2. Asteroids

> I surmise (again) that possibly numbers of such small bodies that have not matter enough in them to hurt one another by attraction, or to disturb the planets, may possibly be running through the great vacancies, left perhaps for them, between the other planets, especially Mars and Jupiter.
>
> – William Herschel, *Observations on Two Newly Discovered Bodies (Vesta and Ceres)* [1]

> This may serve as a specimen of the dreams in which astronomers, like other speculators, occasionally and harmlessly indulge.
>
> – Sir John Herschel, on the possibility of more than four asteroids [2]

When we look at a scale map of the Solar System, it's immediately obvious that there's a disproportionately large gap between the orbits of Mars and Jupiter. After he had deduced the relative sizes of the planetary orbits, Johannes Kepler modestly wrote, "Between Mars and Jupiter I have put a planet." The gap is dramatically illustrated by the image of Earth, Moon and Jupiter taken by the Mars Global Surveyor, and the corresponding orbital geometry (Fig. 2.1a, b).

In the late eighteenth century an international group of astronomers started a search, calling themselves the Celestial Police, and on January 1, 1801, Piazzi found Ceres, the first of the asteroids to be discovered. It was immediately obvious that it wasn't large enough to be classed as a true planet, so the search continued. Even though Ceres is the largest of the asteroids, it's less than 1,000 km in diameter, and the surface gravity can't be much more than 0.03 g.

Wilhelm Olbers discovered Pallas, the second known asteroid, on March 28, 1802, and Harding of Lilienthal discovered Juno on September 2, 1804. Vesta, the fourth to be discovered in the Main

D. Lunan, *Incoming Asteroid!: What Could We Do About It?*,
Astronomers' Universe, DOI 10.1007/978-1-4614-8749-4_2,

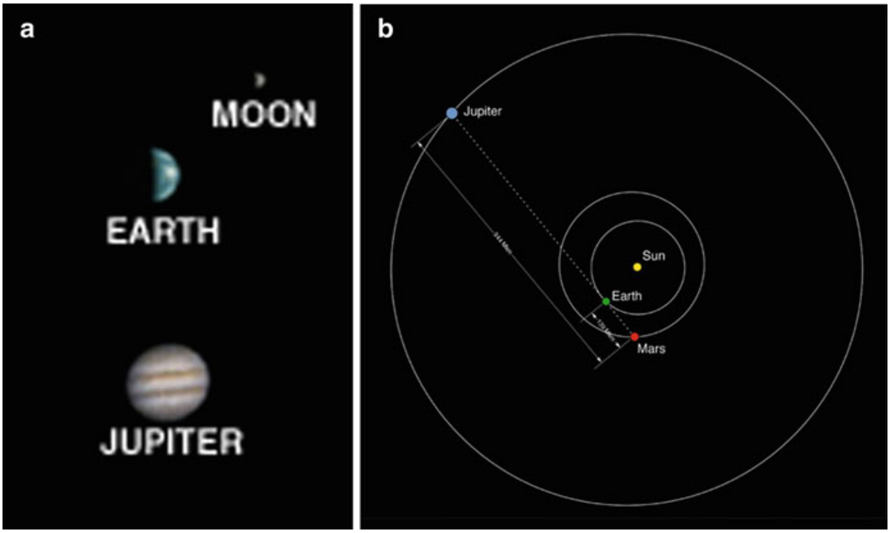


Fig. 2.1 (**a**) Jupiter in conjunction with Earth and the Moon, imaged by Mars Global Surveyor, May 2003 (NASA). (**b**) Orbits and positions of Earth, Mars and Jupiter, May 2003 (NASA)

Belt, was found by Olbers on March 29, 1807, and since then many thousands have been found, more than the Herschels dreamed of in their wildest moments. Vesta is visually the brightest, at the limit of naked-eye visibility when it's overtaken by Earth. About the size of Arizona, in the southern hemisphere it has a huge crater 465 km across and 12 km deep, as wide as Vesta itself; the equivalent on Earth would be the size of the Pacific basin. More than 50 smaller asteroids with similar compositions, 'Vestoids,' were formed in the collision, and many fragments blasted off it make up a family of asteroids [3]. Some of them reach Earth as meteorites.

At first it was thought that there had originally been a planet between Mars and Jupiter, where the Asteroid Belt is now (Fig. 2.2). Instead, we now know that Jupiter's gravitational pull caused the protoplanets in that area of the Solar System to collide with too much violence for their fragments to coalesce. Some of those protoplanets were large enough to have been heated internally by radioactive decay, causing them to be gravitationally differentiated, with crusts, mantles and cores—pieces of which now reach Earth as stony meteorites, stony-irons and metallic ones of nickel-iron.

Protoplanets in the outer region also had significant concentrations of water and possibly organic compounds. So in the multiple

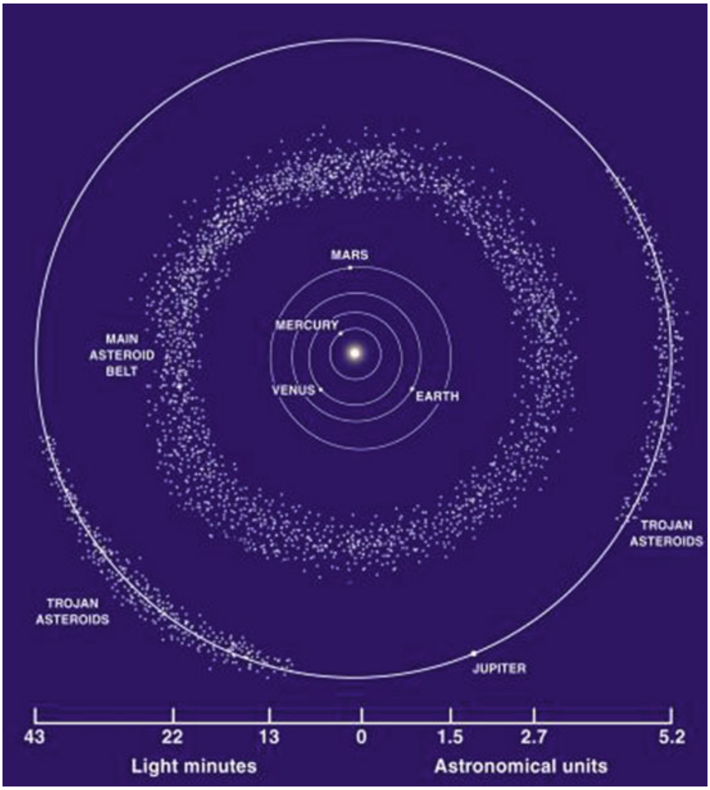


Fig. 2.2 The Asteroid Main Belt and Trojan groups (NASA)

collisions asteroids of many different types were formed, and although there is a general difference in composition between the inner and outer belts, all kinds are represented, as far as we know, in the population of asteroids whose orbits have been perturbed sufficiently to pass near Earth and occasionally collide with it.

Generally, carbonaceous asteroids come from the outer edge of the belt, stony ones from the middle and metallic ones from the inner edge. Some of them have undergone virtually no evolution from the primal days of the Solar System, and they contain the decay products of radioactive transuranic elements that were formed in the supernovae whose shockwaves caused the original Solar System nebula to collapse. The oldest material is often found in chondrules, which are fragments of the earliest condensates, embedded in more recent rock. The fragments collected from the asteroid that exploded over Chelyabinsk in Russia on February 15,

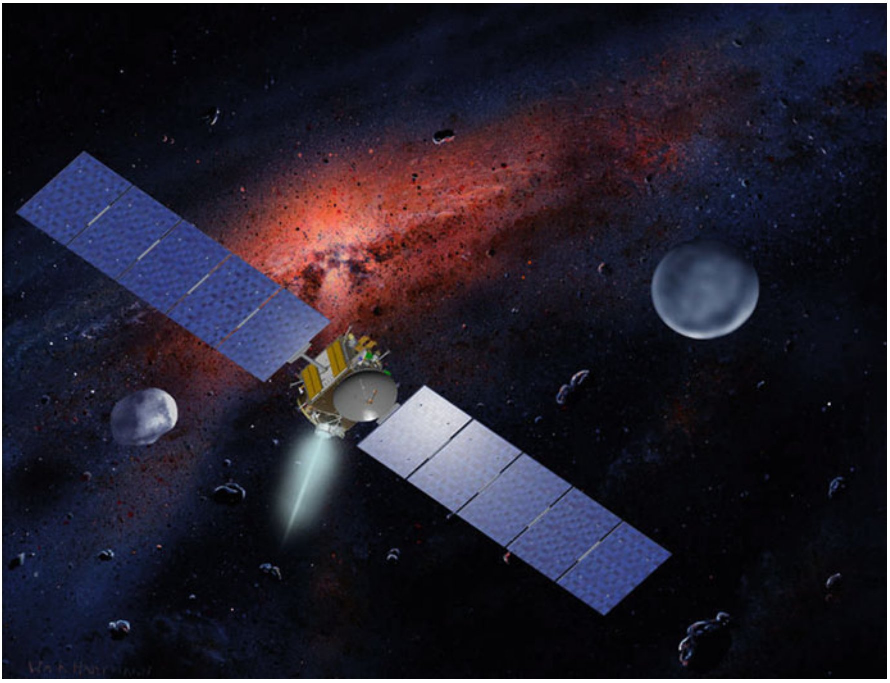


Fig. 2.3 Dawn among the asteroids (NASA)

2013, showed it to have been a rocky chondritic body, with a 10% content of nickel-iron, shot through with veins of once-molten material from a collision and fragmentation event, much earlier in its history.

Writers, artists and film producers (even today) like to portray dense asteroid fields (Fig. 2.3). The pulls of the planets have separated the Main Belt into three main bands and a lesser one, separated by 'Kirkwood gaps' (Fig. 2.4), and although occasional collisions between asteroids produce streams of asteroids in near-identical orbits (Fig. 2.5), there's so much space between them that normally one could spend a lifetime on an asteroid without ever having another come within naked-eye range. If the Asteroid Belt were really as dense as portrayed, maybe it would lend weight (literally) to the idea that the belt is the debris of a shattered planet. In fact the total mass of the belt is less than 10% of Earth's, possibly much less.

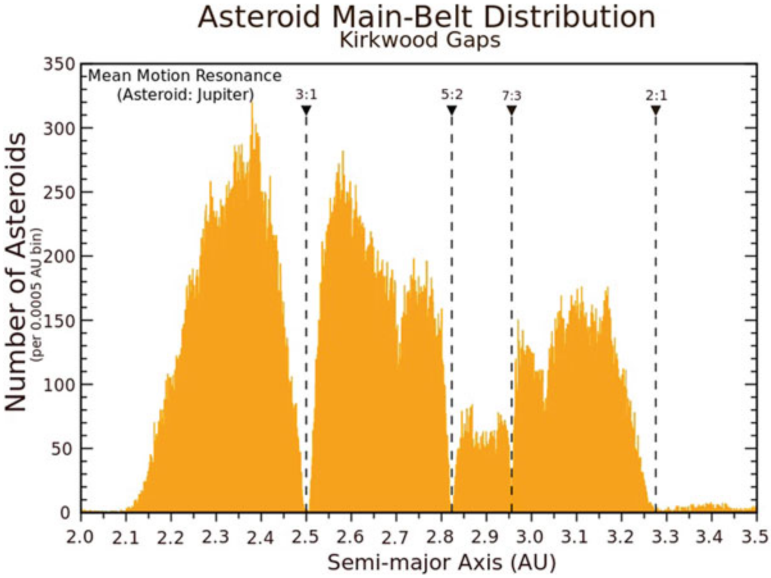


Fig. 2.4 The Kirkwood gaps (NASA)

Fig. 2.5 Hubble Space Telescope image of asteroid 2010 A2 LINEAR collision (NASA)

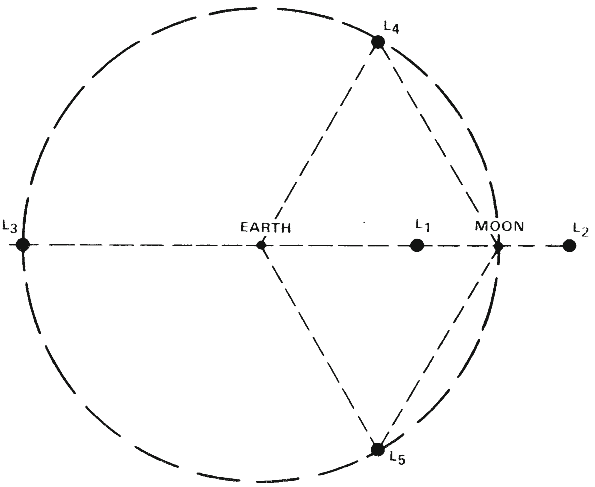


Fig. 2.6 Lagrange points in Earth-Moon system (NASA)

Thule is the Greek and Roman word for the north, as in Ultima Thule = furthest north, and it was allocated to an asteroid at 4.3 astronomical units, which was thought to mark the outer limit of the Asteroid Belt, until the Trojan asteroids were found sharing the orbit of Jupiter. The Trojan asteroids are in the same orbit around the Sun as Jupiter itself, equidistant from the planet and the Sun. They circulate around the fourth and fifth position calculated by Lagrange as special solutions to the problem of gravitational attraction between three bodies, which has no general solution even today. Lagrange points are generated whenever one massive body orbits another, for example Earth and the Moon (Fig. 2.6), Earth and Sun (whose L1 and L2 points were mentioned in Chap. 1), or Jupiter and the Sun. An asteroid has recently been discovered occupying the Sun-Earth L4 point, Mars has at least seven such companions, Neptune at least four [4], and Uranus has at least one [5]. Several of the moons of Saturn have companions at L4 and L5, which are also known as 'equilateral points' because the satellites maintain a fixed triangular relationship with the planet and the larger moon.

Orbits around equilateral points are more stable than those around L1 and L2, which are conditions of unstable equilibrium in which artificial satellites require regular station-keeping. Originally, the asteroids around one of the Jupiter equilaterals

Fig. 2.7 Venus from Toro during sunward pass (© Andy Paterson, 2000)

were to be called Trojans and the ones in the other were to be Greeks, all named after characters in the *Iliad*, but not all astronomers have full classical educations and the two groups quickly became mixed up.

In recent years a number of asteroids have been found circling the Sun in orbits that are resonant with Earth's, producing recurring close encounters. Cruithne (1986 TO) is an example [6], one designated 2002 VE68 has a similar bound relationship to Venus and Toro has a recurring pattern of encounters with Earth and Venus (Fig. 2.7). Some of them follow highly complex, unstable 'horseshoe' orbits, from which they will soon drift away, and Uranus has at least three companion asteroids like that [5]. Although these small bodies are of great interest for future space missions (see Chap. 8), none of them pose immediate threats to Earth, although that could change in the long term due to the pulls of the other planets.

(Note that asteroids are designated by the year of discovery, followed by a letter saying in which of 24 half-months it was found, and another letter indicating the day, followed by a number if more than one was found on the same day. As the discovery rate goes up, such designations are becoming increasingly cumbersome and are eventually replaced by single numbers in a full catalog. Names are usually proposed by discoverers, and ratified by the International Astronomical Union after due consideration. At least one participant in this project, the late Prof. Archie Roy, has already been honored—5806 Archieroy has been official since May 1995.)

The majority of meteorites come from the Asteroid Belt, where protoplanets formed and shattered in the early history of the Solar System. Since they had a range of chemical compositions, and had differentiated internally to different extents, the fragments contain a bewildering range of materials that took a long time to interpret. The important class of carbonaceous chondrites, containing organic compounds and the oldest, unaltered solid material, come from the outer Asteroid Belt, or from cometary nuclei, and as noted earlier, some 'Earth-grazing' asteroids, which come this far in towards the Sun, may be the nuclei of dead comets.

The Dawn probe (Fig. 2.3), launched in September 2007, was boldly targeted to orbit both Vesta and Ceres. Little was known of either, even the best images from the Hubble Space Telescope being little more than silhouettes, though a lot could be guessed about Vesta from comparison with meteorites, and there were great hopes that the crater at the south pole would let us see the interior of it.

Nothing in the Solar System has turned out to be what we expected. The author's *New Worlds for Old* (1979) was subtitled *The New Look of the Solar System* [7], and every space mission changes that 'look' again. Dawn entered orbit around Vesta in July 2011 and the asteroid has turned out to be far more complex and interesting than anyone had imagined. Hubble images of Vesta showed a marked point at the south pole, which had been thought to be a ridge between craters. But instead it's a mountain, 15 miles high—more like Olympus Mons on Mars than Mt. Everest, to which it was compared—planked on the pole as if by a gentle impact. Curving around it was a long, scalloped line of overlapping rings from two very large, superimposed impacts, and on the other side, there were roughly parallel grooves in the shape of a chevron. At first glance they resembled features on Miranda, the innermost of the five large moons of Uranus, which has been blown apart by a

Fig. 2.8 Dawn spacecraft image of Vesta, showing equatorial grooves and 'snowman' craters (NASA)

huge impact, with the fragments reassembled in the wrong order, like pieces of a jigsaw forced into places where they don't belong. But further evidence now shows that Vesta, like Lutetia below, is a single piece—intact since the origin of the Solar System, large enough to have been differentiated internally by radioactive heating, but with its surface much altered by collisions. Standing on the equator, three craters of increasing size in a row resemble a negative image of a snowman. Also on the equator huge parallel grooves were found, like those on Phobos (see below), but the largest of them, 10 km across, is as wide as Phobos itself (Fig. 2.8).

Craters with dark markings proved to be the impact points of carbonaceous asteroids, confirmed by releases of hydrogen from dark deposits on the surface, with pits like those formed by escapes of water from below the surface of Mars. There was even apparent evidence of erosion by water action, presumably in the presence of temporary atmospheres. And among many unexplained features, there was a pyramidal peak. Similar ones in terrestrial deserts are shaped by wind-blown sand, as presumably are the larger ones a kilometer wide found on Mars—but this was a jaw-dropping 5 km.

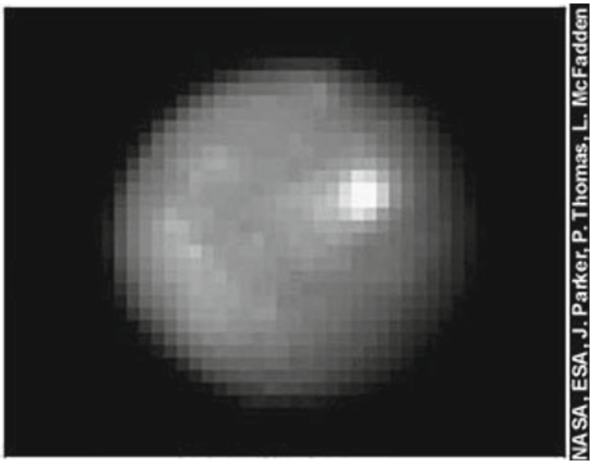


Fig. 2.9 Hubble Space Telescope image of Ceres (NASA/ESA)

It all promises great things when Dawn gets to Ceres. After over a year of taking pictures from orbit at various heights over Vesta, Dawn is due to arrive at Ceres in 2015. The largest of the asteroids has a very intriguing feature (Fig. 2.9), a bright spot reflecting sunlight as if it's water—presumably ice. But there have been suggestions of liquid water, which isn't possible at that distance from the Sun, still less in vacuum—unless it's under glass! After what we've seen on Vesta, it's tempting to add that nothing would come as a surprise—but we can be sure that there will be.

Encounters with Asteroids

> …the ways by which men arrive at knowledge of the celestial things are hardly less wonderful than the nature of the things themselves.
>
> – Johannes Kepler

From 1971 to 2010, it was believed that the first asteroids to be photographed by spacecraft were Phobos and Deimos, the two tiny moons of Mars discovered by Asaph Hall in 1877. However, the close flyby of Phobos by Europe's Mars Express probe in 2010 detected hydrated rocks of types that had already been located on the Martian surface. The startling conclusion was that Phobos and

Fig. 2.10 Galileo spacecraft image of the asteroid Gaspra, 1991 (NASA)

presumably Deimos were formed from material blasted off the surface of Mars in big impacts—like the formation of Earth's Moon, but on a smaller scale. It ruled out the idea that the moons of Mars are captured asteroids, which until then had been widely believed.

So the first true asteroid pictures, after all, were the ones which the Galileo spacecraft obtained of the asteroid Gaspra on its way to Jupiter in October 1991. Gaspra is a stony asteroid about 12 km in diameter near the inner edge of the Main Belt. It proved to have a faceted appearance (Fig. 2.10), having been broken off from a larger body about 200–300 million years ago, and the only real surprise was that enhanced contrast showed up many hundreds of small craters, partly masked, it seemed, by thick regolith 'soil' composed of broken rock, as mysterious as the surface layers of Phobos and Deimos. It's not yet understood how such small bodies can accumulate regolith, when the debris from impacts should be blasted off into space and they don't have sufficient gravity to pull it back.

In Galileo's photographs of another asteroid, Ida, in August 1993, there was an unexpected satellite named Dactyl. Until the Ida flyby, professional astronomers insisted that asteroids were too small to have satellites. Amateur observers and meteor experts were less surprised because there had been a number of occasions

Fig. 2.11 Clearwater Lakes, Canada (NASA)

when asteroids passed in front of stars, and amateurs reported double occultations. In Canada there's a matched pair of impact craters called the Clearwater Lakes (Fig. 2.11), and a number of the asteroids were known to have dumbbell shapes, though nobody could explain how such small bodies might bump together gently enough to stick. But perhaps it does happen, because Ida and Dactyl are quite different in composition (Fig. 2.12), so Dactyl isn't a fragment detached from Ida by a collision, although capture of one asteroid by another is even less likely. Nevertheless, large numbers of binary asteroids have now been found, and several with more than one satellite.

It was thought that dumbbells have been formed by mergers, and that seemed to be confirmed by a deep valley found on Ida, plus a second one on Eros found by the NEAR-Shoemaker probe (Fig. 2.13). Nevertheless, despite having a huge saddle-shaped bite

Fig. 2.12 Ida and Dactyl, 1993, in enhanced color to show differences in composition (NASA)

Fig. 2.13 NEAR-Shoemaker image of stony asteroid Eros in 2000 (NASA)

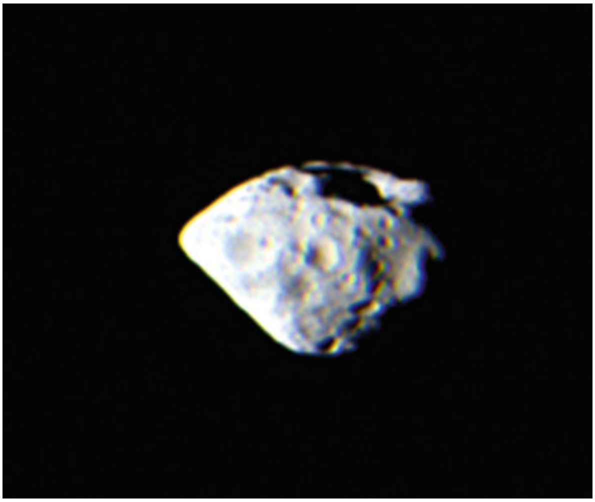


Fig. 2.14 Asteroid Steins from Rosetta, 2008 (ESA)

out of it, Eros is still a single object. In 2008 the Rosetta probe flew by asteroid Steins, and found it to be so faceted by multiple collisions that it looked like a gemstone, a diamond in the sky (Fig. 2.14). The biggest crater was nearly half the asteroid's diameter at 2.1 km, suggesting that it had to have a really solid structure. But the Main Belt asteroid Annefrank, visited in 1992 by the Stardust probe, shows genuine variations in composition and appears to be a contact binary, formed by merger of two or more objects.

In June 1997 the Near Earth Asteroid Rendezvous mission, renamed NEAR-Shoemaker in honor of the late co-discover of Comet Shoemaker-Levy (Chap. 1), flew past Mathilde, a carbonaceous Main Belt asteroid 50 km in diameter, in a comparatively eccentric orbit, ranging out to the belt's outer edge. The biggest difference from Gaspra and Ida was that Mathilde showed very large craters, and their sharp edges indicated that a lot of material had been removed by 'spalling,' in which the crust peels away from the impact site. Its low density indicated large voids within the asteroid, yet there was little variation in the appearance of its dark surface, suggesting a very even composition (Fig. 2.15). There was an even bigger surprise in 2010 when the Rosetta probe passed the asteroid Lutetia. With a diameter of about 100 km Lutetia was

Fig. 2.15 NEAR-Shoemaker image of carbonaceous asteroid Mathilde (NASA)

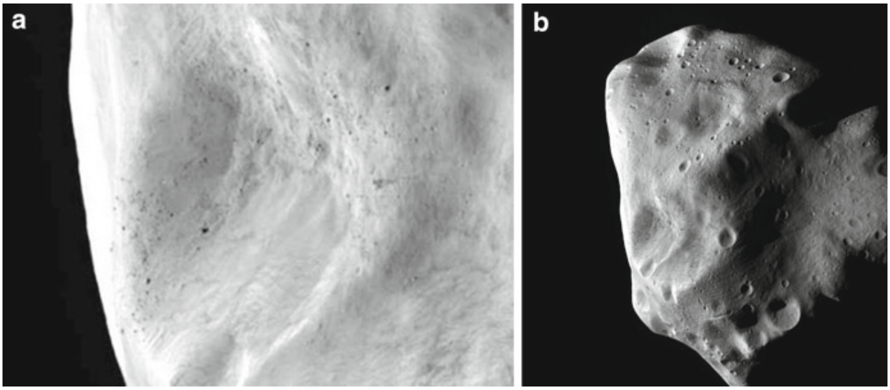


Fig. 2.16 (**a**) Lutetia regolith and boulders in close-up. (ESA). (**b**) Asteroid Lutetia imaged by Rosetta, 2010, with parallel grooves at bottom center (ESA)

much larger than the other asteroids surveyed so far, and again a 45-km crater suggested that it was solid, although surface features suggested extensive internal fracturing. Lutetia had been thought to be metallic and may have a metal core (see Chap. 8), though the outer layers appear to be metal-rich carbonaceous chondrite. Its regolith cover was 600 m thick, again strewn with boulders (Fig. 2.16a), and intriguingly it showed parallel grooves (Fig. 2.16b). Similar ones are found on Phobos, but straight; perhaps both are due to the flow processes now being found on many other small bodies. It appears that even Lutetia is not a collision fragment but a body that has remained intact since the formation of the Solar System, initially possessing a molten core.

Near Earth Asteroids

> What you don't know about won't hurt you.
>
> – common misconception

In the last few years there has been a big increase in the number of asteroids discovered and classified (see Chap. 4), and it is becoming apparent that most of the ones approaching Earth are the products of collisions in the main belt, rather than simply being perturbed in our direction by Jupiter. The first near-Earth asteroid to be visited was Eros, the 433rd asteroid to be discovered, by Witt, at Berlin in 1898. It immediately became important because it can approach to within 23 million km of Earth (Fig. 2.17) and could be used to gain a more accurate value of the astronomical unit, Earth's mean distance from the Sun, which gives the scale of the whole Solar System. In 1900 Von Oppolzer noticed big changes in magnitude as the asteroid rotated, indicating an elongated shape, about 37 km long and 16 km wide. With a rotation of only 5 h 16 min, that would give it a gravity of about one-hundredth of Earth's at the poles, but only one thousandth at the equator because of centrifugal force. In their book *Islands in Space, the Challenge of the Planetoids* (1966), Cole and Cox argued that the United States should abandon its target of a Moon landing before 1970 and go for a mission to an Earth-grazing asteroid instead [10]. Some of them could be reached with less fuel expenditure than the Moon itself, but their mission plan would take weeks longer than a Moon landing and put a severe demand on life support. They proposed landing Apollo tail-first on the target, and the difficulty of that was discussed, using Eros as an example, in the author's *Man and the Planets* [9].

Despite its dumbbell shape it has a uniform composition, and another mystery is that its surface was dotted with small boulders, although its surface gravity is too low to pull impact debris back. One possible explanation was that they've been left exposed

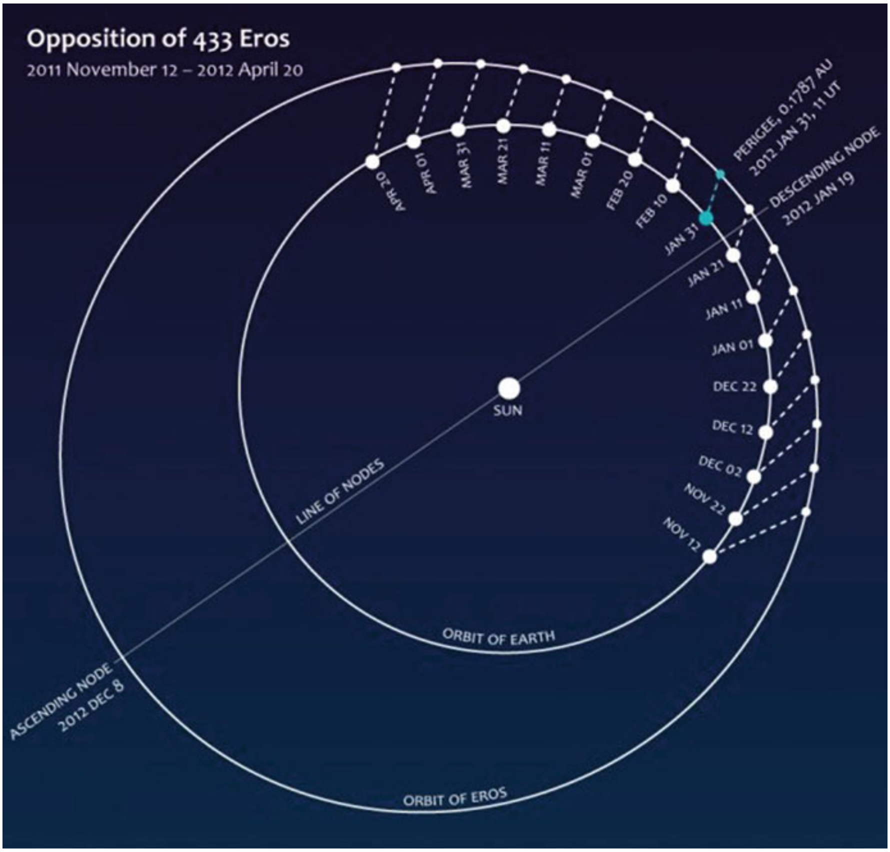


Fig. 2.17 Orbit of Eros, passing Earth in 2011–2012 (NASA)

as softer material was worn away by thermal and micrometeorite erosion, but grooves on the surface indicated that regolith material was flowing downhill towards the center of mass, even in the very low gravities of 0.001 g or less (Fig. 2.18). At the end of its mission NEAR-Shoemaker touched down on Eros. It wasn't designed to do it, but the landing proved much easier than expected, and contact with Earth continued for two more weeks, though no pictures could be transmitted from the surface.

Eros is technically an Amor-class asteroid, meaning that its orbit brings it relatively close to Earth's but doesn't actually cross it (Fig. 2.19). Apollo-class asteroids do cross Earth's orbit, Aten-class ones orbit entirely within the orbit of Mars, and Atira-class move entirely within Earth's orbit. All these are what we used

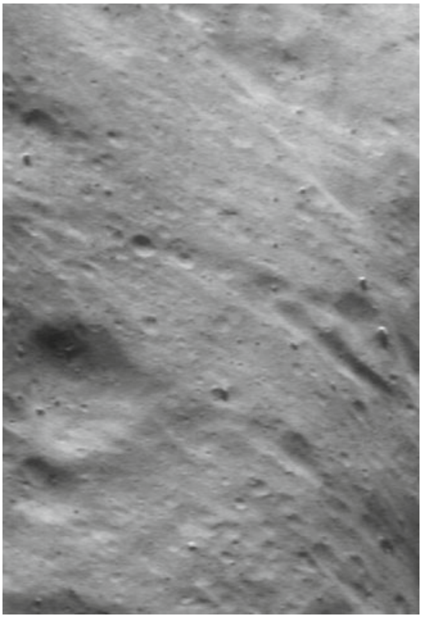
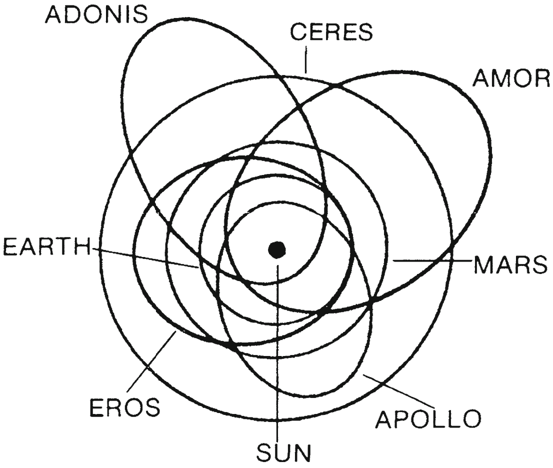


Fig. 2.18 Boulders and grooves on Eros (NASA)



Nature of the orbits of some characteristic asteroids.

Fig. 2.19 Orbits of Earth, Mars and some asteroids (NASA)

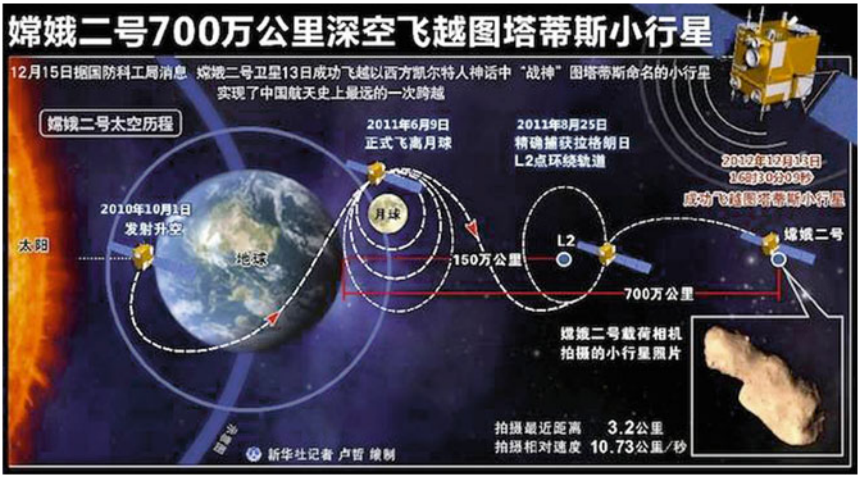


Fig. 2.20 Chang'e 2 mission including Toutatis flyby (© news.xinhuanet.com, 2012)

to call Earth-grazers, now more neutrally known as near Earth objects (NEOs). Most pose no immediate threat to Earth, although it can be shown mathematically that all of them will hit Earth, the Moon or Venus over the next 100 million years [10]. As most of the NEOs are stony in composition, it can be said that Eros is our first close-up glimpse of the threat.

At the time of writing the most recent encounter with an asteroid was in December 2012, when the Chinese space probe Chang'e 2, diverted from orbit around the Moon via the L2 point (Fig. 2.20), passed an asteroid called Toutatis at 3.2 km. Toutatis is a stony Apollo asteroid, 4.5 km long by 1.9 km across, in a resonant orbit with Earth and Jupiter and so creates recurring encounters with Earth every 4 years. It had previously been imaged by radar from Arecibo and other sites and found to be a dumbbell (Fig. 2.21a), almost certainly two merged objects and perhaps a 'rubble pile.' The Chang'e 2 images showed the asteroid as more angular than had been supposed, but with the same regolith, small craters, boulders and smooth areas seen by other missions, though there seemed to be some major variations in the composition of the surface (Fig. 2.21b).

In November 2005 the Japanese Hayabusa probe used low-thrust propulsion for a rendezvous with Apollo asteroid Itokawa.

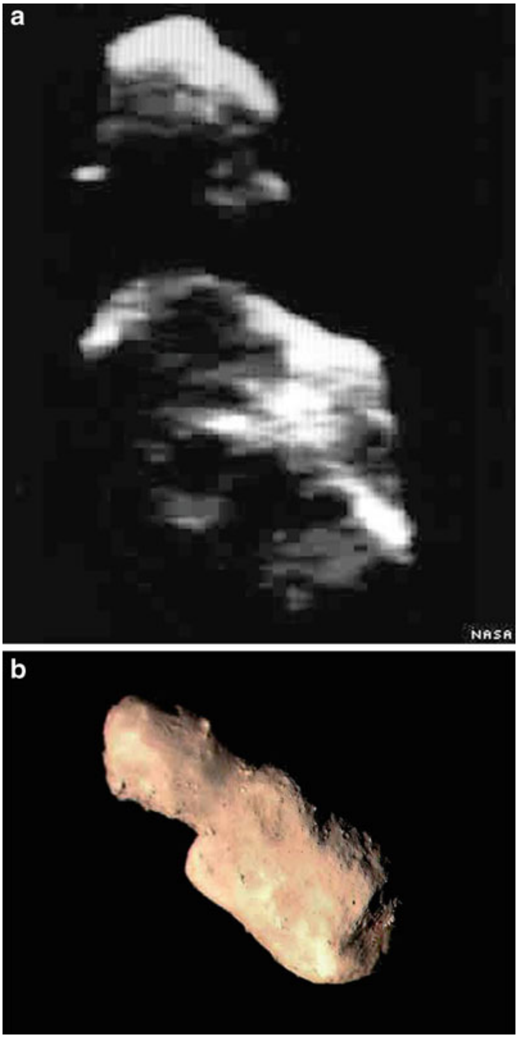


Fig. 2.21 (**a**) Toutatis radar image (NASA). (**b**) Toutatis from Chang'e 2 (Montage © Daniel Macháček, The Planetary Society, images © Chinese Academy of Sciences, 2012)

Two landing attempts were only partly successful, but some dust samples were gathered and brought back to Earth in 2010. They resembled rocky chondritic meteorites, incorporating material from very early in the Solar System, but Itokawa appeared to have split away from a larger body about 8 million years ago. Again there was a two-lobed structure, but this time, the surface was strewn with boulders and the 'neck' was remarkably smooth,

Fig. 2.22 Asteroid Itokawa from Hayabusa (© JAXA, 2005)

making it look more like the nuclei of Borelly and Hartley 2, presumably due to similar processes at work (Fig. 2.22). The low density suggested that internally Itokawa was little more than a rubble pile, much more fragile than Steins, for example. A tiny space hopper probe called Miranda was released at the wrong time and failed to make contact with the asteroid; however the JAXA space agency proposes a Hayabusa 2 mission for launch in 2014 and sample return in December 2020, this time with an impactor fired into the surface by shaped charge.

In late 2016 NASA plans to launch a mission called OSIRIS-Rex (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer). The target is a carbonaceous Apollo asteroid roughly 500 m in diameter, designated (101955) 1999 RQ36; a competition to name it was held in 2012 and the name Bennu, from Egyptian mythology, was the winner. This name was suggested by Mike Puzio, a 9-year-old from North Carolina [11]. The mission profile involves rendezvous and sample gathering, separation from the asteroid in 2021 and sample return to Earth in late 2023. The security aspect is that Bennu is currently considered to be the most dangerous known asteroid, with a 1:1,800 chance of impacting Earth in the late twenty-second century, particularly in the year 2188. So this will be the first mission to a potentially hazardous asteroid (PHA), and well worth doing for that reason alone.

Carbonaceous bodies generally fragment in the atmosphere before hitting the ground, and already from optical and radar studies there's reason to think that Bennu may have an aggregate structure, possibly with large voids within it (though the apparent solidity of Mathilde gives grounds for caution here). But while Bennu may not be a *very* hazardous asteroid, the 'resource identification' may be very important for human expansion beyond Earth (see Chap. 8).

Incoming Asteroids

> There comes a time when every scientist, even God, has to write off an experiment.
>
> – P.D. James [12]

At the other end of the size scale from the giant asteroids, which pose no threat to us, neither does the dust that causes the zodiacal light (Fig. 2.23) and the gegenschein (Fig. 2.24).

Fig. 2.23 Zodiacal light over Cerro Paranal, Chile (ESO)

Fig. 2.24 Gegenschein over the European Southern Observatory (ESO)

Coming partly from the Asteroid Belt, partly from comets passing through the inner Solar System, it spirals towards the Sun due to the Poynting-Robertson effect, in which light from the Sun exercises a slight but significant braking influence. If that was all that came our way from the Asteroid Belt, there would be no cause for concern; but unfortunately larger objects can be perturbed by mutual encounters and collisions, or by the pull of Jupiter, into orbits that throw them, too, in our direction.

On February 15, 2013, the 50-m asteroid 2012-DA14 passed Earth from north to south, moving within the ring of geosynchronous communications satellites 36,000 km above the equator (Fig. 2.25). The angle at which it passed us was a resultant of Earth's orbital velocity and its own, because its orbital plane was actually quite close to the ecliptic. Previous close passes had included 2003 SQ222, about the size of a small house, which came within 88,000 km of Earth on September 27 that year—the closest approach of a natural object then recorded, and at just over twice the distance of the geostationary satellites (There was a time when

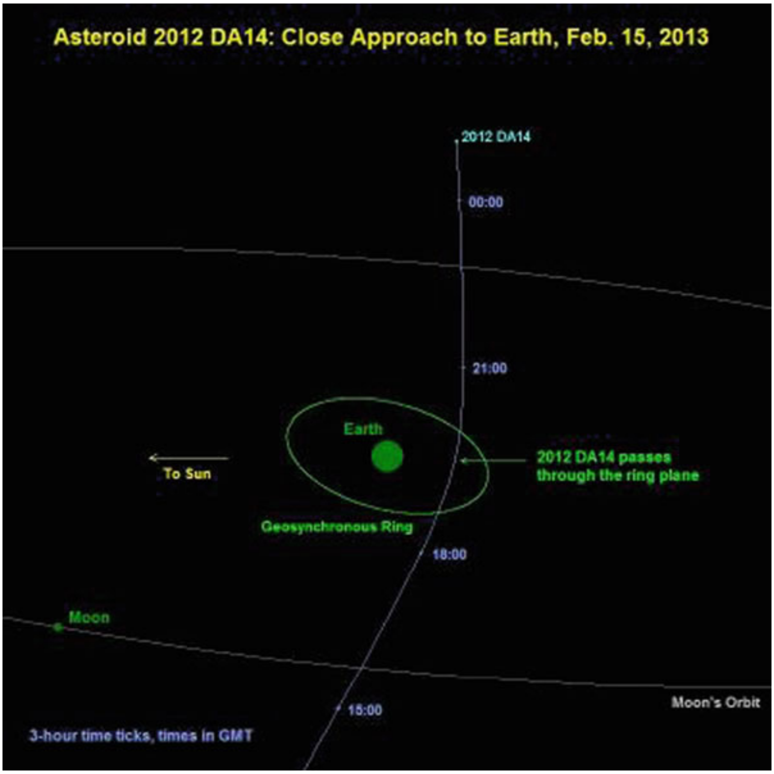


FIG. 2.25 Trajectory of asteroid 2012 DA 14 (NASA)

passing distances were related to the orbit of the Moon, but the Comsat ring has become the new yardstick).

Like so many that narrowly miss us, the asteroid came from inside Earth's orbit and wasn't spotted until after it went past. It was first seen on September 28 by the Lowell Observatory Near-Earth Object Search program in Arizona. Brian Marsden (see Chap. 1) calculated that its orbit is eccentric, with a period of just 1.85 years. Less than 10 m in diameter, it might have made a spectacular fireball had it entered the atmosphere—or it might have destroyed a city, depending on what its composition was, from a ball of dust to a stone to a solid lump of nickel-iron.

This object passed Earth at about 2300 GMT, only 10 h after a bright fireball and meteorite fell in the Orissa region of India, but the two events were not connected. The previous record for closest approach of an asteroid—108,000 km, measured from the center of Earth—was set in 1994 by another 10-m object named 1994 XM1, and the third closest was object 2002 MN, about 80 m in diameter, at 120,000 km [13]. At that size an impact would have caused a huge amount of damage.

Again by chance, on the same day that 2012-DA14 flew past in 2013, a smaller Apollo asteroid about 15 m in diameter, with a mass of about 7,000 metric tons, entered the atmosphere at a 20° angle, traveling east to west at about 19 km per second, and exploded 14–20 km above the city of Chelyabinsk in Russia with a force that was thought at the time to be at least 300 kilotons of TNT. Later estimates put the blast at 440 kilotons, roughly 30 times the yield of the atomic bomb over Hiroshima [14]. Nearly 1,500 people were injured, most of them by flying glass broken by the sonic boom.

At the 2003 seminar in this book project, Al Gore was quoted as having said that a Tunguska-type event over a city in the Midwest might have to happen before the asteroid threat was taken seriously. At the 2013 Planetary Defense Conference, one speaker suggested that the Chelyabinsk one was an ideal wake-up call—brilliant, damaging, but not a tragedy, over an area not too heavily populated, but where everybody had dashboard cameras (seemingly for social reasons, to do with false accident claims and accusations of traffic offenses).

Clearly this was one of Isaac Asimov's 'city-busters' (Chap. 1), and the consequences would have been far worse if it had hit the ground. Even so, its comparatively low velocity was again a resultant of the asteroid's speed and Earth's, having been overtaken by the planet [15]. Asimov calculated that at typical asteroid velocities, a city could be destroyed by a nickel-iron object massing only dozens of tons, the size of a large desk [16]. One of those fell at Sikhote-Alin in Siberia in 1947, again breaking up in the air before impact but forming hundreds of small craters at ground level. Observations from the Mars Reconnaissance Orbiter have now confirmed that Mars, nearer the Asteroid Belt and with a much thinner atmosphere, takes around 200 such hits every year (Fig. 2.26a, b) [17].

In *New Worlds for Old* in 1979, the author wrote "From that point of view, probably the most terrifying photos of the decade appeared in *Sky & Telescope* for July 1974. They show a meteorite,

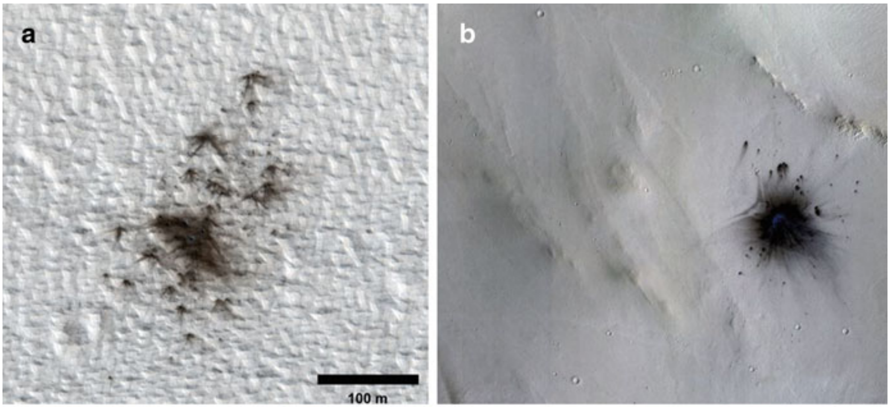


Fig. 2.26 (**a**) A fresh crater field, less than 5 years old, found by the Mars Reconnaissance Observer. (NASA). (**b**) A fresh impact with secondary craters (NASA)

whose mass may have been as high as several thousand metric tons, passing through Earth's atmosphere without striking the ground. It passed within 58 km of the surface at 15 km/s, causing sonic booms; its flight was from Utah, over Montana, and out into space again over Alberta. The Flying Saucer movement claims it for a spaceship; would that it had been anything so innocuous" [7]. We don't know its composition for certain, but it held together while subject to strong atmospheric forces. This suggested that it was nickel-iron, even at the time; comparison with the Chelyabinsk object makes that a lot more likely. *New Worlds for Old* continued, "In a very low-key assessment of what could have happened, Luigi G. Jacchia wrote: 'It seemed strange not to have any report of an impact…. A body capable of producing a fireball having the observed brilliance impacted with the energy of an atomic bomb, and seismic disturbances should have been recorded.' [18] Military and political ones, too, I fear…. In pursuing 'deterrence' based on nuclear weapons, one of the craziest aspects of a crazy philosophy is that we have reduced the impact mass necessary to bring about our annihilation by about nine orders of magnitude." The fear of global nuclear conflict has receded with the ending of the Cold War, but Prof. Colin McInnes has published a chilling fictional version of what might ensue from a similar strike on the border between India and Pakistan [19].

As a possible example of a city-buster, Asimov had considered the biblical flood, which he suggested might have been due to a city-buster scale impact in the Persian Gulf. In the 1920s, it caused a sensation when C. Leonard Wooley discovered a flood layer at Ur in Mesopotamia.

> During the seasons 1927–8 and 1928–9 our work on the prehistoric graveyard had resulted in the excavation of a huge pit some 200 feet across and between 30 and 40 feet deep…. The shafts went deeper, and suddenly the character of the soil changed. Instead of the stratified pottery and rubbish we were in perfectly clean clay, uniform throughout, the texture of which showed that it had been laid there by water. The workmen declared that we had come to the bottom of everything, and at first, looking at the sides of the shaft, I was disposed to agree with them, but then I saw that we were too high up. It was difficult to believe that the island on which the first settlement was built stood up so much above what must have been the level of the marsh, and after working out the measurements I sent the men back to work to deepen the hole. The clean clay continued without change… until it had attained a thickness of a little over 8 feet. Then, as suddenly as it had begun, it stopped, and we were once more in layers of rubbish full of stone implements, flint cores from which the implements had been flaked off, and pottery… Taking into consideration all the facts, there could be no doubt that the flood of which we had thus found the only possible evidence was the Flood of Sumerian history and legend, the Flood on which is based the story of Noah…. This deluge was not universal, but a local disaster confined to the lower valley of the Tigris and Euphrates, affecting an area perhaps 400 miles and 100 miles across; but for the inhabitants of the valley that was the whole world! [20].

The oldest surviving account of the biblical flood is in the Sumerian *Epic of Gilgamesh* and dates from c. 2250 BC [21]. It's the most detailed account and clearly attributes the event to an impact. Versions of the legend are found in Egypt, the Hittite kingdom, India and China [22], and the biblical one—which was picked up by Jewish exiles in the Babylonian captivity—is the only one that leaves out the impact [21].

Not knowing that, in *The Rocks of Damocles* Asimov nevertheless suggested that there had been one. It began with "a cloud no bigger than a man's hand" (a distant mushroom?), *then* a tsunami ("the same day were all the fountains of the great deep broken up," and the Ark was carried inland to Ararat), and only after that the sky grew dark and "the windows of heaven were opened" with torrential rain (Genesis 7, 11). But the Sumerian account has a heat-flash, an incandescent rising cloud with ejecta ("the Annunaki lifted up their torches, setting the land ablaze with their glare"), a groundshock ("the god of the underworld tore out the posts of the world-dam"), an air-blast, and only then the tsunami and the deluge.

Hittite legend says the flood was caused by the Moon falling to Earth (descending fireball) [21], and the Egyptian Coptic account says it began with fire from the constellation Leo, while divine personages stalked the land striking down the populace with iron maces [23]. The ancient Egyptians knew iron only from meteorites, and the Leonid meteors still provide spectacular displays every 33 years (Chap. 1). It's been suggested that parts of the story of Samson are a confused account of a Leonid fire-storm, although other writers associate him with Orion and its January meteors [24].

The Henbury craters in Australia were formed by a nickel-iron asteroid that broke up at low altitude, around 2700 BC. The flood could have been generated by a similar impact, perhaps in the Persian Gulf as Asimov suggested. In 2354–45 BC there was an abrupt cooling in global climate, and there is now evidence that the impact may instead have been in the Iraqi marshes and a century before the Gilgamesh text [25]. As previously noted, it's remarkable that one nineteenth-century estimate put the date of biblical deluge at 2349 BC, though it's probably a coincidence because other Bible studies of the time put it much further back [26].

Around 2000 BC a so-called bouncing asteroid (probably twinned, as many asteroids are) created a double crater at Campo Cielo in Argentina; this was the largest impact of modern times, with an energy release of about 300 megatons [27]. All this ties in with Victor Clube and Bill Napier's belief in an ongoing series of events from the break-up of a 'super-comet' in the inner Solar System around 3000 BC (Chap. 1).

Alan Bond and Mark Hempsell have presented evidence that a low density 1-km rock asteroid with a mass of 800 million metric

Fig. 2.27 Meteor crater, Arizona (Shane Torgerson, Wikipedia Commons)

tons passed over Sumeria at 14 km/s on June 29, 3123 BC, clipping the Gamskogel ridge and impacting the Köfels area in the Austrian Tyrol, triggering a massive landslide that erased the main crater, while smaller fragments caused other impact features in the area:

> As the object travelled up the Adriatic Sea…and across the Alps the supersonic shock would have caused considerable destruction on the ground beneath the trajectory. The impact…would release energy equivalent to 1.4 x 10^{10} metric tons TNT. [The plume] would rise… to some 900 km before falling over the Levant and Sinai causing considerable destruction over a wide area….There would have been many direct casualties, near 100% mortality over areas of thousands of square kilometres in both the Alps and the Near East. There would also have been a severe global climate change that caused further death and social disruption [28].

Although newspaper reports very frequently cite the Tunguska event when discussing the effects of impacts, a much better example is Meteor Crater in Arizona, also known as Barringer Crater and before that as Canyon Diablo Crater (Fig. 2.27), with a diameter of 1,186 km (0.737 miles). The event took place about 50,000 years ago, and the nickel-iron impactor was about 50 m across, with an energy release on the order of 10 megatons.

At first the crater was thought to be a volcanic feature, but in 1903 Daniel Barringer suggested it was caused by an impact and was proved to be correct by Eugene Shoemaker in 1960, identifying the types of shock features in surrounding rock that have since been used to identify impact features worldwide. Barringer's attempts to excavate iron ore from the crater were less successful, because most of it had vaporized on impact, and he had drastically overestimated the mass, now thought to have been about 50,000 tons.

A great deal of underestimating the destructive effect of impacts stems from a painting by Chesley Bonestell, Plate LXI of *The Conquest of Space* by Willy Ley, in which he superimposed a similar crater on Manhattan Island. He showed parts of the city on fire and some of the bridges broken, but roads, piers and other features were still recognizable [29]. Compare that with the description by Larry Dean Marshall, a paleontologist on the Kansas University investigating team, of the 'football-field-size' object mentioned in Chap. 1 that hit Earth between 500 and 1,000 years ago at Merna, 20 miles west of Broken Bow, Nebraska. The impact created a depression a mile across, originally 500 ft deep and even now 70 ft below the local surface. "If you were in the vicinity and looked at it, you'd be blinded. And there would be a tremendous roll of thunder followed by a shock wave" [30]. The heat would have been intense enough to ignite anything for about a 20-mile radius, and after the blast wave nothing manmade would be recognizable in the Bonestell painting.

Australia's terrain has preserved some very fine impact features, and more are being discovered even today. One of the better known, Wolfe Creek in Western Australia, wasn't discovered until 1947, when an oil survey party flew over it, although it's 875 m across (Fig. 2.28). A 1980s tourist book described it as "the second biggest meteorite crater on Earth" [31], which was long out of date even then, unless you add the words 'immediately recognizable.' Wolfe Creek was formed about 300,000 years ago by another iron meteorite, with a mass of about 50,000 tons.

As noted in Chap. 1, a problem with larger, older craters is the difficulty in assigning them to asteroid or cometary impacts.

Fig. 2.28 Wolfe Creek Crater, Kimberleys, Western Australia (© W. Pederson, Australian News and Information Bureau Photograph)

But there's no ambiguity about the Nordlinger Ries, discussed in Chap. 3, nor about the Sudbury impact crater in Canada, 1.85 billion years old, which is the source of much of the world's nickel. The Vredevoort Dome in South Africa, which until recently had the distinction of being the oldest known impact feature at 2.023 billion years (Fig. 2.29), has now been surpassed by a 100-km (62 mile) wide crater near the Maniitsoq region of western Greenland, believed to be 3 billion years old and also thought to be due to a nickel-iron body, 30 km in diameter, twice the size of the Vredevoort object (Fig. 2.30) [32].

J. E. Enever's 1966 article, cited in Chap. 1, assumed that the Vredevoort impactor was a nickel-iron body about a mile in diameter [33]. If his calculations of the energy released were correct, as well as the 15 km diameter that is now estimated, this would suggest it was a rocky body rather than metallic. Enever went on to suggest that a big marine impact could have wiped out the dinosaurs, one of the biggest 'megadeaths' in the history of evolution.

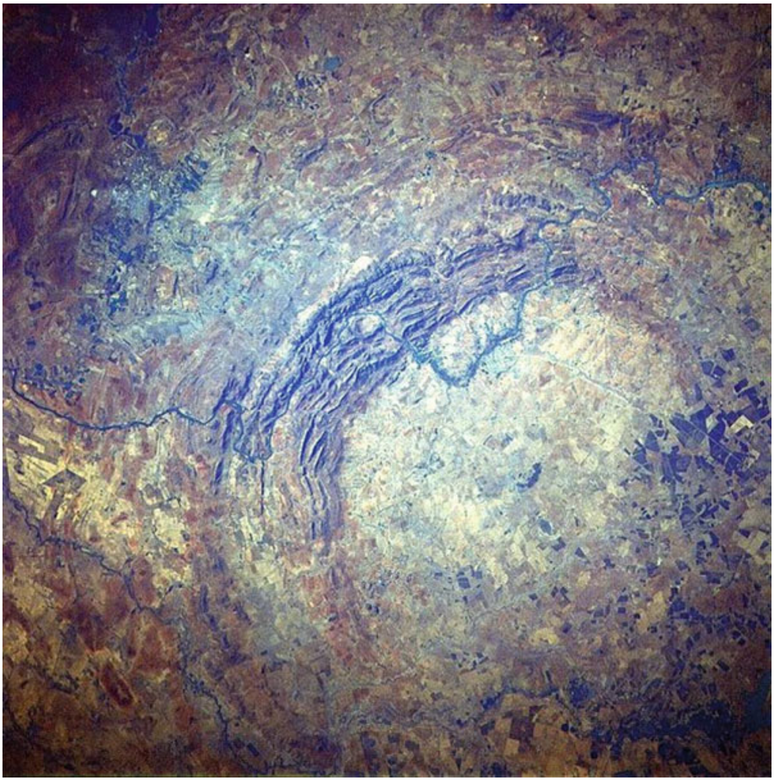


Fig. 2.29 Vredevoort Dome multiple ring impact feature, South Africa. STS-51i, August 1985 (NASA)

As noted earlier, a big enough impact on sea or land will punch a crater right through Earth's crust into the magma, but in a land impact most of the energy is re-radiated back into space, and only one continent is devastated. But a sea impact generates tsunamis of colossal size; then, as the sea tries to quench the rising magma, a terrible storm ensues whose effects, together with the dust thrown into the upper atmosphere, may be enough to block off all sunlight from Earth's surface—perhaps for years. In his novel *The Hermes Fall*, John Baxter generally underestimates the effects of the marine impact portrayed, but he does paint a chilling picture of a storm unlike anything in the experience of the human race [34].

Then in 1980 came the discovery of a worldwide stratum enriched with iridium, too much to explain by volcanic activity, coinciding with the dinosaurs' disappearance and also containing

Fig. 2.30 Location of Maniitsoq impact feature, Greenland (© Geological Survey of Denmark and Greenland (GUES), 2012)

evidence of conflagration over much of the globe. Earth's air is balanced between having too little oxygen for animal metabolism and having so much that everything becomes super-inflammable. Air bubbles in amber, formed shortly before the disappearance, show a high oxygen content. It may have enabled the pterosaurs to fly despite their huge wingspans, giving them a high metabolic rate, but the consequences were drastic. The iridium layer in the geological strata world-wide at the Cretaceous-Tertiary boundary contains a micro-thin layer of carbon, showing that the impact was followed by fires over enormous areas. A similar event 135 million years ago gave flowering plants their first advantage over ferns [36].

At first it was argued that there was no crater on Earth of the appropriate size and date, but the Chicxulub feature off the coast of Yucatán emerged as a strong candidate [37]. Below the marine deposits covering it, shattered and melted rock has been found matching the composition of the sediments at the Cretaceous/Tertiary (K/T) boundary. The *Lunar and Planetary Information Bulletin* reported: "Prior to the analyses of the basement rock at the crater, other workers suggested that several simultaneous impacts might be needed to explain the material at the boundary layer….

Chicxulub seems to be able to account for it all — singlehandedly." An initial uncertainty of several hundred thousand years in the dating has been narrowed down to less than 32,000 years, making it virtually certain that the events were causally linked [38].

We still don't know whether the incomer was a comet or an asteroid, but we have enough evidence of big asteroid impacts above to say that it could have been either. It seems that the iridium levels in deep-sea sediments may be higher than on land, and if that's due to a process of concentration, the lower levels found elsewhere may indicate that it was a comet after all [39].

However, the good news is that it's estimated that over 90% of the current potentially hazardous asteroids (PHAs) over 1 km in diameter have now been detected, and none of those pose near-term threats [40]. But there are literally thousands in that size range down to 100 m (see Chap. 4), and a strike by any of those could have global consequences.

Playing the Odds

> Most of Target Earth is Target Ocean… there is at least a 1% chance that all of the cities around the Pacific rim will be obliterated by an asteroid-induced tsunami within the next century.
>
> – Dr. Duncan Steel [41]

"One of the most feckless arguments on this subject is that 'the chances are millions to one.' As just over half the people who have played Russian Roulette can testify, the small chance that a given chamber will go off is a mathematical fiction: similarly for the asteroid and Earth there's one day that counts and the rest are immaterial. Nor can anything, at present, alter the odds on the day itself — asteroids hardly ever have misfires…" [9].

As John G. Kramer pointed out in *Analog,* at the time of Comet Swift-Tuttle's return in 1992, how impact risks are assessed is a matter of definition. Three years earlier, David Morrison and Clark Chapman had calculated that the chances of dying in an asteroid impact are slight, on a day to day basis, but so many deaths would result that the risk over 50 years is greater than from airplane accidents, tornadoes or electrocution [42]. Duncan Steel recalculated the odds for his book *Rogue Asteroids and Doomsday Comets*, concluding that death by asteroid was twice as likely as they had estimated. For U. S. residents, that makes it less likely than death by automobile accident (at the top of the list), homicide, fire, accidental shooting or electrocution (in that order), but more likely than an airplane accident, a flood or a tornado—against all of which people take out insurance [41].

A still more abstract calculation put the global insurable loss per year, averaged over 50 years, at $20 billion, updated to $28 billion by 2001. For the United States alone the figure would be $750 million per year, £150 million for the United Kingdom—about the cost of a small housing estate, as rocket engineer Roy Dommett pointed out [43]. In relation to that, the annual cost of a proposed Spaceguard system of six dedicated 2-m telescopes, at $300 million over 25 years, to identify all possible hazards (see Chap. 4), could be compared to insuring an automobile for a dollar [41]. Here's another way to look at it. In any given year, a regionally destructive impact is only 150 times less likely than a major earthquake in Japan, only 500 times less likely than a flood in Bangladesh, and death by impact on a global scale is 10 times more likely than a regional one [44].

In July 1997 a conference at Cambridge concluded that because of the tsunami hazard, the risk to the UK from impacts was greater than that from Russian nuclear reactors or from plane crashes such as Lockerbie. Whether the risk evaluation was actuarial or statistical, it well exceeded the allowable limits of current Health and Safety legislation: "If anyone owned Near Earth Objects, they'd be in jail." If there's a 1-km impact every 100,000 years, which kills 25% of the world population, the UK's statistical share of that is £12.5 million, at £850,000 per life, so the cost per year in lives alone is £123 million, before considering the infrastructure, property, heritage and commercial losses. Comparison with the actual costs of the 9/11 terrorist attacks suggested those could increase the loss by a factor of 7–8.

Nigel Holloway, a risk analyst at the UK Atomic Energy Authority, assessed the risks as being at the limit of tolerance, adding, "It is some time since astronomers have been called upon to serve in a directly useful fashion at the expense of their more theoretical aspirations. The discovery of the NEO risk changes that" [44]. Bringing the tsunami probability into the equation made the total risk package far beyond acceptable, putting even Tunguska-type events on a par with Chernobyl-type reactors. Even a 100-m impact in the Atlantic could wreck the UK economy.

If the threat was proven and the timescale known, as our scenario supposes, the most likely reaction in the financial world was summed up in the "Alex" cartoon of the *Daily Telegraph*'s financial section. After reading in an issue of *Science* that an asteroid impact could wipe out a continent and cause a mass extinction, Alex and his colleague are reassured by the thought that the universities are producing science graduates who "might be able to figure out a way to save us from being wiped out… brilliant scientific brains… engineers, physicists and those in the field of pure maths. Then we can lure them off into the derivatives market for tons of money as usual…"

> "Quite. We *still* pay more than NASA, and we'll want those eggheads to work out quick ways of shifting our risk exposure into a safe hemisphere if Earth gets hit [45]".

Surprisingly perhaps, some of the people who insure against risk took a different view. One might think that the predicted consequences of an actual event might outweigh the actuarial ones, calculated over 80 years. If 25–50% of the human race died in a 1-km impact event, how many claims would be filed, and how many paid out? To quote Tom Lehrer, "No one will have endurance to collect on his insurance." But to this author's surprise, seemingly those arguments did carry weight and cause the impact hazard to be taken more seriously in government and financial circles. At the 2003 conference, under the heading 'New U. S. Initiatives,' Jay Tate reported that the goals for all related programs were to be stated in terms of statistical risk and cost/benefit analysis [49].

This section of this book began with the question, 'Is there a danger?' The answer is yes. But as Lesley Wright pointed out, to act on a danger one has to recognize it. Babies will try anything. Adults believe others' accounts, even of events they've never experienced or can't experience. Men believe women's accounts of childbirth. But acceptance of the threat from NEOs remains abstract. To make it concrete we'd have to ask the dinosaurs, because only they have experienced it (Actually we should ask the crocodiles, because they survived it). Anything that makes an event easy to recall enhances public belief in its frequency; the more media coverage it receives, the more its frequency is overestimated, and vice versa. The risk of fatal cancer is overestimated, relative to diabetes, although statistically they're about equal; likewise death by fire and death by drowning.

Movies tell us that governments can deal with impactors, given a few months' warning (Both *Deep Impact* and *Armageddon* assume secret government space vehicles, just waiting to be called upon). What we don't know can kill us, but so can what we refuse to know. The 'ostrich effect' is especially pronounced with cancer. But fear, too, can be disempowering, leading to disjunction in response to the danger. The spacing in time between major impact events leads to a misunderstanding of the probability—the odds may be millions to one, but somebody wins the lottery every week [47].

Governments tend to think in 4–5 year cycles when assessing cost effectiveness. Investment in detecting and countering NEOs, when there is no apparent threat, is unlikely to win votes. The counter-argument will always be that the money would be better spent on health issues, or any other immediate concern—as witness John Braithwaite's question in the Preface. Changing government policy is a big hurdle to cross. The lesson of the last 20 years is that it won't be easy to arrange protection for Earth without a quantifiable menace to give it the necessary urgency. All we can do is keep watching, in hopes of finding something that is going to hit us, but not too soon to do anything about it—which brings us to the topic of Chap. 3.

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