Astronomers' Universe

David A.J. Seargent

Weird Comets and Asteroids

The Strange Little Worlds of the Sun's Family

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For Claudia, Andrew,
Theodore, Persephone and Anastasia

Preface

In many ways, the small members of the Sun's family must be considered "weird". While the major planets continue in their sedate, nearly circular, orbits for millions of years, many smaller members of the Solar System loop across their paths in highly elongated tracks that change radically within the span of a human lifetime. Not only do their orbits change over short lapses of time, but it is not unusual for the objects themselves to undergo rapid and (in certain cases) extreme transformations. A bright comet may fade out whilst under observation. An asteroid may literally fly to pieces before our very eyes.

Thanks to the small dimensions of these bodies, as well as the obviously fragile nature of many of their number, these so-called minor members of the Solar System were for a long time not taken very seriously by the astronomical community. This situation has changed in recent decades, in part due to the recognition that objects of this type have likely played important roles in the history of life on Earth. In particular, the role played by an asteroid in the demise of the dinosaurs caught the imagination of the wider public. Actually, the end of the era of these giant creatures was probably more complex than the simple "death by asteroid" scenario, but there can be little doubt that the asteroid impact was an important contributor to the mass extinction that occurred at the end of the Cretaceous era. In short, whereas the great lizards would probably have become extinct with or without the assistance of a colliding asteroid, this catastrophic event undoubtedly hastened their demise, maybe by several tens of millions of years.

Less catastrophically, although no less importantly, comets and asteroids have increasingly been seen as sources of both the water and organic material acquired by the ancient Earth. In this way, these objects are now widely credited for preparing the way for terrestrial life itself. This too has caught the public imagination, maybe not to the same degree as the role exercised by these bodies in catastrophic extinctions, but significantly nevertheless. Maybe the wider interest in the catastrophic role of comets and asteroids stems from the nervous realization that because these dramatic events have happened in the past, they will almost certainly happen again—and next time it might be humanity's turn to follow the dinosaurs into oblivion! That this fear is a serious one and not simply the theme of a science fiction horror story is demonstrated by the number of search programs dedicated to the discovery of potentially hazardous asteroids and comets, hopefully sufficiently in advance to ward off an oncoming catastrophe!

These new discoveries, as to the place of comets and asteroids in the grand scheme of things, have been largely responsible for the reawakening of interest in these bodies and, as interest grows, so does the impetus for further research uncovering more information as to their true nature. In its turn, this new knowledge has given us a better appreciation as to just how weird objects of this class can be. In the course of the pages which follow, we will look at some of the oddities exhibited by these objects. Contrary to what was once believed—that the line of demarcation between comets and asteroids is a sharp and well-defined one—we will see how these classes actually merge together. We will look at asteroids with tails and comets that look like mere specks of light. We will see asteroids break apart, comets simply vanish and even find hints of bodies that are comprised of both typical "cometary" and typical "asteroidal" material. In short, we will see just how interesting, frequently bizarre, and certainly not unimportant these so-called "minor" members of the Sun's family truly are!

Cowra, NSW, Australia David A.J. Seargent

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Lastly, I would like to thank all those observers and researchers who, over the course of many years, have worked to provide us with the fascinating picture of the Sun's "minor" objects that we have today.

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1. Unsung Little Worlds

Piazzi's Moving "Star" … and Its Many Companions

On the night of January 1, 1801, astronomer Giuseppe Piazzi was conducting a stellar survey for what would become the great *Palermo Star Catalogue* of some 7600 stars, when he noted the presence of something unusual. One of the apparent stars was moving! His initial thought was that he had found a new comet, however if this was a comet, it was a strange one as it appeared consistently starlike and, during the following days and weeks, revealed no tendency toward developing a fuzzy coma and tail. Moreover, the orbit that was eventually calculated for this body was unlike anything ever computed for a comet. The orbit was that of a planet, lying neatly within the broad and apparently empty region between Mars and Jupiter.

Piazzi had apparently found a new planet. But if this thing really was a planet, it was a tiny one. Early estimates ranged from 1579 miles (2526 km) as determined by J. Schröter to just 162 miles (259 km) as figured by W. Herschel. The true value actually lies between these extremes by some 582.5 miles or 932 km. That is small, even by the standards of Earth's Moon, let alone when compared with the other Solar System planets. In a move that by today's standards would surely be of doubtful political correctness, the petite nature of this body was recognized by the granting of a feminine name from the realm of mythology: Ceres, the name of the goddess of the harvest.

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Project 1: Finding Ceres

Ceres attains a brightness of about magnitude seven or eight at its best, making it an easy object for small telescopes and tripod-mounted binoculars. The orbital elements (epoch 2017 February 16.0) for its next perihelion passage are:

T = 2018 April 27.4372.
q = 2.5584.
e = 0.07568.
i = 10.5924.
ω = 72.90779.
Ω = 80.30986.

From these elements, an ephemeris may be calculated and the dwarf planet's position plotted on a star chart, preferably one showing stars to at least as faint as magnitude nine. During the next decade, the closest approaches to Earth by Ceres will see the dwarf planet at about magnitude seven. Details of these are as follows:

2018 February 1.6 (distance from Earth = 1.602 AU, distance from Sun = 2.57 AU).

2023 March 21.1 (distance from Earth = 1.599 AU, distance from Sun = 2.568 AU).

2027 January 9.5 (distance from Earth = 1.626 AU, distance from Sun = 2.604 AU).

Not all astronomers were convinced that Ceres was a lone planet however. Maybe it had companions? Perhaps there was a veritable host of similar objects awaiting discovery!

This suspicion was partially verified a little over a year after its discovery, on March 28, 1802 to be more precise, when H. W. Olbers found a second object of similar nature. Remarkably this second body was actually found during the course of Olbers' observation of Ceres! A third object was subsequently found in 1804 and a fourth in 1807. These three new objects were given the names of Pallas, Juno and Vesta, respectively. Today they are, together with Ceres, sometimes referred to as "the big four"; although "big" is certainly a relative term when used in this context (Fig. 1.1)!

Figure 1.1 Vesta and Ceres with the moon for comparison. Credit: NASA

With the discovery of this quartet of mini-planets, the idea that they were part of some greater assemblage of similar objects was given a further boost. Just about any large group of randomly sized objects will have most of its population consisting of its smaller members, albeit with most of its mass confined to a few large objects. Presumably, the four bodies discovered between 1801 and 1807 represented the few more massive members of the collection, implying that a large—maybe a *very* large—population of small bodies also inhabited the region between Mars and Jupiter, although the discovery of these would be a more challenging pursuit in view of their presumed faintness.

The members of this class of object became variously known as "asteroids" (because they appeared star-like when observed through a telescope), "planetoids" or (more formally and accurately) "minor planets". "Asteroids" however has been the term that has caught on with the wider public.

Granted that such a "belt" of these small bodies was probably a fact, the question was "Why?" Why should such a distribution of small objects of this type exist in the Solar System?

Two alternative answers were proposed. One approach was represented by Olbers who looked toward a catastrophic explanation for the existence of these bodies. According to this hypothesis, asteroids are the remains of a shattered planet that once orbited in the region between Mars and Jupiter. The parent body is supposed to have, either, exploded for some reason or other or (more plausibly) to have been smashed to pieces through collision with another large object.

An alternative hypothesis was proposed in 1807 by J. Huth. According to this line of thought, asteroids are composed of material that never came together to form a planet in the first place, presumably because of the gravitational perturbations of the giant Jupiter. Ironically, it was Olbers, Huth's principal opponent who gave the most succinct summary of this thesis, namely "that the matter which formed the planets had coagulated into many small spheres in the space between Mars and Jupiter". Although Olbers did not have a high opinion of Huth's hypothesis, it is essentially the one that is accepted by nearly all planetary astronomers today.

Nevertheless, Olbers' alternate viewpoint is not entirely incorrect. Although the asteroid belt is not the wreckage of a single shattered planet, the existence of groups or "families" of asteroids within the belt (about which more will be said shortly) are known to have arisen through the collisional disruption of large asteroids at various times throughout the history of the Solar System. In the distant past, there were more relatively large asteroids orbiting within the belt, but over time many of these have been broken down into groups of numerous smaller objects. Moreover, the force of these collisions has also deflected some of the resulting fragments into orbits that no longer follow the regular ones of their parents. No longer confined to stable orbits of low eccentricity, the motion of these fragments is further perturbed by the gravitational action of the major planets, in particular, of Jupiter. Straying further from the fold, many of these smaller bodies end up in orbits of rather high eccentricity that carry them well beyond the boundaries of the main belt, crossing the orbits of Jupiter, Mars, Earth, Venus and even, in a few instances, Mercury. We shall return to these errant asteroids in a little while.

It is possible that some of the "original" asteroids were even larger than Ceres and some astronomers have taken a position between those of Olbers and Huth in postulating an original small population of large “planetesimals” populating the region within Jupiter’s orbit, prior to the early chaos of the evolving Solar System and the collisional disruption of such bodies. Or maybe not *all* of the large early bodies. The suggestion has even been put forward that one of the original “proto-asteroids” managed to survive and that we know it today as the planet Mars! Fortunately, this suggestion was not accompanied by a recommendation to “demote” Mars from planetary to asteroidal (or perhaps proto-asteroidal) status as, after the howls that ascended to the skies following the “demotion” of Pluto, the mind boggles at what might happen should Mars lose its full planetary pedigree!

Following the discovery of Vesta, the last of the “big four” in 1807, no further discoveries were made until 1845 when the little world now known as Astraea was found by K. Hencke. This discovery by Hencke, an amateur astronomer, seems to have started a wave of further finds, many by fellow amateurs, and by 1852 the total number of known asteroids stood at 21. By the 1890s, this list had further swelled to 300.

The real upsurge in asteroid discoveries had, however, only just begun. In 1891 Maximilian Wolf, the director of Königstuhl Observatory at Heidelberg, introduced the new technology of astro-photography to the search for asteroids. Wolf used a pair of 6-in. (15 cm) diameter portrait lenses with focal lengths of 25 in. (63 cm) and 30 in. (76 cm). Duplicate plates were exposed using these two lenses; plate A for one hour and plate B for another hour. Then, plate A was exposed again for a further hour. If an asteroid was moving through the field, part of the space occupied by its trail on A would be vacant on B and vice versa. Wolf then placed both plates, one on top of the other, on a retouching frame, and examined each with a magnifying glass. By employing this technique, he single-handedly almost doubled the number of asteroids known at that time, finding a grand total of 231 new objects throughout his career.

Wolf’s method was soon taken up by other astronomers with equally impressive results. For the first time, there came an inkling that the realm of the asteroids extended beyond the gulf bordered on one side by Mars and on the other by Jupiter.

Trojans, Amors, Apollos … and Other Wandering Asteroids

The year 1898 witnessed a surprising and completely unexpected discovery by G. Witt, director of the Urania Observatory in Berlin. Unlike all asteroids discovered prior to that year, Witt's object moved along an orbit with a perihelion distance well inside that of Mars! This, the first known Mars-crossing asteroid, is the object now known as 433 Eros. Eros did not long remain the only known asteroid to venture outside of the Mars/Jupiter region. On February 22, 1906, Wolf discovered a distant body moving in the same orbit as Jupiter, albeit preceding the giant planet by 55.5 AU. The position of this object (subsequently designated 588 Achilles) was recognized by C. V. Charlier of Lund Observatory to coincide with one of the Lagrangian points associated with Jupiter's orbit. These so-called "points" mark the five positions in an orbital configuration where a small object affected by gravity alone can theoretically remain stationary relative to two larger objects. With respect to Achilles, the two relevant larger objects are Jupiter and the Sun. By end of that same year, a second asteroid sharing Jupiter's orbit was discovered, this one *leading* the planet by 55.5°. This asteroid is now known as 617 Patroclus. Achilles and Patroclus became the first recognized members of a large group of asteroids known as *Trojan asteroids* or, simply, *Trojans*. The number of Trojans associated with Jupiter and having diameters larger than 1 km is estimated to be in the order of one million. This is about the same as the number of similarly sized bodies thought to reside within the region between Mars and Jupiter; the region now known as the "main belt" of asteroids.

Trojans have also been found at the Lagrangian L4 and L5 points of other planets. Neptune has a small number, even diminutive Mars has a couple and in 2010 the space-based infrared observatory *WISE* found a tiny Trojan associated with Earth. This object—simply known as 2010 TK7—is a mere 1000 ft (about 300 m) in diameter.

In the year 1932, a pair of asteroid discoveries were reported that subsequently gave the search for these bodies a new and, in the minds of some folk, more ominous twist. March of that year witnessed the discovery of a body subsequently designated as 1221 Amor and in April the asteroid now known as 1862 Apollo was first detected. What is exiting or concerning (depending upon one's point of view) about these objects is that each follows an orbit that almost crosses that of Earth. These two discoveries raised, for the first time, the serious prospect that objects of this type may actually hit our planet! The subsequent discoveries of asteroids following similar types of orbits—now designated as Amor-Apollo objects—provides the motivation for the setting up of several sky patrols using robotic telescopes and CCDs to try to assess the number of near-Earth asteroids posing a potential threat to our planet and (hopefully) finding any such threat sufficiently in advance to deflect the offending body or deal with it in some other suitable manner. Thus far, no confirmed threat to our planet has been found, but the constant stream of discoveries being made by these surveys has certainly demonstrated, in a spectacular manner, that Olbers and others were correct in their speculations about the existence of Ceres' many companions. Incidentally, the dividing line separating the classes of Apollo and Amor asteroids is rather blurred. Technically an asteroid having its perihelion distance slightly outside of Earth's orbit is an Amor whereas one that ventures within our planet's orbit is an Apollo. Members of each class can make close approaches to Earth, and some objects move in orbits that oscillate between the two classes, sometimes having their perihelia inside and sometimes outside of Earth's orbit, thereby fudging what is an already ill-defined boundary.

A weird feature encountered in the motion of Amors is worth mentioning. Asteroids having orbits beyond that of Earth normally move from west to east from our perspective, relative to the background fixed stars. That is to say, they, in common with the outer planets, have *direct* motion across our skies. Nevertheless, also in common with the outer planets, around the time of opposition, they can be temporally overtaken by Earth (moving with higher relative velocity) and for a while appear to move backward, that is to say, in westward relative to the fixed stars. This *retrograde* motion is only temporary, but is a feature of the apparent movement across our skies of Mars, Jupiter and the other outer planets, in addition to the tracks of Amor asteroids. However, Amor asteroids are also capable of coming very close to Earth during those times when they arrive at opposition more or less simultaneously with the moment of their perihelion passage. On such occasions, the asteroid's apparent rate of motion through our skies will be very rapid; so rapid indeed that no retrograde loop will occur. The asteroid will continue its direct motion free from the interruption of a typical retrograde interlude. The strange consequence of this is the occurrence of three oppositions during a single close approach! Oppositions that occur during times when the asteroid is relatively far from perihelion, and therefore at greater distance from Earth do not, however, produce this triple opposition effect. During these more remote oppositions, the usual retrograde loop is faithfully followed by Amor asteroids.

In the year 1949, an asteroid was discovered with a perihelion distance of just 0.19 AU—well within the orbit of the innermost major planet, Mercury. Numbered as 1566 and named Icarus, for reasons that are fairly obvious, this asteroid's very small perihelion remained for many years the smallest known for this class of body. Asteroid 1566 Icarus appeared to be unique and sufficiently weird to attract the attention of one science fiction writer who posed it as a sort of death camp for interplanetary criminals! Nevertheless its infamous record did not hold forever. It was broken in 1983 when the infrared survey satellite IRAS found a small asteroid, since given the designation and name of 3200 Phaethon, which ventures to just 0.14 AU of the Sun at perihelion. Not long after its discovery, this unusual object gave astronomers an ever bigger surprise when noted astronomer Fred Whipple found its orbit to be strikingly similar to that of the annual Geminid meteor shower, but more about that later. Other asteroids having even smaller perihelion distances have since been found. Asteroid 2000 BD19 (137924) passes the Sun at 0.092 AU—so close that its surface becomes hot enough (at an estimated 920°K or 647 C) to melt lead and zinc and almost hot enough to turn aluminum into a liquid. Another asteroid, 2006 HY51 (394130) comes to 0.08 AU of the Sun while the present record holder is the "hot rock" designated simply as 2005 HC4 and boasting a perihelion distance of just 0.07 AU.

Contrasting with objects such as these, the asteroid 944 Hidalgo pursues an elongated elliptical orbit taking it from not far beyond the region of Mars out to near Saturn at an aphelion distance of 9.6 AU. This object may be an escaped Jupiter Trojan or a past denizen of the outer asteroid belt that experienced some serious gravitational perturbations at some point in its life.

Then we have the curious group of so-called Aten asteroids, named for their paradigm member, 2062 Aten which was discovered in 1976. The orbits of these objects have semi-major axes smaller than that of Earth's, so that they can only come close to our planet around the time of their aphelia.

Some asteroids are known to have had some pretty weird encounters with our planet—and I am not here referring to those that have slammed into us, like the large one that hit at the end of the Cretaceous period or the (thankfully!) far more modest example that exploded above the Russian city of Chelyabinsk in 2013. The ones being referred to here are those that have displayed strange orbits under the perturbing influence of our planet's gravity.

The strangest asteroid paths may be the so-called horseshoe orbits that occur when a small object moves in an orbit that almost coincides with that of a far larger body. The orbit is displayed as a "horseshoe" when plotted relatively to the larger body and the primary about which both bodies are orbiting. In the present instances, the small bodies are asteroids, the larger one is Earth and the primary is, of course, the Sun. Asteroids 54509 YORP, 2002 AA29 and 419624 (2010 SO16) are known to display this type of orbital characteristic. The latter body is especially interesting in that its orbit appears to be far more stable than those of the other two. Simulations of its future motion indicate that it will remain in the horseshoe orbit for at least 120,000 years into the future and may even remain in essentially the same orbit for over a million years.

A hypothetical observer on this asteroid would get a really weird view of our Earth and it may be that some future space-tourist company will run trips there just so that adventurous folk can have the experience, although as we shall shortly see, the trips would be far between and very special. As the asteroid and Earth draw near to one another, an observer on the asteroid would see our planet approaching and growing larger in apparent size, just as one might expect. Earth would be observed to come quite close, but then it would appear to suddenly reverse and recede once more into the distance. About 175 years later, a descendent of the first observer would see Earth again coming close, but this time it would be approaching from the rear. As before, it will draw close, then appear to suddenly reverse course and recede into the distance. Add another 175 years, and the cycle will repeat. At its closest approach, asteroid 419624 approaches Earth to a distance of around 50 times that of the Moon.

April 27, 2016 witnessed the discovery of a tiny but very interesting asteroid designated 2016 HO3. Measuring between 40 and 100 m in diameter, this little body has been described by Paul Chodas as a "quasi-satellite" of Earth. Moving between 0.1 and 0.26 AU of Earth (38–100 times the Earth-Moon distance), the diminutive rock follows an orbit in which it alternates between travelling sunward and slightly ahead of Earth for 6 months and then slightly further from the Sun and behind our planet for the following 6 months. Its orbit is tilted somewhat relative to the ecliptic plane, resulting in a corkscrew twist spanning several decades. The asteroid has been locked into this orbit for at least a century and is set to remain following it for several hundreds of years to come, unlike an earlier discovery—2003 YN107—which was a quasi-satellite of Earth when discovered by the LINEAR program back in 2003, but has since left our neighborhood and ceased to be locked into a leap-frog orbital relationship with Earth.

Some asteroids can even become true, albeit temporary, satellites of planets, including Earth. One such object is the tiny 6 or 7 m-diameter asteroid (almost qualifying as an oversized meteoroid) known as 2006 RH120 that became a moonlet of Earth between April 2006 and September of the following year. Objects of this type are known as Temporarily Captured Objects or TCOs and, although 2006 RH120 is the only such body known to date, astronomer Mikael Granvik of the University of Helsinki in Finland, estimates that at any given time there are probably about 100 TCOs larger than 20 cm (8 in.) in diameter, about 12 larger than 50 cm (20 in.) and one or two larger than 1 m (3.3 ft), in orbit around our planet. In order to join the ranks of the TCOs, an asteroid must pass through one of the two Lagrangian points (L1 or L2) that are located 1.5 million kilometers sunward of Earth (L1) or the same distance in the opposite direction (L2) at the very low velocity of 1 or 2 km per second relative to Earth. This causes them to fall into the region where Earth's gravitational influence exceeds that of the Sun and the body goes into orbit around the planet. The estimated length of the Earth-orbital sojourn of most TCOs is between about 1 and 20 years, but maybe Earth will succeed in permanently capturing a similar object someday. Perhaps it already has and we might already have several moons without realizing it. Indeed, objects have at times been reported transiting across the face of the Moon and although some of these are probably terrestrial debris wafted high into the atmosphere (and, these days, maybe artificial space debris) some reports appear to have been consistent with transits of very small (natural) satellites of our planet. If that is the correct interpretation of these mysterious observations, maybe they indicate asteroidal/meteoroidal satellites of a more permanent nature than 2006 RH120 and its tribe.

If not actually a second moon, as some popular science articles have actually described it, the asteroid 1685 Toro has been more properly called "a little brother" of Earth in so far as there is a true dynamical relationship with our planet that keeps the asteroid on a sort of invisible leash that brings it relatively close every 8 years. Having an orbit with a 1.6 year period, Toro loops around between 0.8 and 2 AU of the Sun in a 5:8 resonance with our planet and a near 5:13 resonance with Venus. In reference to its resonance with Earth, this means that the asteroid completes five orbits of the Sun for every eight of Earth's. Every 8 years it experiences a relatively close approach to Earth, rather like being pulled towards us on an invisible tether. But it cannot come too close and there is no chance of it actually hitting our planet. This resonance will persist for thousands of years, however it is not permanent and eventually Toro will break free of its tether and cease being tied to Earth.

Incidentally, Toro has been suspected of being the parent object of the Sylacauga meteorite of 30 November 1954, the first meteorite that was authenticated as having struck a human being. Mrs. Ann Hodges was struck on the arm, sustaining a degree of bruising, after the meteorite punched through the roof of her house and bounced off some furniture before striking her on the arm. She may be the only person to have been struck by a fragment from a known asteroid, although I'm sure that did not make the experience any less painful!

Potentially Dangerous Asteroids (But Not Too Much to Worry About!)

Certain Apollo, Aten and Amor asteroids can make close approaches to our planet. The threat of these "potentially hazardous asteroids" is real enough although there is no reason to live in perpetual fear of the "sky falling". To give some idea of the numbers of Earth approaching objects (not all of which are potentially hazardous), the count as of 8 August 2016 stood at 14,723. These range in size from what are essentially meteoroids just 1 m or thereabouts in diameter to the relatively large 1036 Ganymed (not to be confused with the similarly named moon of Jupiter!) which measures some 32 km, or about 22 miles, in diameter. Despite the science fiction writers' concentration on the danger posed by comets, only 107 of these Earth approaching objects are classified as comets and none of these poses any danger to our planet in the foreseeable future. Our planet has a far greater chance of being hit by an asteroid than by a comet.

Some of these asteroids have made very close approaches to Earth. A spectacular example was the meter-sized rock that actually passed through our planet's atmosphere on August 10, 1972, generating a brilliant daylight fireball widely seen over Canada, before retreating back once more into outer space. This body came to within 57 km or 34 miles of the Earth's surface and sufficient observations of the fireball were obtained for an approximate orbit to be calculated. This body, being faint and tiny, has not been observed in its solar orbit however.

Very close approaches of somewhat larger asteroids that were observed in space include those of March 18, 2004 when the 30-m asteroid designated 2004 FH passed just 42,600 km of 26,500 miles (that is to say, approximately just one tenth of the distance between the Earth and the Moon), closely followed by the Earth grazing flyby of 2004 FU162 at just 6500 km or 4000 miles on March 31. The estimated diameter of this latter object is just 6 m (20 ft), so it did not present a threat to the survival of humanity, although it would not have been healthy to be too close to the point of impact had it actually hit our world!

A slightly smaller asteroid, about 4 m in diameter, was discovered in 2008 shortly before it did strike our planet. This object, designated 2008 TC3, entered Earth's atmosphere over the Sudan on October 7, 2008 generating a brilliant fireball as it broke apart above the Earth's surface. A number of fragments were later recovered from the Nubian Desert and the fall is now officially listed as the Almahata Sitta meteorite. This name actually means "Station Six" and refers to a railway station about 60 km away from where the meteorite fragments were found. Presumably this is the nearest named feature to the fall site in that rather empty region.

It is fortunate that 2008 TC3 was observed whilst still in solar orbit and that a reflectance spectrum could be obtained. This showed the body to be an F-Type asteroid and when the fragments were found, they were discovered to be examples of a rare meteorite type known as ureilites. This discovery therefore associates ureilites with F-Type asteroids, something which had not hitherto been known.

Yet, excluding the 1972 event, the impact of 2008 TC3 and the occasional very large fireball, what may turn out to be, in many respects, the most spectacular asteroidal flyby for many years is still to come! On April 13 in the year 2029, the asteroid 99942 Apophis will pass just 0.00025 AU (approximately 40,000 km or 26,000 miles) of Earth—just a little closer than the far smaller 2004 FH passed by our planet in 2004. This asteroid is predicted to become a naked-eye object at that time, reaching a magnitude of around 3.4 as it speeds across the heavens at a rate of 42° per hour! Younger readers will need to note that in their diaries!

Asteroid Families, Groups and Pairs

Not all asteroids can be thought of as lone travelers. As more of these objects have been discovered, groups and families of bodies have been found. Some of these result from what we might call "convergent dynamical evolution". The Apollo asteroids, for example, probably have a wide range of origins, but have apparently been shepherded into orbits of a broadly similar type by the gravitational perturbations of the planets, principally Jupiter.

Other closer-knit familial groupings, however, are a different matter. In a later chapter, we will take a closer look at one of the major groupings of near-Earth asteroids, a vast system forming part of what is believed to be the debris complex of a very large comet that disrupted thousands of years ago. Other small groups have also been suspected. For example, in 1997 Duncan Steel presented strong evidence for an asteroid pair consisting of Adonis and 1995 CS. These two Apollo asteroids move along very similar orbits and, according to Steel's research, are very likely to be two major fragments of a single object that split apart at least 30,000 years ago.

Groupings and families are not confined to asteroids that stray from the Mars/Jupiter gap. In fact, it was back in 1918 (before any of the Apollo and very few of the other asteroids outside of the main belt had been discovered) that Kiyotsugu Hirayama discovered an interesting feature of the main asteroid belt, namely, that a significant proportion of its members are grouped together in orbital families. Initially, he found just three of these *Hirayama families* (as they are now called in his honor), namely the Themis, Eos and Kronos families, each named for its best known member. It is now thought that as many as half of the asteroids comprising the main belt are members of Hirayama families. Even sub-families are now recognized. These are second generation groupings within older and broader families that are thought to have been formed by the fragmentation of one of the members of the older family. A well-known example is the Beagle sub-family present within the larger Themis family.

As well as showing asteroid groupings, the main belt also contains sparse regions in which few, if any, observable objects can be found. Percival Lowell once compared such "gaps" to the divisions found in the rings of Saturn's although, of course, on a very different scale. These gaps were first noticed by Daniel Kirkwood (1814–1895) in 1857, although he did not officially announce his discovery until 9 years later. They were subsequently named "*Kirkwood gaps*" in his honor. Kirkwood noted that the gaps occurred at distances from the Sun where the orbital period of objects in solar orbit at these distances are in resonance with the orbital period of Jupiter. The principal Kirkwood gaps are found at mean orbital radii of 2.06, 2.5, 2.82, 2.95 and 3.27 AU. These distances correspond to resonances of 4:1 (i.e. where an object in orbit at 2.06 AU from the Sun completes four orbits for each single orbit of Jupiter), 3:1, 5:2, 7:3 and 2:1. Narrower and/or weaker gaps are also found at the 9:2 resonance (1.9 AU), 7:2 (2.15 AU), 10:3 (2.33 AU), 8:3 (2.71 AU), 9:4 (3.03 AU), 11:5 (3.075 AU), 11:6 (3.47 AU) and 5:3 (3.7 AU). In a 1982 study, Jack Wisdom computed the dynamical evolution of 300 hypothetical "test asteroids" in the neighborhood of the 3:1 resonance at 2.5 AU from the Sun, in order to test whether a Kirkwood gap corresponding to the one actually located at that position, would actually eventuate. The answer was a clear positive. Asteroids were indeed removed from the region of the resonance; 84 of the hypothetical bodies became Mars crossing within 300,000 years and 88 achieving orbital eccentricities as high as 0.3 within a million years. A parallel study undertaken 4 years later by Carl Murray similarly found that asteroids near the center of the 2:1 resonance (located around 3.27 AU from the Sun) will end up in Jupiter-crossing orbits during realistic periods of time.

This dynamical removal of asteroids from Kirkwood gap regions is believed to play an important role in the convergent dynamical evolution of asteroids into Apollo and Amor orbits that we mentioned above. Not all of the Apollo and Amor bodies have been removed from the main belt however, as some of them are almost certainly dormant comets or (as shall be discussed later in this book) possibly asteroid fragments that have been incorporated into large cometary nuclei and later set free as these nuclei have dissipated over time. The question as to what percentage of near-Earth asteroids are from the main belt and what percentage are of cometary origin has, however, not been settled and opinions differ as to the relative importance of each source.

Light and Dark Asteroids

Asteroids come in two broad varieties. The majority are dark bodies that have a low reflectivity or albedo and are widely thought to be similar in appearance and (presumably) composition to carbonaceous meteorites. The second broad classification are relatively light colored objects with a reflectivity closer to that of the most common type of meteorite; the stony "ordinary chondrite".

Objects belonging to the first general class are known as C-type asteroids and the second as S-type bodies. Needless to say, these are generalized types and have become increasingly split up into sub-classifications as more detailed information concerning the reflectivity, colors and surface properties of asteroids has been gained. Nevertheless, the broad division will suffice for the present purposes.

Asteroids of the C-type strongly dominate the outer main belt, outward from distances greater than about 3 AU the Sun. The largest of all the main-belt objects—1 Ceres—is a member of one of the sub-species of this class. Other close relatives of the C-types, once known as RD-type but now more simply as D-type, are the dominant inhabitants of the most remote regions of the main belt, namely, the region out to around 5 AU or almost to the orbit of Jupiter. These are dark, low reflectivity, objects but are distinctly more reddish than the typical C-types. Objects of this type also comprise the population of Jupiter Trojans. At the other edge of the main belt, the innermost region not too far beyond the orbit of Mars or around 1.5–2.0 AU from the Sun, S-types dominate. C-types become less prominent as we move inward through the main belt, comprising only a small minority of the bodies within 2.5 AU of the Sun and effectively vanishing altogether from the population within 2 AU. Conversely, S-types pretty much disappear from the main belt beyond 3.5 AU. The Earth-approaching population of asteroids includes some that are S-type or a close variation thereof as well as others that are, broadly speaking, C-type. Whether most Earth-approachers are S or C types remains a debatable issue as the more reflective S-types are easier to discover than the dark C-types and the numbers of each represented in catalogues of known near-Earth objects must be influenced by this observational bias and may not reflect the true makeup of the near-Earth population. Asteroids located beyond the orbit of Jupiter seem, on the other hand, to be exclusively of the darker variety.

Turning now from this overview of the asteroid population of the Solar System, let us now take a closer look at two members of the "big four"—the two that have recently been observed close up via space probes—and see just how interesting these small bodies truly are.

Vesta—The Brightest Asteroid

Space exploration achieved a new goal on July 16, 2011, when *DAWN* became the first spacecraft to go into orbit around the main-belt asteroid 4 Vesta, the brightest but last discovered of the "big four". Being some 331 miles (530 km) in diameter, Vesta is the second largest of the main belt asteroids, actually comprising almost 10% of the mass of the entire population of the main belt. Nevertheless, its diameter is significantly less than that of Ceres which, as we saw earlier, sports a diameter of 582.5 miles or 932 km. Nevertheless, although it is neither the largest nor the closest of the main belt asteroids, Vesta outshines its companions and during a good opposition is relatively easily spied with the naked eye if one has a suitably dark sky and knows exactly where to look. Its relatively high level of brightness is due to a surface composition that is quite highly reflective by the standards of these bodies.

Project 2: Finding Vesta

At its most favorable oppositions, that is to say, at those times when opposition occurs close to the time of Vesta's perihelion, this asteroid can become visible with the naked eye, attaining a magnitude of 5.2 at its very best. It will be almost at its brightest (at a predicted magnitude of 5.3) during the opposition of 2018 June 20, when it will be located within the constellation of Sagittarius at a distance of 1.142 AU from Earth and 2.157 AU from the Sun. It is expected to be brighter than sixth magnitude (the nominal naked-eye limit under dark rural skies) from 2018 May 30 until 2018 July 20.

The next nominal naked-eye opposition of this minor planet will be 2021 March 5, when it will be located within the constellation of Leo at a distance from Earth of 1.363 AU while at 2.345 AU from the Sun. It will only be a marginal naked-eye object however, not expected to become brighter than sixth magnitude but should remain visible sans optical aid for observers under very good skies from February 25 until March 12 of that year.

(continued)

Orbital elements for this minor planet's 2018 perihelion passage (Epoch 2017 February 16.0) are as follows:

T = 2018 May 10.23055.
q = 2.150824.
e = 0.089136.
i = 7.140516.
ω = 151.07636.
Ω = 103.842086.

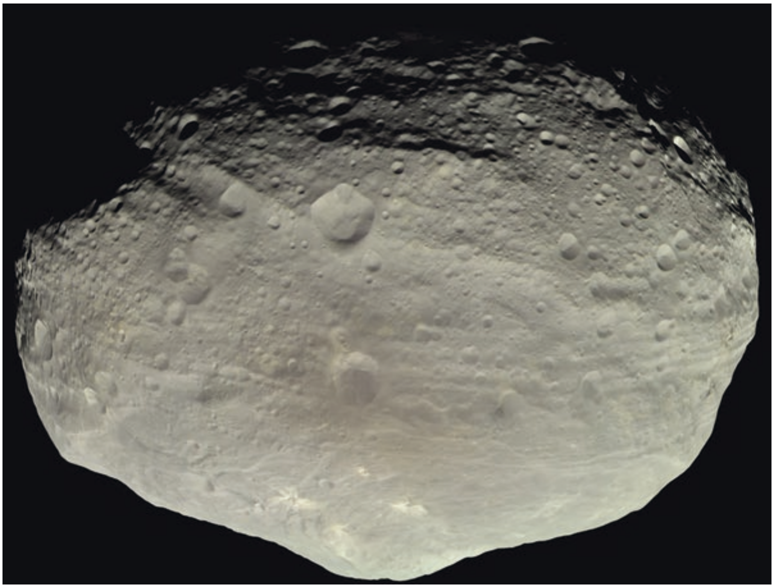

FIGURE 1.2 Vesta as imaged from the DAWN spacecraft. Credit: NASA/JPL/MPS/DLR/IDA/Bjorn Jansson

The surface of this asteroid is comprised of materials that have remarkable similarities to the volcanic rocks and minerals that largely comprise the crusts of Earth, the Moon and the other terrestrial planets, Venus and Mars. One of the minerals discovered on Vesta is the common iron-and-magnesium-bearing silicate olivine which is also a component of volcanic rocks formed deep within the crust of the Earth. That this mineral should be found on Vesta as well, appears to imply the existence of volcanic activity not unlike that witnessed on Earth; a rather weird discovery considering how vastly different these two bodies are in size (Fig. 1.2)!