

2. Minor Planets and Asteroids

A Curious Grouping

The term ‘minor planet’ is an astronomical classification that encompasses minor planets and asteroids. However, to arrive at this classification, the understanding of where other bodies fit in is necessary. The International Astronomical Union defines a planet as a body in orbit around a star, which has the ability to pull its mass into a rounded shape. The path on which the planet travels has also been cleared of smaller bodies, so that the planet has total dominance.

Disregarding any natural satellite that a planet may have, a dwarf planet has the characteristics of a planet but does not possess the size to have swept its orbit of other debris. Dwarf planets include Pluto (declassified from being a fully-fledged planet), Ceres, Eris, Haumea and Makemake. The term ‘minor planet’ can encompass not only dwarf planets but also asteroids, Trojans, centaurs, Kuiper Belt objects, and trans-Neptunian objects—all of which are discussed in more detail in the coming chapters. With the orbits of 700,000 of these minor planets already recorded by the Minor Planet Center, the cataloging of such objects is ongoing, and with the potential for reclassification always a possibility, it would seem to be a lengthy task that may never be completed.

Although asteroids fall into the category of minor planets, or planetoids, as some scientists suggest they should be termed, there remain others who are at odds with classifying asteroids alongside such a great diversity of other bodies. There would seem to be justification to the objection, with the Asteroid Belt—where so many such bodies collectively lie—a major part of the argument.

Trojans are known and cataloged objects that orbit the Sun, subdivided into the vicinity in which they circuit our star. The first grouping is Earth Trojans, bodies that share the same space as Earth shares the space with the Sun, orbiting in the same fashion, and displaying a constant regularity in motion as Earth does.

One such Earth Trojan, which does not add to a substantial cataloged list by any means, is 2010 TK, measuring 300 m in diameter and discovered by WISE, the Wide-field Infrared Survey Explorer.

Named after characters in Homer's *Iliad*, there are specific guidelines to make a Trojan body what it is, and it is these guidelines that consequently discount several other known bodies orbiting Earth that don't quite fall into the same category as 2010 TK.

The criteria for the Trojan relates to Lagrangian points. Lagrangian points are any positions in an orbital configuration of two large bodies (in the case of 2010 TK, the Sun and Earth) where such a body, affected only by gravity, can maintain a stable position. These points mark the position where the Sun and Earth offer their greatest gravitational pull on 2010 TK, providing the exact force to allow this body to orbit with them. There are five Lagrangian points (L1 to L5), named after an essay published in 1772 by Italian mathematician and astronomer Joseph-Louis Lagrange (1736–1813), entitled "Essay on the Three-Body Problem".

The Asteroids

The common perception of an asteroid is not a favorable one, despite it also having the potential to deliver life as well as take it away. The general assembly of asteroids within the Asteroid Belt pose little threat if order and conformity reigns, but as we will discover later in the book, it appears to be the intervention of a 'foreign' body into the order of the belt that causes the equilibrium to be disturbed.

Our asteroid journey starts with our understanding of them—what they are, how they work, and what place they have in our universe. It is also necessary to take away the idea that asteroids are merely a nuisance, bodies that have to be sought out and identified. Their presence in the universe is both necessary and important, for balance if nothing else.

The vast majority of these metallic, rocky bodies orbit the Sun in the Asteroid Belt positioned between Mars and Jupiter.

There are a number of theories as to how the Asteroid Belt came into existence, and the absolute conclusion remains a matter of much debate.

It is probably the vast and extensive gravitational field of Jupiter that prevented the contents of the belt from forming into a planet-sized body, with the 'binding' motion of material being continually disturbed, preventing any long-term melding. Given that the total estimated mass of all the asteroids combined would present an object of around 1497 km in diameter that, in itself, would cause a problem of classification, as the body would be less than half the size of our own Moon. However, the formation would have taken place long before anyone even considered categorizing them, so it's all pretty irrelevant.

Whether pulled apart prior to its complete formation by external forces, or possibly destroyed before evolving sufficiently far, could this planet possibly have existed in the formation of the Solar System? It seems unlikely. The more accepted theory is that the asteroids in the belt are not those of a planet that never formed but the debris left by the formation of other planets. The Asteroid Belt may well just be a dumping ground for a substantial amount of leftover material from the early evolution of the Solar System, where, with gravitational forces at work, debris of all sizes became shepherded into an orbit, with the debris itself becoming the gravitational attraction over time for yet more rubble.

These airless rocks would appear to be nicely contained within the parameters of the belt, but all is not constant within the asteroid community, with plenty of jostling, and of course always the prospect of the intervention from a foreign body in the established domain. Such an intervention would have a knock-on effect of destabilizing an area, with perhaps far-reaching consequences.

Compared to the planets in our Solar System, although the Asteroid Belt orbit has been likened to a doughnut in shape, the asteroids generally match the average orbital eccentricity of the major planets. The bulk of the belt's contents are inclined at 20 or 30 degrees to Earth's orbit, with a smaller proportion holding a more radical path around the Sun.

The belt is not an overly congested place; in fact, the distribution of asteroids within it makes for a rather vacant appearance, given the volume of space through which they have to travel. It has

been calculated that the average distance between objects is 965,606 km, therefore making the 'gap' between asteroids some 24 Earth circumferences.

Despite our mind's eye visualization offering us this vast area of tumbling rocks, varying in proportion and size, it is in fact comprised mostly of empty space. Astronomers know of the existence of clumping in the belt, where some asteroids do travel together.

In 1866, astronomer Daniel Kirkwood (1814–1895) noticed that certain gaps or dips in the distribution of asteroids corresponded with the locations of orbital resonances with Jupiter. It was almost as if asteroids had been pulled out of position at these "meeting points," leaving significant gaps in the belt, completely void of any bodies.

Kirkwood explained the disappearance of the asteroids with the regular interventions by Jupiter during its orbital period. In essence, whenever Jupiter approached, whatever lay in the belt would be drawn or pushed clear, creating a Kirkwood gap. There is significant research to suggest that these resonances may well force debris from the Asteroid Belt towards Earth, or, at least in part, offer an explanation for the realignment of many an asteroid's orbital path.

As for the actual amount of asteroids contained not just in the belt but in the entire Solar System, this again is a figure continually on the rise as observational methods become more refined. At the present time, 150 million seems a conservative but plausible estimation.

Ceres—King of the Asteroids

Within the belt a vast array of sizes and shapes exist, the largest of which is Ceres. The vast majority of the bodies follow a stable, slightly elliptical orbit, revolving in the same direction as the Earth, with a full circuit of the Sun taking from three to six years (Fig. 2.1).

Ceres, Vesta, Pallas, and Hygiea account for about half the total mass of the Asteroid Belt. Ceres measures 945 km in

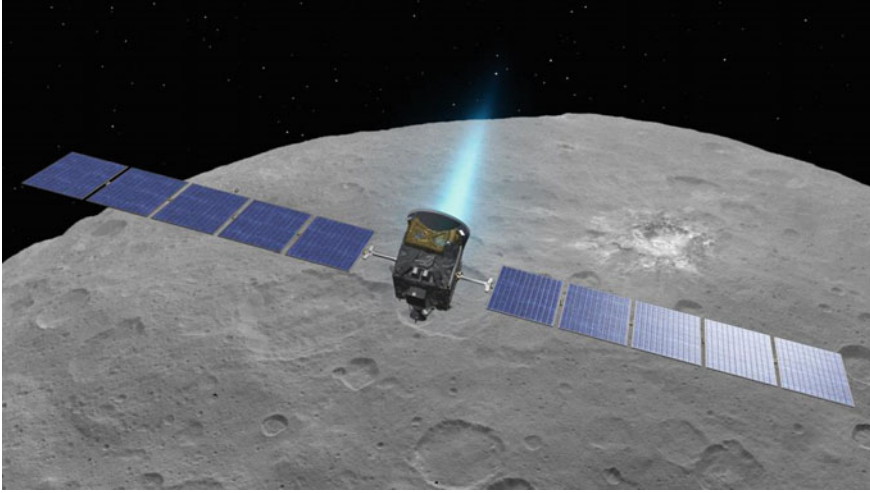


Fig. 2.1 Artist's impression of NASA's Dawn mission to Ceres (courtesy of NASA)

diameter, with Vesta measuring 525 km in diameter and Pallas a close disputed third, at 512 km in diameter. Hygiea measures 499 km in diameter with its oblong shape affording it a range of size from 349 to 499 km.

Positioned 299 to 595 km away from the Sun, it is, as you would expect, a cold existence for the asteroids in the belt. Tumbling and spinning, temperatures on these worlds can vary greatly from whichever side is facing first solar radiation to the vast depths of the stellar background faced by the other side. A typical average temperature on an asteroid would therefore range between -73°C and -108°C .

Ceres was discovered by Sicilian monk and astronomer Giuseppe Piazzi (1746–1826) at Palermo, Sicily, on January 1, 1890. It was discovered after Piazzi had followed up on mathematical calculations that indicated that there was a planet positioned in between the orbits of Mars and Jupiter. Piazzi named his discovery after the Roman goddess of harvests and corn.

Despite the calculations being somewhat awry, Ceres was spotted, and originally classed as a planet until being reclassified in the 1850s as an asteroid, after subsequent objects of a similar nature were discovered. Piazzi's work and discovery also at the time undermined research that was being conducted at the time by a group of scientists calling themselves the "Celestial Police."

Working as a team and with the use of the then prominent observatory owned by German astronomer Johann Hieronymus Schröter (1745–1816) at Lilienthal in Bremen, the “Himmelspolizei” were so-called for the ambitious project of wanting to bring order to the Solar System, through the discovery and subsequent classification of bodies. The group, which included the then current British astronomer royal, Rev. Dr. Nevil Maskelyne (1732–1811) and French astronomer Charles Messier (1730–1817), was completely driven by the prospect that another planet existed. With an allocated 15-degree arc allocated to each member to locate this postulated body, they worked tirelessly in its pursuit, only to be thwarted in the quest by lone observer Piazzi.

Observing from the Palermo Observatory, Piazzi originally believed that the point of light he had spotted in the night sky might be a comet. Over the coming weeks, he began to think differently, as the initial finding, first sighted in the constellation of Taurus, did not conform to that of a comet. For one thing, its appearance was not fuzzy or diffused and, for another, its slow and uniform movement did not agree with that of a comet against the stars.

In the early seventeenth century, German astronomer Johannes Kepler (1571–1830) had speculated that somewhere between the orbits of Mars and Jupiter a planet must exist. Kepler, discoverer of the basic laws of planetary movement, along with his countryman Johann Titius (1729–1996), showed that simple mathematical calculations produced a numerical formula giving the conclusion that, given the spacing of then known planets from our Sun, it was a natural matter of order that a planet should exist in an orbit beyond that of Mars and before the orbit of gas giant Jupiter. Granted, there were a number of striking anomalies in the formula, but basically it held true. However, despite these apparent flaws, the formula did predict the location of the planet Uranus in 1781.

However, it seems that coincidence rather than mathematics governed its working, as the numbers simply didn’t add up following the discovery of Neptune in 1846 and later Pluto, in 1930. With chance seeming to play more of a part, the formula rapidly lost credibility over time. Therefore, the discovery of Ceres—

which caused initial delight at the apparent confirmation that the formula did work in the predicting of a planet in between the orbits of Mars and Jupiter—quickly turned to puzzlement, as other bodies in the then unknown Asteroid Belt were found.

Between 1801 and 1808, astronomers tracked down a further three asteroids in the region of space where Ceres had been located, namely Pallas, Juno, and Vesta, each smaller than Ceres. A new explanation was now required to account for the presence of these bodies, and for the probability that these four were not alone. This new finding acted as a catalyst in the astronomical community to find answers, and it was deemed that perhaps a new class of celestial object should be created. As further years passed and new discoveries were indeed made, it became clear that there appeared to be an entire belt of these objects orbiting the Sun.

However, following the success of finding Pallas, Juno, and Vesta in relatively quick succession, there was a distinct gap in new findings of any object in that region of space, so much so that many astronomers, having initially been whipped up in the enthusiasm to find more asteroids, declared that there were simply no more to be found, and turned to other studies. For a time, the search that had initially captured the world of science was readily abandoned by most.

However, German amateur astronomer Karl Ludwig Hencke (1793–1866) was to pick up the thread of searching for asteroids in 1830, and after 15 years of scouring the skies discovered Astraea, the first new asteroid to be found in 38 years. Less than two years later he struck gold again, with the discovery of Hebe. Upon seeing the discoveries made by Hencke, many other astronomers now turned their own ‘scopes away from current projects back to prospecting for asteroids, believing that more were yet undiscovered. In the years that followed, the discovery rate was to average out as a find a year, with the exception of 1945.

Hencke’s initial new finding also acted as a catalyst in the astronomical community to find answers, and it was deemed that perhaps a new class of celestial object should be created. In 1891, astrophotography was the new tool in the hunt, with German astronomer Max Wolf (1863–1932) pioneering its use to detect further bodies, which appeared as short streaks on long-exposure photographic plates. Wolf went onto find an incredible 248

asteroids using this method, going somewhere near to doubling the amount of those already cataloged by using standard search patterns.

With the rate of discoveries at such a high, an ironic twist in the hunt occurred. From the painstaking searches of yesteryear—where calculations followed by more calculations and then ultimate triumph and disappointment were endured—Max Wolf's revolutionary method of seeking out asteroids had turned searching on its head. An era had now been entered into wherein it was generally considered that there must be literally hundreds of these objects orbiting between Mars and Jupiter, and the pursuit became akin to shooting fish in a barrel—easy pickings, if you will, and not worthy of pursuit. So great was the disdain towards the prospect of just finding yet another asteroid that astronomers now simply referred to asteroids as “vermin of the skies,” a phrase variously attributed to Eduard Suess (1831–1914) and Edmund Weiss (1837–1917).

Types of Asteroids

The majority of asteroids fit into three distinct groups, although there are other, lesser groups. The first is C-type (carbonaceous), which accounts for more than 75% of all known bodies. These asteroids are very dark in nature, more red in hue than other bodies, offering little in the way of reflectivity. Reflectivity is measured in terms of albedo, or intrinsic brightness. A body that reflects light with a perfect surface for doing so has an albedo of 1.0. A body whose surface is black—a surface perfect for absorbing light and returning no reflective nature—is classed as 0.0. The C-type asteroids fall within an albedo bracket of 0.03–0.09, generally positioning themselves to the outer regions of the belt. Chemically, their spectra match the primordial composition of the early Solar System, with the omission of only the lighter elements removed.

The second most predominant class of asteroid is S-type (siliceous, silicate-rich), which accounts for 17% of all known bodies. S-type asteroids are relatively bright in nature, with an albedo of 0.10–0.22. Positioned and tending to dominate the inner

portion of the Asteroid Belt, they are metallic in nature, with iron and magnesium silicates. No significant carbonaceous compounds are to be found within them. The overall composition of the S-type indicates that their materials have been significantly modified from their primordial composition, probably through a process of melting and reformation.

The third tier of classification makes up the rest of the belt's bodies, M-type (metallic, metal-rich). Their composition is generally dominated by the presence of iron. Dwelling in the middle region of the asteroid belt, they are, like the S-type asteroid, classed as relatively bright, 0.10–0.18. Although there remains some doubt as to whether all M-type asteroids are compositionally similar, a proportion is believed to have formed from the metallic cores of other bodies whose components were disrupted through collision. Therefore the M-type category could be considered a bit of a dumping ground classification for all asteroids that don't fit into either the C-type or S-type—a miscellaneous collection that generally accounts for the makeup of every other known asteroid. As with all classifications, if numbers of a certain type of asteroid within the M-type were to show a high percentage, this would undoubtedly force another class to come into being. This was to become apparent when subsequent discoveries were made, largely thanks to the plethora of spacecraft that were to make close-up studies of the Asteroid Belt and its contents.

The Galileo Spacecraft

We largely have three main sources to thank for the classification of asteroids. The most notable source has been the flybys of NASA's Galileo spacecraft, launched in October 1989, with the mission to make two close-up observations of asteroids 951 Gaspra and 243 Ida, before moving on to study Jupiter. The Galileo mission consisted of two spacecraft, an orbiter and an atmospheric probe (Fig. 2.2).

Costing NASA \$1.39 billion with a further contribution of \$110 million from international sources, the mission, which involved contributions from 800 people, seemed a far and distinct echo from the man it was named after, Galileo Galilei (1564–1642).



Fig. 2.2 A study of Europa, as part of NASA's Galileo mission to Jupiter (courtesy of NASA)

Often referred to as “the father of science” Galileo’s contributions reach far beyond the time period in which he lived, with the NASA mission reflecting in some way a physical representation of just how far Galileo’s mind could extend. This craft symbolized his insight into worlds beyond, as in 1610, when he spotted what we now know are the four moons of Jupiter.

Although Jupiter was the main target of the Galileo mission, astronomers with more of an interest in asteroids were to receive, during the course of the craft’s epic journey, a fascinating insight into these worlds. With the largest planet in the Solar System as a target, the accuracy of Galileo’s trajectory lay in the navigation to the much smaller bodies of our Solar System, a logistical execution requiring a high level of precision. Ultimately, though, these rendezvous were also a great success.

Launched off the back the space shuttle Atlantis on mission STS-34, Galileo would cleverly use the gravitational fields of both Venus and Earth to build up enough velocity to propel it towards Jupiter. Observations were made during this inward part of the journey of Venus, Earth, and the Moon, before its outward trip

towards the Asteroid Belt and then onto its primary target of Jupiter.

Galileo was the first spacecraft to orbit Jupiter and launch an entry probe into the planet's atmosphere. However, there was to be an unexpected and substantial bonus to the mission. This came in the form of the infamous strike on Jupiter by Comet Shoemaker-Levy, with NASA scientists afforded front row seats to witness the fragments of the comet as they ploughed into Jupiter's clouds. How fortuitous that a probe just happened to be in the vicinity at the time, there on hand, to capture the remarkable spectacle that was to unfold.

However, prior to this landmark astronomical surprise, back in 1991 after two months plowing through the Asteroid Belt, Galileo notched up another astronomical first, rendezvousing at close range with an asteroid.

Passing just 1593 km from 951 Gaspra, Galileo was able to photograph, take measurements, and assess the composition and physical properties of the asteroid. The photographs revealed a cratered, very irregular body, measuring roughly 19 by 11 km.

In 1993, Galileo made its second rendezvous, this time flying within 2414 km of asteroid 243 Ida, which gave scientists yet another first. This particular revelation was the discovery that 243 Ida was not alone in the vastness of space, appearing to be accompanied by its own moon, which was subsequently dubbed Dactyl, measuring just below 2 km in diameter. This in itself produced amazement and provided a further puzzle in the world of cosmic debris. Here we had an asteroid that had a moon! With measurements and analysis taken, little Dactyl was discovered to be spectrally different from 243 Ida, subsequently classed as an SII subtype S-type asteroid. In later years, more than 150 asteroids were shown to boast a moon for company and, in some cases, even two moons.

It also became apparent that the asteroid/moon relationship would not necessarily be governed by size. Some asteroids were discovered with almost equal size, making them a sort of binary system, orbiting each other, as they both orbit the Sun.

Galileo had also opened our eyes to yet another twist in the cosmic debris tale, with the spacecraft's journey making significant advances in our understanding of Jupiter and its four inner

moons, Io, Europa, Ganymede, and Callisto. The latter three moons yield support for the theory of a liquid ocean under the icy surface of Europa, with indications of similar liquid saltwater layers under the surface of Ganymede and Callisto.

Like all missions, it was with a strange yet inevitable sadness that, having delivered so much, this extraordinary space journey would come to an end. After 14 years in space and having spent eight years studying the Jovian system, Galileo was to meet its end with a final dive into Jupiter's atmosphere at 48 km/s. Even as it descended into the Jovian clouds, this plucky craft was still able to transmit data. Its destruction, although honorable, was also necessary, as Galileo could not be left to roam the Jovian system unattended, as there was the possibility that one day the craft could have crash landed on one of Jupiter's moons, potentially contaminating it with terrestrial bacteria. Therefore, Galileo had to be destroyed.

The list of Galileo's achievements is remarkable, all despite problems that saw NASA technicians constantly battling to keep the craft functioning during its mission. One of the most serious difficulties encountered by NASA was Galileo's failure to deploy the main antenna, an issue that was corrected by rewriting the probes on-board software in order for Galileo to deploy its reserve antenna. If that had failed, the mission would have sunk without trace.

The diary of Galileo encounters started with the initial flyby of Venus in 1990. The craft would use Venus's gravity to gain the necessary velocity for the next phase of its trip—from Venus to 951 Gaspra in 1991, then on to the 243 Ida encounter in 1993. The intervening year, 1992, saw a flyby of Earth before the main rendezvous at Jupiter. Galileo's encounter with Jupiter coincided in July 1994 with observations of the 20 fragments of Comet Shoemaker-Levy as it plunged into Jupiter's night-side atmosphere over a six-day interval.

Galileo also managed to confirm a supposed but not substantiated feature on our own Moon. The craft discovered an ancient impact basin in the southern hemisphere of the far side of the Moon, something previous Apollo missions had inferred but had never had the chance to properly map. The spacecraft also discovered that the Moon probably had much more in the way of

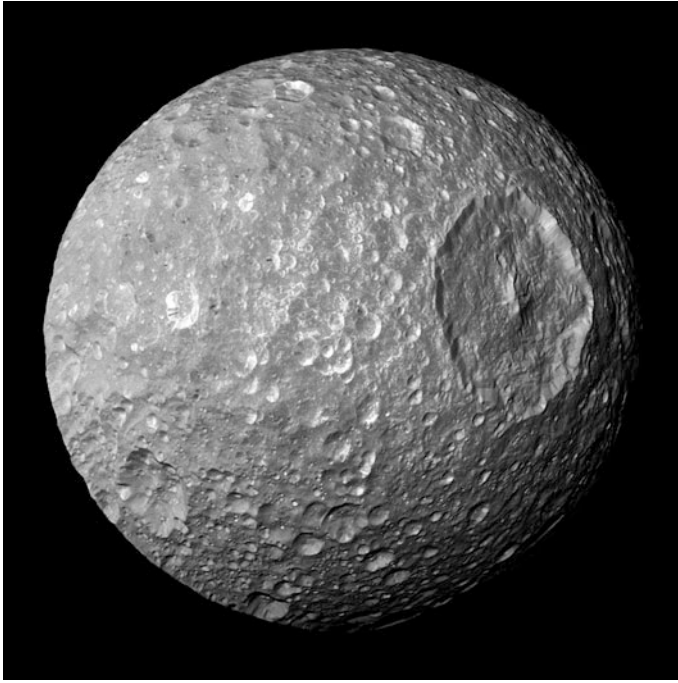


Fig. 2.3 NASA's Cassini spacecraft took this photograph during the closest-ever flyby of Saturn's moon Mimas. The giant Herschel impact crater, measuring 246 km in diameter, dominates (courtesy of NASA)

lunar volcanism than previously thought, adding to the rich tapestry of not only impact craters on the Moon's surface but perhaps a more internal explanation for its outward appearance.

Galileo represents one of the many missions to have visited asteroids. Other notable expeditions have included a joint mission by NASA and the ESA in 1997 that, en route to Saturn, took the Cassini spacecraft directly through the Asteroid Belt; the European Space Agency's Comet Mission, which flew past the asteroids Steins and Lutetia in 2004; and NASA's Dawn mission, which encountered Ceres and Vesta in 2007 (Fig. 2.3).

The NEAR Mission

It was NASA's Near-Earth Asteroid Rendezvous (NEAR) mission that took visiting and photographing asteroids to a new level.

Towards the end of its time spent encountering 433 Eros, an S-type asteroid, the decision was taken to attempt to actually land on its surface.

Discovered by German astronomer Carl Gustav Witt (1866-1946) on August 13, 1898, 433 Eros is a near Earth asteroid (NEA), part of a group of NEAs known as Amor asteroids, named after 1221 Amor. Amor asteroids approach the orbit of Earth but do not intersect it, with the majority of these bodies tending to cross the orbit of Mars instead. It is worth noting that, although credit has been allocated to Witt for this discovery, it was in fact jointly discovered with observations noted on the same date by Auguste H. Charlois (1864–1910) in Nice, France.

Witt, director of the Urania Observatory in Berlin, discovered two asteroids, of which 433 Eros was the most notable, being the first NEA to be discovered and the first asteroid to be given a male name. Measuring $34 \times 11 \times 11$ km, 433 Eros registered its closest approach to Earth on January 23, 1975, at a distance of 22 million km. However, bar a collision to alter its course, 433 Eros is not a threat to Earth. Witt's second discovery was 422 Berolina, found within the main Asteroid Belt.

Launched in 1996, the NEAR mission's epic journey to 433 Eros was to take 14 years, with February 2000 seeing the craft finally achieve orbit around the asteroid. NEAR and its whole mission program had not been designed for such an eventuality but, late into the mission, NEAR Shoemaker, to give the probe its full title (Shoemaker being in honor of planetary scientist Gene Shoemaker), made a daring and unscheduled descent onto the surface of the asteroid.

During its final 4–5 km before landing, NEAR was able to take dozens of detailed pictures of its soon to be host, transmitting back to Earth the most comprehensive photographic images ever obtained of an asteroid. With less than 400 feet to go, objects down to the size of golfballs were photographed, with NEAR finally touching down on 433 Eros near a large depression on the surface named Himeros. With the final stages to touchdown speed at just 4 mph, NEAR made a gentle landing on the asteroid's surface and, given the terrain, a most fortunate one.

NEAR, now operating outside of its stated mission, continued to transmit data from the surface of 433 Eros, sending back priceless information about the composition and chemistry of this small world. It was a truly remarkable feat, with data continually being sent until it finally ceased operating in February 2001.

NASA's mission statement for NEAR included that the probe would make the first-ever attempt to orbit an asteroid, with other objectives including examining 433 Eros' magnetic field, its interaction with the solar wind and, ultimately, to link 433 Eros to meteorites that had been recovered on Earth.

If NEAR were to collect sufficient information on chemical composition, then a causal link could be established between 433 Eros and other S-type asteroids and, more importantly, with meteorite pieces of S-type that had been found on Earth—perhaps even linked to 433 Eros itself.

In essence, NEAR's mission was to attempt to answer by its discoveries some of the fundamental questions about the origin of asteroids that were close to Earth's orbit. In turn, these objects could contain pointers and clues about the formation of Earth and other planets in the Solar System. 433 Eros itself and the various possibilities made it a tempting proposition for NASA, for here we had an asteroid whose surface looked in pristine condition, perhaps offering itself up as a relic from a time in space, some 4.5 billion years ago, when conditions had evolved to the point when our very own Earth came into existence.

The data collected from NEAR was groundbreaking as, from it, a significant and thorough profile of an asteroid was to be established, the like of which had never been documented before. 433 Eros presented itself as a solid, undifferentiated, primitive body, a distant throwback to the creation of our Solar System. The chemical composition analysis allowed scientists to determine that 433 Eros was not just a "rubble pile" but, rather, a consolidated object. In turn, this would enhance our understanding of the relationship between asteroids and meteorite debris found on Earth. Littered with impact craters from its turbulent past—over 100,000 discerned from the 160,000 images taken by NEAR—this asteroid proved to be a museum piece from time, a 'hands-on' chunk of history.

Near Earth Asteroids

The relationship between asteroids and meteorites has been continually unraveling over time as more and more is discovered about them. Ultimately, however, the link does remain a mystery, a very gray and somewhat annoying puzzle.

The most common meteorite, the ordinary chondrite, is composed of small grains of rock, with the overall appearance of a chondrite being unchanged since the creation of our Solar System. Other types of meteorites discovered, being stony-iron, are probably the remnants from the melting of much larger bodies, so that the heavier metals and lighter rocks subsequently separated into different layers. Considering that S-type asteroids are the most common of known asteroids, could there be a link between these asteroids and the abundance of ordinary chondrites? Spectral analysis suggests that S-type asteroids may be geochemically processed bodies, as opposed to meteorites of a stony-iron composition. If S-types are unrelated to ordinary chondrites, then what are they related to? By the same token, if there is a link between S-type asteroids and ordinary chondrites, an explanation for this spectral disagreement must be found.

Aside from the main Asteroid Belt, which harbors the vast majority of bodies, another classification of asteroid (not involving their composition but their movement in relation to Earth) is that of NEA's or near Earth asteroids. As mentioned with 433 Eros, these bodies don't conform to the relatively stable and consistent orbit offered to us from within the belt but travel their own path in the Solar System and are so-called because their orbits bring them within 190 million km of Earth.

These more maverick bodies may well be the result of knocks and bumps from other asteroids in the main belt, with perhaps the body eventually sprung from the belt by the influence of Jupiter, sending them into a different orbital plane around the Sun and, on occasion, a deflected passage that takes them near to Earth. The analogy of pinball, billiards or snooker within the Asteroid Belt has a serious edge to it, for it is here during, perhaps, a weighty engagement between two bodies that an asteroid could be directed in our path.

Apart from the aforementioned Amor asteroids, there are several other NEA groupings of note. The first of these are the Apollo asteroids, which dissect Earth's orbit over a period greater than one year, and the Atens, which cross Earth's orbit in a period of less than one year.

Estimates vary as to how many NEAs exist, but what has been discovered probably only accounts for a small proportion of what is actually out there. NEAs are essentially a young population, with their orbits having been tempered and tailored over a 100-million-year timescale, following possible collisions inside and outside of the Asteroid Belt, and the influence from the larger outer planets. Within the ever-changing estimates, it is thought that at least a thousand NEAs exist outside of a 0.5–1 km sweep of our orbit and, given their size and speed, are subsequently considered to pose a threat to Earth.

On average, three new NEAs are discovered daily, with discoveries by the end of 2015 totaling 13,024. A total of 1609 of these are classed as potentially hazardous asteroids, (PHAs). All have the ability to cause destruction, but, as of yet, none of these has a specified orbit in the future that will bring them into contact with Earth. There may be near misses in astronomical terms, but no direct hit.

Phobos and Deimos

So what of other asteroids that aren't either corralled into the Asteroid Belt, or classed as NEAs? Could a small proportion of asteroids be orbiting the planets either side of the belt? In particular, the Martian moons, Phobos and Deimos?

Although it is likely that Jupiter has caught a fair share of asteroids, largely small in nature and generally situated in the outer reaches of the 70-plus known Jovian system, the debate over how the Martian moons came to be remains.

For many years it was considered that Mars had no moon. German mathematician, astronomer, and astrologer Johannes Kepler suggested the possibility of the existence of bodies orbiting the planet (Fig. 2.4).

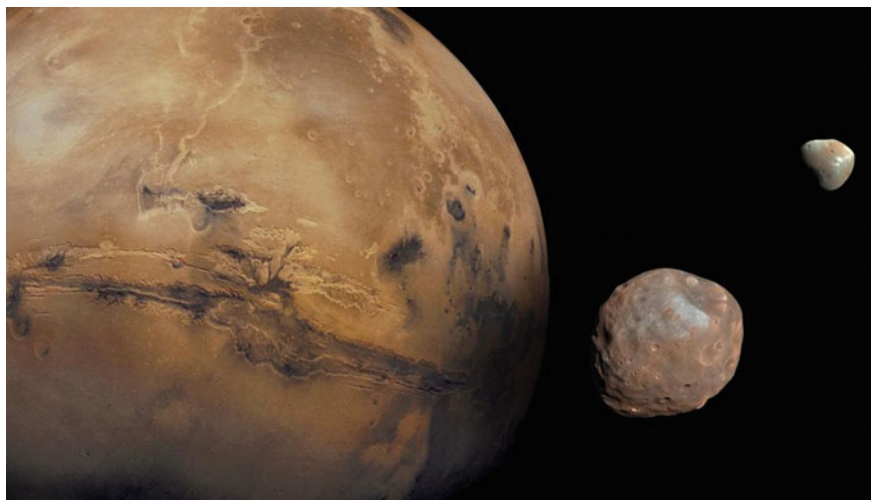


Fig. 2.4 The Martian moons, Phobos (nearest) and Deimos (courtesy of NASA)

The same possibility was referred to by Jonathan Swift (1667–1745) in his satire *Gulliver's Travels* (1726), with speculation on what was to become a truth, possibly founded in the common belief that if Earth had one moon, and Jupiter at the time was known to have four moons, surely Mars must also have a moon or moons, given that Mercury or Venus didn't have any at all.

Whatever the reasoning, Swift, an essayist, poet and cleric, produced substantial calculations to reinforce his belief that Martian moons existed, his later work probably combined with input from his close friend John Arbuthnot (1667–1735), a physician and mathematician.

In honor of the contributions of Swift and of writer Francois-Marie Arouet (1694–1778), who wrote under the non de plume Voltaire, two craters on Deimos were subsequently named Swift and Voltaire. In his short story of 1750 entitled "Micromegas," Voltaire had predicted that Mars had two moons.

American astronomer Asaph Hall (1829–1907), with the use of a 26-inch refractor, made the discovery of Deimos on August 12, 1877, followed six days later by that of Phobos. At the time, Hall was actively searching for moons around Mars, with an earlier sighting that he had made being thwarted by bad weather, which meant he was unable to confirm what he had seen. No matter, his

persistence paid off after this setback on August 10 as, two days later, he was able to confirm the existence of Deimos.

Phobos, meaning panic or fear, and Deimos, meaning terror or dread, were named after the horses that pulled the chariot of the Greek war god Ares, known as Mars to the Romans. However, according to other sources, the two moons are named after the two sons of Ares, who attended their father in battle.

Phobos, measures just below 23 km in diameter, with an orbital period of 7.66 h. Deimos is slightly smaller at just under 13 km, with a far greater but still rapid orbit of 30.35 h.

It is known that the orbits of the two moons aren't stable, and that Phobos is making a slow but steady descent towards the Martian surface, some 6 feet every century. This is not an immediate issue, but this spiraling orbit will see Phobos eventually destroyed on the planet's surface or, perhaps before that fate, torn into a subsequent ring of rubble around Mars. As for Deimos, the second of the two moons is showing signs of drifting away from Mars. The moon seems set in its orbit, with the only possible alteration coming from outside influence, or following the demise of Deimos in some way. Phobos orbits at a distance of 5955 km from the Martian surface, while Deimos is much further away, at 20,069 km.

The speculation that Phobos and Deimos are captured asteroids is well founded, as they bear more of a resemblance to asteroids than they do to our own Moon. To start with, both are small, classing them as some of the smallest known moons in the Solar System. Secondly, both are made up of material akin to carbonaceous chondrites. Thirdly, their shape is elongated, as opposed to the more accepted and rounded moon-like shape. All the evidence seems to suggest that these moons are in fact asteroids that have perhaps been nudged by the gravitational field of Jupiter into the path of Mars, and subsequently, over time, came within the gravitational pull of the Red Planet and eventually into an orbit. Although Mars seems an unlikely candidate to be making such a capture, this doesn't mean to say that in the past it wasn't capable of influencing bodies to a much greater extent. Indeed, were the pull of Mars substantially greater in the past, the planet may not have needed Jupiter to nudge bodies in its direction, being capable of capturing its own unassisted.

The orbits of both Phobos and Deimos are not considered to be erratic ones; in fact they are near circular in nature. So if these are indeed captured bodies, surely they would have a more unstable, eccentric orbit, wouldn't they? If anything, their path mirrors that of Earth's own Moon. The 'normalizing' of the orbits of the Martian moons, which brings their paths into line with the orbital plane of Mars, could be explained by atmospheric drag and, considering time-frames involved, by possible tidal forces.

The captured asteroid theory still holds much sway, but this remains strongly challenged by two other theories. One is that they are fragments left over from the creation of Mars, with gravity perhaps shaping the fragments into these two oddly shaped rocks. The other is that the moons are the product of a collision of some sort near to the planet. Another avenue of speculation promotes the possibility of Phobos and Deimos once being a binary asteroid, torn apart from each other under the influence of Martian tidal forces. Is it possible that once the Martian skies were full of debris, orbiting the planet in belt format? If so, what happened to the belt, and why are only two of the original abundance of rocks remaining?

Both moons are tidally locked into their orbits, much like Earth's moon, always presenting the same face towards Mars. The reason for Phobos' decay in orbit is thought to be tidal, and this tidal pull may have accounted for earlier, smaller moons that possibly orbited Mars, the craters of which are littered on the planet's surface. In certain areas, strings of craters have been identified—generally speaking, the further from the equatorial region, the older (Fig. 2.5).

Jupiter Trojans and the Hilda Group of Asteroids

Aside from the Jovian and Martian moons, there are other 'colonies' that exist outside of the asteroid belt, notably Jupiter's Trojans and the Hilda group of asteroids. Trojan asteroids are bodies that revolve around the Sun in the same orbit as a planet, occupying stable positions, Lagrangian points. These points are fixed to the planet's position, lying either 60° ahead or 60° behind.

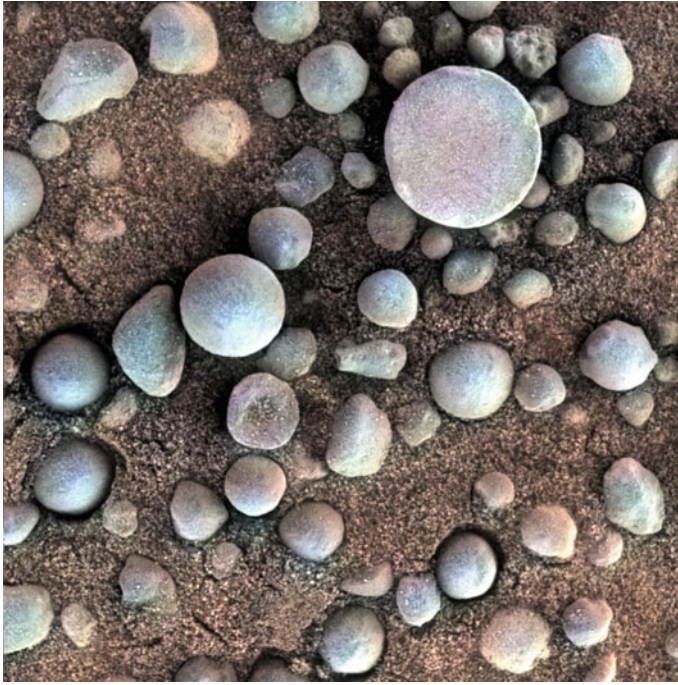


Fig. 2.5 Martian concretions found near the Fram Crater on Mars, which was visited by the Mars Exploration Rover Opportunity during April 2004. The area shown is 1.2 inches (3 cm) across (courtesy of NASA)

Along with the Sun, Jupiter is one of the two largest objects in the Solar System, and although Jupiter orbits the Sun as the other seven planets do, its gravitational pull is very strong, so much so that the planet actually pulls back at the Sun, almost canceling it out. It is here that these Lagrangian points are created, allowing other smaller objects—in the case of Jupiter, the Jovian Trojans—to travel along in Jupiter's orbit without being pulled out of position.

In 1990 an asteroid occupying similar Lagrangian points was discovered around the orbit of Mars. Named Eureka, this particular body has been joined by several other asteroids, collectively comprising the Martian Trojans. Since 2001, Neptune has been found to have its own Trojan. Despite finding other Trojans in the orbit of other planets, the name Trojan itself generally refers to the asteroids that accompany Jupiter.

Of the two groups of Jovian Trojans, there are in excess of 5000 known bodies, about 65% of them belonging to the lead group ahead of the planet with a cluster of 35% trailing behind the planet in the second grouping. The lead group ahead of Jupiter is known as the Greek Camp, with the Trojan Camp following. The first of Jupiter's Trojan asteroids was discovered by Max Wolf on February 22, 1906. It measures 135 km in diameter and was duly named 588 Achilles.

The term "Trojan asteroid" was coined when a decision had been taken to name all of the asteroids found in both camps after warriors in the Trojan War, Greek and Trojan, respectively. There are exceptions to the camp members, with Hector (a Trojan spy in the Greek camp) and Patroclus (a Greek spy in the Trojan camp), the first two Trojan asteroids to be discovered and named before the two camps were established.

The Jupiter Trojans are fairly elongated in their groupings, despite being locked into orbit with the planet. Saturn's gravitational field has been known to have an effect on these Trojans, causing them to oscillate. Although Saturn itself has no associated Trojans on its orbital plane, it is thought their absence is due to the greater gravitational pull of Jupiter, probably removing any such Lagrangian points from Saturn's orbit.

On a separate but equally stable orbit in relation to Jupiter is the Hilda group of asteroids. Sometimes referred to as the Hildian asteroid group, two collisional families exist within the collective: the Hilda family and the Schubart family. The "collisional" tag is given to an assembly of bodies that are thought to have a common collisional origin.

The founding member of the Hilda family is 153 Hilda, discovered by Austrian astronomer Johann Palisa (1848–1925) in 1875, and named after one of his daughters. Palisa was a prolific discoverer of asteroids, finding 122 such bodies.

The Schubart family is the second collisional family. The founding member, 1911 Schubart, was discovered on October 25, 1973, by Swiss astronomer Paul Wild (1925–2014) while working at the Zimmerwald Observatory in Berne, Switzerland. The finding was named in honor of German astronomer Joachim Schubart (b. 1928), who developed a technique for observing the motions of minor planets.

There are in excess of a thousand known Hilda group asteroids, many of which remain unnumbered. The Hildas are not considered to be the same as the Jupiter Trojans, since not all the members are physically related, with the only common ground being their relative closeness and shared orbit.

Although the Jupiter Trojans orbit the Sun with the same period as Jupiter, 11.9 years, the Hilda group takes several years less to make a circuit, 7.9 years, meaning that Jupiter orbits the Sun twice for every three orbits completed by the Hilda group.

Lagrangian points make for a stable 3:2 resonance pattern with the Hilda group, the asteroids confined to a basic triangle shape by the combined pull of Jupiter and the Sun. Jupiter always lies along one of the 'sides' of the triangle, so that each Hilda passes the line between the Sun and Jupiter when the body is near perihelion. In turn, this means the distance between the Hilda group and Jupiter remains the same.

Centaurs and the Kuiper Belt

There are a number of bodies that make up the remainder of asteroid-type objects in our Solar System, although classification does not view some of them as being 'outright' asteroids. The Centaurs are classed as such. In mythology, a centaur is half human, half horse. In astronomy, these mainly icy planetesimals are half asteroid, half comet.

The bulk of Centaurs orbit between Saturn and Uranus, with a lesser number orbiting between Jupiter and Neptune. Centaurs frequently cross the orbits of the outer planets, with gravitational interactions between the planets and the Centaurs, throwing many into very unstable orbits—orbits that are subsequently redefined again by further encounters.

The erratic nature of Centaurs has led some scientists to believe that these bodies could be comets in a very early stage of formation, proto-comets, with their origin in the Kuiper Belt. The Kuiper Belt (also known as the Edgeworth-Kuiper Belt) is a region of the Solar System that exists beyond Neptune, similar to the Asteroid Belt, containing debris left over from the Solar System's formation.

It was after the discovery of Pluto by Clyde Tombaugh on February 18, 1930, that many scientists began to speculate about the existence of similar smaller objects in this region of space, perhaps large in number. By the early 1990s speculation that more objects existed was confirmed, with the discovery of the Kuiper Belt. The Kuiper Belt is vast, substantially more so than the Asteroid Belt—20 times as wide, and perhaps 200 times as massive.

Having left the Kuiper Belt through collision within it or external forces, which could have equally sent them outward into the depths of space, a proportion of Centaurs journey towards the inner part of the Solar System. The inbound journey may see them travel towards the Sun, but more often than not it sees them thrown into highly unstable orbits, through the gravitational pull of one of the outer planets. Occasionally, the pull from one of the planets is so strong that they become captured into orbits around a planet, ending up as moons.

Beyond the Kuiper Belt, as far distant as 144 billion km from the Sun, lie the scattered disk objects (SDOs). These bodies, like Kuiper Belt objects, have very erratic orbits, with only a passing influence from the gravitational pull of Neptune. Most scientists believe that SDOs were probably Kuiper Belt objects, and as much as some of the objects were sent to the inner part of our Solar System through collision, others were dispatched outward. Several SDOs have been cataloged, most notably Eris, discovered on January 5, 2005, which even has a small moon. Sedna is another SDO, discovered two years previous to Eris, on November 14, 2003. Orbiting beyond Kuiper Belt and the SDOs are the “detached objects,” which lie completely outside the influence of Neptune, but with their own highly eccentric orbits.

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