13

COMETS AND ASTEROIDS: DEBRIS OF THE SOLAR SYSTEM

Figure 13.1 Hale-Bopp. Comet Hale-Bopp was one of the most attractive and easily visible comets of the twentieth century. It is shown here as it appeared in the sky in March 1997. You can see the comet's long blue ion tail and the shorter white dust tail. You will learn about these two types of comet tails, and how they form, in this chapter. (credit: modification of work by ESO/E. Slawik)

Chapter Outline

Thinking Ahead

Hundreds of smaller members of the solar system—asteroids and comets—are known to have crossed Earth's orbit in the past, and many others will do so in centuries ahead. What could we do if we knew a few years in advance that one of these bodies would hit Earth?

To understand the early history of life on Earth, scientists study ancient fossils. To reconstruct the early history of the solar system, we need cosmic fossils—materials that formed when our system was very young. However, reconstructing the early history of the solar system by looking just at the planets is almost as difficult as determining the circumstances of human birth by merely looking at an adult.

Instead, we turn to the surviving remnants of the creation process—ancient but smaller objects in our cosmic neighborhood. Asteroids are rocky or metallic and contain little *volatile* (easily evaporated) material. Comets are small icy objects that contain frozen water and other volatile materials but with solid grains mixed in. In the deep freeze beyond Neptune, we also have a large reservoir of material unchanged since the formation of the solar system, as well as a number of dwarf planets.

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.)

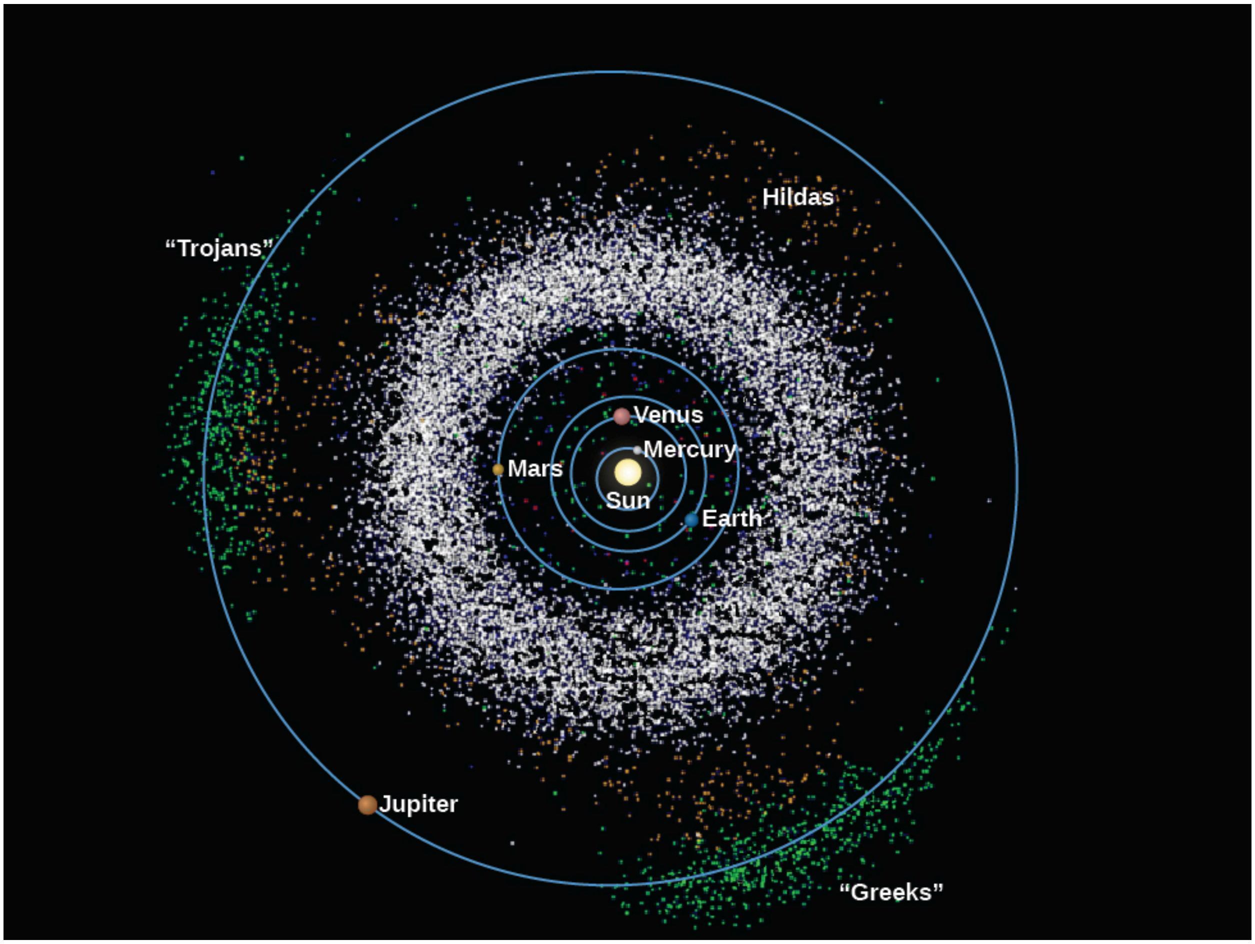


Figure 13.2 Asteroids in the Solar System. This computer-generated diagram shows the positions of the asteroids known in 2006. If the asteroid sizes were drawn to scale, none of the dots representing an asteroid would be visible. Here, the asteroid dots are too big and give a false impression of how 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.

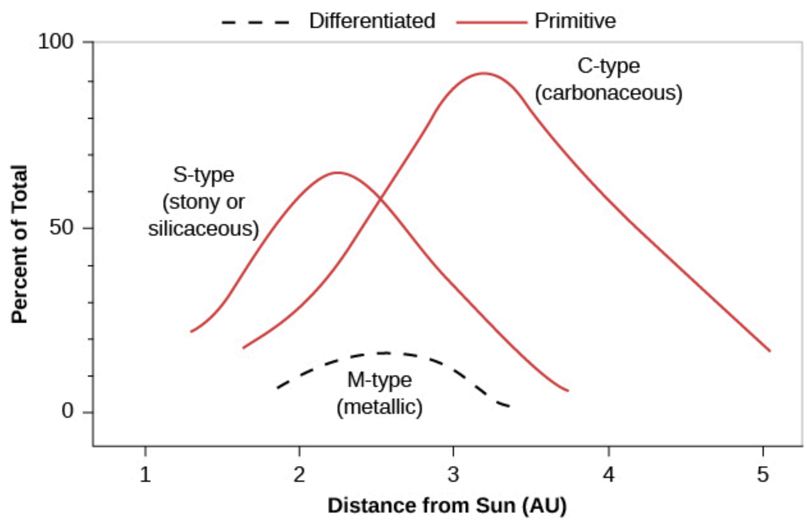


Figure 13.3 Where Different Types of Asteroids Are Found. Asteroids of different composition are distributed at different distances from the Sun. The S-type and C-type are both primitive; the M-type consists of cores of differentiated parent bodies.

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.

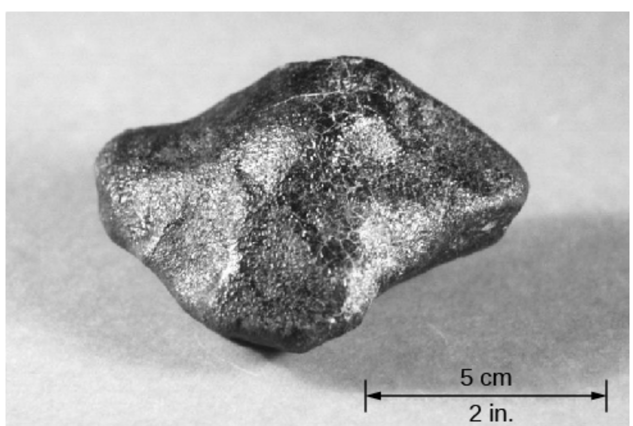


Figure 13.4 Piece of Vesta. This meteorite (rock that fell from space) has been identified as a volcanic fragment from the crust of asteroid Vesta. (credit: modification of work by R. Kempton (New England Meteoritical Services))

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).

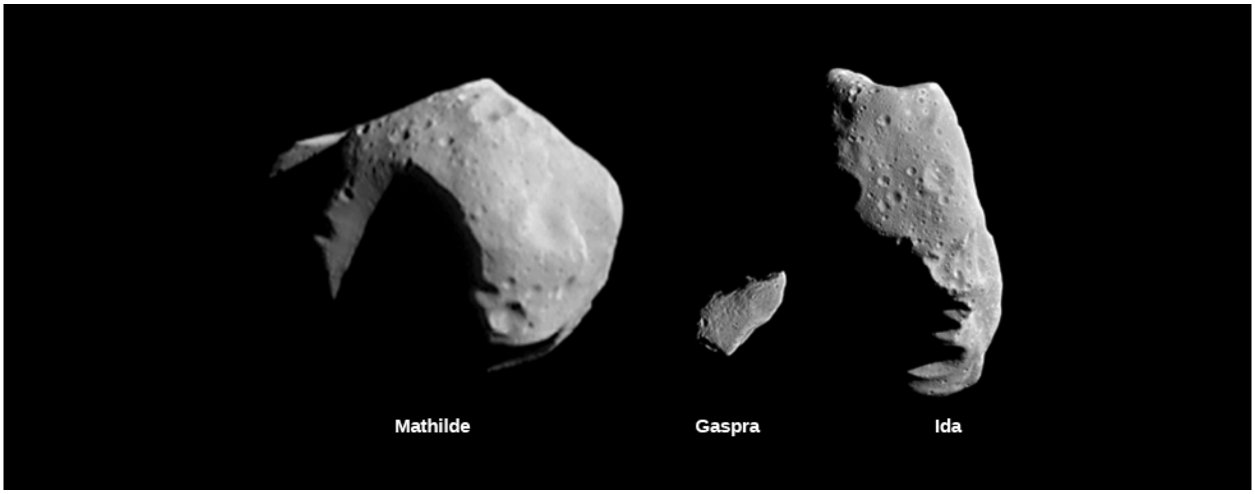


Figure 13.5 Mathilde, Gaspra, and Ida. The first three asteroids photographed from spacecraft flybys, printed to the same scale. Gaspra and Ida are S-type and were investigated by the Galileo spacecraft; Mathilde is C-type and was a flyby target for the NEAR-Shoemaker spacecraft. (credit: modification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

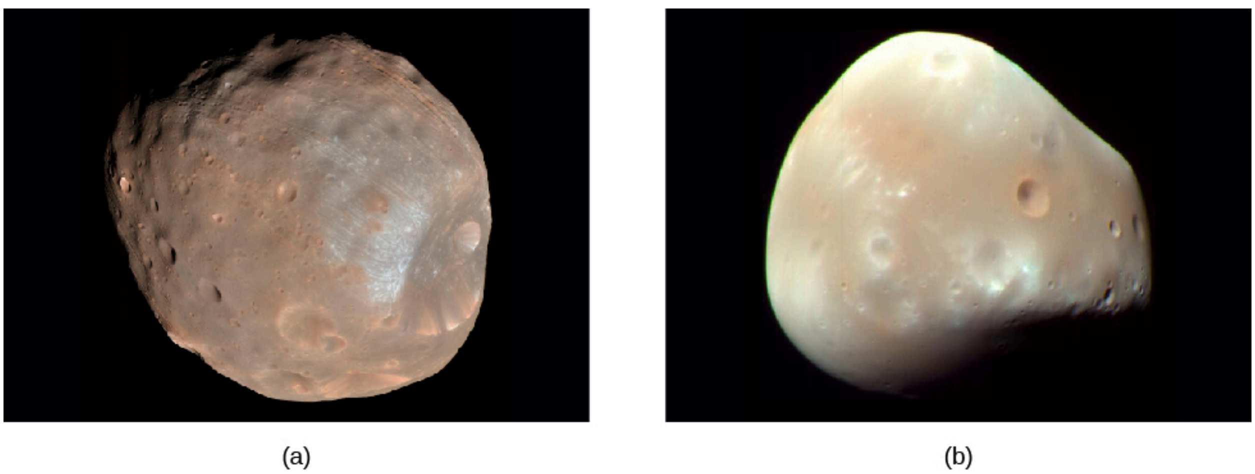


Figure 13.7 Moons of Mars. The two small moons of Mars, (a) Phobos and (b) Deimos, were discovered in 1877 by American astronomer Asaph Hall. Their surface materials are similar to many of the asteroids in the outer asteroid belt, leading astronomers to believe that the two moons may be captured asteroids. (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.

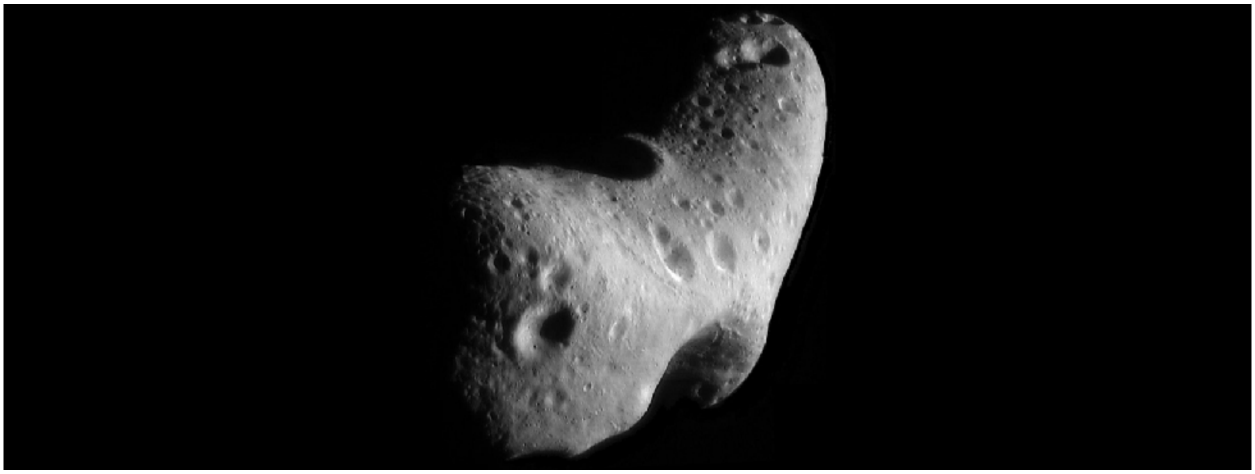


Figure 13.8 Looking Down on the North Pole of Eros. This view was constructed from six images of the asteroid taken from an altitude of 200 kilometers. The large crater at the top has been named Psyche (after the maiden who was Eros' lover in classical mythology) and is about 5.3 kilometers wide. A saddle-shaped 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.

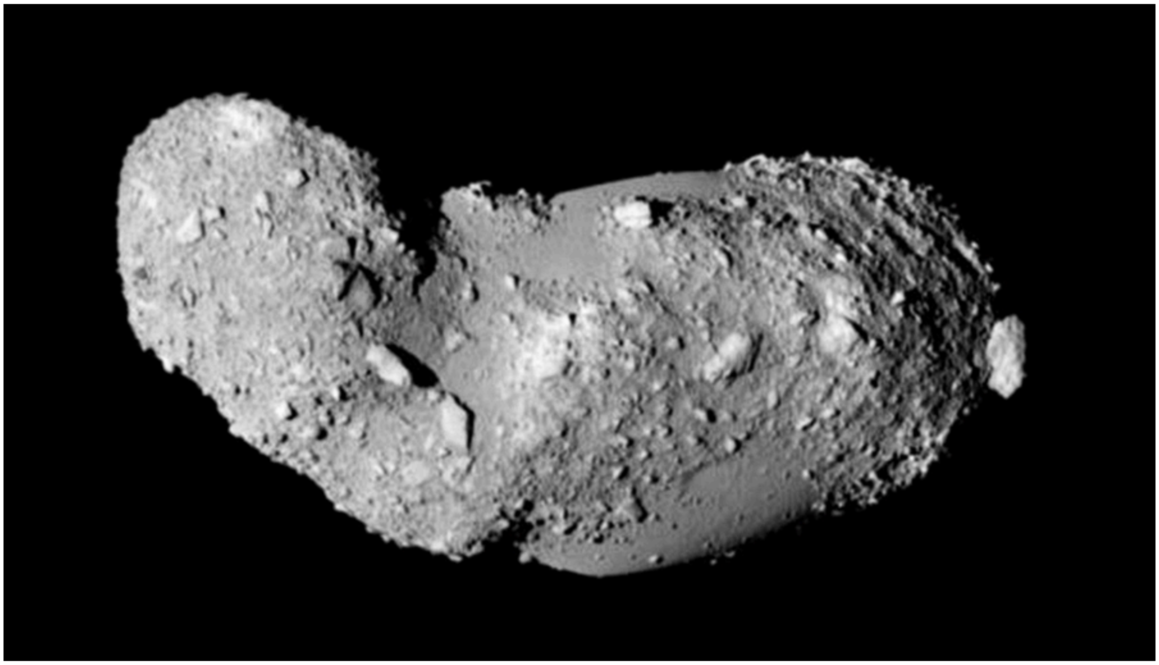


Figure 13.9 Asteroid Itokawa. The surface of asteroid Itokawa appears to have no craters. Astronomers have hypothesized that its surface consists of rocks and ice chunks held together by a small amount of gravity, and its interior is probably also a similar rubble pile. (credit: JAXA)

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.

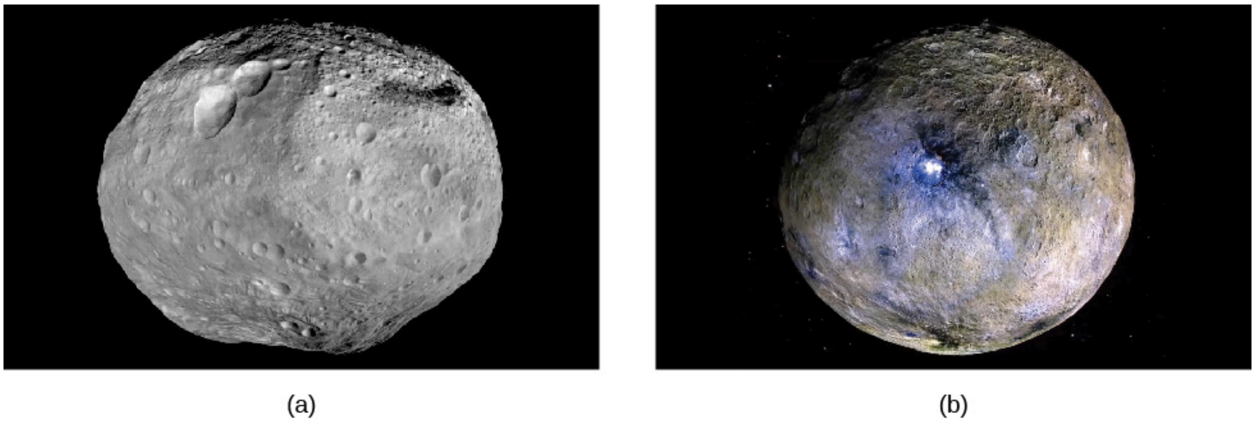
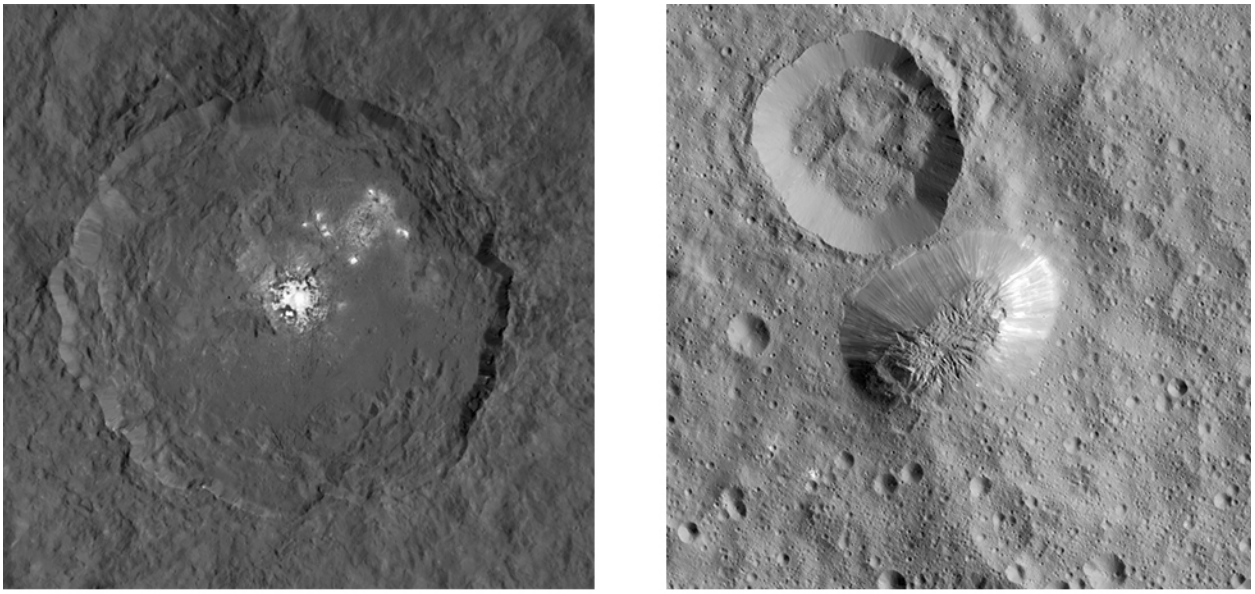


Figure 13.11 Vesta and Ceres. The NASA *Dawn* spacecraft took these images of the large asteroids (a) Vesta and (b) Ceres. (a) Note that Vesta is not round, as Ceres (which is considered a dwarf planet) is. A mountain twice the height of Mt. Everest on Earth is visible at the very bottom of the Vesta 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**).

Together with any comets that come close to our planet, such asteroids are known collectively as **near-Earth objects (NEOs)**. As we will see (and as the dinosaurs found out 65 million years ago,) the collision of a significant-sized NEO could be a catastrophe for life on our planet.

(a) (b)

Figure 13.13 Impacts with Earth. (a) As the Chelyabinsk meteor passed through the atmosphere, it left a trail of smoke and briefly became as bright as the Sun. (b) Hundreds of kilometers of forest trees were knocked down and burned at the Tunguska impact site. (credit a: modification of work by Alex Alishevskikh)

LINK TO LEARNING

Visit the **video compilation (https://openstaxcollege.org/l/30vidcomchelmet)** of the Chelyabinsk meteor streaking through the sky over the city on February 15, 2013, as taken by people who were in the area when it occurred.

LINK TO LEARNING

View this **video of a non-technical talk by David Morrison (https://openstaxcollege.org/l/30davmorrison)** to watch “The Chelyabinsk Meteor: Can We Survive a Bigger Impact?” Dr. Morrison (SETI Institute and NASA Ames Research Center) discusses the Chelyabinsk impact and how we learn about NEOs and protect ourselves; the talk is from the Silicon Valley Astronomy Lectures series.

Astronomers have urged that the first step in protecting Earth from future impacts by NEOs must be to learn what potential impactors are out there. In 1998, NASA began the Spaceguard Survey, with the goal to discover and track 90% of Earth-approaching asteroids greater than 1 kilometer in diameter. The size of 1 kilometer was selected to include all asteroids capable of causing global damage, not merely local or regional effects. At 1 kilometer or larger, the impact could blast so much dust into the atmosphere that the sunlight would be dimmed for months, causing global crop failures—an event that could threaten the survival of our civilization. The Spaceguard goal of 90% was reached in 2012 when nearly a thousand of these 1-kilometer **near-Earth asteroids (NEAs)** had been found, along with more than 10,000 smaller asteroids. **Figure 13.14** shows how the pace of NEA discoveries has been increasing over recent years.

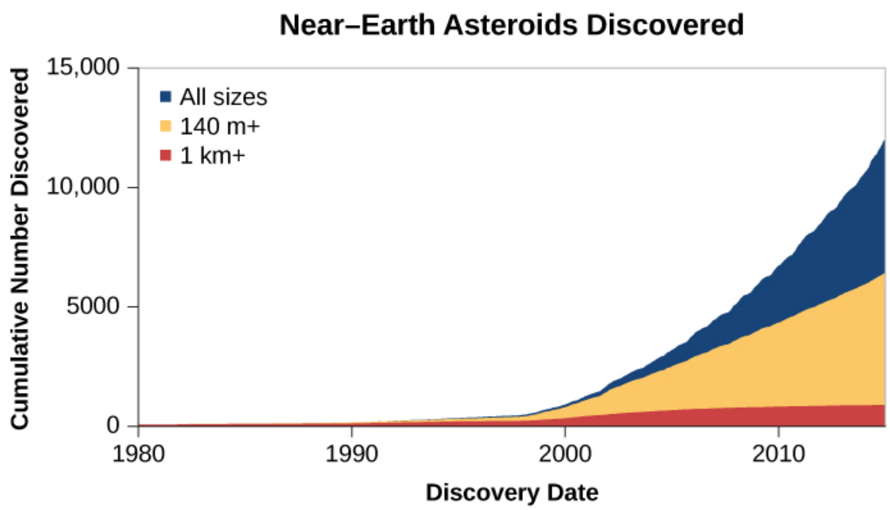


Figure 13.14 Discovery of Near-Earth Asteroids. The accelerating rate of discovery of NEAs is illustrated in this graph, which shows the total number of known NEAs, the number over 140 kilometers in diameter, and the number over 1 kilometer in diameter, the size that poses the dominant impact risk on Earth.

How did astronomers know when they had discovered 90% of these asteroids? There are several ways to estimate the total number, even before they were individually located. One way is to look at the numbers of large craters on the dark lunar maria. Remember that these craters were made by impacts just like the ones we are considering. They are preserved on the Moon's airless surface, whereas Earth soon erases the imprints of past impacts. Thus, the number of large craters on the Moon allows us to estimate how often impacts have occurred on both the Moon and Earth over the past several billion years. The number of impacts is directly related to the number of asteroids and comets on Earth-crossing orbits.

Another approach is to see how often the surveys (which are automated searches for faint points of light that move among the stars) rediscover a previously known asteroid. At the beginning of a survey, all the NEAs it finds will be new. But as the survey becomes more complete, more and more of the moving points the survey cameras record will be *rediscoveries.* The more rediscoveries each survey experiences, the more complete our inventory of these asteroids must be.

We have been relieved to find that none of the NEAs discovered so far is on a trajectory that will impact Earth within the foreseeable future. However, we can't speak for the handful of asteroids larger than 1 kilometer that have not yet been found, or for the much more numerous smaller ones. It is estimated that there are a million NEAs capable of hitting Earth that are smaller than 1 kilometer but still large enough to destroy a city, and our surveys have found fewer than 10% of them. Researchers who work with asteroid orbits estimate that for smaller (and therefore fainter) asteroids we are not yet tracking, we will have about a 5-second warning that one is going to hit Earth—in other words, we won't see it until it enters the atmosphere. Clearly, this estimate gives us a lot of motivation to continue these surveys to track as many asteroids as possible.

Though entirely predictable over times of a few centuries, the orbits of Earth-approaching asteroids are unstable over long time spans as they are tugged by the gravitational attractions of the planets. These objects will eventually meet one of two fates: either they will impact one of the terrestrial planets or the Sun, or they will be ejected gravitationally from the inner solar system due to a near-encounter with a planet. The probabilities of these two outcomes are about the same. The timescale for impact or ejection is only about a hundred million years, very short compared with the 4-billion-year age of the solar system. Calculations show that only approximately one quarter of the current Earth-approaching asteroids will eventually end up colliding with Earth itself.

If most of the current population of Earth-approaching asteroids will be removed by impact or ejection in a hundred million years, there must be a continuing source of new objects to replenish our supply of NEAs. Most of them come from the asteroid belt between Mars and Jupiter, where collisions between asteroids can eject fragments into Earth-crossing orbits (see **Figure 13.15**). Others may be "dead" comets that have exhausted their volatile materials (which we'll discuss in the next section).

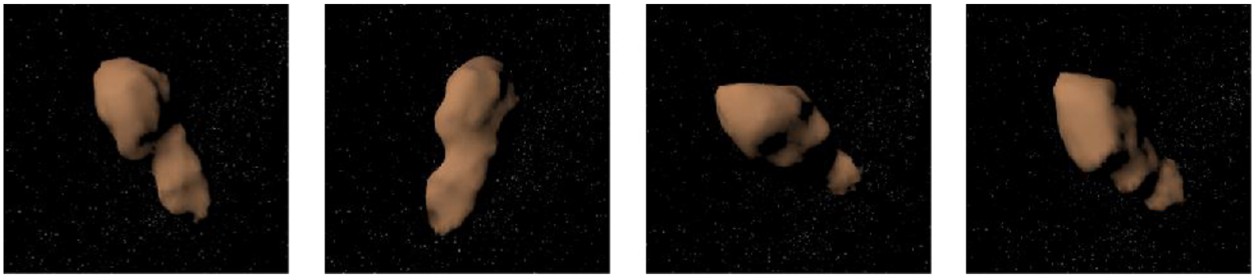


Figure 13.15 Near-Earth Asteroid. Toutatis is a 5-kilometer long NEA that approached within 3 million kilometers of Earth in 1992. This series of images is a reconstruction its size and shape obtained from bouncing radar waves off the asteroid during its close flyby. Toutatis appears to consist of two irregular, lumpy bodies rotating in contact with each other. (Note that the color has been artificially added.) (credit: modification of work by NASA)

One reason scientists are interested in the composition and interior structure of NEAs is that humans will probably need to defend themselves against an asteroid impact someday. If we ever found one of these asteroids on a collision course with us, we would need to deflect it so it would miss Earth. The most straightforward way to deflect it would be to crash a spacecraft into it, either slowing it or speeding it up, slightly changing its orbital period. If this were done several years before the predicted collision, the asteroid would miss the planet entirely—making an asteroid impact the only natural hazard that we could eliminate completely by the application of technology. Alternatively, such deflection could be done by exploding a nuclear bomb near the asteroid to nudge it off course.

To achieve a successful deflection by either technique, we need to know more about the density and interior structure of the asteroid. A spacecraft impact or a nearby explosion would have a greater effect on a solid rocky asteroid such as Eros than on a loose rubble pile. Think of climbing a sand dune compared to climbing a rocky hill with the same slope. On the dune, much of our energy is absorbed in the slipping sand, so the climb is much more difficult and takes more energy.

There is increasing international interest in the problem of asteroid impacts. The United Nations has formed two technical committees on planetary defense, recognizing that the entire planet is at risk from asteroid impacts. However, the fundamental problem remains one of finding NEAs in time for defensive measures to be taken. We must be able to find the next impactor before it finds us. And that's a job for the astronomers.

13.3 THE "LONG-HAIRED" COMETS

Learning Objectives

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

- Characterize the general physical appearance of comets
- Explain the range of cometary orbits
- Describe the size and composition of a typical comet's nucleus
- Discuss the atmospheres of comets
- Summarize the discoveries of the Rosetta mission

Comets differ from asteroids primarily in their icy composition, a difference that causes them to brighten dramatically as they approach the Sun, forming a temporary atmosphere. In some early cultures, these so-called “hairy stars” were considered omens of disaster. Today, we no longer fear comets, but eagerly anticipate those that come close enough to us to put on a good sky show.

Appearance of Comets

A **comet** is a relatively small chunk of icy material (typically a few kilometers across) that develops an atmosphere as it approaches the Sun. Later, there may be a very faint, nebulous **tail**, extending several million kilometers away from the main body of the comet. Comets have been observed from the earliest times: accounts of comets are found in the histories of virtually all ancient civilizations. The typical comet, however, is not spectacular in our skies, instead having the appearance of a rather faint, diffuse spot of light somewhat smaller than the Moon and many times less brilliant. (Comets seemed more spectacular to people before the invention of artificial lighting, which compromises our view of the night sky.)

Like the Moon and planets, comets appear to wander among the stars, slowly shifting their positions in the sky from night to night. Unlike the planets, however, most comets appear at unpredictable times, which perhaps explain why they frequently inspired fear and superstition in earlier times. Comets typically remain visible for periods that vary from a couple of weeks to several months. We’ll say more about what they are made of and how they become visible after we discuss their motions.

Note that still images of comets give the impression that they are moving rapidly across the sky, like a bright meteor or shooting star. Looking only at such images, it is easy to confuse comets and meteors. But seen in the real sky, they are very different: the meteor burns up in our atmosphere and is gone in a few seconds, whereas the comet may be visible for weeks in nearly the same part of the sky.

Comet Orbits

The study of comets as members of the solar system dates from the time of Isaac Newton, who first suggested that they orbited the Sun on extremely elongated ellipses. Newton’s colleague Edmund Halley (see the **Edmund Halley: Astronomy’s Renaissance Man** feature box) developed these ideas, and in 1705, he published calculations of 24 comet orbits. In particular, he noted that the orbits of the bright comets that had appeared in the years 1531, 1607, and 1682 were so similar that the three could well be the same comet, returning to perihelion (closest approach to the Sun) at average intervals of 76 years. If so, he predicted that the object should next return about 1758. Although Halley had died by the time the comet appeared as he predicted, it was given the name Comet Halley (rhymes with “valley”) in honor of the astronomer who first recognized it as a permanent member of our solar system, orbiting around the Sun. Its aphelion (furthest point from the Sun) is beyond the orbit of Neptune.

We now know from historical records that Comet Halley has actually been observed and recorded on every passage near the Sun since 239 BCE at intervals ranging from 74 to 79 years. The period of its return varies somewhat because of orbital changes produced by the pull of the giant planets. In 1910, Earth was brushed by the comet’s tail, causing much needless public concern. Comet Halley last appeared in our skies in 1986 (**Figure 13.16**), when it was met by several spacecraft that gave us a wealth of information about its makeup; it will return in 2061.

Figure 13.16 Comet Halley. This composite of three images (one in red, one in green, one in blue) shows Comet Halley as seen with a large telescope in Chile in 1986. During the time the three images were taken in sequence, the comet moved among the stars. The telescope was moved to keep the image of the comet steady, causing the stars to appear in triplicate (once in each color) in the background. (credit: modification of work by ESO)

VOYAGERS IN ASTRONOMY

Edmund Halley: Astronomy's Renaissance Man

Edmund Halley (Figure 13.17), a brilliant astronomer who made contributions in many fields of science and statistics, was by all accounts a generous, warm, and outgoing person. In this, he was quite the opposite of his good friend Isaac Newton, whose great work, the *Principia* (see Orbits and Gravity), Halley encouraged, edited, and helped pay to publish. Halley himself published his first scientific paper at age 20, while still in college. As a result, he was given a royal commission to go to Saint Helena (a remote island off the coast of Africa where Napoleon would later be exiled) to make the first telescopic survey of the southern sky. After returning, he received the equivalent of a master's degree and was elected to the prestigious Royal Society in England, all at the age of 22.

In addition to his work on comets, Halley was the first astronomer to recognize that the so-called "fixed" stars move relative to each other, by noting that several bright stars had changed their positions since Ptolemy's publication of the ancient Greek catalogs. He wrote a paper on the possibility of an infinite universe, proposed that some stars may be variable, and discussed the nature and size of *nebulae* (glowing cloudlike structures visible in telescopes). While in Saint Helena, Halley observed the planet

Mercury going across the face of the Sun and developed the mathematics of how such transits could be used to establish the size of the solar system.

In other fields, Halley published the first table of human life expectancies (the precursor of life-insurance statistics); wrote papers on monsoons, trade winds, and tides (charting the tides in the English Channel for the first time); laid the foundations for the systematic study of Earth's magnetic field; studied evaporation and how inland waters become salty; and even designed an underwater diving bell. He served as a British diplomat, advising the emperor of Austria and squiring the future czar of Russia around England (avidly discussing, we are told, both the importance of science and the quality of local brandy).

In 1703, Halley became a professor of geometry at Oxford, and in 1720, he was appointed Astronomer Royal of England. He continued observing Earth and the sky and publishing his ideas for another 20 years, until death claimed him at age 85.

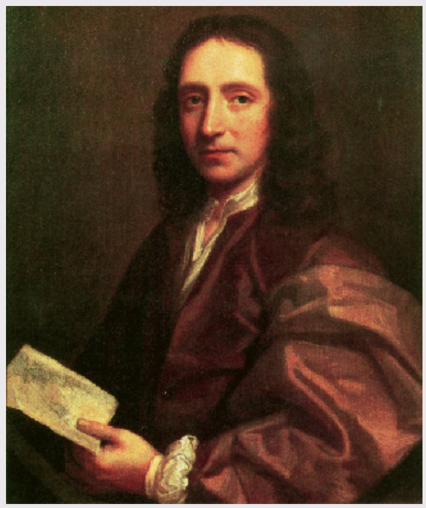


Figure 13.17 Edmund Halley (1656–1742). Halley was a prolific contributor to the sciences. His study of comets at the turn of the eighteenth century helped predict the orbit of the comet that now bears his name.

Only a few comets return in a time measureable in human terms (shorter than a century), like Comet Halley does; these are called *short-period* comets. Many short-period comets have had their orbits changed by coming too close to one of the giant planets—most often Jupiter (and they are thus sometimes called Jupiter-family comets). Most comets have long periods and will take thousands of years to return, if they return at all. As we will see later in this chapter, most Jupiter-family comets come from a different source than the *long-period* comets (those with orbital periods longer than about a century).

Observational records exist for thousands of comets. We were visited by two bright comets in recent decades. First, in March 1996, came Comet Hyakutake, with a very long tail. A year later, Comet Hale-Bopp appeared; it was as bright as the brightest stars and remained visible for several weeks, even in urban areas (see the image that opens this chapter, **Figure 13.1**).

Table 13.2 lists some well-known comets whose history or appearance is of special interest.

Some Interesting Comets

Name	Period	Significance
Great Comet of 1577	Long	Tycho Brahe showed it was beyond the Moon (a big step in our understanding)
Great Comet of 1843	Long	Brightest recorded comet; visible in daytime
Daylight Comet of 1910	Long	Brightest comet of the twentieth century
West	Long	Nucleus broke into pieces (1976)
Hyakutake	Long	Passed within 15 million km of Earth (1996)
Hale–Bopp	Long	Brightest recent comet (1997)
Swift-Tuttle	133 years	Parent comet of Perseid meteor shower
Halley	76 years	First comet found to be periodic; explored by spacecraft in 1986
Borrelly	6.8 years	Flyby by Deep Space 1 spacecraft (2000)
Biela	6.7 years	Broke up in 1846 and not seen again
Churyumov-Gerasimenko	6.5 years	Target of Rosetta mission (2014–16)
Wild 2	6.4 years	Target of Stardust sample return mission (2004)
Tempel 1	5.7 years	Target of Deep Impact mission (2005)
Encke	3.3 years	Shortest known period

Table 13.2

The Comet's Nucleus

When we look at an active comet, all we normally see is its temporary atmosphere of gas and dust illuminated by sunlight. This atmosphere is called the comet's head or *coma.* Since the gravity of such small bodies is very weak, the atmosphere is rapidly escaping all the time; it must be replenished by new material, which has to come from somewhere. The source is the small, solid **nucleus** inside, just a few kilometers across, usually hidden by the glow from the much-larger atmosphere surrounding it. The nucleus is the real comet, the fragment of ancient icy material responsible for the atmosphere and the tail (Figure 13.18).

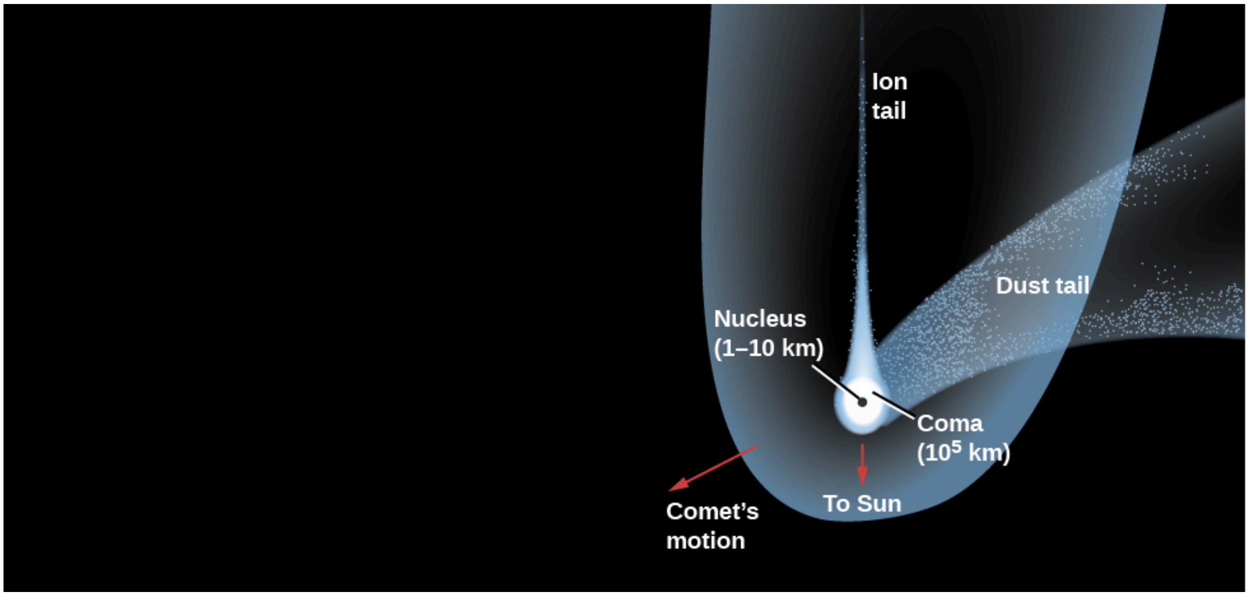


Figure 13.18 Parts of a Comet. This schematic illustration shows the main parts of a comet. Note that the different structures are not to scale.

The modern theory of the physical and chemical nature of comets was first proposed by Harvard astronomer Fred Whipple in 1950. Before Whipple's work, many astronomers thought that a comet's nucleus might be a loose aggregation of solids, sort of an orbiting "gravel bank," Whipple proposed instead that the nucleus is a solid object a few kilometers across, composed in substantial part of water ice (but with other ices as well) mixed with silicate grains and dust. This proposal became known as the "dirty snowball" model.

The water vapor and other volatiles that escape from the nucleus when it is heated can be detected in the comet's head and tail, and therefore, we can use spectra to analyze what atoms and molecules the nucleus ice consists of. However, we are somewhat less certain of the non-icy component. We have never identified a fragment of solid matter from a comet that has survived passage through Earth's atmosphere. However, spacecraft that have approached comets have carried dust detectors, and some comet dust has even been returned to Earth (see **Figure 13.19**). It seems that much of the "dirt" in the dirty snowball is dark, primitive hydrocarbons and silicates, rather like the material thought to be present on the dark, primitive asteroids.

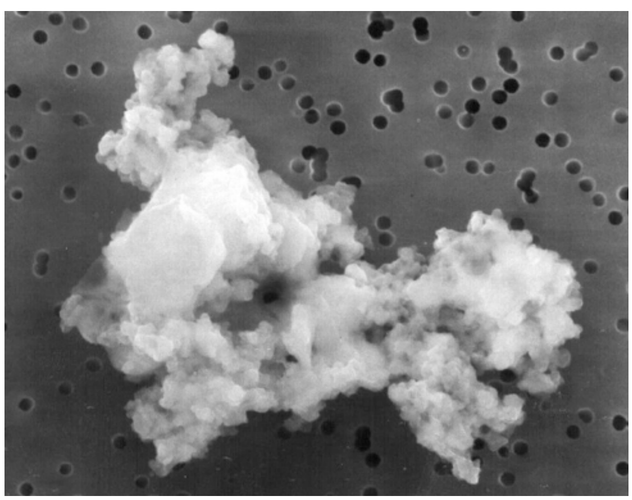


Figure 13.19 Captured Comet Dust. This particle (seen through a microscope) is believed to be a tiny fragment of cometary dust, collected in the upper atmosphere of Earth. It measures about 10 microns, or 1/100 of a millimeter, across. (credit: NASA/JPL)

Since the nuclei of comets are small and dark, they are difficult to study from Earth. Spacecraft did obtain direct measurements of a comet nucleus, however, in 1986, when three spacecraft swept past Comet Halley at close range (see **Figure 13.20**). Subsequently, other spacecraft have flown close to other comets. In 2005, the NASA *Deep Impact* spacecraft even carried a probe for a high-speed impact with the nucleus of Comet Tempel 1. But by far, the most productive study of a comet has been by the 2015 Rosetta mission, which we will discuss shortly.

Figure 13.20 Close-up of Comet Halley. This historic photograph of the black, irregularly shaped nucleus of Comet Halley was obtained by the ESA *Giotto* spacecraft from a distance of about 1000 kilometers. The bright areas are jets of material escaping from the surface. The length of the nucleus is 10 kilometers, and details as small as 1 kilometer can be made out. (credit: modification of work by ESA)

The Comet's Atmosphere

The spectacular activity that allows us to see comets is caused by the evaporation of cometary ices heated by sunlight. Beyond the asteroid belt, where comets spend most of their time, these ices are solidly frozen. But as a comet approaches the Sun, it begins to warm up. If water (H_2O) is the dominant ice, significant quantities vaporize as sunlight heats the surface above 200 K. This happens for the typical comet somewhat beyond the orbit of Mars. The evaporating H_2O in turn releases the dust that was mixed with the ice. Since the comet's nucleus is so small, its gravity cannot hold back either the gas or the dust, both of which flow away into space at speeds of about 1 kilometer per second.

The comet continues to absorb energy as it approaches the Sun. A great deal of this energy goes into the evaporation of its ice, as well as into heating the surface. However, recent observations of many comets indicate that the evaporation is not uniform and that most of the gas is released in sudden spurts, perhaps confined to a few areas of the surface. Expanding into space at a speed of about 1 kilometer per second, the comet's atmosphere can reach an enormous size. The diameter of a comet's head is often as large as Jupiter, and it can sometimes approach a diameter of a million kilometers (**Figure 13.21**).

Figure 13.21 Head of Comet Halley. Here we see the cloud of gas and dust that make up the head, or coma, of Comet Halley in 1986. On this scale, the nucleus (hidden inside the cloud) would be a dot too small to see. (credit: modification of work by NASA/W. Liller)

Most comets also develop tails as they approach the Sun. A comet's tail is an extension of its atmosphere, consisting of the same gas and dust that make up its head. As early as the sixteenth century, observers realized that comet tails always point away from the Sun (**Figure 13.22**), not back along the comet's orbit. Newton proposed that comet tails are formed by a repulsive force of sunlight driving particles away from the head—an idea close to our modern view.

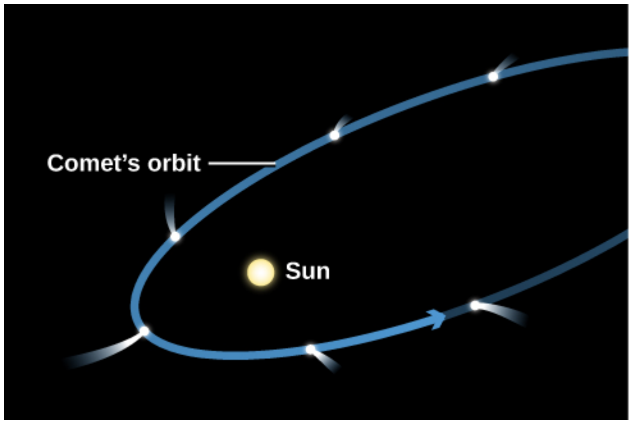


Figure 13.22 Comet Orbit and Tail. The orientation of a typical comet tail changes as the comet passes perihelion. Approaching the Sun, the tail is behind the incoming comet head, but on the way out, the tail precedes the head.

The two different components that make up the tail (the dust and gas) act somewhat differently. The brightest part of the tail is called the *dust tail*, to differentiate it from a fainter, straight tail made of ionized gas, called the ion tail. The ion tail is carried outward by streams of ions (charged particles) emitted by the Sun. As you can see in **Figure 13.23**, the smoother dust tail curves a bit, as individual dust particles spread out along the comet's orbit, whereas the straight ion is tail pushed more directly outward from the Sun by our star's wind of charged particles

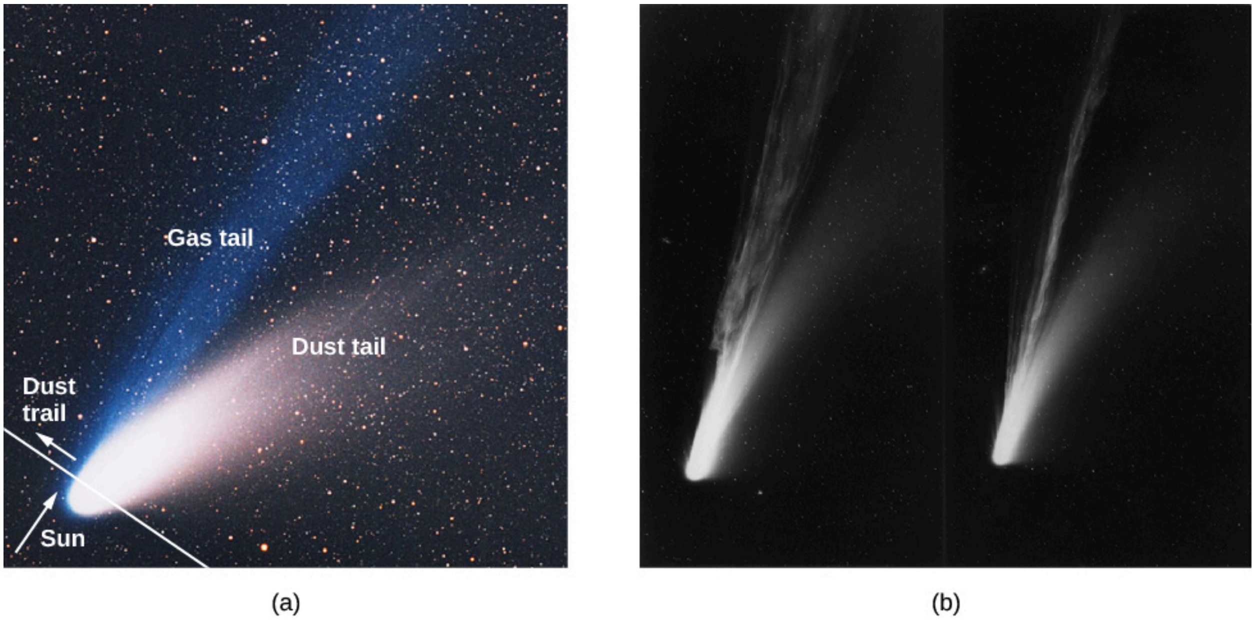


Figure 13.23 Comet Tails. (a) As a comet nears the Sun, its features become more visible. In this illustration from NASA showing Comet Hale-Bopp, you can see a comet's two tails: the more easily visible dust tail, which can be up to 10 million kilometers long, and the fainter gas tail (or ion tail), which is up to hundreds of millions of kilometers long. The grains that make up the dust tail are the size of smoke particles. (b) Comet Mrkos was photographed in 1957 with a wide-field telescope at Palomar Observatory and also shows a clear distinction between the straight gas tail and the curving dust tail. (credit a: modification of work by ESO/E. Slawik; credit b: modification of work by Charles Kearns, George O. Abell, and Byron Hill)

LINK TO LEARNING

These days, comets close to the Sun can be found with spacecraft designed to observe our star. For example, in early July, 2011, astronomers at the ESA/NASA's Solar and Heliospheric Observatory (SOHO) witnessed a **comet (https://openstaxcollege.org/l/30ESANASAcomet)** streaking toward the Sun, one of almost 3000 such sightings. You can also watch a brief video by NASA entitled "Why Are We Seeing So Many Sungrazing Comets?"

The Rosetta Comet Mission

In the 1990s, European scientists decided to design a much more ambitious mission that would match orbits with an incoming comet and follow it as it approached the Sun. They also proposed that a smaller spacecraft would actually try to land on the comet. The 2-ton main spacecraft was named *Rosetta*, carrying a dozen scientific instruments, and its 100-kilogram lander with nine more instruments was named *Philae*.

The Rosetta mission was launched in 2004. Delays with the launch rocket caused it to miss its original target comet, so an alternate destination was picked, Comet Churyumov-Gerasimenko (named after the two discoverers, but generally denoted 67P). This comet's period of revolution is 6.45 years, making it a Jupiter-family comet.

Since the European Space Agency did not have access to the plutonium-fueled nuclear power sources used by NASA for deep space missions, *Rosetta* had to be solar powered, requiring especially large solar panels. Even these were not enough to keep the craft operating as it matched orbits with 67P near the comet's aphelion. The only solution was to turn off all the spacecraft systems and let it coast for several years toward the Sun, out of contact with controllers on Earth until solar energy was stronger. The success of the mission depended on an automatic timer to turn the power back on as it neared the Sun. Fortunately, this strategy worked.

In August 2014, *Rosetta* began a gradual approach to the comet nucleus, which is a strangely misshapen object about 5 kilometers across, quite different from the smooth appearance of Halley's nucleus (but equally dark). Its rotation period is 12 hours. On November 12, 2014, the *Philae* lander was dropped, descending slowly for 7 hours before gently hitting the surface. It bounced and rolled, coming to rest under an overhang where there was not enough sunlight to keep its batteries charged. After operating for a few hours and sending data back to the orbiter, *Philae* went silent. The main *Rosetta* spacecraft continued operations, however, as the level of comet activity increased, with steamers of gas jetting from the surface. As the comet approached perihelion in September 2015, the spacecraft backed off to ensure its safety.

The extent of the *Rosetta* images (and data from other instruments) far exceeds anything astronomers had seen before from a comet. The best imaging resolution was nearly a factor of 100 greater than in the best Halley images. At this scale, the comet appears surprisingly rough, with sharp angles, deep pits, and overhangs (**Figure 13.24**).

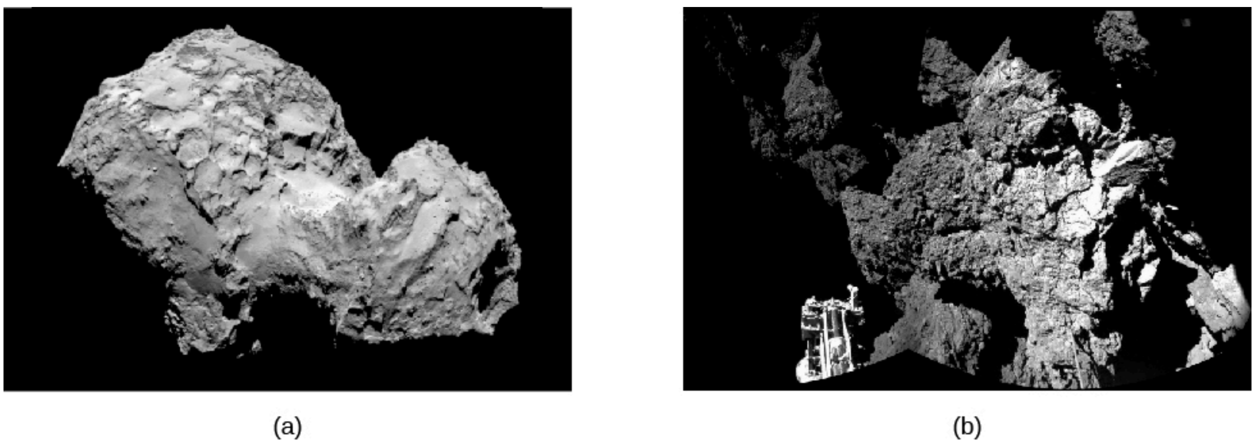


Figure 13.24 Comet 67P's Strange Shape and Surface Features. (a) This image from the *Rosetta* camera was taken from a distance of 285 kilometers. The resolution is 5 meters. You can see that the comet consists of two sections with a connecting "neck" between them. (b) This close-up view of Comet Churyumov-Gerasimenko is from the *Philae* lander. One of the lander's three feet is visible in the foreground. The lander itself is mostly in shadow. (credit a: modification of work by ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; credit b: modification of work by ESA/Rosetta/Philae/CIVA)

The double-lobed shape of 67P's nucleus has been tentatively attributed to the collision and merger of two independent comet nuclei long ago. The spacecraft verified that the comet's dark surface was covered with organic carbon-rich compounds, mixed with sulfides and iron-nickel grains. 67P has an average density of only 0.5 g/cm^3 (recall water in these units has a density of 1 g/cm^3.) This low density indicates that the comet is quite porous, that is, there is a large amount of empty space among its materials.

We already knew that the evaporation of comet ices was sporadic and limited to small jets, but in comet 67P, this was carried to an extreme. At any one time, more than 99% of the surface is inactive. The active vents are only a few meters across, with the material confined to narrow jets that persist for just a few minutes (**Figure 13.25**). The level of activity is strongly dependent on solar heating, and between July and August 2015, it increased by a factor of 10. Isotopic analysis of deuterium in the water ejected by the comet shows that it is different from the water found on Earth. Thus, apparently comets like 67P did not contribute to the origin of our oceans or the water in our bodies, as some scientists had thought.

Figure 13.25 Gas Jets on Comet 67P. (a) This activity was photographed by the *Rosetta* spacecraft near perihelion. You can see a jet suddenly appearing; it was active for only a few minutes. (b) This spectacular photo, taken near perihelion, shows the active comet surrounded by multiple jets of gas and dust. (credit a, b: modification of work by ESA/Rosetta/MPS; credit c: modification of work by ESA/Rosetta/NAVCAM)

LINK TO LEARNING

The European Space Agency is continuing to make **interesting short videos (https://openstaxcollege.org/l/30ESAvideoros)** illustrating the challenges and results of the Rosetta and Philae missions. For example, watch "*Rosetta*'s Moment in the Sun" to see some of the images of the comet generating plumes of gas and dust and hear about some of the dangers an active comet poses for the spacecraft.

13.4 THE ORIGIN AND FATE OF COMETS AND RELATED OBJECTS

Learning Objectives

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

- Describe the traits of the centaur objects
- Chronicle the discovery and describe the composition of the Oort cloud
- Describe trans-Neptunian and Kuiper-belt objects
- Explain the proposed fate of comets that enter the inner solar system

The comets we notice when they come near Earth (especially the ones coming for the first time) are probably the most primitive objects we can study, preserved unchanged for billions of years in the deep freeze of the outer solar system. However, astronomers have discovered many other objects that orbit the Sun beyond the planets.

Centaurs

In the outer solar system, where most objects contain large amounts of water ice, the distinction between asteroids and comets breaks down. Astronomers initially still used the name "asteroids" for new objects discovered going around the Sun with orbits that carry them far beyond Jupiter. The first of these objects is Chiron, found in 1977 on a path that carries it from just inside the orbit of Saturn at its closest approach to the Sun out to almost the distance of Uranus (**Figure 13.26**). The diameter of Chiron is estimated to be about 200 kilometers, much larger than any known comet.

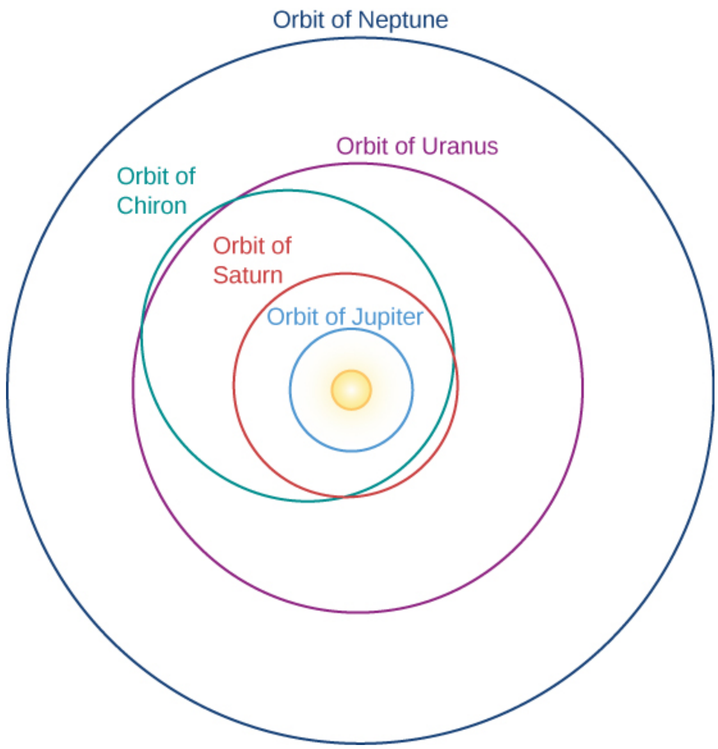


Figure 13.26 Chiron's Orbit. Chiron orbits the Sun every 50 years, with its closest approach being inside the orbit of Saturn and its farthest approach out to the orbit of Uranus.

In 1992, a still-more-distant object named Pholus was discovered with an orbit that takes it 33 AU from the Sun, beyond the orbit of Neptune. Pholus has the reddest surface of any object in the solar system, indicating a strange (and still unknown) surface composition. As more objects are discovered in these distant reaches, astronomers decided that they will be given the names of *centaurs* from classical mythology; this is because the centaurs were half human, half horse, and these new objects display some of the properties of both asteroids and comets.

Beyond the orbit of Neptune lies a cold, dark realm populated by objects called simply trans-Neptunian objects (TNOs). The first discovered, and best known, of these TNOs is the dwarf planet Pluto. We discussed Pluto and the New Horizons spacecraft encounter with it in **Rings, Moons, and Pluto**. The second TNO was discovered in 1992, and now more than a thousand are known, most of them smaller than Pluto.

The largest ones after Pluto—named Eris, Makemake, and Haumea—are also classed as dwarf planets. Except for their small size, dwarf planets have many properties in common with the larger planets. Pluto has five moons, and two moons have been discovered orbiting Haumea and one each circling Eris and Makemake.

The Kuiper Belt and the Oort Cloud

TNOs are a part of what is called the **Kuiper belt**, a large area of space beyond Neptune that is also the source of many comets. Astronomers study the Kuiper belt in two ways. New, more powerful telescopes allow us to discover many of the larger members of the Kuiper belt directly. We can also measure the composition of comets that come from the Kuiper belt. More than a thousand Kuiper belt objects have been discovered, and astronomers estimate that there are more than 100,000 with diameters large than 100 kilometers, in a disk extending out to about 50 AU from the Sun.

The short-period comets are thought to originate in the Kuiper belt, where small gravitational perturbations from Neptune can gradually shift their orbits until they can penetrate the inner solar system. The long-period comets, however, come from a much more distant reservoir of icy objects, called the Oort cloud.

Careful studies of the orbits of long-period comets revealed that they come initially from very great distances. By following their orbits backward, we can calculate that the *aphelia* (points farthest from the Sun) of newly discovered comets typically have values near 50,000 AU (more than a thousand times farther than Pluto). This clustering of aphelion distances was first noted by Dutch astronomer Jan Oort, who, in 1950, proposed an idea for the origin of those comets that is still accepted today (**Figure 13.27**).

Figure 13.27 Jan Oort (1900–1992). Jan Oort first suggested that there might be a reservoir of frozen chunks, potential comet nuclei, at the edge of the region of the Sun's gravitational influence. (credit: The Leiden Observatory)

It is possible to calculate that a star's gravitational *sphere of influence*—the distance within which it can exert sufficient gravitation to hold onto orbiting objects—is about one third of its distance to the nearest other stars. Stars in the vicinity of the Sun are spaced in such a way that the Sun's sphere of influence extends a little beyond 50,000 AU, or about 1 light-year. At such great distances, however, objects in orbit about the Sun can be perturbed by the gravity of passing stars. Some of the perturbed objects can then take on orbits that bring them much closer to the Sun (while others might be lost to the solar system forever).

Oort suggested, therefore, that the new comets we were seeing were examples of objects orbiting the Sun near the edge of its sphere of influence, whose orbits had been disturbed by nearby stars, eventually bringing them close to the Sun where we can see them. The reservoir of ancient icy objects from which such comets are derived is now called the **Oort cloud**.

Astronomers estimate that there are about a trillion (10^{12}) comets in the Oort cloud. In addition, we estimate that about 10 times this number of icy objects could be orbiting the Sun in the volume of space between the Kuiper belt (which is gravitationally linked to Neptune) and the Oort cloud. These objects remain undiscovered because they are too faint to be seen directly and their orbits are too stable to permit any of them to be deflected inward close to the Sun. The total number of icy or cometary objects in the outer reaches of our solar system could thus be on the order of 10 trillion (10^{13}), a very large number indeed.

What is the mass represented by 10^{13} comets? We can make an estimate if we assume something about comet sizes and masses. Let us suppose that the nucleus of Comet Halley is typical. Its observed volume is about 600 km^3. If the primary constituent is water ice with a density of about 1 g/cm^3, then the total mass of Halley's nucleus must be about 6×10^{14} kilograms. This is about one ten billionth (10^{-10}) of the mass of Earth.

If our estimate is reasonable and there are 10^{13} comets with this mass out there, their total mass would be equal to about 1000 Earths—comparable to the mass of all the planets put together. Therefore, icy, cometary material could be the most important constituent of the solar system after the Sun itself.

EXAMPLE 13.1

Mass of the Oort Cloud Comets

Suppose the Oort cloud contains 10^{12} comets with an average diameter of 10 km each. Let's estimate the mass of the total Oort cloud.

Solution

We can start by assuming that typical comets are about the size of Comets Halley and Borrelly, with a diameter of 10 km and a density appropriate to water ice, which is about 1 g/cm^3 or 1000 kg/m^3. We know that density = mass/volume, the volume of a sphere, $V = \frac{4}{3}\pi R^3$, and the radius, $R = \frac{1}{2}D$.

Therefore, for each comet,

$$\begin{aligned} \text{mass} &= \text{density} \times \text{volume} \\ &= \text{density} \times \frac{4}{3}\pi\left(\frac{1}{2}D\right)^3 \end{aligned}$$

Given that 10 km = 10^4 m, each comet's mass is

$$\begin{aligned} \text{mass} &= 1000\ \text{kg/m}^3 \times \frac{4}{3} \times 3.14 \times \frac{1}{8} \times \left(10^4\right)^3\ \text{m}^3 \\ &\approx 10^{15}\ \text{kg} \\ &= 10^{12}\ \text{tons} \end{aligned}$$

To calculate the total mass of the cloud, we multiply this typical mass for one comet by the number of comets:

$$\begin{aligned} \text{total mass} &= 10^{15}\ \text{kg/comet} \times 10^{12}\ \text{comets} \\ &= 10^{27}\ \text{kg} \end{aligned}$$

Check Your Learning

How does the total mass we calculated above compare to the mass of Jupiter? To the mass of the Sun? (Give a numerical answer.)

Answer:

The mass of Jupiter is about 1.9 × 10^{27} kg. The mass of the Oort cloud calculated above is 10^{27} kg. So the cloud would contain about half a Jupiter of mass. The mass of the Sun is 2 × 10^{30} kg. This means the Oort cloud would be

$$\frac{10^{27}\ \text{kg}}{\left(2 \times 10^{30}\ \text{kg}\right)} = 0.0005 \times \text{the mass of the Sun}$$

Early Evolution of the Planetary System

Comets from the Oort cloud help us sample material that formed very far from the Sun, whereas the short-period comets from the Kuiper belt sample materials that were planetesimals in the solar nebula disk but did not form planets. Studies of the Kuiper belt also are influencing our understanding of the early evolution of our planetary system.

The objects in the Oort cloud and the Kuiper belt have different histories, and they may therefore have different compositions. Astronomers are therefore very interested in comparing detailed measurements of the comets derived from these two source regions. Most of the bright comets that have been studied in the past (such as Hyakutake and Hale-Bopp) are Oort cloud comets, but P67 and several other comets targeted for spacecraft measurements in the next decade are Jupiter-family comets from the Kuiper belt (see **Table 13.2**).

The Kuiper belt is made up of ice-and rock planetesimals, a remnant of the building blocks of the planets. Since it is gravitationally linked to Neptune, it can help us understand the formation and history of the solar system. As the giant planets formed, their gravity profoundly influenced the orbits of Kuiper belt objects. Computer simulations of the early evolution of the planetary system suggest that the gravitational interactions between the giant planets and the remaining planetesimals caused the orbit of Jupiter to drift inward, whereas the orbits of Saturn, Uranus, and Neptune all expanded, carrying the Kuiper belt with them.

Another hypotheses involves a fifth giant planet that was expelled from the solar system entirely as the planetary orbits shifted. Neptune's retrograde (backward-orbiting) moon Triton (which is nearly as large as Pluto) may have been a Kuiper belt object captured by Neptune during the period of shifting orbits. It clearly seems that the Kuiper belt may carry important clues to the way our solar system reached its present planetary configuration.

MAKING CONNECTIONS

Comet Hunting as a Hobby

When amateur astronomer David Levy (**Figure 13.28**), the co-discoverer of Comet Shoemaker-Levy 9, found his first comet, he had already spent 928 fruitless hours searching through the dark night sky. But the discovery of the first comet only whetted his appetite. Since then, he has found 8 others on his own and 13 more working with others. Despite this impressive record, he ranks only third in the record books for number of comet discoveries. But David hopes to break the record someday.

All around the world, dedicated amateur observers spend countless nights scanning the sky for new comets. Astronomy is one of the very few fields of science where amateurs can still make a meaningful contribution, and the discovery of a comet is one of the most exciting ways they can establish their place in astronomical history. Don Machholz, a California amateur (and comet hunter) who has been making a study of comet discoveries, reported that between 1975 and 1995, 38% of all comets discovered were found by amateurs. Those 20 years yielded 67 comets for amateurs, or almost 4 per year. That might sound pretty encouraging to new comet hunters, until they learn that the average number of hours the typical amateur spent searching for a comet before finding one was about 420. Clearly, this is not an activity for impatient personalities.

What do comet hunters do if they think they have found a new comet? First, they must check the object's location in an atlas of the sky to make sure it really is a comet. Since the first sighting of a comet usually occurs when it is still far from the Sun and before it sports a significant tail, it will look like only a small, fuzzy patch. And through most amateur telescopes, so will nebulae (clouds of cosmic gas and dust) and galaxies (distant groupings of stars). Next, they must check that they have not come across a comet that is already known, in which case, they will only get a pat on the back instead of fame and glory. Then they must re-observe or re-image it sometime later to see whether its motion in the sky is appropriate for comets.

Often, comet hunters who think they have made a discovery get another comet hunter elsewhere in the country to confirm it. If everything checks out, the place they contact is the Central Bureau for Astronomical Telegrams at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts (http://www.cbat.eps.harvard.edu/). If the discovery is confirmed, the bureau will send the news out to astronomers and observatories around the world. One of the unique rewards of comet hunting is that the discoverer's name becomes associated with the new comet—a bit of cosmic fame that few hobbies can match.

Figure 13.28 David Levy. Amateur astronomer David Levy ranks third in the world for comet discoveries. (credit: Andrew Fraknoi)

The Fate of Comets

Any comet we see today will have spent nearly its entire existence in the Oort cloud or the Kuiper belt at a temperature near absolute zero. But once a comet enters the inner solar system, its previously uneventful life history begins to accelerate. It may, of course, survive its initial passage near the Sun and return to the cold reaches of space where it spent the previous 4.5 billion years. At the other extreme, it may collide with the Sun or come so close that it is destroyed on its first perihelion passage (several such collisions have been observed with space telescopes that monitor the Sun). Sometimes, however, the new comet does not come that close to the Sun but instead interacts with one or more of the planets.

LINK TO LEARNING

SOHO (the Solar and Heliospheric Observatory) has an **excellent collection of videos of comets (https://openstaxcollege.org/l/30SOHOcomvid)** that come near the Sun. At this site, comet ISON approaches the Sun and is believed to be destroyed in its passage.

A comet that comes within the gravitational influence of a planet has three possible fates. It can (1) impact the planet, ending the story at once; (2) speed up and be ejected, leaving the solar system forever; or (3) be perturbed into an orbit with a shorter period. In the last case, its fate is sealed. Each time it approaches the Sun, it loses part of its material and also has a significant chance of collision with a planet. Once the comet is in this kind of short-period orbit, its lifetime starts being measured in thousands, not billions, of years.

A few comets end their lives catastrophically by breaking apart (sometimes for no apparent reason) (**Figure 13.29**). Especially spectacular was the fate of the faint Comet Shoemaker-Levy 9, which broke into about 20 pieces when it passed close to Jupiter in July 1992. The fragments of Shoemaker-Levy were actually captured into a very elongated, two-year orbit around Jupiter, more than doubling the number of known jovian moons. This was only a temporary enrichment of Jupiter's family, however, because in July 1994, all the comet fragments crashed unto Jupiter, releasing energy equivalent to millions of megatons of TNT.

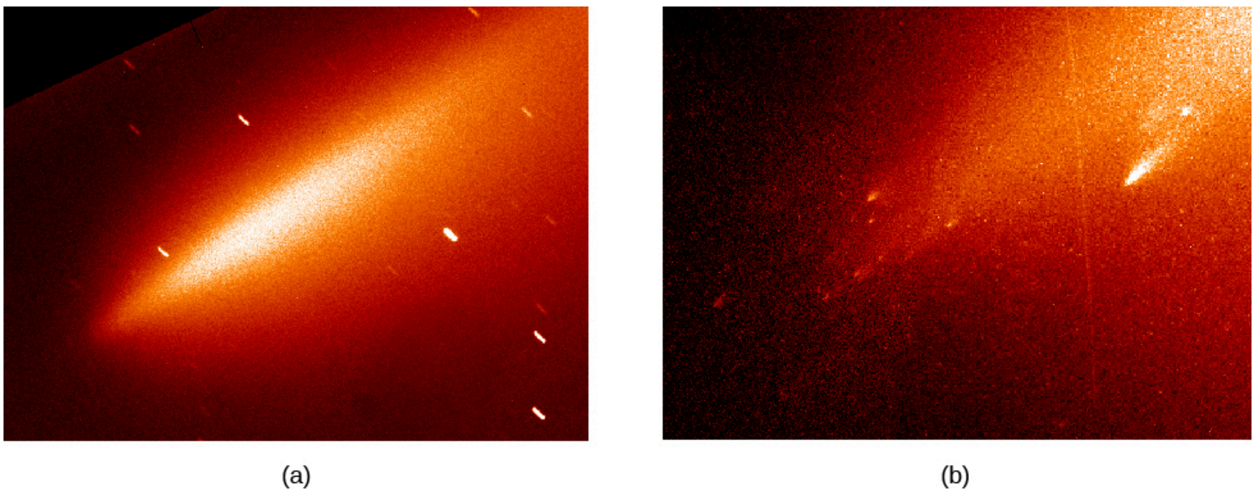


Figure 13.29 Breakup of Comet LINEAR. (a) A ground-based view with much less detail and (b) a much more detailed photo with the Hubble Space Telescope, showing the multiple fragments of the nucleus of Comet LINEAR. The comet disintegrated in July 2000 for no apparent reason. (Note in the left view, the fragments all blend their light together, and can't be distinguished. The short diagonal white lines are stars that move in the image, which is keeping track of the moving comet.) (credit a: modification of work by the University of Hawaii; credit b: modification of work by NASA, Harold Weaver (the Johns Hopkins University), and the HST Comet LINEAR Investigation Team)

As each cometary fragment streaked into the jovian atmosphere at a speed of 60 kilometers per second, it disintegrated and exploded, producing a hot fireball that carried the comet dust as well as atmospheric gases to high altitudes. These fireballs were clearly visible in profile, with the actual point of impact just beyond the jovian horizon as viewed from Earth (**Figure 13.30**). As each explosive plume fell back into Jupiter, a region of the upper atmosphere larger than Earth was heated to incandescence and glowed brilliantly for about 15 minutes, a glow we could detect with infrared-sensitive telescopes.

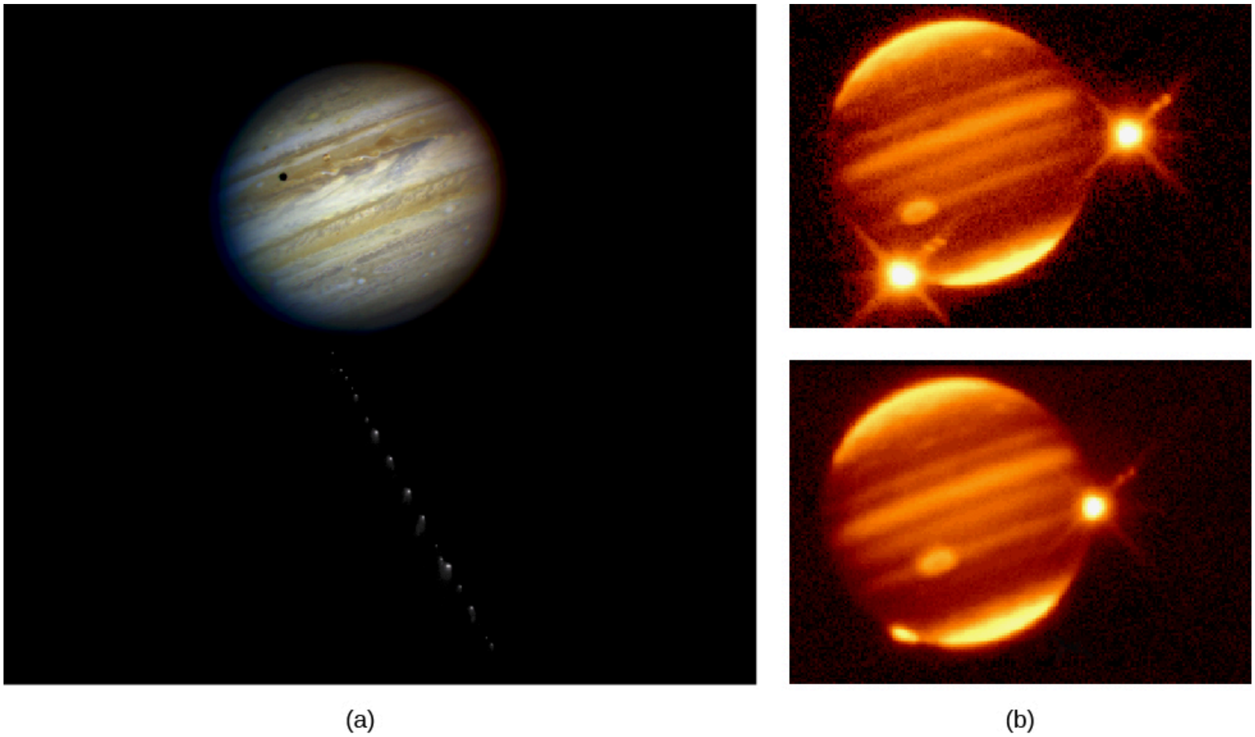


Figure 13.30 Comet Impact on Jupiter. (a) The "string" of white objects are fragments of Comet Shoemaker-Levy 9 approaching Jupiter. (b) The first fragment of the comet impacts Jupiter, with the point of contact on the bottom left side in this image. On the right is Jupiter's moon, Io. The equally bright spot in the top image is the comet fragment flaring to maximum brightness. The bottom image, taken about 20 minutes later, shows the lingering flare from the impact. The Great Red Spot is visible near the center of Jupiter. These infrared images were taken with a German-Spanish telescope on Calar Alto in southern Spain. (credit a: modification of work by ESA; credit b: modification of work by Tom Herbst, Max-Planck-Institut fuer Astronomie, Heidelberg, Doug Hamilton, Max-Planck-Institut fuer Kernphysik, Heidelberg, Hermann Boehnhardt, Universitaets-Sternewarte, Muenchen, and Jose Luis Ortiz Moreno, Instituto de Astrofisica de Andalucia, Granada)

After this event, dark clouds of debris settled into the stratosphere of Jupiter, producing long-lived "bruises" (each still larger than Earth) that could be easily seen through even small telescopes (**Figure 13.31**). Millions of people all over the world peered at Jupiter through telescopes or followed the event via television or online. Another impact feature was seen on Jupiter in summer 2009, indicating that the 1994 events were by no means unique. Seeing these large, impact explosions on Jupiter helps us to appreciate the disaster that would happen to our planet if we were hit by a comet or asteroid.

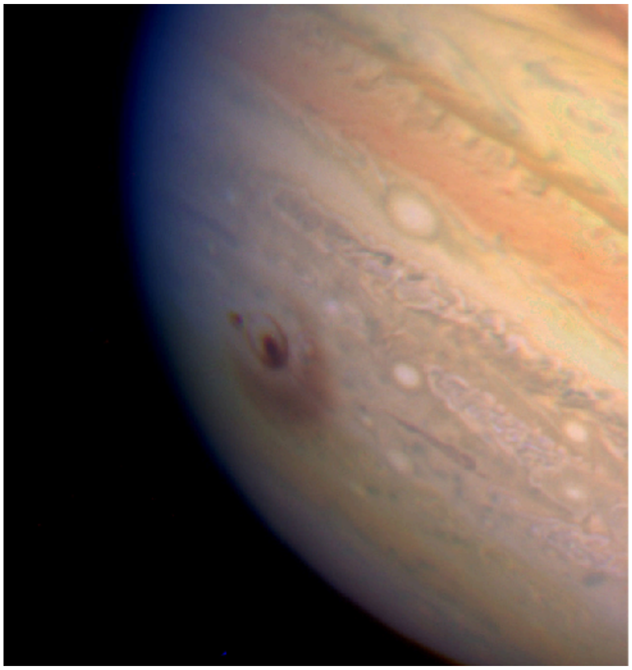


Figure 13.31 Impact Dust Cloud on Jupiter. These features result from the impact of Comet Shoemaker-Levy 9 with Jupiter, seen with the Hubble Space Telescope 105 minutes after the impact that produced the dark rings (the compact back dot came from another fragment). The inner edge of the diffuse, outer ring is about the same size as Earth. Later, the winds on Jupiter blended these features into a broad spot that remained visible for more than a month. (credit: modification of work by H. Hammel, MIT, and NASA/ESA)

For comets that do not meet so dramatic an end, measurements of the amount of gas and dust in their atmospheres permit us to estimate the total losses during one orbit. Typical loss rates are up to a million tons per day from an active comet near the Sun, adding up to some tens of millions of tons per orbit. At that rate, a typical comet will be gone after a few thousand orbits. This will probably be the fate of Comet Halley in the long run.

LINK TO LEARNING

This **History Channel video (https://openstaxcollege.org/l/30hischanUNIV)** shows a short discussion and animation from the TV documentary series *Universe*, showing the collision of Comet Shoemaker-Levy 9 with Jupiter.

CHAPTER 13 REVIEW

KEY TERMS

asteroid a stony or metallic object orbiting the Sun that is smaller than a major planet but that shows no evidence of an atmosphere or of other types of activity associated with comets

asteroid belt the region of the solar system between the orbits of Mars and Jupiter in which most asteroids are located; the main belt, where the orbits are generally the most stable, extends from 2.2 to 3.3 AU from the Sun

comet a small body of icy and dusty matter that revolves about the Sun; when a comet comes near the Sun, some of its material vaporizes, forming a large head of tenuous gas and often a tail

Kuiper belt a region of space beyond Neptune that is dynamically stable (like the asteroid belt); the source region for most short-period comets

near-Earth asteroid (NEA) an Earth-approaching asteroid, one whose orbit could bring it on a collision course with our planet

near-Earth object (NEO) a comet or asteroid whose path intersects the orbit of Earth

nucleus (of a comet) the solid chunk of ice and dust in the head of a comet

Oort cloud the large spherical region around the Sun from which most "new" comets come; a reservoir of objects with aphelia at about 50,000 AU

tail (of a comet) a tail consisting of two parts: the dust tail is made of dust loosened by the sublimation of ice in a comet that is then pushed by photons from the Sun into a curved stream; the ion tail is a stream of ionized particles evaporated from a comet and then swept away from the Sun by the solar wind

SUMMARY

13.1 Asteroids

The solar system includes many objects that are much smaller than the planets and their larger moons. The rocky ones are generally called asteroids. Ceres is the largest asteroid; about 15 are larger than 250 kilometers and about 100,000 are larger than 1 kilometer. Most are in the asteroid belt between Mars and Jupiter. The presence of asteroid families in the belt indicates that many asteroids are the remnants of ancient collisions and fragmentation. The asteroids include both primitive and differentiated objects. Most asteroids are classed as C-type, meaning they are composed of carbonaceous materials. Dominating the inner belt are S-type (stony) asteroids, with a few M-type (metallic) ones. We have spacecraft images of several asteroids and returned samples from asteroid Itokawa. Recent observations have detected a number of asteroid moons, making it possible to measure the masses and densities of the asteroids they orbit. The two largest asteroids, Ceres and Vesta, have been extensively studied from orbit by the *Dawn* spacecraft.

13.2 Asteroids and Planetary Defense

Near-Earth asteroids (NEAs), and near-Earth objects (NEOs) in general, are of interest in part because of their potential to hit Earth. They are on unstable orbits, and on timescales of 100 million years, they will either impact one of the terrestrial planets or the Sun, or be ejected. Most of them probably come from the asteroid belt, but some may be dead comets. NASA's Spaceguard Survey has found 90% of the NEAs larger than 1 kilometer, and none of the ones found so far are on a collision course with Earth. Scientists are actively working on possible technologies for planetary defense in case any NEOs are found on a collision course with Earth years in advance. For now, the most important task is to continue our surveys, so we can find the next Earth impactor before it finds us.

13.3 The "Long-Haired" Comets

Halley first showed that some comets are on closed orbits and return periodically to swing around the Sun. The heart of a comet is its nucleus, a few kilometers in diameter and composed of volatiles (primarily frozen H_2O) and solids (including both silicates and carbonaceous materials). Whipple first suggested this "dirty snowball" model in 1950; it has been confirmed by spacecraft studies of several comets. As the nucleus approaches the Sun, its volatiles evaporate (perhaps in localized jets or explosions) to form the comet's head or atmosphere, which escapes at about 1 kilometer per second. The atmosphere streams away from the Sun to form a long tail. The ESA Rosetta mission to Comet P67 (Churyumov-Gerasimenko) has greatly increased our knowledge of the nature of the nucleus and of the process by which comets release water and other volatiles when heated by sunlight.

13.4 The Origin and Fate of Comets and Related Objects

Oort proposed in 1950 that long-period comets are derived from what we now call the Oort cloud, which surrounds the Sun out to about 50,000 AU (near the limit of the Sun's gravitational sphere of influence) and contains between 10^{12} and 10^{13} comets. Comets also come from the Kuiper belt, a disk-shaped region beyond the orbit of Neptune, extending to 50 AU from the Sun. Comets are primitive bodies left over from the formation of the outer solar system. Once a comet is diverted into the inner solar system, it typically survives no more than a few thousand perihelion passages before losing all its volatiles. Some comets die spectacular deaths: Shoemaker-Levy 9, for example, broke into 20 pieces before colliding with Jupiter in 1994.

FOR FURTHER EXPLORATION

Articles

Asteroids

Asphang, E. "The Small Planets." *Scientific American* (May 2000): 46. On asteroids, including results from the NEAR mission.

Beatty, J. "The Falcon's Wild Flight." *Sky & Telescope* (September 2006): 34. On the Japanese mission to asteroid Itakawa.

Beatty, J. "NEAR Falls for Eros." *Sky & Telescope* (May 2001): 35. On the first landing on an asteroid.

Betz, E. "Dawn Mission Reveals Dwarf Planet Ceres." *Astronomy* (January 2016): 44. First images and discoveries.

Binzel, R. "A New Century for Asteroids." *Sky & Telescope* (July 2001): 44. Nice overview.

Boslaugh, M. "In Search of Death-Plunge Asteroids." *Astronomy* (July 2015): 28. On existing and proposed programs to search for Earth-crossing asteroids.

Cooke, B. "Fatal Attraction." *Astronomy* (May 2006): 46. On near-Earth asteroid Apophis, its orbit, and what we can learn from it.

Durda, D. "Odd Couples." *Astronomy* (December 2005): 54. On binary asteroids.

Durda, D. "All in the Family." *Astronomy* (February 1993): 36. Discusses asteroid families.

Oberg, J. "2013's Historic Russian Meteorite Fall" *Astronomy* (June 2012): 18. On the Chelyabinsk event.

Sheppard, S. “Dancing with the Planets.” *Sky & Telescope* (June 2016): 16. On Trojan asteroids that “follow” planets like Jupiter.

Talcott, R. “Galileo Views Gaspra.” *Astronomy* (February 1992): 52.

Yeomans, D. “Japan Visits an Asteroid.” *Astronomy* (March 2006): 32. On the *Hayabusa* probe exploration of asteroid Itakawa.

Zimmerman, R. “Ice Cream Sundaes and Mashed Potatoes.” *Astronomy* (February 1999): 54. On the NEAR mission.

Comets

Aguirre, E. “The Great Comet of 1997.” *Sky & Telescope* (July 1997): 50. On Comet Hale-Bopp.

Bakich, M. “How to Observe Comets.” *Astronomy* (December 2009): 50. A guide for amateur astronomers.

Gore, R. “Halley’s Comet ’86: Much More Than Met the Eye.” *National Geographic* (December 1986): 758. (Also, the March 1987 issue of *Sky & Telescope* was devoted to what we learned from Halley’s Comet in 1986.)

Hale, A. “Hale-Bopp Plus Ten.” *Astronomy* (July 2005): 76. The co-discoverer of a naked-eye comet tells the story of the discovery and what followed.

Jewett, D. “Mysterious Travelers: Comet Science.” *Sky & Telescope* (December. 2013): 18. Nice summary of what we know about comets and questions we have.

Rao, J. “How Often do Bright Comets Appear?” *Sky & Telescope* (November 2013): 30. Nice summary of bright comets in the last century and what factors make a comet spectacular in our skies.

Sekanina, Z. “Sungrazing Comets.” *Astronomy* (March 2006): 36.

Sheppard, S. “Beyond the Kuiper Belt.” *Sky & Telescope* (March 2015): 26. On Sedna and the Oort cloud.

Stern, S. “Evolution at the Edge.” *Astronomy* (September 2005): 46. How comet nuclei evolve with time.

Talcott, R. “Rendezvous with an Evolving Comet [Rosetta at Comet 67P/C-G].” *Astronomy* (September 2015): 44.

Tytell, D. “Deep Impact’s Hammer Throw.” *Sky & Telescope* (October 2006): 34. On the mission that threw a probe at the nucleus of a comet. See also (June 2005): 40.

Weissman, P. “A Comet Tale.” *Sky & Telescope* (February 2006): 36. A nice review of what we know and don’t know about the physical nature of comets.

Websites

Asteroids

Dawn Mission: **http://dawn.jpl.nasa.gov (http://dawn.jpl.nasa.gov)** . Discover more about this mission to the largest asteroids.

NEAR-Shoemaker Mission: **http://near.jhuapl.edu/ (http://near.jhuapl.edu/)** . Review background information and see great images from the mission that went by Mathilde and Eros.

Comets

Deep Impact Mission: **http://www.nasa.gov/mission_pages/deepimpact/main/ (http://www.nasa.gov/mission_pages/deepimpact/main/)** .

Kuiper Belt: **http://www2.ess.ucla.edu/~jewitt/kb.html (http://www2.ess.ucla.edu/~jewitt/kb.html)** . David Jewitt of the University of Hawaii keeps track of the objects that have been discovered.

Missions to Comets: **http://solarsystem.nasa.gov/missions/target/comets (http://solarsystem.nasa.gov/**

missions/target/comets) . Read about NASA's current and past missions to comets.

Stardust Mission: **http://stardust.jpl.nasa.gov/home/index.html (http://stardust.jpl.nasa.gov/home/index.html)** . Learn about this mission to collect a sample of a comet and bring it back to Earth.

Videos

Asteroids

Sweating the Small Stuff: The Fear and Fun of Near-Earth Asteroids: **https://www.youtube.com/watch?v=5gyAvc5OhII (https://www.youtube.com/watch?v=5gyAvc5OhII)** . Harvard Observatory Night Lecture by Jose-Luis Galache (1:18:07).

Unveiling Dwarf Planet Ceres: **https://www.youtube.com/watch?v=_G9LudkLWOY (https://www.youtube.com/watch?v=_G9LudkLWOY)** . A vonKarman Lecture by Dr. Carol Raymond, Oct. 2015, also includes Vesta results (1:18:38).

Comets

Great Comets, Comets in General, and Comet ISON: **https://www.youtube.com/watch?v=DiBkYAnQ_C (https://www.youtube.com/watch?v=DiBkYAnQ_C)** . Talk by Frank Summers, Space Telescope Science Institute (1:01:10).

Press Conference on the Impact of Comet Shoemaker-Levy 9 with Jupiter: **https://www.youtube.com/watch?v=B-tUP8afEIo (https://www.youtube.com/watch?v=B-tUP8afEIo)** . Day 2 after impact; July 17, 1994; with the discoverers and Heidi Hammel (1:22:29).

Rosetta: The Story So Far: **https://www.ras.org.uk/events-and-meetings/public-lectures/public-lecture-videos/2726-rosetta-the-story-so-far (https://www.ras.org.uk/events-and-meetings/public-lectures/public-lecture-videos/2726-rosetta-the-story-so-far)** . Royal Astronomical Society Lecture by Dr. Ian Wright (1:00:29).

COLLABORATIVE GROUP ACTIVITIES

A. Your group is a congressional committee charged with evaluating the funding for an effort to find all the NEAs (near-Earth asteroids) that are larger than 0.5 kilometers across. Make a list of reasons it would be useful to humanity to find such objects. What should we (could we) do if we found one that will hit Earth in a few years?

B. Many cultures considered comets bad omens. Legends associate comets with the deaths of kings, losses in war, or ends of dynasties. Did any members of your group ever hear about such folktales? Discuss reasons why comets in earlier times may have gotten this bad reputation.

C. Because asteroids have a variety of compositions and a low gravity that makes the removal of materials quite easy, some people have suggested that mining asteroids may be a way to get needed resources in the future. Make a list of materials in asteroids (and comets that come to the inner solar system) that may be valuable to a space-faring civilization. What are the pros and cons of undertaking mining operations on these small worlds?

D. As discussed in the feature box on **Comet Hunting as a Hobby**, amateur comet hunters typically spend more than 400 hours scanning the skies with their telescopes to find a comet. That's a lot of time to spend (usually alone, usually far from city lights, usually in the cold, and always in the dark). Discuss with members of your group whether you can see yourself being this dedicated. Why do people undertake such quests? Do you envy their dedication?

E. The largest Kuiper belt objects known are also called dwarf planets. All the planets (terrestrial, jovian, and dwarf) in our solar system have so far been named after mythological gods. (The dwarf planet names have moved away from Roman mythology to include the gods of other cultures.) Have your group discuss whether we should continue this naming tradition with newly discovered dwarf planets. Why or why not?

F. The total cost of the Rosetta mission to match courses with a comet was about 1.4 billion Euros (about $1.6 billion US). Have your group discuss whether this investment was worth it, giving reasons for whichever side you choose. (On the European Space Agency website, they put this cost in context by saying, “The figure is barely half the price of a modern submarine, or three Airbus 380 jumbo jets, and covers a period of almost 20 years, from the start of the project in 1996 through the end of the mission in 2015.”)

G. If an Earth-approaching asteroid were discovered early enough, humanity could take measures to prevent a collision. Discuss possible methods for deflecting or even destroying an asteroid or comet. Go beyond the few methods mentioned in the text and use your creativity. Give pros and cons for each method.

EXERCISES

Review Questions

1. Why are asteroids and comets important to our understanding of solar system history?

2. Give a brief description of the asteroid belt.

3. Describe the main differences between C-type and S-type asteroids.

4. In addition to the ones mentioned in **Exercise 13.3**, what is the third, rarer class of asteroids?

5. Vesta is unusual as it contains what mineral on its surface? What does the presence of this material indicate?

6. Compare asteroids of the asteroid belt with Earth-approaching asteroids. What is the main difference between the two groups?

7. Briefly describe NASA’s Spaceguard Survey. How many objects have been found in this survey?

8. Who first calculated the orbits of comets based on historical records dating back to antiquity?

9. Describe the nucleus of a typical comet and compare it with an asteroid of similar size.

10. Describe the two types of comet tails and how each are formed.

11. What classification is given to objects such as Pluto and Eris, which are large enough to be round, and whose orbits lie beyond that of Neptune?

12. Describe the origin and eventual fate of the comets we see from Earth.

13. What evidence do we have for the existence of the Kuiper belt? What kind of objects are found there?

14. Give brief descriptions of both the Kuiper belt and the Oort cloud.

Thought Questions

15. Give at least two reasons today’s astronomers are so interested in the discovery of additional Earth-approaching asteroids.

16. Suppose you were designing a spacecraft that would match course with an asteroid and follow along its orbit. What sorts of instruments would you put on board to gather data, and what would you like to learn?

17. Suppose you were designing a spacecraft that would match course with a comet and move with it for a while. What sorts of instruments would you put on board to gather data, and what would you like to learn?

18. Suppose a comet were discovered approaching the Sun, one whose orbit would cause it to collide with Earth 20 months later, after perihelion passage. (This is approximately the situation described in the science-fiction novel *Lucifer’s Hammer* by Larry Niven and Jerry Pournelle.) What could we do? Would there be any way to protect ourselves from a catastrophe?

19. We believe that chains of comet fragments like Comet Shoemaker-Levy 9’s have collided not only with the jovian planets, but occasionally with their moons. What sort of features would you look for on the outer planet moons to find evidence of such collisions? (As an extra bonus, can you find any images of such features on a moon like Callisto? You can use an online site of planetary images, such as the *Planetary Photojournal*, at photojournal.jpl.nasa.gov.)

20. Why have we found so many objects in the Kuiper belt in the last two decades and not before then?

21. Why is it hard to give exact diameters for even the larger objects in the Kuiper belt?

Figuring For Yourself

22. Refer to **Example 13.1**. How would the calculation change if a typical comet in the Oort cloud is only 1 km in diameter?

23. Refer to **Example 13.1**. How would the calculation change if a typical comet in the Oort cloud is larger—say, 50 km in diameter?

24. The calculation in **Example 13.1** refers to the known Oort cloud, the source for most of the comets we see. If, as some astronomers suspect, there are 10 times this many cometary objects in the solar system, how does the total mass of cometary matter compare with the mass of Jupiter?

25. If the Oort cloud contains 10^{12} comets, and ten new comets are discovered coming close to the Sun each year, what percentage of the comets have been “used up” since the beginning of the solar system?

26. The mass of the asteroids is found mostly in the larger asteroids, so to estimate the total mass we need to consider only the larger objects. Suppose the three largest asteroids—Ceres (1000 km in diameter), Pallas (500 km in diameter), and Vesta (500 km in diameter)—account for half the total mass. Assume that each of these three asteroids has a density of 3 g/cm^3 and calculate their total mass. Multiply your result by 2 to obtain an estimate for the mass of the total asteroid belt. How does this compare with the mass of the Oort cloud?

27. Make a similar estimate for the mass of the Kuiper belt. The three largest objects are Pluto, Eris, and Makemake (each roughly 2000 km). In addition, assume there are eight objects (including Haumea, Orcus, Quaoar, Ixion, Varuna, and Charon, and objects that have not been named yet) with diameters of about 1000 km. Assume that all objects have Pluto’s density of 2 g/cm^3. Calculate twice the mass of the largest 13 objects and compare it to the mass of the main asteroid belt.

28. What is the period of revolution about the Sun for an asteroid with a semi-major axis of 3 AU in the middle of the asteroid belt?

29. What is the period of revolution for a comet with aphelion at 5 AU and perihelion at the orbit of Earth?