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.
### The Largest Asteroids

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

**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.
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.
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.
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.

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.](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.
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.

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.
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.
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.

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.

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).
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.
ASTERoids.

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.

![Figure 13.13 Impacts with Earth.](image)

(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)

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.
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).

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.
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.
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.

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

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

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).
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.
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$_2$O) 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$_2$O 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.](image)

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 tail is pushed more directly outward from the Sun by our star’s wind of charged particles.
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