the court in the Hungarian city of Pest. He moved to Paris and London, where he entered the circles of astronomers such as Pierre de Laplace and William Herschel. On their recommendation he became the director of the Seeberg Observatory near Gotha, Germany, later of the observatory in Naples. He founded the journal *Monatliche Correspondenz zur Beförderung der Erd- und Himmelskunde,* which was the main medium for exchange and improvements in observation and data treatment of the first asteroids. He organized the first ever astronomical conference, in Gotha in 1798, where, among other topics, the attending astronomers discussed Bode's Law and the gap between Mars and Jupiter, and whether a planet might be found in it.

Zach himself started a search. He limited the area of the sky that he searched to the zodiac, the zone of the sky over which the planets move. As an aid, he produced a catalog of zodiacal stars, so that he could identify any interloper that had moved into the zone; but his search was without success. He did learn from this experience what a large task it would be to search the sky for the missing planet. In 1799 in Lilienthal, Zach founded an astronomical society, the *Vereinigten Astronomischen Gesellschaft* (the United Astronomical Society), from whom the idea of a coordinated program of several astronomers to find the missing planet emerged: "It was the opinion of these men of discernment, that to get onto the trail of this so-long-hidden planet, it cannot be a matter for one or two astronomers to scrutinise the entire Zodiac down to the telescopic stars."

On September 21, 1800, six astronomers from Zach's society met again in Lilienthal: von Zach himself; Johann Schröter, (4983) Schroeteria, the chief magistrate of Lilienthal; Wilhelm Olbers, (1002) Olbersia, a physician from nearby Bremen; and long-time collaborator with Schröter; Karl Harding, (2003) Harding, who was employed by Schröter; *Freiherr* Ferdinand Adolf von Ende, a local official; and Johann Gildemeister, a senator of the government of Bremen. They were concerned, though, that at six astronomers, they were still too few for the job, and decided to create what today we would term a task-force to tackle it. They decided to divide the zodiac into 24 equal zones, each 15 degrees square, and to found "an exclusive society" of 24 astronomers, one for each zone, to search for the planet that, they were convinced, filled the gap in Bode's law.

The zones were allocated one to each member by lottery. As Zach reported, "Each member was to draw up a very exact star chart including the smallest telescopic stars of his section, and through repeated revisions was to ascertain the unchanging state of his district, or every wandering celestial body. Through such a strictly organised policing of the heavens, divided into 24 sections we hoped eventually to find a trace of this planet, which had so long escaped our scrutiny, if it did exist and would make itself visible."

Von Zach, as secretary, sent out invitations to those not present to join the society, but who had been nominated for the task. From the metaphor that Zach used to describe the task at hand, they came to be known informally as the Celestial Police (*Himmelspolizei*). The 24 included very eminent astronomers from throughout Europe. For completeness the original six founder members mentioned above are repeated in Table 8.5. Of course, the list was notional. Only six of the 24 were present to agree to be part of the task force. The rest were listed without prior consent.

Letters were sent out to all of them more or less immediately, inviting them to participate. Some, like Lalande, declined because of the pressure of other work. In other cases, it is not clear that the letters got through to their intended recipient; there is no record in his extensive archives that William Herschel received such a letter, for example. Giuseppe Piazzi did not receive his letter, either. As we have already seen, his discovery of Ceres in the gap was completely independent of the formation of the Celestial Police.

Table 8.5 Astronomers invited to join the Celestial Police

Johann Bode (Berlin; 1747–1826)
Johann Huth (Frankfurt/Oder; 1763–1818)
Georg Klügel (Halle; 1739–1812)
Julius Koch (Danzig; 1752–1817)
Johann Wurm (Blauebeuren; 1760–1833)
Ferdinand von Ende (Celle; 1760–1817)
Johann Gildemeister (Bremen; 1753–1837)
Karl Harding (Lilienthal; 1765–1834)
Wilhelm Olbers (Bremen; 1758–1840)
Johann Schröter (Lilienthal; 1745–1816)
Franz von Zach (Gotha; 1754–1832)
Joseph Bürg (Vienna; 1766–1834)
Thomas Bugge (Copenhagen; 1740–1815)
Daniel Melanderhjelm (1726–1810)
Jons Svanberg (Uppsala; 1771–1851)
Theodor Friedrich von Schubert (St. Petersburg; 1758–1825)
Jean-Charles Burckhardt (Paris; 1773–1825)
Pierre Méchain (Paris; 1744–1804)
Charles Messier (Paris; 1730–1817)
Jacques-Joseph Thulis (Marseilles; 1748–1810)
Nevil Maskelyne (Greenwich; 1732–1811)
William Herschel (Slough; 1738–1822)
Barnaba Oriani (Milan; 1752–1832)
Giuseppe Piazzi (Palermo; 1746–1826)

Table 8.6 Titius-Bode's law filled in

Planet	n	2^n	0.3×2^n	$0.4+0.3\times2^n$	Compare
Mercury	$-\infty$	0	0	0.4	0.39
Venus	0	1	0.3	0.7	0.72
Earth	1	2	0.6	1.0	1.00
Mars	2	4	1.2	1.6	1.52
Ceres and Pallas	3	8	2.4	2.8	2.76
Jupiter	4	16	4.8	5.2	5.20
Saturn	5	32	9.6	10.0	9.54
Uranus	6	64	19.2	19.6	19.2

And although Olbers was a fully signed up member of the Celestial Police, his discovery of Pallas, the second minor planet to be discovered, was also fortuitous. It occurred while he was studying Ceres, not while he was searching his zone of the zodiac.

Ceres and Pallas orbit the Sun at a distance of 2.76 AU. They almost exactly filled the gap in the Bode-Titius law (Table 8.6). The Bode-Titius Law had made three successful predictions about the locations of undiscovered planets, Uranus, Ceres and Pallas.

There was some concern about the fact that two planets filled the gap at 2.8 AU, and they were small compared with the major planets that surrounded them. Bode in particular was very unhappy at the idea that there were two planets there. The second planet weakened his arithmetical progression. There was no room in his scheme for more than one planet in the gap. He resisted Obers' proposal that Pallas was a planet. "I consider it a very distant comet, maybe to be found beyond Ceres' orbit." Schröter, too, was sceptical: "Undoubtedly Pallas does not describe a circular but a parabolic orbit. In the strict sense it cannot be called a planet."

When Carl Gauss showed that the orbit of Pallas was similar to that of Ceres, Bode had to yield, and made the best of it: "Where I expected only one planet between Mars and Jupiter, two of them race around the Sun on equally sized orbits needing the same amount of time, and the beautiful progression of the distances of the planetary orbits remains intact."

In general in science, if some generality is proposed from which a prediction is made, and it turns out to be true, the law is regarded as having been increased in strength. Two successful predictions, and it could be regarded as confirmed. On this criterion the Titius-Bode law should be thought of as confirmed; it predicted Uranus and minor planets. But, in spite of this, the status of the Titius-Bode law remains controversial.

Some astronomers say the Titius-Bode law is mere numerology, and everything has been made to fit. The "law" is really just a "rule": it works but there is no meaning behind it. The arbitrary assumptions are several. Earth's orbit fits because we have chosen to scale all the distances to its distance from the Sun. Mercury fits because we have chosen to use minus-infinity for the first line of the progression, when according to the logic of the progression we ought to use $n=-1$, the integer that is next in the countdown series $n=6, 5, 4, 3, 2, 1, 0$. There are two more arbitrary numbers (0.3 and 0.4) in the formula. There is the problem of two planets, Ceres and Pallas (and indeed more than a million other asteroids!), occupying one level of the progression. If there were only four planets we could always make a formula like the Titius-Bode law fit the data, no matter at what distances they orbited. So what has the initial appearance of a powerful formula that fits the distances of eight (or nine or a million) planets really fits the equivalent of only four—not so impressive.

Other astronomers have been convinced by the predictive power of the Titius-Bode law. After the discovery of Uranus and Ceres, the law was held so firmly that it was used as a basis on which to build future work. For example, when Le Verrier was trying, successfully, to explain the perturbations of the orbit of Uranus by an unseen planet further out in the Solar System, he assumed in his calculations that it was at a distance of 38.8 AU from the Sun, the next in the progression of the Titius-Bode law, with $n=7$. His guess worked well enough to discover Neptune, although Neptune does not fit the law so well as the more inward planets. Neptune's actual distance from the Sun is 30.1 AU from the Sun, not 38.8.

Now that a number of extrasolar planetary systems have been found, it is starting to be possible to see whether the Titius-Bode law has the degree of universal applicability that would be convincing evidence that there is some powerful science behind it. In 2013, two Australian astronomers, Timothy Bovaird and Charles H. Lineweaver, studied 68 extrasolar planetary systems that have four or more planets and showed that all save three evidence something like the Titius-Bode relation. Is that significant? To this day, there is no convincing explanation of what might lie behind this fact. Is it the consequence of some regular feature arising from the way the planets developed from the formless nebula that swirled around the Sun at the start of the Solar System?

One problem with this idea is that planets migrate from their original positions, and may even swap their order out from the Sun, so their distances from the Sun do not exactly correlate with the point of their formation. Is the Titius-Bode law therefore the consequence of the dynamical interaction of a planet with its neighbors? Possibly. The jostling of the planets as they move around the Solar System, tugging and pulling at each other, might produce some regular patterns. A number of eminent astronomers have offered explanations of the Titius-Bode Law without a convincing theory having emerged.

The discovery of planets in orbit around stars other than the Sun has offered the possibility to discover a convincing demonstration that the Titius-Bode law is a feature of all planetary systems. Many astronomers have been trying their hand at generalizing the law, to tease out what might underlie it. But most astronomers seem to have given up; they regard the Titius-Bode law as a curiosity, but they set it on one side and work on something else.

JUNO: THE THIRD PIECE OF THE PICTURE

Ceres and Pallas had been discovered by luck. Ceres was discovered by Piazzi as a side effect from his work compiling a catalog of star positions, and Pallas was discovered by Olbers as a side effect of observing Ceres. Both asteroids were outside the 15 degree squares that had been drawn up by Zach and the Celestial Police as their search areas. So neither planet would have been discovered by the search strategy. But the discovery of the third asteroid, Juno, was much more according to plan.

Given that two planets had been discovered in the zone of the missing planet between Mars and Jupiter and they were small, it was clearly a possibility that there were further small planets there, especially if, as Olbers had proposed, the two new planets were the result of some disaster that caused the fragmentation of a larger planet. If there are two pieces from the broken planet there might be more. Olbers attempted to calculate where the explosion might have occurred by looking at the intersection of their orbits, and focused his attention on that region of the sky in the expectation that other pieces might orbit through that point, the place from which the pieces had been flung and through which they would pass over and over again.

The German astronomer Karl Ludwig Harding, (2003) Harding, was one of the original six forerunners of the Celestial Police, and he was dedicated to the subject. Even after Ceres and Pallas had been discovered and the objective of the Celestial Police had been achieved, he continued to search for new planets, comparing the stars that he found along the zodiac with their positions in the best catalog then available, the *Histoire Celeste*. Harding had studied theology, mathematics and physics at Göttingen University, where he became interested in astronomy. He became a private tutor to the children of Johann Schröter at Lilienthal, near Bremen. Schröter had been a courtier for King George III in Hanover, and had met the family of bandmaster Isaak Herschel through their common interest in music. They also had in common an interest in astronomy, through Isaak's son, William. When William Herschel discovered Uranus in 1781, Schröter was inspired to take up astronomy more seriously, left his busy job at the court and moved to become a more leisured government official in a village, Lilienthal, where he constructed an observatory to house a telescope that he bought from William Herschel, the first of many larger and larger instruments that he erected there to indulge his interest. This interest sustained Schröter for 30 years, until it was brought to a tragic end in 1813 in the anti-Napoleonic War of Liberation. Lilienthal was the scene of a skirmish between the French troops and Cossacks and was burned to the ground. Schröter's papers were destroyed, and his observatory was ransacked by French troops who carried off his clocks and plundered his brass instruments, mistaking them for gold.

However, before this event, in 1796 Schröter had employed Harding and in 1800 made him his observatory inspector. When in that year Zach formed the Celestial Police at the meeting hosted by Schröter in Lilienthal, Harding was naturally a member and took an active part in creating new star charts to aid the search for further new planets beyond Ceres and Pallas. His efforts paid off when, concentrating his observing program in the regions of the constellations Cetus and Virgo where the orbits of Ceres and Pallas intersected, he found on September 1, 1804, a new star in the region where Olbers had predicted any further planets would orbit. It was minor planet (3) Juno.

The discovery of the third minor planet added credibility to Olbers' hypothesis that the minor planets had been formed by the disruption of a larger planet, but other ideas surfaced. Another member of the Celestial Police, Johann Huth, (3203) Huth, suggested what has become the main theory in modern times about the origin of the asteroids:

> *I hope that this [planet] is not the last one that will be found between Mars and Jupiter. I think it very probable that these little planets are as old as the others and that the planetary mass in the space between Mars and Jupiter has coagulated in many little spheres, almost all of the same dimensions, at the same time in which happened the separation of the celestial fluid and the coagulation of the other planets.* (Letter of September 21, 1804)

VESTA: FOURTH—AND LAST?

Motivated by his idea that there were numerous fragments of a planet that are now minor planets Olbers kept looking in the area where the orbits of the three planets intersected. His idea had some foundation, and some asteroids do indeed have this origin, although not Ceres, Pallas and Juno. And his use of the present orbits of the planets to find out where the break up occurred could never have worked because of the perturbations on the orbits caused by the other planets. The asteroids no longer follow their original orbits. Olbers was indifferent to this, since he believed, as was common at the time, that the universe was only 6000 years old, so there had been little time for perturbations to build up. Amazingly his luck held, and his faulty reasoning led him to the fourth planet. On March 29, 1807, Olbers, observing in the same regions of the sky where Ceres, Pallas, and Juno had been discovered, found his second asteroid, which Gauss named Vesta.

(4) Vesta is one of the largest asteroids, and its surface is more reflective than most. It is therefore the brightest asteroid, and sometimes can be seen with the naked eye. But from Earth it is very difficult to see it as more than a point of light. The Hubble Space Telescope has a sharper view from its position in the clarity of space. When it imaged Vesta, it revealed that the minor planet is broadly spherical, but it has a gigantic piece missing at its south pole, a giant crater.

Vesta has a diameter of 530 km (330 miles), and is by far the largest, brightest member of a family of much smaller, 10-km (10 mile)-diameter asteroids that have identical orbits, and that appear to be related by some single incident that is common to their recent history. The natural inference is that meteoroids and smaller asteroids originated in the impact of an asteroid on Vesta. It could well have been the impact that created the giant crater. This theory is boosted by the similarity between the color distribution of light reflected from Vesta and the color of the surface of a kind of meteorite called HED meteorites, from the initials of the minerals of which they are made (howardite, eucrite and diogenite). These meteorites are a significant fraction of all meteorite falls onto Earth, about 5 %.

It is a very economical theory to link the HED meteorites, the family of small asteroids that follow Vesta, and the giant crater on Vesta all together in one explanation.

In 2011–2012 Vesta was visited by NASA's Dawn space probe, which stayed in orbit for about a year before moving on towards Ceres. Measurements of the gravity of Vesta determined by careful plotting of the trajectory of the spacecraft show that Vesta has an iron core just over 100 km (70 miles) in diameter. Vesta is pitted by many craters, some of them quite fresh (Fig. 8.1). The range of heights from the peaks of the highest mountains to the shallowest valleys is a surprisingly large 30 km (about 20 miles). The cavity at its south pole is in fact two overlapping craters (Fig. 8.2 and Fig. 8.3), the younger receiving the name Rhesilvia, and identified as the source of the HED meteorites. Vesta shows a varied geology, its surface covered by minerals including eucrite and diogenite. Howardite as such does not exist as a separate mineral, but its properties are intermediate between the other two, and the thought is that the impact that created the HED meteorites ejected eucrite and diogenite in their pure form and mixed up the two into howardite.

It was nearly 40 years after the discovery of Vesta that the fifth minor planet was discovered. (5) Astraea was discovered on December 8, 1845, by the amateur astronomer Karl Hencke. At the climax of his search, Hencke drew up extremely detailed star charts as a basis for his examination of the sky for new stars, and he spent a fifth of his lifetime, 15 years, on this single-minded quest. (He also found the next asteroid, (6) Hebe, 18 months later.)

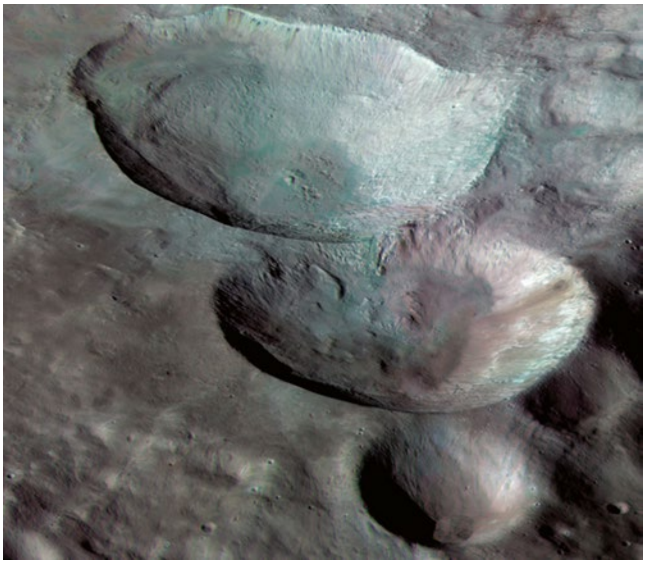


Fig. 8.2 The surface of Vesta. Three impact craters of different sizes are arranged in the shape of a snowman (upside down in this image). The largest crater, Marcia, has a diameter of about 60 km (40 miles). The central crater, which is about 50 km (30 miles) in diameter, is named Calpurnia. These two craters are of similar age and may have been made by a double asteroid. The smallest crater, Minucia (diameter 22 km, or 14 miles), was formed by a later impact (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

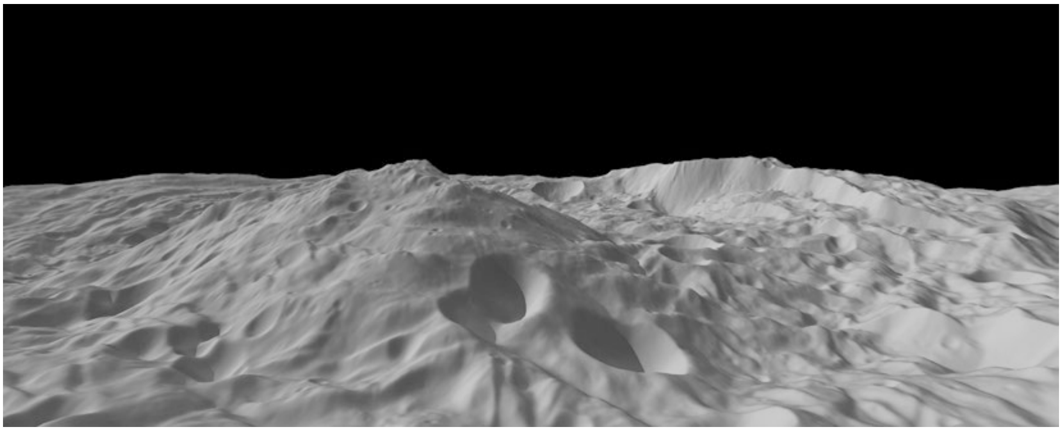


Fig. 8.3 A computer-generated image, in which the curvature of the asteroid has been removed, shows the giant crater that dominates Vesta's south pole (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI)

The question of why there was such a long time of famine for minor planet discoveries between the appetizers of the first four and the feast that followed the fifth and sixth has been addressed by a number of historians of astronomy. One reason is that some astronomers put too much weight in Olbers' theory, and concentrated their searches on too limited an area of sky. Others thought that a systematic search would be a waste of time and that any further discoveries would turn up through chance discoveries. The French astronomer Jean Delambre, (13962) Delambre, director of the Paris Observatory and the author of a number of books on the history of astronomy, wrote in 1806:

> *We further remark that these four planets [Uranus, Ceres, Pallas, and Juno] were found while searching for something else, and conclude that the real way to deserve and to encounter such accidents is to be occupied in some grand undertaking, which in itself is of real use, and keeps us constantly on the route to such discoveries; it is, for example, to work, as M. Piazzi, to perfect and augment the stellar catalogue, observing each star repeatedly for several days: this method has the double advantage to register in the catalogue only the reliable positions, and to evidence in the long run the planets that could still be confused among the innumerable quantity of very faint stars scattered in the sky.*

Certainly, the techniques that were available to discover new planets, of repeatedly looking for small, uncataloged stars was very tedious, especially given the need to search among fainter and fainter and much more numerous stars, for which the star charts were inadequate, incomplete or non-existent. It took the application of photography by Max Wolf in 1891 to look for moving stars, rather than new stars, to discover asteroids by the dozen, not one by one.

Alternatively, some astronomers, Olbers in particular, had the belief that when a large planet disrupted it would break up into only four pieces. This was based on a fanciful interpretation of the Book of Revelation, referring to planetary catastrophe: "Every mountain and island moved out of their places … and afterwards I saw four angels…" Given the tedium of the methods of the time to discover asteroids, and the expectation that there were only four, it is not surprising that the search for yet more asteroids lost momentum. Of course, in addition, the turbulence of European politics, wars and the economy at that time gave people other important things to worry about.

However, once the fifth and sixth asteroids had been discovered the floodgates opened. By 1857, 50 were known. The very number of asteroids became one of their distinguishing features. The French astronomer and scientific director of the Paris Observatory, François Arago, wrote: "The large number of these bodies known today leads one to believe that there are other causes for their birth. The intersections of pairs of orbits of the small planets are far from being all in agreement with Olbers' hypothesis [that they all originated from the break-up of a single larger planet]; nevertheless, the interlacing of their orbits suggests an intimate relationship between many of these bodies, and this is a curious subject of research for astronomers in the phenomena they present."

Arago's words were astute. It was the American astronomer Daniel Kirkwood, (1578) Kirkwood, who originated what is now the key idea about the formation of many of the asteroids, that they formed from a ring of gaseous and dusty material between Mars and Jupiter that was prevented from forming a single planet by the gravitational pull of Jupiter. Nevertheless, Olbers' original idea that some asteroids are broken pieces of larger worlds is also true for a number of them.

SNICK METEORITES: ASTEROIDS FROM MARS AND EARTH

HED meteorites come from Vesta, having spent millions of years orbiting in space as meteoroids or asteroids. But Vesta is not the only world that is the origin of rocks in space. Some meteorites are rocks from the surface of other worlds in our Solar System. As well as meteorites from Vesta, we have important specimens from Mars.

About 100 individual meteorites from about 34 meteorite falls have been linked with Mars. They were shot into space from the surface of the Red Planet by the impact of asteroids. They are collectively known as SNC (pronounced "snick") meteorites, after the initials of the names of the three first examples that were identified. Meteoriticist Kevin Kichinka has exhaustively researched the circumstances of their discovery.

Meteorites are conventionally named from the post office nearest to their fall and the C in SNC stands for the French commune of Chassigny. The first SNC meteorite to be picked up came to ground at 8:30 in the morning with a sound like the discharge of numerous muskets on October 3, 1815, near Chassigny, in the Burgundy region. It left a smoking trail. A man starting work early in the day in a nearby vineyard saw something fall from the cloud with a hissing sound, like a passing cannonball. (This fall occurred as France ended the decades of the Napoleonic Wars; military noises such as muskets and cannon would have been familiar to too many Frenchmen.) The viticulturist ran to see what it was. In a small hole in the freshly ploughed ground, he collected stones, hot to the touch as if warmed in direct sunlight. The stones proved to be meteorites. The fall was investigated by M. Pistollet, the town's physician who visited the site 2 days later and collected 4 kg of fragments.

The S in SNC stands for Shergotty. This meteorite was seen to fall on August 25, 1865, by Hanooman Singh near in Shergotty in the state of Bihar, India. According to a report in the *Calcutta Gazette:* "A stone fell from the heavens accompanied by a very loud report, and buried itself in the earth knee-deep. At that time, the sky was cloudy and the air calm, no rain." It was retrieved by W. C. Costley, the deputy magistrate of Shergotty. The Shergotty meteorite is made of a distinctive mineral now called shergottite. The mineral was, unsurprisingly, unfamiliar to Costley, who wrote in his report (which used an obsolete term for "meteorite"): "I at first doubted whether it was a true aerolite or not, in consequence of the colour being different from the one that fell in the Furreedpore District in 1850… but I find from Mr. Peppe, the Sub-Deputy Opium Agent, that there can be no doubt of its being a true aerolite, as he has seen two that fell in the District…" The city of Patna is near to Shergotty and was a center for processing and shipping to China opium grown in the surrounding farmland. T. F. Peppe was responsible for organizing this trade on behalf of the British government. Without Peppe's intervention this rock from Mars would likely have been discarded, perhaps used to build a farm building. It is not often that science advances as a result of action by a government-sponsored drug dealer.

The N in SNC stands for Nakhla. The fall occurred near Nakhla outside of Alexandria, Egypt, on June 28, 1911. About 40 pieces of the meteorite, weighing a total of about 10 kg (25 lb), were recovered in the fields of the farmland around the village, among the okra, cucumbers and strawberries. The fall was investigated by William Hume, the director of the Geological Survey of Egypt, who visited the site only a few days after the fall, interviewed eyewitnesses and collected fragments. According to a local newspaper, the meteor produced a white column-like cloud and explosions, frightening local residents. An eyewitness, a farmer named Mohammed Ali Effendi Hakim, was reported as saying: "The fearful column which appeared in the sky at [the village of] Denshal was substantial. The terrific noise it emitted was an explosion which made it erupt several fragments of volcanic materials. These curious fragments, falling to earth, buried themselves in the sand to a depth of about one metre. One of them fell on a dog at Denshal, leaving it like ashes." This graphic and much-repeated account, which would describe the only non-fictional example of an earthling killed by a Martian, is, sadly the exaggerated product of a lively imagination. A report of the Geological

Survey established discrepancies in the circumstances surrounding the story: Denshal is 33 km south of Nakhla; no meteorites have been collected from this far away from the strewn field; meteorites this small are unlikely to bury themselves a meter deep (all the pieces of the Almahata Sitta meteorites were found on the surface, not even in pits) and are unlikely to get hot enough to make anything combust; and the witness reported the wrong date. But even if this particular report is a fiction, the fall at Nakhla was real enough.

The history of the SNC meteorites is as follows. All of them had last been molten and solidified 1370 million years ago, much more recently than most meteorites, which solidified 4000 million years ago, or more. Their chemical composition is similar to analyses of rocks on the surface of Mars made in 1976 by the Viking landers. A meteorite with the same mineral composition as the Shergotty meteorite, which had been picked up in 1979 in Antarctica, contains bubbles of gas trapped in its glass-like material that have the composition of the atmosphere of Mars as analyzed by the Viking landers. This proves that the SNC meteorites come from Mars, from a magma field on that planet that solidified after a volcanic eruption 1370 million years ago. Most of them come from a big piece of Mars ejected by an asteroid impact 200 million years ago. The big piece orbited like an asteroid in space and was broken into smaller pieces by a collision with another asteroid 10 million years ago. The small bits showered in all directions and continued orbiting in space for a further 10 million years before some of them fell to Earth. But it follows that some remain in orbit.

So, among the asteroids are rocks from Mars. We also have meteorites from our Moon, and some asteroids originating from that world must also be orbiting in space. It is likely that there are rocks orbiting in space that have originated in many, if not all, the planets and satellites in the Solar System that have solid surfaces, such as the planet Mercury. Indeed, some asteroids must be rocks from Earth. The Río Cuarto craters in the province of Córdoba in Argentina are ten elliptical craters spread in a line about 15 km (10 miles) long, oriented with their long axes to the southwest. The larger craters are 700 m (750 yards) wide and 3.5 km (2.2 miles) long. They were created about 10,000 years ago by a very oblique impact by an asteroid that had split into several pieces on its passage through the atmosphere. They made a spray of impact debris that shot out in the forwards direction, some of which may have been ejected from Earth and would therefore now be in orbit as asteroids and meteoroids in interplanetary space.

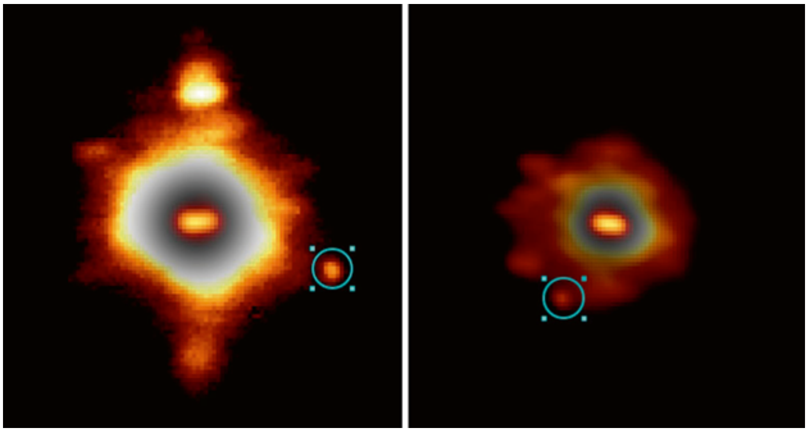


Fig. 9.1 Two views of Hektor in July 2006 and October 2008, made with the Keck II telescope and its adaptive optics system, show at the center the asteroid's elongated shape. Its small, faint moon is circled, caught at two points in its 3-day orbit (WMKO/Marchis)

Chapter 9

Ruled by the Planets

LAGRANGEA AND CHARLIER: TROJAN ASTEROIDS

Jupiter, the largest planet, was responsible for the birth of the Main Belt asteroids as small planets, and continues to govern his children. If you look at a plot of the orbits of the asteroids, they look at first glance like a hollow, tangled nest of twigs assembled by a bird, with no sense of order or aesthetics. But, on further careful scrutiny, you can find several groups of asteroids that fly together, more like a flock of starlings than the wing of fighter aircraft in formation. You can also find spaces where asteroids do not go. These groups and gaps are in the main controlled by Jupiter, whose gravity is second only to the gravity of the Sun in this region of the Solar System. In this section we describe the so-called Trojan asteroids, groups gathered by Jupiter in conjunction with the Sun.

In his book *Principia*, Isaac Newton in 1687 gives a solution of what became known as the "two-body problem," the motion of point-like, or spherical, masses under their mutual gravitational attraction. This theoretical problem approximates to the motion of an individual planet around the Sun, if the pulls of the other planets are ignored. The Swiss mathematician Daniel Bernoulli, (2034) Bernoulli, won a prize in 1734 for his more general mathematical solution to the two-body problem, and the problem was further worked on and generalized by his compatriot Leonhard Euler, (2002) Euler, in 1744.

Since the planets are so well separated that the pull of one planet on another is weak, compared to the pull of the Sun, the solutions to the two-body problem work well for the motion of planets in the Solar System. They do not work for the motion of the Moon around Earth, since the attraction between the Moon and Sun is comparable to the attraction of the Sun on each. This is known as the "three-body problem." Newton considered the problem and explained why he could not solve it. As a result, a number of mathematicians who followed Newton were inspired to test how their skill measured up against Newton's by solving the problem that he couldn't.

One good technique for approaching a difficult problem is to sidle up to it rather than tackling it head on. If you can solve a simplified version of the problem, its solution might shed light how to solve the general problem. In 1772 the French astronomer and mathematician Joseph Louis Lagrange, (1006) Lagrangea, articulated a theorem in celestial mechanics known as "Lagrange's three particles," a special case of the three-body problem. If a planet like Jupiter is in orbit around the Sun, and if a small, third body like an asteroid is projected into the same orbit, placed so that the Sun, Jupiter and the asteroid make an equilateral triangle, then they will continue in orbit, all of them maintaining their places. In 1875, another mathematician, from Cambridge, Edward John Routh, showed that the asteroid would be would be stable at its station. If deflected a bit, it would

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_9

return towards its original position, probably slowly oscillating back and forth. There are three other similar positions that lie on a straight line between Jupiter and the Sun, one outside and one inside its orbit, and one on the far side of the Sun, but they are not as stable as the two positions that form the equilateral triangle. All these positions are now called Lagrangian points, designated L1 to L5. The stable Lagrangian points are L4 and L5, with L4 being 60° ahead of Jupiter, L5 60° behind.

These studies were originally regarded as a theoretical exercise, unrelated to reality. But early in 1906, Max Wolf found an asteroid, whose orbit was then studied by the German astronomer Adolf Berberich, (776) Berbericia, and the Swedish astronomer Carl Charlier, (8677) Charlier. Within a matter of weeks, Berberich had found that the asteroid was moving in the same orbit as Jupiter, preceding it in its orbit by some 55°. Charlier matched the actual orbit to Lagrange's theorem, and concluded that the asteroid sits near L4. Later that same year, one of Wolf's students, August Kopff, (1631) Kopff, discovered another asteroid, which sits at L5, following Jupiter by 57°. Kopff went on in a successful career to become director of the Astronomisches Rechen-Institut in Berlin. Early in 1907 Kopff discovered a third asteroid, with an orbit similar to the other two, at L4. They all stir slowly around their respective Lagrangian points in an eddy with a period of 146 years.

Later in 1907, Johann Palisa suggested that the three should be named as a trio, and chose (588) Achilles, the Greek hero of the Trojan War, (617) Patroclus, the friend of Achilles, and (624) Hektor (originally spelled Hector), the son of Priam, and the Trojan champion slain by Achilles, all as recorded in Homer's *Iliad*. Wolf discovered a fourth example, (659) Nestor, in 1908. It became conventional to name asteroids at the L4 point after Greek characters in the *Iliad*, the "Greek camp," and those at the L5 point after Trojans, the "Trojan camp." (617) Patroclus and (624) Hektor were named before this distinction was made in the naming convention, so there is a Greek spy in the Trojan camp and a Trojan spy in the Greek camp.

By 2012 there were 3404 asteroids at Jupiter's L4, 1749 at L5. Although the *Iliad* suggests that 1200 Greek ships sailed to Troy, carrying perhaps 120,000 soldiers, and they were resisted by a Trojan army of between 10,000 and 15,000, this is poetic exaggeration of the importance of the Trojan War. Archaeological excavation of Troy reveals a citadel that could house 1000 soldiers, and a surrounding city whose total population could have been perhaps 3000. Presumably the Greek army that opposed the Trojan army would have been of roughly the same size. The war was not a walk through for either side, so they must have been balanced, the invaders somewhat more numerous since the defenders had the home advantage. There are thus about as many Trojan asteroids known as there were Trojans and Greeks in the Trojan War. There are few if any names recorded in the *Iliad* that remain free to be assigned to asteroids. The most recent was (248183) Peisandros, discovered in 2005. (Peisandros, the son of Antimachos, was a Trojan warrior killed by Agamemnon.)

Both Hektor and Patroclus are binary asteroids. Pictures of the two asteroids of amazing sharpness have been gathered by a team led by Franck Marchis, (6639) Marchis), a French-born astronomer at UC Berkeley, with the Keck 10-m telescope on Mauna Kea in Hawaii and a camera working with adaptive optics. Marchis's amazing pictures (Fig. 9.1) show that Hektor is highly elongated, 370 × 200 km (230 × 120 miles) in size, and its moonlet is 15 km (9 miles) in size orbiting at a distance of 1000 km (620 miles). Patroclus is two asteroids of comparable size, one 122 km (78 miles) in diameter, the smaller 112 km (70 miles). They orbit each other with a period of 4.28 days, separated by 680 km (420 miles). The name Patroclus is now restricted to the larger asteroid, with the smaller named Menoetius, Patroclus's father.

The significance for astronomers of an asteroid having a satellite is that it becomes possible to measure its mass, which, combined with its size, yields its density and gives a clue as to what the asteroid is made of. Patroclus and Menoetius each have a density of 0.8 g per cubic cm, about the same as ice. They are dirty snowballs, similar to comets, not rocks such as meteorites.

Jupiter is not the only planet to have "Trojan" asteroids at the L4 and L5 points of its orbit around the Sun, although it has many more than other planets because it is so massive and able to control its Lagrangian points. Earth has one known Trojan, at its L4 point, very recently discovered and provisionally designated 2010 TK7. Neptune has eight known Trojans. Mars has four known Trojans, including (5261) Eureka. Eureka was discovered in 1990 by Henry Holt, (4435) Holt), and David Levy, (3673) Levy; it oscillates back and forth around L5 by a considerable distance, ±40°. Mars is smaller than Jupiter and has less rigid control over its Trojans. Eureka was recognized as the first Martian Trojan by Ed Bowell and named by Brian Marsden with the expression of sudden discovery attributed to Archimedes. ("Eureka!" means "I have found it!", the word that Archimedes is said to have shouted as he leaped from his overflowing bath when he realized how to measure the density of a crown, allegedly gold but suspected to be silver, by determining its volume, suspending it in water.)

It is not known whether the Trojan asteroids were born where they are or whether they migrated there. They have some similarities of composition, which argues that they might have a common origin. One suggestion is that they are captured planetesimals and have been in their position for most of the history of the Solar System; this is supported by the discovery of the low density of Patroclus, suggesting that it is icy rather than rocky. Franck Marchis, who discovered the low density, referred to this as "a nice story." He added: "We need to discover more binary Trojans and observe them to see if low density is a characteristic of all Trojans." An alternative theory is that the Trojans are related to the satellites from Jupiter. The two outermost of the larger satellites, Ganymede and Callisto, are quite low density, less than 2 g per cubic cm and are ice-rich. The Trojans might be escaped satellites from Jupiter. A counter-suggestion is that they are not quite stable where they are and will eventually escape from the Lagrangian points; circling in the same orbit as Jupiter, they will eventually be captured and become its satellites.

KIRKWOOD: THE ASTEROID NO-FLY ZONES

Daniel Kirkwood, (1578) Kirkwood, started his career as a mathematics teacher with an interest in astronomy and became a mathematics professor in 1856 at Indiana University. By the time he arrived in Bloomington, 55 asteroids were known that had their orbits computed. Although the number of orbits available for analysis was relatively small, Kirkwood discovered that there were gaps in the distribution of the period of the asteroids of the Main Belt. Asteroids missing were ones with periods that were 1/2, 1/3, 2/5, etc.

It was remarkable that Kirkwood's discovery, which was probably not, at the time he first made it, statistically significant, has been confirmed as the number of asteroids has grown. Statistical evaluation is not everything; there is no way to measure the significance added to data by a thought in the mind of a talented theoretician. If you look at data with no idea in your head and find a pattern, you need statistical tests to judge whether the pattern is significant. If you have a reasoned expectation and can see that the expected pattern is there, even though the data is sparse, it is significant that there is nothing in the data to contradict it, even if that is not quite a definite proof.

Kirkwood first mentioned the gaps at a meeting in 1866, and documented his idea over the next 2 years by which time he had at first 87 and then 100 asteroids to discuss. He realized that the gaps correspond to the orbits that resonate with Jupiter. What that means is that, for example, in a 1:3 resonance, an asteroid might make three orbits of the Sun while Jupiter makes one. The gravitational nudge that Jupiter gives to the asteroid every three of its orbits repeats over and over again, so the effect of the nudges builds up, somewhat like the repeated push by a parent of a child on a swing, which causes the displacement of the swing to build up. The asteroid is moved out of the resonant orbit, so a gap develops at that location, an asteroid no-fly zone.

Kirkwood noticed the similarity between the gaps in the orbits of the asteroids and the gaps in the rings of Saturn. Percival Lowell remarked that "If the asteroids were numerous enough we should actually behold on the sky a replica of Saturn's rings." Saturn's rings are due to myriads of tiny moonlets that orbit that planet. There is one particularly noticeable large gap, called the Cassini Division. There are no moonlets in the gap. If a moonlet strays into the gap and starts to orbit there, it would have a period of revolution around Saturn of exactly half of one of Saturn's large moons called Mimas, which orbits outside the rings. In that case, every two orbits of the moonlet it would repeat its configuration with respect to Mimas, experiencing the same tug as the last time it was there. The cumulative effect of these repeated periodic tugs of Mimas would move the moonlet out of that region and re-create the gap.

THULE: A FAR LAND

Kirkwood continued to study the motions of the asteroids and predicted a paradox in the theory of resonances that enables some asteroids to continue to orbit in the Kirkwood gaps. Some asteroids have an orbit in a gap that is quite elliptical and also oriented in exactly the right way such that, when the asteroid is furthest from the Sun and closest to the orbit of Jupiter, it is actually opposite Jupiter, furthest away from the planet itself. The asteroids do not make close approaches to Jupiter. This minimizes the resonant tug of Jupiter, and the asteroids form a family of stable orbits. (153) Hilda was the first such asteroid discovered in the 3:2 orbital resonance with Jupiter. It is the prototype of the Hilda family of asteroids. They are a heterogeneous bunch of asteroids, which have been randomly forced into a common configuration.

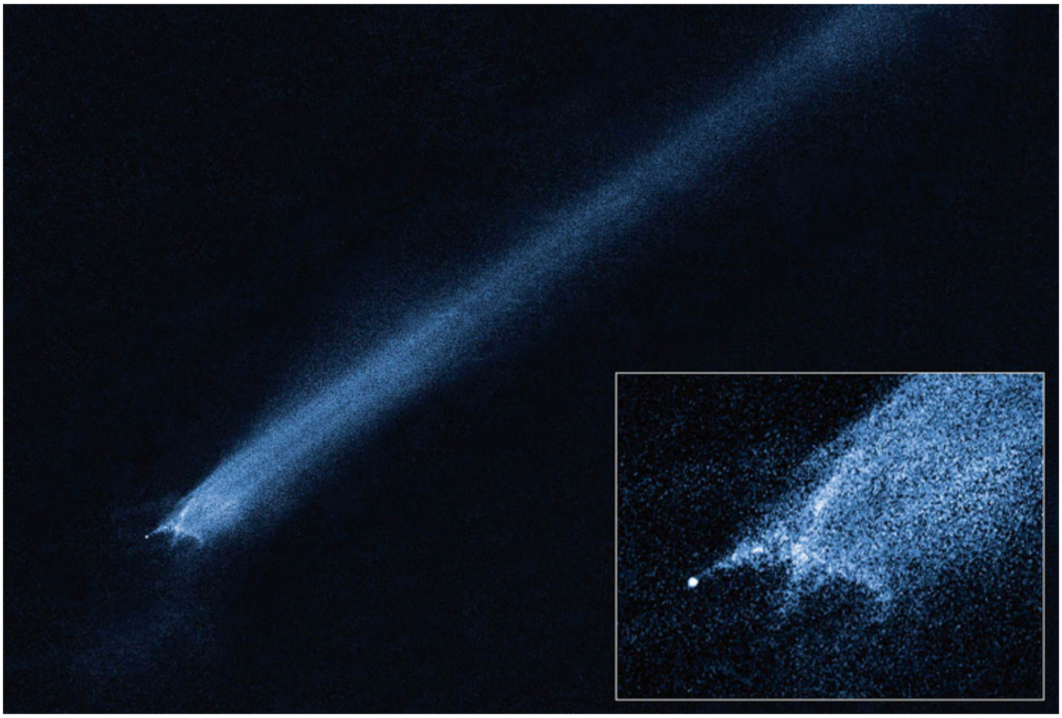
(279) Thule orbits at the 4:3 resonance, and, apart from the Trojan asteroids, it was at the time of its discovery by Johann Palisa the most distant of the Main Belt asteroids. Hence its name, after the unidentified island, six days sail north of Britain, in the Arctic regions of the North Sea, which was thought by Hellenistic geographers to be the northern limit of the habitable world, and to which they gave the name Thule. The Latin poet Virgil used the phrase "Ultima Thule" (furthest land), not only literally for the distant island but also for a goal that is out of reach.

CRUITHNE: "EARTH'S SECOND MOON"

By contrast with Thule, at one time the most distant asteroid known, there is a nearby asteroid with a curious relationship to our Earth. It is a fellow traveler to Earth as it orbits the Sun. This asteroid is said to be co-orbital with Earth. In other words, its orbital period is almost exactly the same as Earth's: 364.0 days for the asteroid as against 365.25 days for Earth. It is asteroid (3753) Cruithne. Pronounced "krooy-nuh," Cruithne was the name of a legendary king of the Pict. This christening was a tribute to his birth nation by Cruithne's discoverer, Scottish astronomer Duncan Waldron, working with a telescope in Australia in recent times. The orbit of Cruithne around the Sun is quite elliptical. It dips inside the orbit of Mercury and soars out beyond Mars. The orbit is tilted relative to Earth's orbit. Currently, the asteroid comes as close as 12 million km

(7.5 million miles) to Earth in November each year. It is 5 km (3 miles) in size. It lags a little behind Earth. Although it is a close neighbor, making repeated approaches to us as it oscillates in its orbit, there is little or no chance that Cruithne will collide with Earth.

As seen from Earth, Cruithne describes an orbit that is the shape of a squashed circle, or a bean, referred to as a horseshoe orbit. This kind of orbit was first identified in 1911 by the British-born American mathematician, Ernest W Brown, (1643) Brown, but the idea languished for half a century or more as simply a mathematical curiosity without an application. The unusual orbit of Cruithne was discovered in 1997 by Kimmo Innagen, (3497) Innagen, Seppo Mikkola, (3381) Mikkola, and Paul Wiegert, (5068) Wiegert. Earth is a bit off to one side of the bean-shape. Although Earth is not actually inside its orbit, Cruithne is sometimes referred to as Earth's second moon. There are a few other recently identified asteroids that might be in similar orbits. Saturn has two moons, Epimetheus and Janus, in the same configuration as Cruithne and Earth.



Chapter 10

The Chaos of the Solar System

Fig. 10.1 Asteroid P/2010 A2. The Hubble Space Telescope imaged a strange asteroid with a comet-like tail in January 2010. The asteroid shows as a point-like object about 140 m (500 ft) in size, a curious structure nearby and a tail that contains no gas, only dust. The tail extended up to 85,000 km in length (NASA, ESA and D. Jewitt-UCLA)

MORIARTY, SHERLOCK AND DOCTORWATSON: THE RAREFIED HEIGHTS OF MATHEMATICS

Three asteroids were discovered in 1981 by Ed Bowell at Anderson Mesa, AZ. (5048) Moriarty was named for Professor James Moriarty, the villain so often behind the criminal plots exposed and solved in the works by the author Sir Arthur Conan Doyle, (7016) Conandoyle. Moriarty was defeated by the fictional private detective, Sherlock Holmes and his assistant and chronicler, Dr. John Watson, for whom the asteroids (5049) Sherlock and (5050) Doctorwatson were named. (Asteroid (5050) could not be named simply "Watson," for fear of confusion with asteroid (729) Watsonia.)

Holmes was, according to Watson, almost completely ignorant about astronomy. In *A Study in Scarlet*, Watson was astounded when he learned that Holmes was "ignorant of the Copernican Theory and of the composition of the Solar System":

> *"That any civilized human being in this nineteenth century should not be aware that the earth travelled round the sun appeared to me to be such an extraordinary fact that I could hardly realize it."*
>
> *"You appear to be astonished," he said, smiling at my expression of surprise. "Now that I do know it I shall do my best to forget it."*
>
> *"To forget it!"*
>
> *"You see," he explained, "I consider that a man's brain is like a little empty attic, and you have to stock it with such furniture as you choose … It is of the highest importance, therefore, not to have useless facts elbowing out the useful ones."*
>
> *"But the Solar System!" I protested.*
>
> *"What the deuce is it to me?" he interrupted impatiently: "you say that we go round the sun. If we went round the moon it would not make a pennyworth of difference to me or to my work."*

It could be that Watson's assessment of Holmes' (complete lack of) knowledge of astronomy is an exaggeration. In *the Musgrave Ritual,* Holmes carries out calculations of the Sun's position in order to recover the buried treasure of the ancient crown jewels of England, noting that "it was unnecessary to carry out any correction for the personal equation, as astronomers have called it." And, at the start of *The Greek Interpreter,* Holmes and Watson discuss the causes of the change of obliquity of the ecliptic.

Moriarty was fiercely intelligent, a worthy foe of Holmes, who described him as the Napoleon of crime. Both Holmes and Moriarty were published academics. Holmes, according to his own testimony in *The Sign of the Four*, had published several monographs, all on technical subjects, including *Upon the Distinction Between the Ashes of the Various Tobaccos*. Moriarty knew more astronomy than Holmes. He had at least two mathematical works to his credit, on the basis of which he had become a professor, although a failed one. According to Holmes in *The Final Problem*:

> *He is a man of good birth and excellent education, endowed by nature with a phenomenal mathematical faculty. At the age of twenty-one he wrote a treatise upon the binomial*

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_10

> *theorem which has had a European vogue. On the strength of it, he won the mathematical chair at one of our smaller universities [Leeds or Durham, it is said], and had, to all appearances, a most brilliant career before him. But the man had hereditary tendencies of the most diabolical kind. A criminal strain ran in his blood, which, instead of being modified, was increased and rendered infinitely more dangerous by his extraordinary mental powers. Dark rumours gathered round him in the University town, and eventually he was compelled to resign his chair and come down to London.*

The plodding Scottish policeman, Inspector Alec MacDonald of Scotland Yard, learned about eclipses from Moriarty. He tells Holmes he has investigated the man:

> *"I made some inquiries myself about the matter. He seems to be a very respectable, learned, and talented sort of man."*
>
> *"I'm glad you've got so far as to recognize the talent."*
>
> *"Man, you can't but recognize it! After I heard your view I made it my business to see him. I had a chat with him on eclipses. How the talk got that way I canna think; but he had out a reflector lantern and a globe, and made it all clear in a minute. He lent me a book; but I don't mind saying that it was a bit above my head, though I had a good Aberdeen upbringing."*

As well as the treatise on the binomial theorem, Moriarty had published a book on the orbits of asteroids. In *The Valley of Fear*, Holmes warns Watson to take care on attacking Moriarty:

> *But in calling Moriarty a criminal you are uttering libel in the eyes of the law—and there lie the glory and the wonder of it! The greatest schemer of all time, the organizer of every deviltry, the controlling brain of the underworld, a brain which might have made or marred the destiny of nations—that's the man! But so aloof is he from general suspicion, so immune from criticism, so admirable in his management and self-effacement, that for those very words that you have uttered he could hale you to a court and emerge with your year's pension as a solatium for his wounded character. Is he not the celebrated author of* The Dynamics of an Asteroid, *a book which ascends to such rarefied heights of pure mathematics that it is said that there was no man in the scientific press capable of criticizing it? Is this a man to traduce?*

Moriarty's work on *The Dynamics of an Asteroid* is cited in the professional mathematical literature, although it cannot be found in any library.

Astronomers believe that the character of Moriarty is based on Simon Newcomb, (855) Newcombia, the Canadian-American astronomer who wrote on the binomial theorem, the orbits of asteroids, eclipses and the obliquity of the ecliptic, and whose character echoed some of the traits exhibited by Moriarty. Arthur Conan Doyle seems to have learned about the man from a friend, an astronomy instructor Alfred Drayson, who worked at the Royal Observatory at Greenwich at times when Newcomb visited.

MORBIDELLI: A NICE STORY FROM NICE

Arthur Conan Doyle used the dynamics of an asteroid as a benchmark for the mathematical ability of Holmes' brilliant, evil foe Professor Moriarty. The way that asteroids now move around the Solar System is a branch of mathematics that still tests the technical ability of mathematicians. The way that they used to move around the Solar System and came to their present orbits tests mathematicians' ability in a different way. Some might have said that the mathematics of the orbits of asteroids had moved on from Professor Moriarty's era and was no longer cutting-edge research. However, the discoveries of the 1990s and 2000s made while investigating how the Solar System has evolved over billions of years put the theory of the orbits of asteroids right back in the front line again.

You might think that, with computers, and given that the theory of gravity is well understood, it would all be easy. Indeed, the theory of gravity was developed 300 years ago by Isaac Newton, and its finer points have been well worked out. Newton's theory has stood the test of time in all except the most exceptional circumstances, when it is surpassed in accuracy by the even finer points of the General Theory of Relativity. With the calculating ability of modern computers, intelligently programmed, it is possible to calculate the orbits of the planets with exquisite precision. Astronomers and space engineers launch spacecraft across the Solar System on trajectories that virtually always (save for some terrible blunders) lead to the right place, millions of miles from Earth. Likewise, in order to find and observe an asteroid, the calculations of where it will be in the future is routine and precise. You might think therefore that, since the equations work equally well forwards and backwards in time, we can find out where asteroids were in the past as well as in the future.

It is true that calculations about the positions of asteroids are accurate in the short term, and to a very good approximation. For example, one asteroid orbits one sun precisely in an ellipse. But an ellipse is only a good approximation to the orbit of an asteroid in the Solar System because the Sun is dominant and the other planets negligible. In the longer run, the orbits of an asteroid in a Solar System with other planets is chaotic, the planets deflecting the asteroid, looping it in non-repeating orbits, which eventually become literally incalculable.

The reason is that the orbits of asteroids are "chaotic." If you displace the starting position of an asteroid by just one cm, you might expect that to make a difference in the position of the asteroid in the future by about the same amount—1 cm or so error in 100 years, 1 cm error in 100 million years. If that were true, the error would be immaterial. But in fact, the nature of the equations is such that the uncertainty builds up in time. Perhaps the error might grow from 1 cm to an insignificant couple of cm in 100 years, but it might be 10 million km in 100 million years. The asteroid could literally be anywhere in its orbit. That 1 cm causes such large alterations in the asteroid's interactions with the other planets that errors in the asteroid's orbit build up and the forecast of its position entirely changes.

In modern physics, "chaos" is the word used to describe behavior like this. Predictions may be reliable in the short term, but in the long term they depend so much on where you start the calculations that you cannot reliably calculate the long term. The weather is an example of chaotic behavior. The weather can be predicted, through calculation, more or less accurately, 1 day or even 1 week ahead. However, no one can make accurate enough and geographically dense enough measurements of the weather today as a starting point for the forecast. The striking image that is used is that, since meteorologists cannot know about the flapping wings of every butterfly in Brazil they cannot predict now what the weather will be like 1 year from now.

The fact that the motions of the planets are "chaotic" was discovered more than 100 years ago, but only in the last, say, 30 years has the scope of the discovery dawned on astronomers. This realization has revolutionized the field. It had been growing into a dusty field of study in which there were few i's remaining to be dotted and t's crossed, and was revived into an exciting, vibrant developing field of study very attractive to researchers and students.

The very concept of chaos, in the scientific sense, was actually discovered in 1887 as a feature of planetary orbits by the French mathematician Henri Poincaré, (2021) Poincaré. He was responding to an offer of a prize for the solution of the three-body problem, the exact calculation of the orbits of just three bodies under mutual gravitational attraction. Isaac Newton had given an exact solution to the two-body problem—the orbit of one asteroid around its sun, for example. The orbit is an ellipse that repeats regularly, and the position of the asteroid can be calculated to arbitrary accuracy indefinitely far in advance. This is the reverse of chaotic, but it is possible only if there are two bodies (the asteroid and the Sun). Suppose there are three bodies (the asteroid, the Sun and Jupiter). Where will the asteroid go under such circumstances? The solution to this three-body problem proved elusive.

Poincaré was able to calculate the orbits of three bodies numerically—we would nowadays do this by computer, he did it by hand—but the orbits were "so tangled that I cannot even begin to draw them." Moreover, Poincaré found that when the three bodies were started from slightly different initial positions, the orbits could be entirely different. "It may happen that small differences in the initial positions may lead to enormous differences in the final phenomena. Prediction becomes impossible." This is chaotic behavior, in the mathematical sense.

As a result of this chaotic behavior, it is impossible to calculate realistically the orbits of a dozen or more planets over a long period of time. If the problem that you are tackling is to trace back the origin of the asteroids to the start of the Solar System about 4.5 billion years ago, you have to resign yourself to the fact that it cannot be done exactly. This is not because you do not understand the theory or you do not have the mathematical ability; it cannot be done even in principle.

What can be done is to make lots of calculations starting with different possible arrangements of planets and see what happens in each case. These calculations are called simulations. They show what might have happened but not necessarily what actually happened. If you can afford enough calculations and do not get bored by repeating the same calculations over and over again with only minor variations, the simulations can study a number of theoretically possible planetary systems more or less like our Solar System and try to draw out the likely reasons for some general features in the mathematical models that correspond to what we now see of the Solar System in which we actually live. Weather forecasting now works in a similar way. Meteorologists use the observations of the weather at a given moment to forecast the weather in the future. They realize that the prediction depends sensitively on the input data so they run the forecast a second time after making small changes at random, but within the likely range of possibility, to the data. They do this again and again and look for common features in the predicted outcomes, and hope that the most commonly predicted outcomes are the ones that will come to pass. They then constitute the weather forecast. This technique does not always work. If the present weather is poised on a knife-edge, so to speak, the future weather might fall towards an extreme: a fearful hurricane on one side, or mild showers of rain on the other. The weather knows what it will do but we do not. This is why weather forecasts can sometimes go horribly wrong. "Don't worry," said meteorologist Michael Fish of the UK Meteorological Office on October 15, 1987, "there is no hurricane on the way." His prediction was spectacularly disproved within 24 h when a hurricane-force storm devastated southern England and northern France, killing 22 people and felling 15 million trees. The same uncertainties affect long-range forecasting of the positions of planets in the Solar System.

The most interesting scenario for the history of the Solar System that has emerged in the years since 2005 as a result of what is known by astronomers is the Nice Simulation, Nice pronounced "niece." It was developed by Rodney Gomes da Silva, (17856) Gomes; Hal Levison, (6909) Levison; Alessandro Morbidelli, (5596) Morbidelli; and Kleomenis Tsiganis, (21775) Tsiganis; all part of an international group of mathematicians centered on the Côte d'Azur Observatory in the French city of Nice. According to the Nice Simulation, what happened in the first billion years or so of the history of the Solar System was like a gigantic game of interplanetary billiards played by hyperactive children let loose around a billiard table.

The Nice Simulation starts off with a conjecture about the shape of the early Solar System, at the stage of its development in which the planets had just formed. Almost all the dust and gas of an interstellar cloud that had not accumulated into the Sun had consolidated into solid material, or had been blown out of the Solar System. The solid lumps were in orbit around the Sun, much like the planets, comets and asteroids now, but there were more of them. The lumps of solid material that had mostly lumped together to form planets are called planetesimals, and a lot of planetesimals were left over from this process. They moved everywhere among the planets, which at that time included the four outer, giant planets that we know today but perhaps half a dozen inner "terrestrial planets," a few more than we now have: Mercury, Venus, Earth and Mars, and a few others. The giant planets were near to their current orbits.

According to the Nice Simulation, there were occasional close encounters between the planetesimals, and between individual planetesimals and the planets. Some of the planetesimals were ejected from the Solar System, perhaps the vast majority. These now constitute interstellar asteroids, little worlds traveling forever in the cold darkness of space, lost to the light and warmth of the Sun, meandering around the galaxy. As the planetesimals were ejected, they gave the planets a little backward kick, and the giant planets gradually migrated in further towards the Sun. After hundreds of millions of years this brought the two innermost giant planets, Jupiter and Saturn, into resonance, with two of Jupiter's orbits taking exactly the same time as one of Saturn's. This had a profound effect on the other planets and the myriad smaller bodies of the Solar System, the bits and pieces left over from the process of planet-building.

Some of the inner planets were ejected into space or into the Kuiper Belt at this time, leaving behind just the four we know today. Some of the larger Kuiper Belt objects such as Pluto may have originated in this way, moved from the inner parts of the Solar System to their present icy darkness. There was at that time a counter-factual future for Earth, in which Earth became a trans-Neptunian planet or even an interstellar planet, roving around the galaxy like a lone coyote on the steppes, frozen suddenly into a stasis that we can only imagine. This did not happen to Earth, but it may have happened to one of Earth's neighbors.

The chaos in the Solar System that resulted from all of this had the effect of knocking minor planets out of their orbits. Some of them, jay-walking across the orderly circular paths of the planets, collided with the planets, bombarding them and making craters. This is how most of the craters originated on the Moon. But some became settled into the region between Jupiter and Mars and became members of the Main Belt of asteroids.

In a paper in the journal *Nature* in 2005, Morbidelli and colleagues suggested that some of the planetesimals would have been captured at this time in Jupiter's Lagrangian points. According to their scenario, the Trojan asteroids should be comet-like. It was a great success of their theory that subsequently it was discovered that the Trojan asteroid Petroclus had a density like ice, similar to a comet. The Trojans might thus be Kuiper Belt objects, a migrating flock that stopped off on their intended route to the outer Solar System, becoming settled in warmer climes.

Uranus and Neptune were also affected by the repeated, coordinated tug of the two innermost giant planets. They moved outwards into more eccentric orbits, and seem to have changed places. They ploughed through the vestigial planetesimals left orbiting in the outer Solar System. The giant planets swept up most of the planetesimals nearby. Some may have been scattered back down into the inner Solar System. Most were kicked right out of the Solar System, and now orbit in the galaxy in interstellar space. Some did not quite make it into space and were left as members of a slowly moving cloud extending up to a light year from the Sun (the Oort Cloud). Yet others orbit now in the Kuiper Belt as Trans-Neptunian objects. They are all fossils left over from the process of planet formation. Their significance for astronomers is that they are unique probes for what was going on in the youthful ages of the Solar System. It is good fortune for astronomers that their attempts to detect what happened at the birth of the planets is helped by having such a variety of forensic traces left behind, although analysis of the crime scene is made problematic by the way the evidence has been muddled up.

After the Solar System was cleared of many of its surplus planets and planetesimals by all these interactions, like a snooker table cleared of the red balls to leave just the other colored ones, the planets settled down to a more orderly existence, by and large taking up orbits that were nearly circular, although not quite. Interactions between the planets and other forces still cause perturbations of the asteroids and deflect them from their orbits, and we still are potentially at risk from impacts of asteroids with Earth. But the risk has been greatly reduced by the episode in which Jupiter and Saturn were brought into resonance.

DAMOCLES: DEAD COMET

The risks that fate might deliver are symbolized in Greek mythology by the legend of the Sword of Damocles. Damocles was a courtier of Dionysius, the Tyrant of Syracuse. Flattering his master, he made a speech emphasizing how fortunate the king was, surrounded by every luxury. Dionysius made Damocles change places, inviting him to sit on the throne at a feast. Damocles was made to sit below a sword, hanging point down, suspended from the handle by a hair from a horse's tail. Though surrounded by good fortune, Damocles found the uncertainty of imminent death too spooky and did not enjoy the occasion; Damocles had demonstrated the uncertainty of everyone's existence. The phrase, the "Sword of Damocles" is symbol of impending disaster.

The minor planet (5335) Damocles was discovered in 1991 by Rob McNaught, (3173) McNaught, who has discovered 480 asteroids and 82 comets and is one of the most successful discoverers of asteroids. Minor planet Damocles orbits more like a comet than a typical asteroid, in an ellipse of very high eccentricity (0.88; this describes a long, thin orbit), inclined at an angle of 61°. It crosses the orbits of the planets Mars, Jupiter, Saturn and Uranus. As it is now, it does not go too near to Jupiter or Saturn, so its orbit is stable for perhaps up to 50,000 years. However, its orbit is highly chaotic. It is likely to evolve into an Earth-crossing asteroid. It probably spends a quarter of its time in such a configuration. Alternatively, it may be making the transition from a distant orbit in the outer Solar System to an orbit nearer to the terrestrial planets. Either way the change will bring it into an orbit where it might strike Earth. Damocles is probably about 10 km in diameter and, to use another phrase that is associated with the legend of Damocles, life on Earth will then hang by a thread.

Damocles is the type object of a group of asteroids known as Damocloids. Damocloids are minor planets with orbits like the long-period comets but have no tail or coma. They may originate in the Oort Cloud, and they may be dead or dying comets.

CHIRON: THE MOST DANGEROUS OBJECT IN THE SOLAR SYSTEM?

(2060) Chiron is named after the centaur Chiron. It was discovered in 1977 by Charles T. Kowal, and was the first-recognized member of a class of objects known as centaurs, with an eccentric orbit that ranges from just inside Saturn's to just outside Uranus's. Its size is not well determined. Estimates range from 150 to 230 km in diameter. At first it was thought to be simply an asteroid in an unusual orbit. In February 1988, near to its closest approach to the Sun, at 12 times Earth's distance, Chiron brightened by 75 % and developed a coma, like comets do; in 1993 it developed a tail. It therefore also has a designation like a comet, 95P/Chiron. Its hybrid nature gives it its name—the name of a centaur (half man, half horse).

Chiron's orbit is unstable, perturbed severely by the two gas giant planets. It may not have been in its current orbit long, and may have migrated from the Kuiper Belt, beyond Neptune. It will be further diverted at some time closer to the Sun, into the inner Solar System, when from time to time it will cross both Jupiter's and Earth's orbits. Given its Earth-crossing orbit, it could collide with Earth and, given its size, it has been described as "the most dangerous object in the Solar System," although there are other contenders for the title. The scale of the potential impact can be judged by comparison with the Chicxulub asteroid that is credited with the K-T mass extinction (i.e., the death of the dinosaurs), which was 10 km in size. The energy of the impact of Chiron would be perhaps 10,000 times more than the energy of the Chicxulub impact. We can hope that Jupiter might eject Chiron from the Solar System before such an event devastates Earth. Other centaurs include (54598) Bienor, (10370) Hylonome, (8405) Asbolus, (7066) Nessus, and (5145) Pholus, all with centaur-themed names.

THEMIS AND ELST-PISARRO: WATER ON ASTEROIDS

An asteroid impact may have made the dinosaurs extinct, but not every impact with Earth has been bad. When Earth was first formed it was dry, because it was hot. Its water was evaporated from several sources of heat. The Sun's heat warmed Earth. The rain of small planetesimals that built up Earth heated its surface. Radioactivity heated its core. A large asteroid crashed into Earth and created the Moon, as we will shortly tell, and the impact heated the whole planet. All these factors dried up Earth. The water that Earth now contains was brought here since these early times, imported by the planetesimals that continued to build Earth into a planet and by the impacts of asteroids and comets since.

The environment on the surface of dry, dusty asteroids, as imaged by visiting spacecraft, does not at first seem to be a place where there is water. However, comets certainly contain gushing geysers of icy water, bursting from vents on their surface, pressurized by water turning into steam in caverns below their surface. A few asteroids even show faint tails, like comets. (7968) Elst-Pizarro is one. When it was first seen in 1979 it looked like a typical asteroid and was designated 1979 OW7; its orbit was also typical, in the Main Belt of asteroids. In 1996, as it passed at its closest to the Sun, it was imaged by the Belgian astronomer Eric W. Elst, (3936) Elst, and the Chilean astronomer Guido Pizarro. (4609) Pizarro is named after both Guido and his brother Oscar. The pictures revealed that asteroid (7968) Elst-Pizarro had a tail like a comet. The same was true at the passes close to the Sun that followed in 2002 and 2008. As a consequence, this object has two sets of names. If viewed as an asteroid, it is called (7968) Elst-Pisarro. If viewed as a comet, it is called 133P/Elst-Pizarro. In either case, it is named not after its discoverers but after the two people who realized its significance.

There are other asteroids that have tails and comet-like behavior. Given that the tail of a comet is dusty material released when the ice of which it is composed melts, this has made astronomers think that some asteroids have water on their surfaces. Direct evidence for this was discovered in 2010 by two groups of astronomers using the NASA Infrared Telescope Facility (IRTF) on Mauna Kea in Hawaii. The surface of the Main Belt asteroid (24) Themis is covered with a frosty coating, somewhat like the surface of a comet.

Themis is only about 200 km (120 miles) in diameter and has no atmosphere, so the presence of surface ice is surprising. If the ice was put there on the surface 4500 million years ago when the planetary system formed and the asteroid had been in the Main Belt for this long, warmed by the Sun, one might have expected that the ice should have been gone long ago. It is theoretically possible that the asteroid has recently migrated to the Main Belt from more distant, colder regions, where the ice had persisted, but no solid flesh has been put on the bare bones of this scenario. Perhaps the ice has been held in ice caverns under the asteroid's surface, shielded from the Sun. The ice may have been dug up recently through a collision with a smaller asteroid, or brought to the surface by a collision with a comet.

P/2010 A2: ASTEROID COLLISION

The space between asteroids is large and asteroids are small, so you might think that collisions are between asteroids are unlikely. But there are many asteroids, crowded into distinct zones, and collisions between asteroids are actually rather common. All the asteroids whose surfaces have been seen by space probes are covered with impact craters caused by collisions with meteoroids or other asteroids. One collision was identified a few months after it happened. In January 2010 the Lincoln Near-Earth Research (LINEAR) Program Sky Survey spotted a curious object with no obvious comet-like head but a comet-like tail—hence its comet-like name, although the object orbits in the Main Belt of the asteroids. A detailed picture by the Hubble Space Telescope (Fig. 10.1) showed a bizarre X-shaped object at the head of a comet-like trail of material. Given its almost circular orbit near the Sun, it seems unlikely that the trail of dust had been released by progressive warming of the comet and the vaporization of the ice of which it would be composed if it was a comet. Astronomers hypothesize that the slowly expanding dust cloud is the result of a collision between two asteroids or an asteroid and a comet that occurred in the Main Belt in February 2009, around the 10th of the month. The dusty cloud around the new object, P/2010 A2, which is an asteroid some 120 m (390 ft) in size, is probably the result of a collision with a smaller rock, perhaps 3–5 m wide (10–15 ft). The collisional speed was probably about 18,000 km an hour (11,000 mph), releasing about the same energy as a small atomic bomb. The collision likely made a crater in the larger asteroid about 20–30 m in diameter (60–100 ft). Although this is the first such event to be observed (well, at least its immediate aftermath, if not the collision itself), modest-sized asteroids may smash into each other roughly once a year.

GEFION: ASTEROID AND METEORITE FAMILY

Should a planet pass near to a cloud of asteroid fragments it would experience a sudden meteor shower, a bombardment of meteoroid fragments. There is evidence for such an event happening to Earth in the Ordovician geological period, approximately 470 million years ago. Ordovician limestone rocks in Scandinavia contain fossil meteorites. The first was discovered in 1952 by stone workers in a quarry. It was about 10 cm (4 in.) in size, and languished in a geological collection until 1979 when its nature was realized. Now 90 similar fossil meteorites are recognized, all of them of the same type, and all of them fell to Earth at about the same time. The quarry is one of the densest fields, if not the densest field, of meteorites in the world. Associated with the recognizable lumps of fossil rock that are meteorites are tiny bits of original meteorite material in the form of little dust grains. At the other extreme of size, there are at least four meteor craters whose age matches the right time span, possibly caused by large fragments of the same shower.

The surface of the Moon also contains evidence of this shower of dusty fragments. The surface skin of lunar grains brought back by Apollo astronauts is permeated with elements that have been implanted from the solar wind, the gaseous atmosphere of the Sun against which the surface of the Moon is not protected by an atmosphere. Yet the composition of the skins does not match the composition of the Sun. There is something else that also infuses into the lunar grains, and that is, apparently, the impact of small interplanetary particles. The composition of the material can be related to its age because some of the material is radioactive and shows that the influx of non-solar material jumped by a factor of five about 470 million years ago, the same time that the fossil meteorites fell in the Swedish limestone.

Even today, 20 % of meteorite falls on Earth are of the same type as the Swedish meteorites, resulting from the same asteroid collision.

The spectrum of the asteroid (1272) Gefion, discovered in 1931 by Karl Reinmuth, matches the composition of the Ordovician meteorites. It is the largest of hundreds, perhaps a thousand or more, of asteroids with the same orbits; these asteroids make up the Gefion family. The hypothesis is that there was a collision between two asteroids, the larger being 200 km (150 miles) in diameter that created numerous fragments, large and small, that all have approximately the same orbit, and that we now see as asteroids and meteorites. The collision took place about a billion years ago in what Swedish geologist Birger Schmitz described as the "biggest bang in the Solar System for a billion years."

There have been about 20 asteroid collisions in the last billion years almost as big, the most recent the one that created the family of (832) Karin that occurred only 5,800,000 years ago. About 50 asteroid families have been identified altogether, including Vesta's family, all produced by past collisions.

HARTMANN AND DAVIS: ASTEROID THEIA MADE THE MOON

One collision that was particularly important for us here on Earth was the collision that occurred which created the Moon. It took place between the embryonic Earth and a planetesimal or asteroid dubbed Theia. In Greek mythology, Theia was a Titan (one of the earliest deities of the Greek pantheon), who gave birth to daughter, Selene, the Moon goddess. The theory originated with a suggestion in 1946 by Harvard geologist Reginald Aldworth Daly and was rediscovered in 1974 by Arizona planetary scientists William K. Hartmann and Donald R. Davis.

According to this theory, Theia struck the proto-Earth a glancing blow, scattering much of the mantle of each body into space, while the two liquid metal cores coalesced into one planet, like raindrops running together on a window pane. The glancing blow caused the larger body, Earth, to rotate more quickly, while its mantle material flew into orbit around Earth, condensing over time into a core-less second planet, the Moon. This theory is known as the Giant Impactor Theory, informally as the Big Splash. There is some controversy about the exact circumstances of the impact, and different versions envisage that the impactor itself could be the size of a small planet (like Mars) or a large asteroid (like Ceres). If the impactor is small, it is referred to as the Gentle Giant Impactor. The theory explains the fast rotation speed of Earth and the surprising fact, gathered from the lunar material brought back by the Apollo astronauts, that the Moon and Earth are all but identical in composition.

The theory also explains why Earth has a particularly large iron core. Because the core is so large, it has remained warm and liquid because of energy released by the decay of abundant radioactive elements within. The warm liquid rises and falls in strong currents through convection caused by the rapid rotation. This causes the strong magnetic field of Earth. Mars by contrast has a small iron core that has frozen solid, and its magnetic field has collapsed. A magnetic field shields a planet from the impact of particles from the Sun. Mars, without a magnetic field, lost its atmosphere, and its surface is irradiated by solar particles and sterile. Earth, with a strong magnetic field, has a surface that has been protected from solar particle radiation and maintained a benign environment in which life has flourished.

The chaotic Solar System and the role of asteroids within it have had a profound effect on the development of life here on Earth over long periods of time.

ASAPH: ASTEROIDS CAPTURED BY MARS?

Asaph Hall, (2023) Asaph, discovered Phobos and Deimos, the satellites of Mars. In Greek mythology Phobos (panic/fear) and Deimos (terror/dread) were the sons of Ares (Mars is the Roman equivalent) and accompanied their father into battle. Both satellites were discovered in August 1877 at the US Naval Observatory in Washington DC Hall had set out deliberately to try to discover whether Mars had moons and struggled for a week through summer fog and thunderstorms to confirm his first glimpses, first of the outer moon, Phobos, and then the inner moon, Deimos. The names were suggested to Hall by Henry Madan, Science Master of Eton School, using Book XV of the *Iliad* as his source:

> *Mars smote his two sturdy thighs with the flat of his hands, and said in anger, "Do not blame me, you gods that dwell in heaven, if I go to the ships of the Achaeans and avenge the death of my son, even though it end in my being struck by Jove's lightning and lying in blood and dust among the corpses." As he spoke he gave orders to yoke his horses Panic and Terror, while he put on his armour.*

The family has the distinction of having christened three Solar System bodies through classical allusions. Henry Madan was the brother of Falconer Madan, the librarian of the Bodleian Library of the University of Oxford. Falconer's 11-year old granddaughter, Venetia Burney, suggested the name Pluto for the planet, discovered in 1930.

Both moons are small, 22 and 13 km (13 and 8 miles) in diameter, respectively, and both are heavily cratered—especially Phobos—and dusty (Figs. 10.2 to 10.4). The largest feature on the surface of Phobos is a crater with a diameter about 9.5 km (6 miles). It is called Stickney, which was the maiden name of Asaph Hall's wife. Large grooves radiate from the crater.

Both moons look like captured asteroids, although there are other theories of their origin, such as that they formed as material ejected from Mars in a big impact gathered together. Phobos in particular looks a lot like the asteroid (953) Gaspra, which was the first asteroid imaged close up by a spacecraft, when it was approached by the Galileo space probe in 1991 on its way to Jupiter (Fig. 10.5). When ESA's Mars Express spacecraft entered the Martian system for a protracted investigation, it was deflected slightly in its orbit by the Martian moons. This enabled the controllers to measure the mass of Phobos. Its density is rather low. Phobos contains cavities, just like asteroids.

If something looks like a duck and quacks like a duck, maybe it is a duck. Maybe the moons of Mars are indeed asteroids, captured as they passed by. But the way that this might have happened is not clear. To be captured, a passing asteroid needs to give up some of its orbital energy, usually to some third body, like another satellite. Otherwise the asteroid will indeed pass on by. There is no sign that Mars ever had a satellite that would help it to capture two more. Perhaps the encounters were more complicated, such as the capture of double asteroids.

There are other issues that have not been solved. The passing asteroid is likely to be approaching the potential host planet at an arbitrary angle. But the moons of Mars orbit around the equator of Mars. It is considered unlikely that two asteroids would approach Mars in just the right way to line up so exactly.

Although there is no accepted scenario that allows Mars to gather two asteroids and bring them into orbits like the present orbits of the moons, it may have been common in the early history of the Solar System for the large planets to capture asteroids. (This kind of event is not as common now, the Solar System having become more orderly as the larger planets gathered up asteroids or shepherded them into specific holding zones, like the Asteroid Belt or the Kuiper Belt, as suggested by the Nice simulation.) Perhaps half of the 67 moons of Jupiter are small and rather distant from their parent planet, often orbiting in eccentric orbits that are tilted relative to the orbit and the rotation of the planet itself. This indicates that these small moons have their origin as captured asteroids, events that have been aided by the pre-existing large moons of Jupiter acting as the third body in the capture.

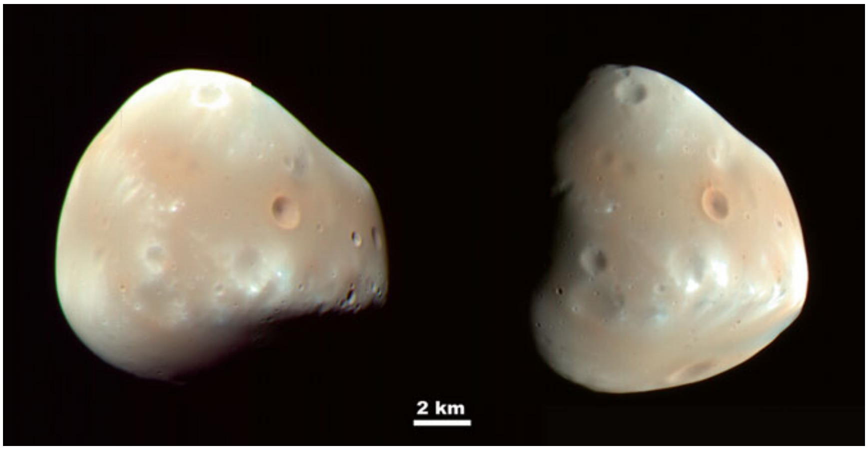


Fig. 10.2 The surface of Deimos is blanketed by pulverized rock and dust ("regolith") and smooth, except for impact craters. It is a dark and reddish object, with brighter and fainter red surface materials the most recent (NASA/JPL-Caltech/ University of Arizona)

Fig. 10.3 The larger of Mars's moons is shown to be heavily cratered in this image from ESA's Mars Express. The surface is covered with grooves and streaks that radiate outwards from a particular point. Phobos is locked in orbit around Mars and always moves with the same face forwards. The center of the radiating grooves lies at the leading point. The theory is that the grooves have been formed by collisions between the moon and other rocks that were orbiting Mars, perhaps ejected into space from the surface of Mars itself after a big asteroid impact on the surface. Imagine a car traveling at high speed through a cloud of gravel chips dropped from a truck ahead. The scratches on the bodywork would radiate out from the nose of the car (G. Neukum [FU Berlin] et al., Mars Express, DLR, ESA)

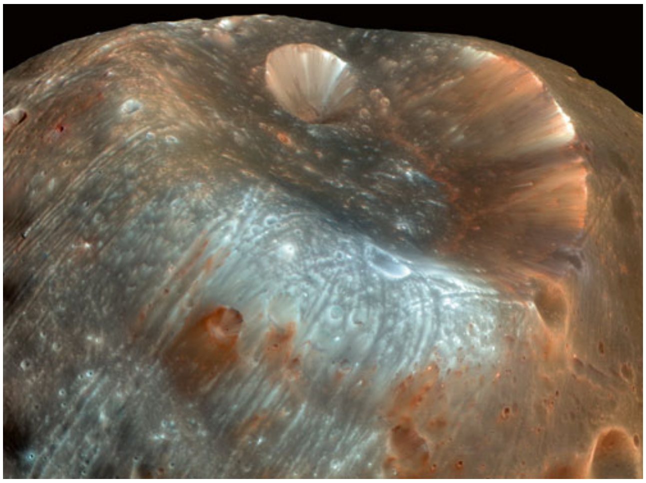


Fig. 10.4 The crater Stickney on Phobos is about 9 km (6 miles) across. Landslides slip down from the crater's rim into its interior. Impacts have excavated material from below the ground and spread it onto the surface. Colors are much exaggerated and indicate the freshness of the surface material, red being older (NASA/JPL-Caltech/University of Arizona)

Fig. 10.5 The Galileo spacecraft imaged Gaspra in 1991. Its surface has many small craters. Perhaps it was created in a collision with the craters, the result of which was a cascade of small pieces on to its surface. Gaspra is rather similar to Mars's larger satellite, Phobos (NASA/USGS)

Chapter 11

The Fate of Asteroids

NEMESIS: DUST TO DUST

Nemesis in Greek mythology was the goddess of retributive justice or vengeance. Her name was given to asteroid (128) Nemesis discovered in 1872 by James Watson at Ann Arbor, Michigan and independently by the French astronomer Alphonse Borrelly, (1539) Borrelly, at Marseilles. Borrelly discovered 20 minor planets and 18 comets. One of the 18, Comet 19P/Borrelly, is periodic. It was visited by the spacecraft Deep Space 1 in 2001, and punctured to reveal its interior composition by slamming the spacecraft into the comet at the end of its mission. The goddess's name has been absorbed into general language as a term for a source of harm or ruin. "Nemesis" is fate in its negative aspects. Nemesis aptly describes the two fates to which most asteroids are subjected—total rejection or total absorption.

Most of the early minor planets in our Solar System were ejected into interstellar space by Jupiter and Saturn, as described by the Nice simulation (see Chap. 10). Some of the ones that did not leave now occupy the far zones of the Kuiper Belt and the Oort Cloud. They are vulnerable to disturbance by passing stars or massive clouds of gas orbiting our galaxy. They may get themselves detached from our Solar System and fly off at any time. Presumably, similar events took place in other planetary systems. Interstellar space must be pervaded by all these wandering, alien worlds, wandering in the cold and dark, frozen. Space is large and minor planets are small. Probably interstellar minor planets almost never encounter anything else. They have been mostly put into eternally suspended animation.

However, rarely, one of them might venture into another planetary system. It would enter at an arbitrary angle and have an eccentric orbit, long and thin. We can wonder whether such a thing has ever occurred in our own Solar System. Perhaps Sedna is such a captured dwarf planet, an exotic intruder in our Solar System. Alternatively, the captured object might plunge further into the Solar System, in an orbit like a comet, falling in at critically high speed past our Earth before zooming off back into interstellar space.

Have any minor planets like this been seen? A number of comets have been observed whose orbits do indeed have the same characteristics as the orbits of comets that originated in interstellar space. They travel fast through the Solar System and will escape from it on the way out. However, the comets that do this only just do this. It could well be that these comets are ordinary Solar System comets, but there are small errors in the measurements, and we erroneously think they are speeding. Or, perhaps, there has been some small effect on these Solar System comets that has pushed them to go a little faster, like an encounter with another planet. Comets often pass near to Jupiter and can be given extra speed by being swerved around it. Another idea originates from the jets of material that have been seen spurting from some comets, like fountains. If the fountain points

P. Murdin, *Rock Legends*, Springer Praxis Books, DOI 10.1007/978-3-319-31836-3_11

backwards, it gives the comet a push forwards, and could speed it up in its orbit. Effects like these could also account for all these apparently interstellar comets, and, really, they might all have originated in our Solar System. Like a crafty motorist, they are speeding, but only just over the speed limit. It all depends on what the evidence shows.

Another indication that a comet or an asteroid comes from interstellar space would be that its composition would be typical of the planetary system where it originated, rather than similar to our own Solar System. Attempts to identify “foreign” comets over the past few decades using this criterion have all been negative, or equivocal.

So, not many minor planets that leave their planetary system find another home. The fate of minor planets that have left or may still leave their planetary systems is a lonely, frozen eternity. The eventual fate of the minor planets that remain, the minor planets that are in our Solar System now, is warmer.

In about 5 billion years our Sun, like all stars of about its mass, will swell up to red giant size. It will have lost some of its mass in this process, loosening its hold on the planets and asteroids. They will have moved outwards from their present orbits. The net result is that the Sun will swell out to just about the then orbit of Mars, completely engulfing Mercury, Venus and Earth. Mars might just about survive for a time, but roasted. Any ices and volatiles in the nearer asteroids will be evaporated, and most of the Main Belt asteroids will be diminished in size.

The Sun will swell up at first into a large red giant and then shrink to become a white dwarf, quite quickly fading away and dying. As it does this, it will puff off its outer layers as a so-called planetary nebula. The Sun will lose about half its mass in this process, and its hold on the remaining planets will be loosened still further. A white dwarf star is very hot, pouring out ultraviolet radiation, so the remaining planets and minor planets will be strongly irradiated.

The chaotic effect of the larger outer planets on the minor planets that remain in orbit around the white dwarf will be to cause some of them to alter their orbits, in much the same way that near-Earth asteroids are constantly being created in the Solar System in our own time. Some will venture too near their parent white dwarf sun and be broken up by tidal forces, creating much dust. The white dwarf star will have rings, like the rings of Saturn, and about the same size. Jostling in orbit, the bits of asteroids will, as they do now, bump, grind and collide, creating more dust. Some of the dust will stream into the white dwarf. The asteroids will be absorbed into their parent sun.

There is evidence for this scenario. The force of gravity at a white dwarf’s surface is high because the star is not much less massive than the Sun, but all that mass is compressed into a body the size of Earth. The strong surface gravity of a white dwarf causes the heavier elements in its atmosphere to sink towards the bottom, leaving the lighter elements, hydrogen and helium, at the top, much as oil might float on the surface of the sea. Yet, although this is so, astronomers looking from the outside into the top of the atmospheres of white dwarfs can see evidence for heavier elements, particularly iron, silicon, oxygen and magnesium. This paradox has been a puzzle to astronomers for nearly 50 years, the source of these elements unknown. The solution that has recently been emerging is that these heavier elements come from asteroids in orbit around the white dwarfs. The evidence has built up, bit by bit; for example, the heavy elements that have been detected in white dwarfs are exactly as abundant as they are in meteorites. Just as meteorites are fragments of asteroids that have fallen to Earth, so also rocky material has fallen into white dwarf stars.

It is not possible for terrestrial astronomers directly to detect individual asteroids and minor planets in orbit around other stars. But there is further evidence that they exist in orbit around white dwarfs. Half a dozen white dwarfs stars have been seen with the infrared-sensitive telescope on the Spitzer spacecraft that are orbited by dust that looks exactly like shredded asteroids.

We have the evidence to put together the big picture of the birth of asteroids and their probable fate. Our asteroids formed in the dust left over from the birth of the Sun at the origin of our Solar System. The indications are that they disappear either by being ejected into space or by turning into dust again and being absorbed into the dying white dwarf that the Sun will become. Dust to dust.

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"…glaube ich den Wunsch äußern zu dürfen, dass die Controverse über den, in wissenschaftlicher Beziehung unerheblichen Gegenstand, in diesen Blättern nicht weiter gefürht werde." (Schmadel, p. 6)

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Et pour la dénomination, ne pourroit-on pas appeler les petites planètes, planetoides? Car je vous avoue, le nom d'Asteroides me paraît plus propre aux petites étoiles

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