13.1 ASTEROIDS

Learning Objectives

By the end of this section, you will be able to:

- Outline the story of the discovery of asteroids and describe their typical orbits
- Describe the composition and classification of the various types of asteroids
- Discuss what was learned from spacecraft missions to several asteroids

The asteroids are mostly found in the broad space between Mars and Jupiter, a region of the solar system called the *asteroid belt*. Asteroids are too small to be seen without a telescope; the first of them was not discovered until the beginning of the nineteenth century.

Discovery and Orbits of the Asteroids

In the late 1700s, many astronomers were hunting for an additional planet they thought should exist in the gap between the orbits of Mars and Jupiter. The Sicilian astronomer Giovanni Piazzi thought he had found this missing planet in 1801, when he discovered the first asteroid (or as it was later called, “minor planet”) orbiting at 2.8 AU from the Sun. His discovery, which he named Ceres, was quickly followed by the detection of three other little planets in similar orbits.

Clearly, there was not a single missing planet between Mars and Jupiter but rather a whole group of objects, each much smaller than our Moon. (An analogous discovery history has played out in slow motion in the outer solar system. Pluto was discovered beyond Neptune in 1930 and was initially called a planet, but early in the twenty-first century, several other similar objects were found. We now call all of them dwarf planets.)

By 1890, more than 300 of these minor planets or **asteroids** had been discovered by sharp-eyed observers. In that year, Max Wolf at Heidelberg introduced astronomical photography to the search for asteroids, greatly accelerating the discovery of these dim objects. In the twenty-first century, searchers use computer-driven electronic cameras, another leap in technology. More than half a million asteroids now have well-determined orbits.

Asteroids are given a number (corresponding to the order of discovery) and sometimes also a name. Originally, the names of asteroids were chosen from goddesses in Greek and Roman mythology. After exhausting these and other female names (including, later, those of spouses, friends, flowers, cities, and others), astronomers turned to the names of colleagues (and other people of distinction) whom they wished to honor. For example, asteroids 2410, 4859, and 68448 are named Morrison, Fraknoi, and Sidneywolff, for the three original authors of this textbook.

The largest asteroid is Ceres (numbered 1), with a diameter just less than 1000 kilometers. As we saw, Ceres was considered a planet when it was discovered but later was called an asteroid (the first of many.) Now, it has again been reclassified and is considered one of the dwarf planets, like Pluto (see the chapter on **Moons, Rings and Pluto**). We still find it convenient, however, to discuss Ceres as the largest of the asteroids. Two other asteroids, Pallas and Vesta, have diameters of about 500 kilometers, and about 15 more are larger than 250 kilometers (see **Table 13.1**). The number of asteroids increases rapidly with decreasing size; there are about 100 times more objects 10 kilometers across than there are 100 kilometers across. By 2016, nearly a million asteroids have been discovered by astronomers.

LINK TO LEARNING

The **Minor Planet Center (https://openstaxcollege.org/l/30minplancen)** is a worldwide repository of data on asteroids. Visit it online to find out about the latest discoveries related to the small bodies in our solar system. (Note that some of the material on this site is technical; it's best to click on the menu tab for the "public" for information more at the level of this textbook.)

The Largest Asteroids

#	Name	Year of Discovery	Orbit's Semimajor Axis (AU)	Diameter (km)	Compositional Class
1	Ceres	1801	2.77	940	C (carbonaceous)
2	Pallas	1802	2.77	540	C (carbonaceous)
3	Juno	1804	2.67	265	S (stony)
4	Vesta	1807	2.36	510	basaltic
10	Hygiea	1849	3.14	410	C (carbonaceous)
16	Psyche	1852	2.92	265	M (metallic)
31	Euphrosyne	1854	3.15	250	C (carbonaceous)
52	Europa	1858	3.10	280	C (carbonaceous)
65	Cybele	1861	3.43	280	C (carbonaceous)
87	Sylvia	1866	3.48	275	C (carbonaceous)
451	Patientia	1899	3.06	260	C (carbonaceous)
511	Davida	1903	3.16	310	C (carbonaceous)
704	Interamnia	1910	3.06	310	C (carbonaceous)

Table 13.1

The asteroids all revolve about the Sun in the same direction as the planets, and most of their orbits lie near the plane in which Earth and other planets circle. The majority of asteroids are in the **asteroid belt**, the region between Mars and Jupiter that contains all asteroids with orbital periods between 3.3 to 6 years (**Figure 13.2**). Although more than 75% of the known asteroids are in the belt, they are not closely spaced (as they are sometimes depicted in science fiction movies). The volume of the belt is actually very large, and the typical spacing between objects (down to 1 kilometer in size) is several million kilometers. (This was fortunate for spacecraft like Galileo, Cassini, *Rosetta*, and New Horizons, which needed to travel through the asteroid belt without a collision.)

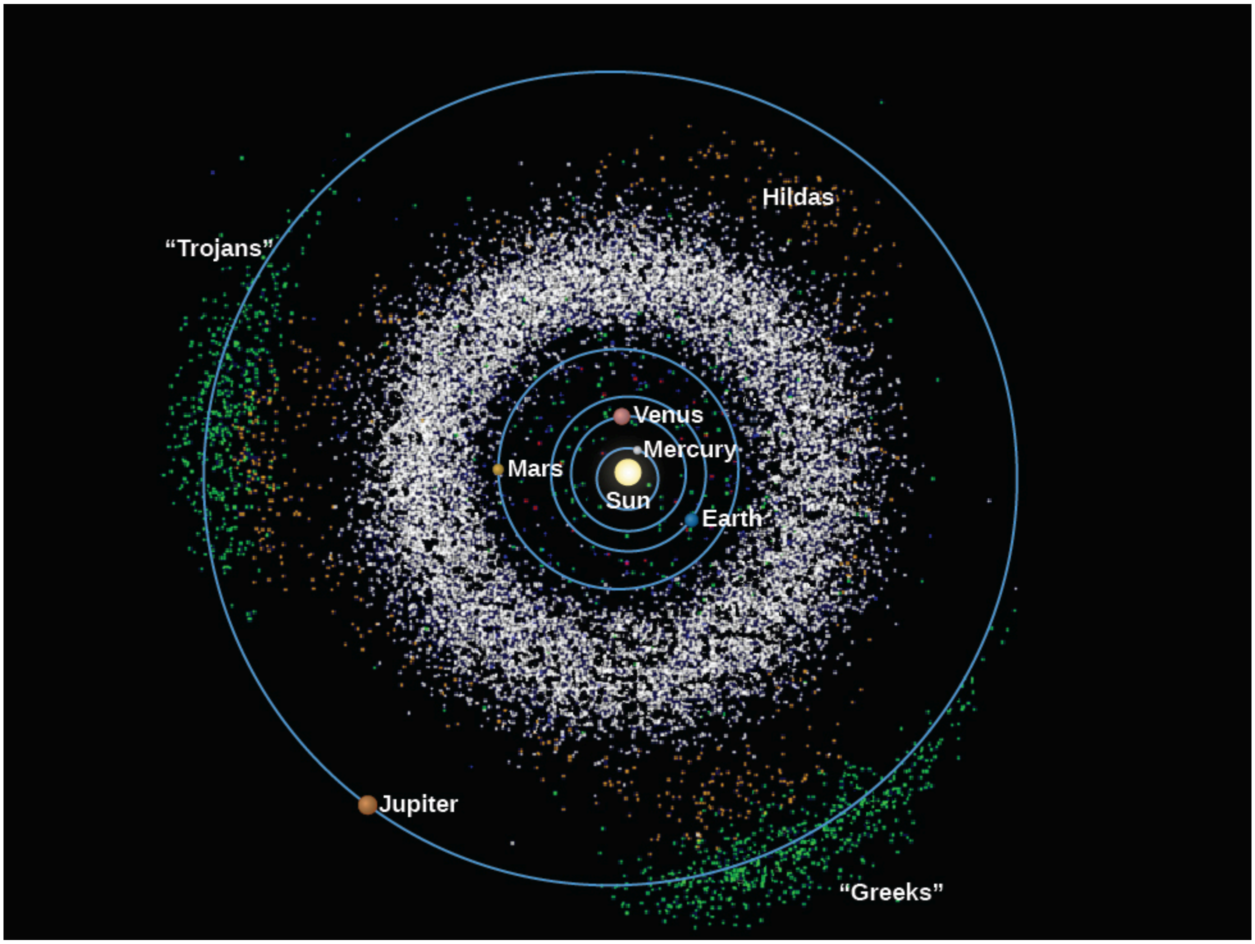

Figure 13.2 Asteroids in the Solar System. This computer-generated diagram shows the positions of the asteroids known in 2006. If the asteroid sizes were drawn to scale, none of the dots representing an asteroid would be visible. Here, the asteroid dots are too big and give a false impression of how crowded the asteroid belt would look if you were in it. Note that in addition to those in the asteroid belt, there are also asteroids in the inner solar system and some along Jupiter's orbit (such as the Trojans and Greeks groups), controlled by the giant planet's gravity.

Still, over the long history of our solar system, there have been a good number of collisions among the asteroids themselves. In 1918, the Japanese astronomer Kiyotsugu Hirayama found that some asteroids fall into *families*, groups with similar orbital characteristics. He hypothesized that each family may have resulted from the breakup of a larger body or, more likely, from the collision of two asteroids. Slight differences in the speeds with which the various fragments left the collision scene account for the small spread in orbits now observed for the different asteroids in a given family. Several dozen such families exist, and observations have shown that individual members of most families have similar compositions, as we would expect if they were fragments of a common parent.

LINK TO LEARNING

You can see a **dramatic animated video (https://openstaxcollege.org/l/30anividastorb)** showing the orbits of 100,000 asteroids found by one sky survey. As the 3-minute video goes on, you get to see the orbits of the planets and how the asteroids are distributed in the solar system. But note that all such videos are misleading in one sense. The asteroids themselves are really small compared to the distances covered, so they have to be depicted as larger points to be visible. If you were in the asteroid belt, there would be far more empty space than asteroids.

Composition and Classification

Asteroids are as different as black and white. The majority are very dark, with reflectivity of only 3 to 4%, like a lump of coal. However, another large group has a typical reflectivity of 15%. To understand more about these differences and how they are related to chemical composition, astronomers study the spectrum of the light reflected from asteroids for clues about their composition.

The dark asteroids are revealed from spectral studies to be *primitive* bodies (those that have changed little chemically since the beginning of the solar system) composed of silicates mixed with dark, organic carbon compounds. These are known as C-type asteroids (“C” for carbonaceous). Two of the largest asteroids, Ceres and Pallas, are primitive, as are almost all of the asteroids in the outer part of the belt.

The second most populous group is the S-type asteroids, where “S” stands for a stony or silicate composition. Here, the dark carbon compounds are missing, resulting in higher reflectivity and clearer spectral signatures of silicate minerals. The S-type asteroids are also chemically primitive, but their different composition indicates that they were probably formed in a different location in the solar system from the C-type asteroids.

Asteroids of a third class, much less numerous than those of the first two, are composed primarily of metal and are called M-type asteroids (“M” for metallic). Spectroscopically, the identification of metal is difficult, but for at least the largest M-type asteroid, Psyche, this identification has been confirmed by radar. Since a metal asteroid, like an airplane or ship, is a much better reflector of radar than is a stony object, Psyche appears bright when we aim a radar beam at it.

How did such metal asteroids come to be? We suspect that each came from a parent body large enough for its molten interior to settle out or differentiate, and the heavier metals sank to the center. When this parent body shattered in a later collision, the fragments from the core were rich in metals. There is enough metal in even a 1-kilometer M-type asteroid to supply the world with iron and many other industrial metals for the foreseeable future, if we could bring one safely to Earth.

In addition to the M-type asteroids, a few other asteroids show signs of early heating and differentiation. These have basaltic surfaces like the volcanic plains of the Moon and Mars; the large asteroid Vesta (discussed in a moment) is in this last category.

The different classes of asteroids are found at different distances from the Sun (**Figure 13.3**). By tracing how asteroid compositions vary with distance from the Sun, we can reconstruct some of the properties of the solar nebula from which they originally formed.

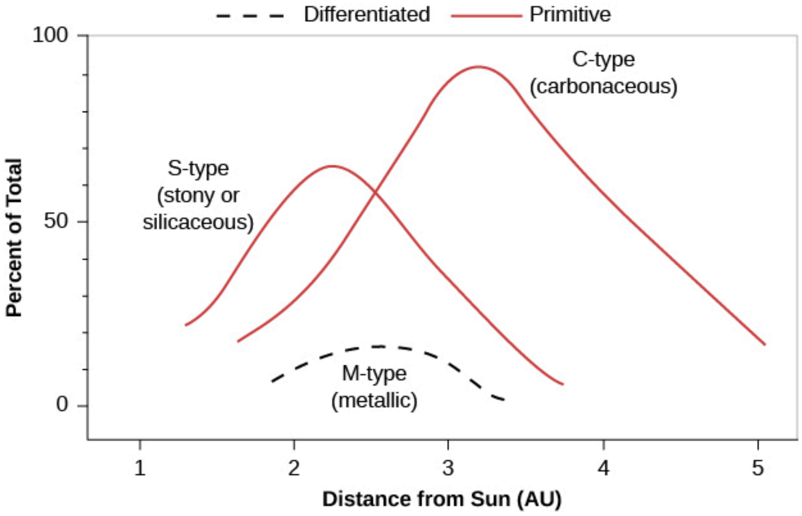

Figure 13.3 Where Different Types of Asteroids Are Found. Asteroids of different composition are distributed at different distances from the Sun. The S-type and C-type are both primitive; the M-type consists of cores of differentiated parent bodies.

Vesta: A Differentiated Asteroid

Vesta is one of the most interesting of the asteroids. It orbits the Sun with a semi-major axis of 2.4 AU in the inner part of the asteroid belt. Its relatively high reflectivity of almost 30% makes it the brightest asteroid, so bright that it is actually visible to the unaided eye if you know just where to look. But its real claim to fame is that its surface is covered with basalt, indicating that Vesta is a differentiated object that must once have been volcanically active, in spite of its small size (about 500 kilometers in diameter).

Meteorites from Vesta’s surface (**Figure 13.4**), identified by comparing their spectra with that of Vesta itself, have landed on Earth and are available for direct study in the laboratory. We thus know a great deal about this asteroid. The age of the lava flows from which these meteorites derived has been measured at 4.4 to 4.5 billion years, very soon after the formation of the solar system. This age is consistent with what we might expect for volcanoes on Vesta; whatever process heated such a small object was probably intense and short-lived. In 2016, a meteorite fell in Turkey that could be identified with a particular lava flow as revealed by the orbiting *Dawn* spacecraft.

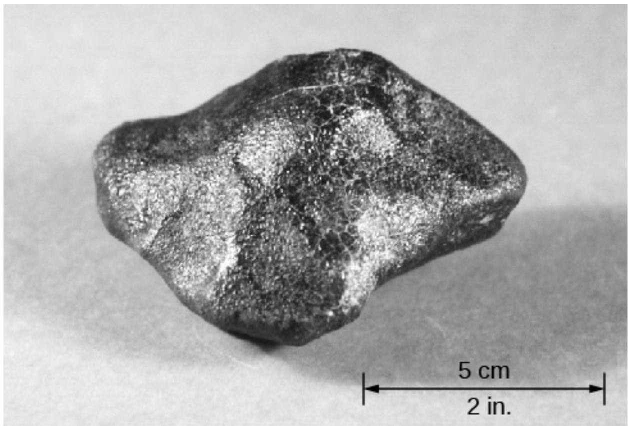

Figure 13.4 Piece of Vesta. This meteorite (rock that fell from space) has been identified as a volcanic fragment from the crust of asteroid Vesta. (credit: modification of work by R. Kempton (New England Meteoritical Services))

Asteroids Up Close

On the way to its 1995 encounter with Jupiter, the Galileo spacecraft was targeted to fly close to two main-belt S-type asteroids called Gaspra and Ida. The Galileo camera revealed both as long and highly irregular (resembling a battered potato), as befits fragments from a catastrophic collision (**Figure 13.5**).

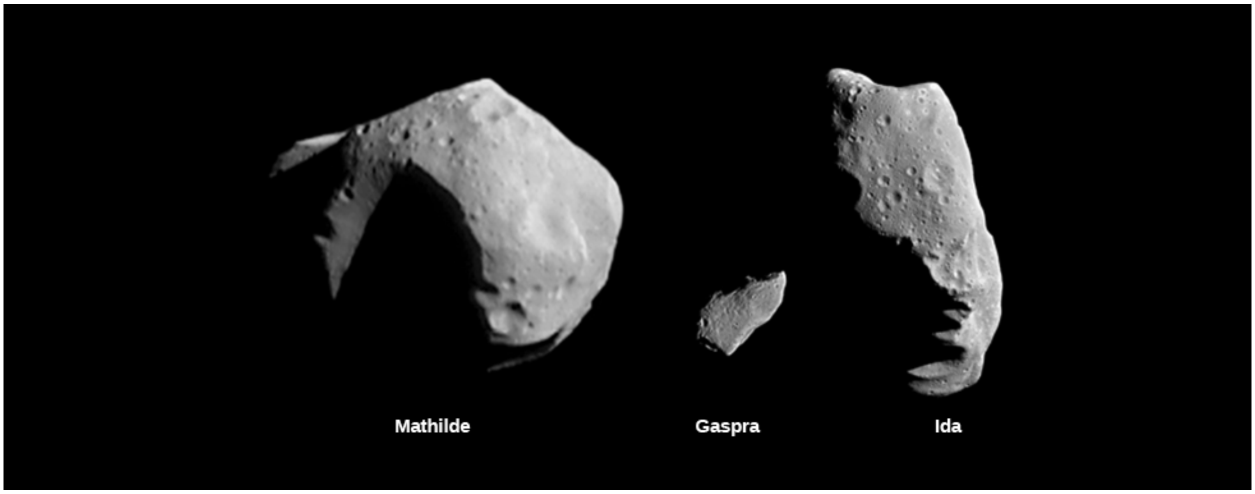

Figure 13.5 Mathilde, Gaspra, and Ida. The first three asteroids photographed from spacecraft flybys, printed to the same scale. Gaspra and Ida are S-type and were investigated by the Galileo spacecraft; Mathilde is C-type and was a flyby target for the NEAR-Shoemaker spacecraft. (credit: modification of work by NEAR Project, Galileo Project, NASA)

The detailed images allowed us to count the craters on Gaspra and Ida, and to estimate the length of time their surfaces have been exposed to collisions. The Galileo scientists concluded that these asteroids are only about 200 million years old (that is, the collisions that formed them took place about 200 million years ago). Calculations suggest that an asteroid the size of Gaspra or Ida can expect another catastrophic collision sometime in the next billion years, at which time it will be disrupted to form another generation of still-smaller fragments.

The greatest surprise of the Galileo flyby of Ida was the discovery of a moon (which was then named Dactyl), in orbit about the asteroid (**Figure 13.6**). Although only 1.5 kilometers in diameter, smaller than many college campuses, Dactyl provides scientists with something otherwise beyond their reach—a measurement of the mass and density of Ida using Kepler’s laws. The moon’s distance of about 100 kilometers and its orbital period of about 24 hours indicate that Ida has a density of approximately 2.5 g/cm^3, which matches the density of primitive rocks. Subsequently, both large visible-light telescopes and high-powered planetary radar have discovered many other asteroid moons, so that we are now able to accumulate valuable data on asteroid masses and densities.

Figure 13.6 Ida and Dactyl. The asteroid Ida and its tiny moon Dactyl (the small body off to its right), were photographed by the Galileo spacecraft in 1993. Irregularly shaped Ida is 56 kilometers in its longest dimension, while Dactyl is about 1.5 kilometers across. The colors have been intensified in this image; to the eye, all asteroids look basically gray. (credit: modification of work by NASA/JPL)

By the way, Phobos and Deimos, the two small moons of Mars, are probably captured asteroids (**Figure 13.7**). They were first studied at close range by the Viking orbiters in 1977 and later by *Mars Global Surveyor*. Both are irregular, somewhat elongated, and heavily created, resembling other smaller asteroids. Their largest dimensions are about 26 kilometers and 16 kilometers, respectively. The small outer moons of Jupiter and Saturn were probably also captured from passing asteroids, perhaps early in the history of the solar system.

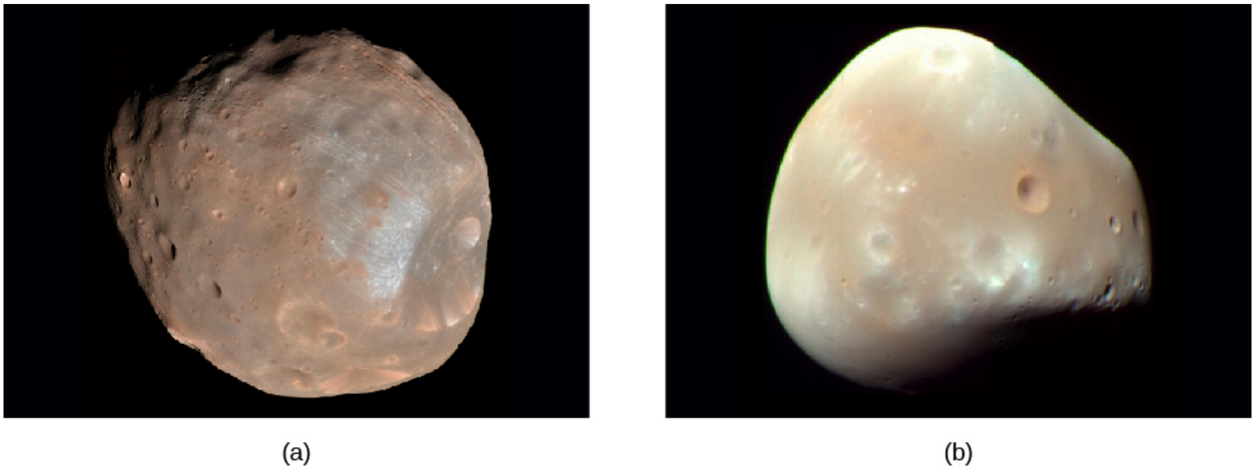

Figure 13.7 Moons of Mars. The two small moons of Mars, (a) Phobos and (b) Deimos, were discovered in 1877 by American astronomer Asaph Hall. Their surface materials are similar to many of the asteroids in the outer asteroid belt, leading astronomers to believe that the two moons may be captured asteroids. (credit a: modification of work by NASA; credit b: modification of work by NASA/JPL-Caltech/University of Arizona)

Beginning in the 1990s, spacecraft have provided close looks at several more asteroids. The Near Earth Asteroid Rendezvous (NEAR) spacecraft went into orbit around the S-type asteroid Eros, becoming a temporary moon of this asteroid. On its way to Eros, the *NEAR* spacecraft was renamed after planetary geologist Eugene Shoemaker, a pioneer in our understanding of craters and impacts.

For a year, the NEAR-Shoemaker spacecraft orbited the little asteroid at various altitudes, measuring its surface and interior composition as well as mapping Eros from all sides (**Figure 13.8**). The data showed that Eros is made of some of the most chemically primitive materials in the solar system. Several other asteroids have been revealed as made of loosely bound rubble throughout, but not Eros. Its uniform density (about the same as that of Earth’s crust) and extensive global-scale grooves and ridges show that it is a cracked but solid rock.

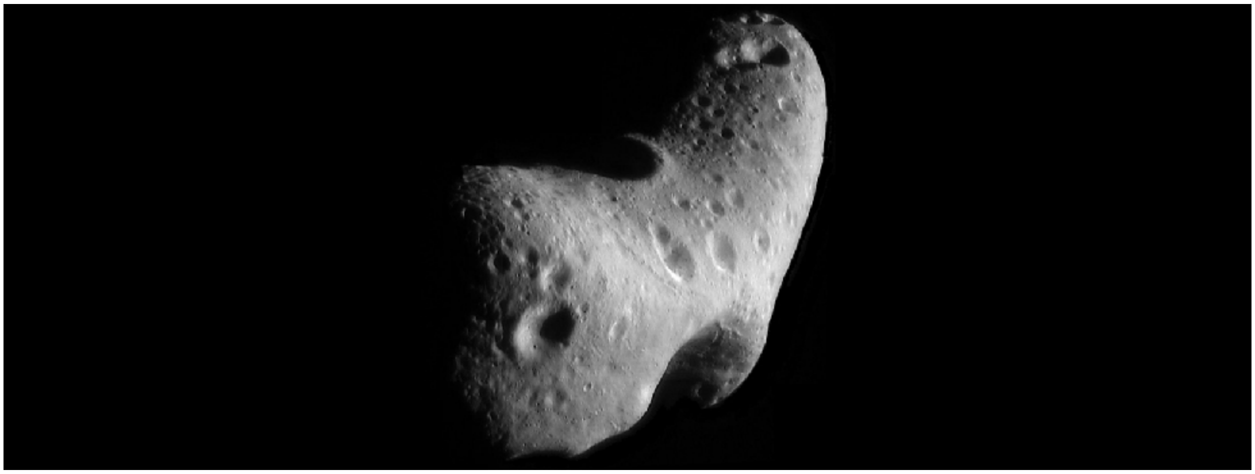

Figure 13.8 Looking Down on the North Pole of Eros. This view was constructed from six images of the asteroid taken from an altitude of 200 kilometers. The large crater at the top has been named Psyche (after the maiden who was Eros' lover in classical mythology) and is about 5.3 kilometers wide. A saddle-shaped region can be seen directly below it. Craters of many different sizes are visible. (credit: modification of work by NASA/JHUPL)

Eros has a good deal of loose surface material that appears to have slid down toward lower elevations. In some places, the surface rubble layer is 100 meters deep. The top of loose soil is dotted with scattered, half-buried boulders. There are so many of these boulders that they are more numerous than the craters. Of course, with the gravity so low on this small world, a visiting astronaut would find loose boulders rolling toward her pretty slowly and could easily leap high enough to avoid being hit by one. Although the NEAR-Shoemaker spacecraft was not constructed as a lander, at the end of its orbital mission in 2000, it was allowed to fall gently to the surface, where it continued its chemical analysis for another week.

In 2003, Japan's Hayabusa 1 mission not only visited a small asteroid but also brought back samples to study in laboratories on Earth. The target S-type asteroid, Itokawa (shown in **Figure 13.9**), is much smaller than Eros, only about 500 meters long. This asteroid is elongated and appears to be the result of the collision of two separate asteroids long ago. There are almost no impact craters, but an abundance of boulders (like a pile of rubble) on the surface.

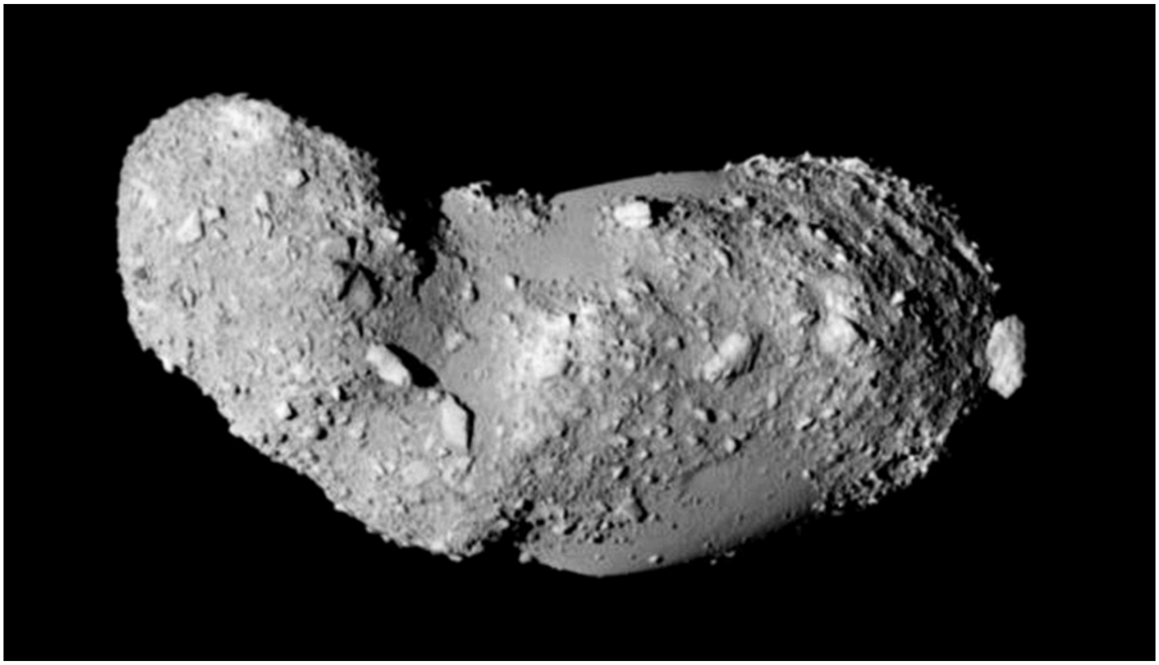

Figure 13.9 Asteroid Itokawa. The surface of asteroid Itokawa appears to have no craters. Astronomers have hypothesized that its surface consists of rocks and ice chunks held together by a small amount of gravity, and its interior is probably also a similar rubble pile. (credit: JAXA)

The *Hayabusa* spacecraft was designed not to land, but to touch the surface just long enough to collect a small sample. This tricky maneuver failed on its first try, with the spacecraft briefly toppling over on its side. Eventually, the controllers were successful in picking up a few grains of surface material and transferring them into the return capsule. The 2010 reentry into Earth's atmosphere over Australia was spectacular (**Figure 13.10**), with a fiery breakup of the spacecraft, while a small return capsule successfully parachuted to the surface. Months of careful extraction and study of more than a thousand tiny dust particles confirmed that the surface of Itokawa had a composition similar to a well-known class of primitive meteorites. We estimate that the dust grains *Hayabusa* picked up had been exposed on the surface of the asteroid for about 8 million years.

Figure 13.10 Hayabusa Return. This dramatic image shows the *Hayabusa* probe breaking up upon reentry. The return capsule, which separated from the main spacecraft and parachuted to the surface, glows at the bottom right. (credit: modification of work by NASA Ames/Jesse Carpenter/Greg Merkes)

The most ambitious asteroid space mission (called Dawn) has visited the two largest main belt asteroids, Ceres and Vesta, orbiting each for about a year (**Figure 13.11**). Their large sizes (diameters of about 1000 and 500 kilometers, respectively) make them appropriate for comparison with the planets and large moons. Both turned out to be heavily cratered, implying their surfaces are old. On Vesta, we have now actually located the large impact craters that ejected the basaltic meteorites previously identified as coming from this asteroid. These craters are so large that they sample several layers of Vesta's crustal material.

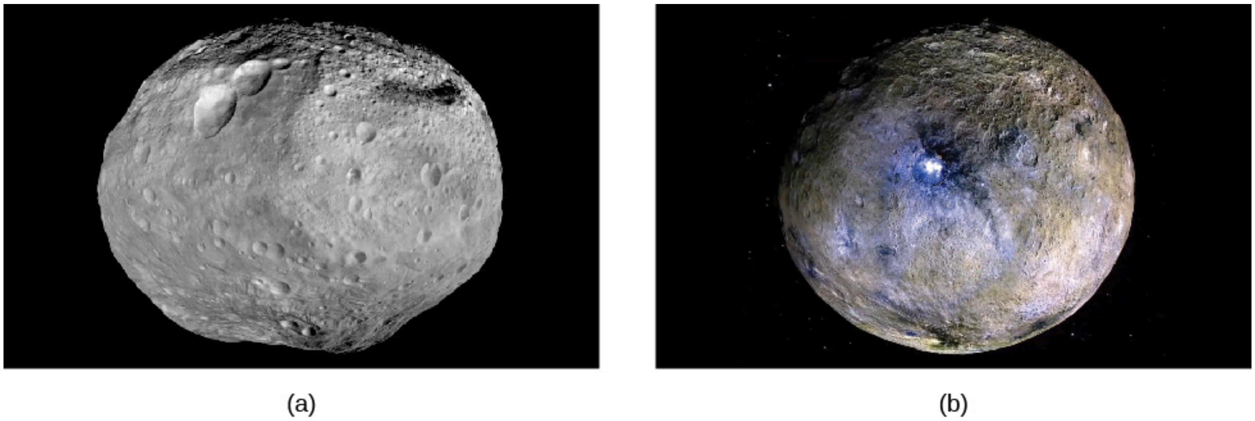

Figure 13.11 Vesta and Ceres. The NASA *Dawn* spacecraft took these images of the large asteroids (a) Vesta and (b) Ceres. (a) Note that Vesta is not round, as Ceres (which is considered a dwarf planet) is. A mountain twice the height of Mt. Everest on Earth is visible at the very bottom of the Vesta image. (b) The image of Ceres has its colors exaggerated to bring out differences in composition. You can see a white feature in Occator crater near the center of the image. (credit a, b: modification of work by NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

Ceres has not had a comparable history of giant impacts, so its surface is covered with craters that look more like those from the lunar highlands. One big surprise at Ceres is the presence of very bright white spots, associated primarily with the central peaks of large craters (**Figure 13.12**). The light-colored mineral is primarily salt, released from the interior. After repeated close flybys, data from the NASA Dawn spacecraft indicated that Ceres has (or has had) a subsurface ocean of water, with occasional eruptions on the surface. The most dramatic is the 4 kilometer tall ice volcano called Ahuna Mons (see **Figure 13.12**).

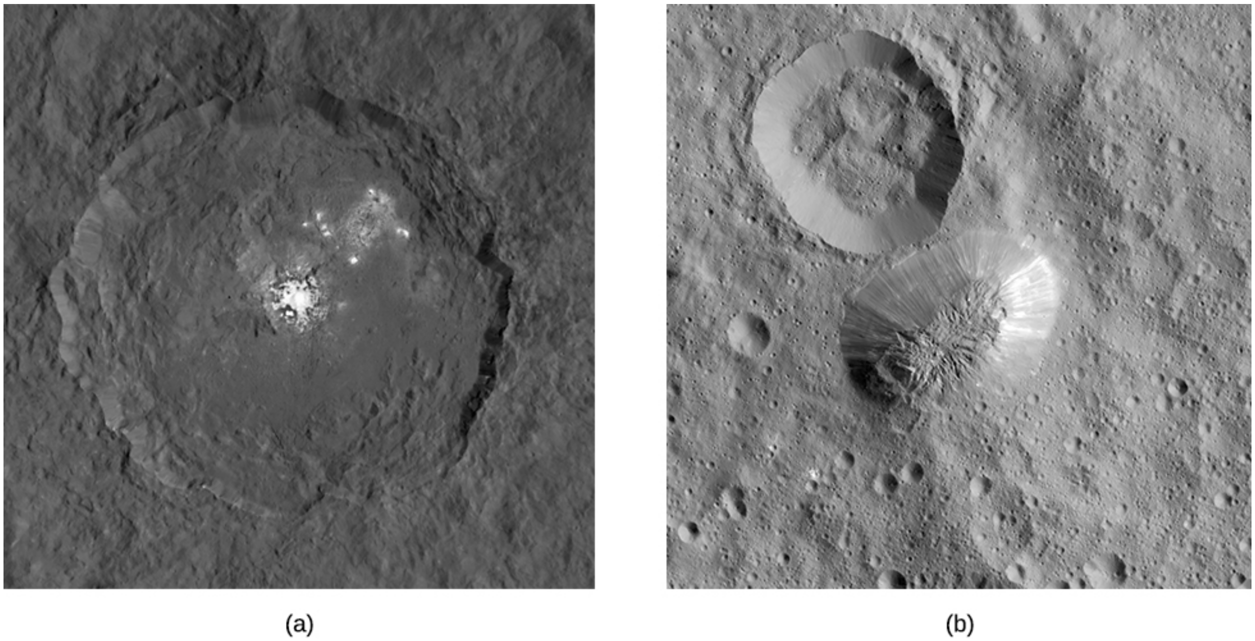
(a)
(b)

Figure 13.12 White Spots in a Larger Crater on Ceres. White Spots in a Larger Crater on Ceres. (a) These bright features appear to be salt deposits in a Ceres crater called Occator, which is 92 kilometers across. (b) Ahuna Mons is an isolated mountain on Ceres, 4 kilometers high. It is thought to be an intrusion of ice from the interior. (credit a: modification of work by NASA/JPL-Caltech/UCLA/MPS/DLR/IDA; credit b: modification of work by NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI)

In late 2017, something entirely new was discovered: an interstellar asteroid. This visitor was found at a distance of 33 million kilometers with a survey telescope on Haleakala, Hawaii. As astronomers followed up on the discovery, it quickly became apparent that this asteroid was travelling far too fast to be part of the Sun's family. Its orbit is a hyperbola, and when discovered it was already rapidly leaving the inner solar system. Although it was too distant for imaging by even large telescopes, its size and shape could be estimated from its brightness and rapid light fluctuations. It is highly elongated, with an approximately cylindrical shape. The nominal dimensions are about 200 meters in length and only 35 meters across, the most extreme of any natural object. Large objects, like planets and moons, are pulled by their own gravity into roughly spherical shapes, and even small asteroids and comets (often described as "potato-shaped") rarely have irregularities of more than a factor of two.

This asteroid was named 'Oumuamua, a Hawaiian word meaning "scout" or "first to reach out." In a way, the discovery of an interstellar asteroid or comet was not unexpected. Early in solar system history, before the planet orbits sorted themselves into stable, non-intersecting paths all in the same plane, we estimate that quite a lot of mass was ejected, either whole planets or more numerous smaller fragments. Even today, an occasional comet coming in from the outer edges of the solar system can have its orbit changed by gravitational interaction with Jupiter and the Sun, and some of these escape on hyperbolic trajectories. As we have recently learned that planetary systems are common, the question became: where are similar debris objects ejected from other planetary systems? Now we have found one, and improved surveys will soon add others to this category.

LINK TO LEARNING

View an artist's rendering of the asteroid 'Oumuamua **(https://www.openstax.org/l/30/oumuamua)**

(https://www.openstax.org/l/30/oumuamua) by the ESO. Although it was not close enough to Earth to be imaged, its long slender shape was indicated by its rapid variation in brightness as it rotated.

LINK TO LEARNING

The space agencies involved with the Dawn mission have produced nice animated "flyover" videos of **Vesta (https://openstaxcollege.org/l/30vestaflyover)** and **Ceres (https://openstaxcollege.org/l/30ceresflyover)** available online.

13.2 ASTEROIDS AND PLANETARY DEFENSE

Learning Objectives

By the end of this section, you will be able to:

- Recognize the threat that near-Earth objects represent for Earth
- Discuss possible defensive strategies to protect our planet

Not all asteroids are in the main asteroid belt. In this section, we consider some special groups of asteroids with orbits that approach or cross the orbit of Earth. These pose the risk of a catastrophic collision with our planet, such as the collision 65 million years ago that killed the dinosaurs.

Earth-Approaching Asteroids

Asteroids that stray far *outside* the main belt are of interest mostly to astronomers. But asteroids that come *inward*, especially those with orbits that come close to or cross the orbit of Earth, are of interest to political leaders, military planners—indeed, everyone alive on Earth. Some of these asteroids briefly become the closest celestial object to us.

In 1994, a 1-kilometer object was picked up passing closer than the Moon, causing a stir of interest in the news media. Today, it is routine to read of small asteroids coming this close to Earth. (They were always there, but only in recent years have astronomers been able to detect such faint objects.)

In 2013, a small asteroid hit our planet, streaking across the sky over the Russian city of Chelyabinsk and exploding with the energy of a nuclear bomb (**Figure 13.13**). The impactor was a stony object about 20 meters in diameter, exploding about 30 kilometers high with an energy of 500 kilotons (about 30 times larger than the nuclear bombs dropped on Japan in World War II). No one was hurt by the blast itself, although it briefly became as bright as the Sun, drawing many spectators to the windows in their offices and homes. When the blast wave from the explosion then reached the town, it blew out the windows. About 1500 people had to seek medical attention from injuries from the shattered glass.

A much larger atmospheric explosion took place in Russia in 1908, caused by an asteroid about 40 meters in diameter, releasing an energy of 5 megatons, as large the most powerful nuclear weapons of today. Fortunately, the area directly affected, on the Tunguska River in Siberia, was unpopulated, and no one was killed. However, the area of forest destroyed by the blast was large equal to the size of a major city (**Figure 13.13**).