15

When in your middle years
The great comet comes again
Remember me, a child,
Awake in the summer night,
Standing in my crib and
Watching that long-haired star
So many years ago.
Go out in the dark and see
Its plume over water
Dribbling on the liquid night,
And think that life and glory
Flickered on the rushing
Bloodstream for me once, and for
All who have gone before me,
Vessels of the billion-year long
River that flows now in your veins.

Kenneth Rexroth
Halley's Comet

Comet over Valles Marineris by Kim Poor.

www.mhhe.com/fix

Small Solar System Bodies

The town of Homestead is about 20 miles west of Iowa City. Homestead, normally a quiet place, was the scene of an extraordinary happening a little more than a century ago. At about 10:15 in the evening on February 12, 1875, a small solar system body made a spectacular arrival in the vicinity of Homestead. Here is a contemporary account by a Mr. Irish:

> From the first the light of the meteor could hardly be tolerated by the naked eye turned full upon it. Several observers who were facing south at the first flash say that upon looking full at the meteor it appeared to them round, and almost motionless in the air, and as bright as the sun. . . .
>
> The observers who stood near to the line of the meteor's flight were quite overcome with fear, as it seemed to come down upon them with a rapid increase of size and brilliancy, many of them wishing for a place of safety, but not having time to seek one. In this fright animals took part, horses shying, and plunging to get away, and dogs retreating and barking with signs of fear. The meteor gave out marked flashes in its course, one more noticeable than the rest, when it had completed about two-thirds of its visible flight. All observers who stood within twelve miles of the meteor's path say that from the time they first saw it, to its end, the meteor threw down "coals" and "sparks."
>
> Thin clouds of smoke or vapor . . . would seem to burst out from the body of the meteor like puffs of steam from the funnel of a locomotive or smoke from a cannon's mouth, and then as suddenly be drawn into the space behind it. The

Questions to Explore

- What causes meteors? Why do meteor showers occur?
- What can meteorites tell us about objects that formed early in the history of the solar system?
- How are meteorites related to asteroids?
- How do comets produce their spectacular comas and tails?
- Where do new comets come from?
- What happens when asteroids and comets strike the Earth?

light of the meteor's train was principally white, edged with yellowish green throughout the greater part of its length, but near to the body of the meteor the light had a strong red tinge. The length of the train was variously estimated, but was probably about nine degrees, or from seven to twelve miles, as seen from Iowa City. . . .

From three to five minutes after the meteor had flashed out of sight, observers near the south end of its path heard an intensely loud and crashing explosion, that seemed to come from the point in the sky where they first saw it. This deafening explosion was mingled with, and followed by, a rushing, rumbling, and crashing sound that seemed to follow up the meteor's path, and at intervals, as it rolled away northward.

After the explosion, a large number of stones rained down on an area of about 50 km^2 around Homestead. About 100 meteorites, weighing a total of 250 kg, were quickly picked up. The largest of them weighed 35 kg. Professor Gustavus Hinrichs of the University of Iowa rushed to the scene and collected several of the meteorites, which are now in the collections of universities and museums.

The incident at Homestead was the result of the encounter between the Earth and a desk-sized chunk of interplanetary debris. Such bodies, although far smaller and less massive than the planets, can affect us more strongly than any objects except the Sun and the Moon. This chapter is about small interplanetary bodies and the ways that they can influence us, both physically and intellectually.

15.1 METEORS

Figure 15.1 shows a **meteor,** a bright streak of light produced when a piece of interplanetary debris moves rapidly through the Earth's atmosphere. The piece of debris is usually referred to as a **meteoroid.** Meteors occur almost continuously. On any clear night it is possible to see a meteor by looking at the sky for 5 or 10 minutes. To be able to see a meteor, someone must be within a few hundred kilometers of it. This means that from a given spot on the Earth's surface it is possible to see only a tiny fraction of all the meteors that occur each day. For 8 or 10 meteors to be visible each hour at a given spot, tens of millions of them must occur each day.

The Meteor Phenomenon

The meteoroids that strike the Earth's atmosphere arrive at speeds that range from about 11 km/s (the Earth's escape velocity) to 72 km/s (about 160,000 mph). Heat generated by friction between atmospheric gas and the meteoroid melts the surface of the meteoroid and then vaporizes it, reducing its size as well as heating and charring it. Atmospheric gas and the vaporized meteoroid material are heated to the point where they glow, producing the meteor. A typical meteoroid begins to glow when it is about 90 km above the ground, and it is completely

FIGURE 15.1
A Meteor
A typical meteor is a brief, bright streak of light that takes place when a small piece of interplanetary debris enters the Earth's atmosphere at great speed. Several meteors can be seen each hour on a clear, dark night.

vaporized by the time it reaches a height of about 80 km. How far the meteoroid penetrates into the atmosphere depends on its mass, its speed when it strikes the atmosphere, and the angle at which it strikes.

Sizes of Meteoroids

Although the glowing region of gas that we see as a meteor can be many meters across, the meteoroid responsible for the meteor is much smaller. Bright meteors can be produced by meteoroids that have masses of about 1 gram and are less than 1 cm in diameter. Faint meteors, produced by less massive meteoroids, are much more numerous than bright ones. A few thousand times each day the atmosphere is struck by a meteoroid big enough (several centimeters across) to produce a spectacularly bright meteor called a **fireball.** Some fireballs are accompanied by thunderlike rumbling and produce luminous trains of glowing gas that can last for an hour.

Although the meteoroids responsible for ordinary meteors are entirely consumed high in the atmosphere, this is not necessarily the case for fireball meteoroids. Air resistance slows them at the same time that it strips away their outer layers. Before a meteoroid larger than the size of a fist can be completely destroyed, the atmosphere slows it to **terminal velocity,** the speed at which air resistance equals the force due to the Earth's gravity. The remaining portion of the meteoroid hits the ground at a few hundred meters per second (in other words, a few times as fast as a well-thrown baseball). The portion of the meteoroid that survives passage through the atmosphere and reaches the ground is called a **meteorite.** Sometimes, as in the case of the Homestead meteor, the meteoroid disintegrates in the air, causing a shower of meteorites.

The height at which a meteoroid is slowed to terminal velocity depends on the mass and the initial speed of the meteoroid. Typically, this occurs tens of kilometers above the ground. A very large meteoroid (larger than the size of an automobile) may strike the ground before it can be slowed to terminal velocity. In such cases an impact crater may be formed.

A meteor is the flash of light that occurs when a small piece of interplanetary matter called a meteoroid strikes the Earth's atmosphere at such high speed that the atmosphere heats up until it glows. Most meteoroids are smaller than 1 cm, but a few are large enough that portions of them reach the ground. The part of a meteoroid that reaches the ground is called a meteorite.

Meteor Showers

About ten times a year, the rate at which meteors can be seen rises dramatically. The rate rises until it reaches a maximum of 15 to 100 per hour and then declines again over several days. These events are called **meteor showers.** Table 15.1 describes some of the major meteor showers. The dates of meteor showers are very predictable, because they recur on nearly the same date each year. The maximum meteor rate during a shower is much harder to predict. Occasionally, spectacular meteor showers occur. For example, in the early morning of November 13, 1833, people all over the eastern part of the United States witnessed a meteor shower in which at least 100,000 meteors per hour could be seen. This amazing shower prompted many preachers to announce that the end of the world was at hand. More recently, on November 17, 1966, observers in the southwestern United States were treated to a display that peaked at a rate of more than 100 meteors per second. During a 40-minute period, 60,000 meteors were seen.

Radiants and Meteor Orbits As Denison Olmstead, a Yale professor, watched the November 1833

Table 15.1 Major Meteor Showers

SHOWER	DATE OF MAXIMUM	DURATION (days)	RATE (number/hour)	PARENT OBJECT
Quadrantid	Jan. 3	0.4	80	
Lyrid	Apr. 22	1	15	Comet Thatcher
Eta Aquarid	May 4	6	60	Comet Halley
Delta Aquarid	Jul. 29	8	30	
Perseid	Aug. 12	3	100	Comet Swift-Tuttle
Orionid	Oct. 21	2	30	Comet Halley
Leonid	Nov. 16	2	20	Comet Tempel-Tuttle
Geminid	Dec. 13	3	90	Asteroid Phaethon

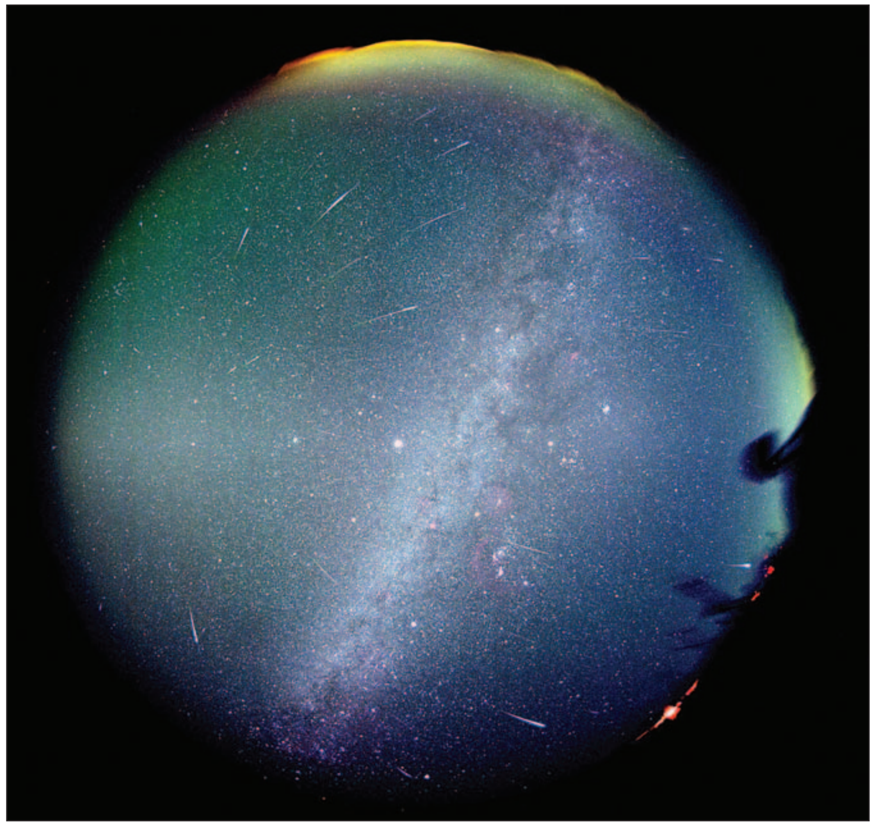


FIGURE 15.2
The Leonid Meteor Shower in 2001
During meteor showers the rate of meteors can rise to hundreds or thousands per hour. The radiant of this meteor shower, in the left center of the image, can be found by extending the meteor trails until they meet.

ANIMATION *A meteor shower*

shower, he noted that the meteors appeared to be coming from a point within the constellation Leo. The spot in the sky from which the meteors in a shower seem to originate is called the **radiant** (Figure 15.2). Meteor showers are named for the constellation within which the radiant is located, so the great shower of November 1833 was an occurrence of the Leonid meteor shower.

Olmstead realized that the radiant point was caused by perspective. Just as snowflakes seem to diverge from a point in front of us when we drive through a snowstorm, the paths of individual meteors appear to diverge from the radiant. In reality, as shown in Figure 15.3, the meteoroids that produce a meteor shower are moving along parallel paths through the solar system when they strike the Earth. A meteor shower, then, occurs when the Earth collides with a swarm of meteoroids that orbit the Sun on nearly identical paths.

Figure 15.4 shows that a given meteor shower recurs about the same date each year because the Earth crosses the orbit of the meteoroids responsible for the shower on approximately that same date each year. If the meteoroids are smoothly distributed around their orbit, the meteor rate will remain stable from year to year. However, if the Earth encounters a relatively dense clump of meteoroids, a spectacular shower will result. The Earth moves about 2.5 million km along its orbit each day. Because meteor showers usually last for several days (though not at their

FIGURE 15.3
The 1997 Leonid Meteor Shower as Seen from Space
This image, taken by the *MSX* satellite, shows many meteors moving along parallel paths through the Earth's atmosphere.

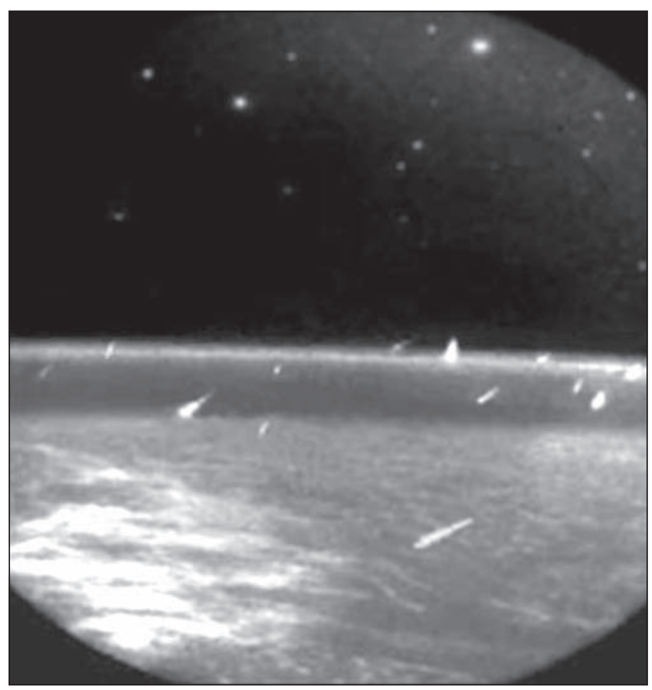


FIGURE 15.4

Why Meteor Showers Occur

Meteor showers occur when the Earth intersects the orbit of a meteoroid swarm. Because the Earth returns to the region of intersection at the same point in its orbit each year, a given meteor shower occurs on approximately the same date each year.

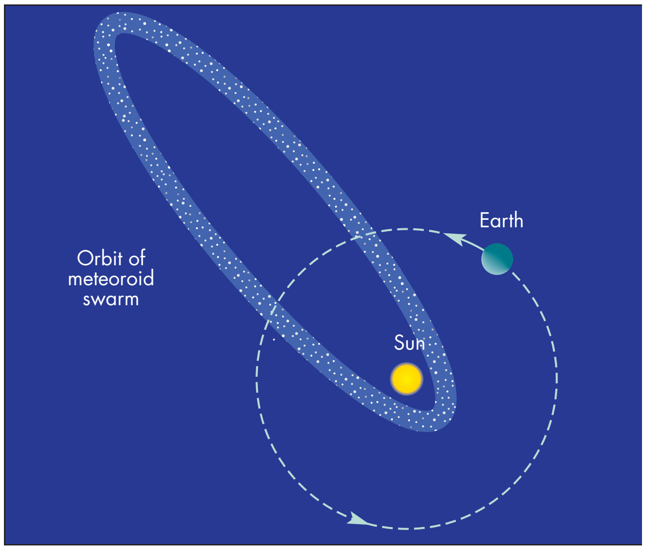
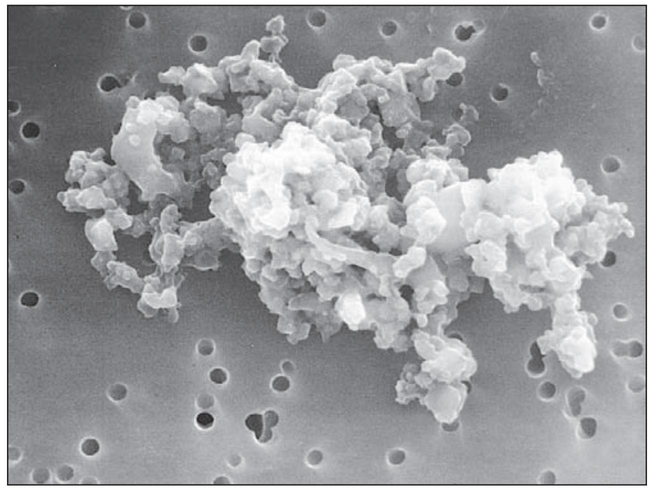


FIGURE 15.5

A Micrometeorite

Most micrometeorites are fragile, fluffy objects that originated in comets. The micrometeorite shown here is about 10^{-5} m across or about one-tenth as big as the thickness of this page.



peak rates), the meteoroid swarms that cause meteor showers must be several millions of kilometers across.

Meteor showers are temporary increases of the rate at which meteors are observed. Showers recur on approximately the same date from year to year. Meteor showers happen when the Earth runs into a swarm of meteoroids that share a common orbit about the Sun.

Micrometeorites

Although most meteoroids are destroyed in the atmosphere, those smaller than about 50 millionths of a meter in diameter are slowed down without becoming hot enough to vaporize. This happens at altitudes near 100 km. These meteoroids are called **micrometeorites** and they slowly settle through the atmosphere until they reach the ground. Astronomers have collected many micrometeorites using high-altitude aircraft. One of these is shown in Figure 15.5. They tend to be very porous, fragile objects that look somewhat like dustballs.

15.2 METEORITES

Until lunar samples were returned to the Earth by the Apollo astronauts, meteorites were the only pieces of material from the rest of the universe that could be analyzed in a laboratory. Important ideas about the development of the solar system were based on the evidence available in meteorites. Yet the conclusion that meteorites are cosmic intruders is surprisingly recent.

Even in prehistory, people recognized that meteorites were unusual objects. In some cases, they also realized that meteorites fell from the sky. In some cultures, meteorites were revered as holy objects. At many Greek and Roman temples, meteorites were worshiped as gods fallen from the heavens. Meteorites were also venerated in Japan, China, India, and Africa. A very common belief about meteorites was that they were omens or that they possessed supernatural powers. For example, after the fall of the Ensisheim (Germany) meteorite in 1492, the Emperor Maximillian was advised by his council that the meteorite was a favorable omen for his wars with the French and the Turks. The meteorite was hung in a local church.

Many Native American cultures treated meteorites with great respect, often burying them in special graves or crypts. Before going to battle, warriors of the Clackamas tribe of Oregon bathed their faces and dipped their arrows in water that had collected in an iron meteorite. Before the development of iron metallurgy, meteorites were an important source of nearly pure metal. They were used for diverse items such as buttons, ear ornaments, and swords.

Although reports of stones falling from the sky were common, most eighteenth-century scientists were skeptical that such events really happened. They even doubted the reliability of eyewitnesses. A meteorite shower that took place in Barbotan, France, in 1790 was witnessed by the mayor and the city council. Nevertheless, French scientists dismissed the event, saying, "How sad it is to see a whole municipality attempt to lend credibility, through a formal deposition, to folktales that arouse the pity not only of physicists but of all sensible people." In the United States, in 1803, President Thomas Jefferson is reported to have doubted that stones could fall from the sky, although his main objection was to the idea that the stones could have formed in the atmosphere.

The first scientist to contradict this skepticism about meteorites was the German physicist E. E. F. Chladni. After collecting many reports of meteorite falls, he concluded in 1794 that meteorites were the surviving bodies of fireballs. He also concluded that the meteorites were extraterrestrial. His views were ridiculed by his contemporaries. After all, no less an authority than Isaac Newton had written that interplanetary space was completely empty. For Newton, it was impossible that meteoroids could exist in space before striking the Earth. Even those who believed that meteorites were real thought that they were ordinary stones that had been swept up by whirlwinds or ejected from volcanos.

In the decade after Chladni published his conclusions about meteorites, there were several well-observed falls, which convinced many other scientists that meteorites were real. The most influential of these falls took place in April 1803 in l'Aigle, France, when about 3000 stones fell in a 40 km^2 region. The French Academy of Sciences dispatched physicist Edouard Biot to investigate the event. His careful investigation convinced nearly all skeptics that meteorites really do fall from the sky. Within about 30 years, even the extraterrestrial origin of meteorites became widely accepted.

How Often Do They Fall?

Meteorite falls are quite rare. To collect one meteorite larger than about 0.1 kg each year, it would be necessary to patrol a region of about 1000 km^2 (about the size of the Washington, D.C., metropolitan area). Larger meteorites are even less common. To collect a 10 kg meteorite each year, it would be necessary to monitor an area of more than 1 million km^2. Because the annual sprinkling of meteorites is spread around the globe, it is hardly surprising that most meteorites are never recovered. In fact, until a few decades ago, the typical harvest of meteorites was only a few dozen per year for the entire planet.

The number of collected meteorites has risen dramatically during the past 20 years, however, thanks to the discovery that the Antarctic ice sheet acts as a natural collector of meteorites. The Antarctic ice sheet is much thicker at the center of the continent than at the coast. Ice flows toward the coast, carrying with it any meteorites that have fallen into the ice. In some places, the flow of the ice is stopped by rock barriers beneath the surface. As the ice evaporates, the meteorites it carries emerge at the surface, where they can be collected in large numbers. Tens of thousands of meteorites have been found in Antarctica. Some of them fell as long as a million years ago.

The discovery that meteorites can be readily found in Antarctic ice fields, where they have been preserved for up to millions of years, has greatly increased the number of meteorites that have been collected.

Meteorite Insurance? Despite rumors to the contrary, there isn't a single documented case of a person being killed by a meteorite. In fact, the chances that a given person will be struck by a meteorite more massive than 0.1 kg during a given year are about 1 in 10 billion. However, an Alabama woman was slightly injured by a meteorite in 1954. Her injuries might have been worse had the meteorite not been slowed by the roof and ceiling of her house before striking her. There are also a few reports of meteorites striking and killing animals. For instance, in 1860 a horse was struck and killed in Ohio, and a dog was killed in Egypt in 1911.

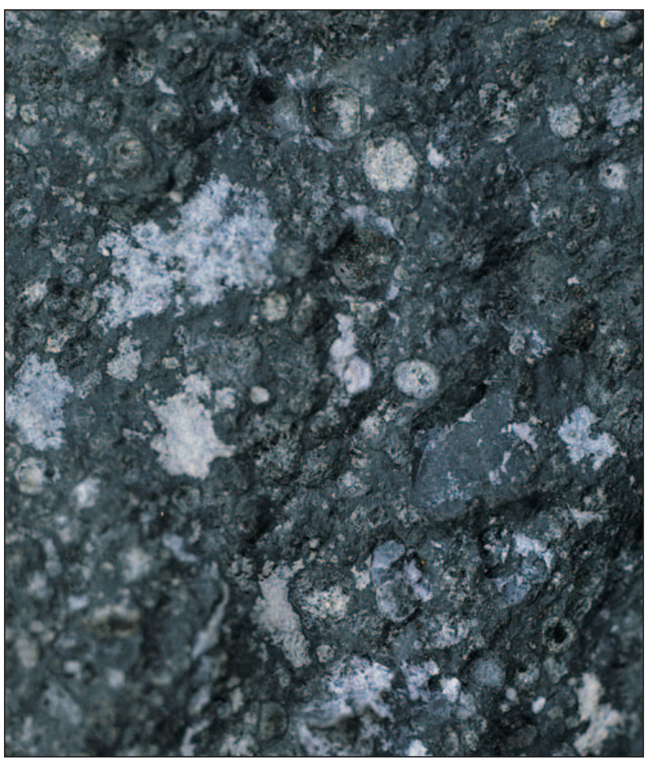
Kinds of Meteorites

ANIMATION *Differentiation in asteroids and their subsequent breakup by collision to form iron and stony bodies*

Meteorites can be divided into three broad categories: stony meteorites, iron meteorites, and stony-iron meteorites. **Stony meteorites,** such as the one shown in Figure 15.6, make up about 94% of all the meteorites that fall to the Earth. Most stony meteorites are **chondrites,** named for the **chondrules** they contain. Chondrules (Figure 15.7) are spheres of silicate rock only millimeters in size. Many of them are glassy. They appear to have been liquid drops that solidified, crystallized, and were then incorporated into chondrites. The origin of chondrules is still quite mysterious. They may have formed directly from the gas cloud that preceded the solar system. Perhaps shock waves or lightning discharges within the gas cloud triggered their formation. Another possibility is that they resulted from liquid droplets sprayed outward during impacts between early solar system bodies.

FIGURE 15.6
A Stony Meteorite
The stony meteorite shown here was part of the Allende meteorite, which fell in Mexico in 1969. This piece is about 15 cm across. After a few years of weathering, stony meteorites are often mistaken for terrestrial rocks.

FIGURE 15.7
Chondrules Within a Chondrite
Chondrites are the most common kind of stony meteorite. This close-up of a piece of the Allende meteorite shows the chondrules as light-colored, round inclusions a few millimeters in diameter.



Carbonaceous chondrites are an important class of chondrites. Because they contain considerable amounts of water (bound in minerals) and other compounds that would have been driven off or decomposed if they had been heated, the carbonaceous chondrites are believed to be samples of early solar system material that have never been altered by high temperatures or pressures.

Carbonaceous chondrites are named for their relatively high content of carbon, much of which is in the form of organic compounds. Among the organic compounds are about 20 amino acids, the building blocks of proteins. However, there is no indication that life developed from the amino acids within carbonaceous chondrites. Instead, the presence of amino acids in carbonaceous chondrites demonstrates that the mixture of materials in the early solar system, in the right environment of temperature and pressure, could yield the basic building blocks of life.

Another type of stony meteorites is the **achondrite,** which contains no chondrules. The achondrites resemble terrestrial igneous rocks. The achondrites may have been formed when chondritic material melted, which would have destroyed the chondrules that chondrites contain. Many of the achondrites contain much less iron than the chondrites. Apparently, the material from which the achondrites formed became separated from iron (and other metals) when melting took place.

Iron meteorites, such as the one shown in Figure 15.8, make up about 5% of the meteorites that fall to Earth. They are nearly pure alloys of iron and nickel. The minerals in iron meteorites occur as large crystals that can only be produced when molten metal cools very slowly. Rapid cooling would produce many small crystals instead. Large crystals suggest that the iron meteorites solidified in an environment where the temperature declined over tens of millions of years.

FIGURE 15.8
An Iron Meteorite
Etching the polished face of an iron meteorite with weak acid makes the pattern of crystals within the meteorite visible. This slab of the Edmonton, Kentucky, meteorite is about 15 cm across.

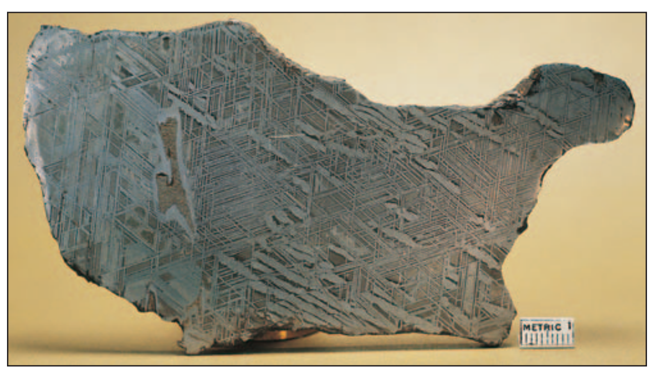


FIGURE 15.9
A Stony-Iron Meteorite
Stony-irons consist of a matrix of silicate rock within which are small pieces of metal. This polished slice of the Pavlodar, Siberia, meteorite is about 10 cm across.

Stony-iron meteorites, shown in Figure 15.9, make up the remaining 1% of the meteorites. The stony-irons are a mixture of metal and silicate rock. They appear to have been formed when molten silicates came in contact with molten metal.

> Most meteorites are stones that resemble terrestrial rocks. One important type of stony meteorite is the carbonaceous chondrite, which contains water and other volatile substances. Carbonaceous chondrites may represent primitive solar system material. Two other types of meteorites are irons, which are nearly pure alloys of iron and nickel, and stony-irons, which are mixtures of stone and metal.

Ages of Meteorites

The **solidification age** of a meteorite is the amount of time that has passed since the meteorite solidified from the molten state. This happened when the parent bodies of the meteorites cooled sufficiently to solidify. Solidification ages can be measured by radioactive dating, and most fall within the narrow range of 4.55 to 4.65 billion years. The solidification ages of meteorites are a little greater than the ages of the oldest Moon rocks brought back to the Earth.

Another important moment in the history of a meteorite is described by its **cosmic ray exposure age.** This is the length of time that has passed since the meteorite broke off from a larger body. Interplanetary space is filled with **cosmic rays,** which can cause nuclear reactions when they strike meteorites. However, cosmic rays can penetrate only about 1 m into a meteorite. As long as a meteorite is buried within a parent body or a large fragment of the parent body, it can't be struck by cosmic rays, and none of the products of cosmic ray-induced nuclear reactions can build up. Typical cosmic ray exposure ages are tens of millions of years. This means that the meteorites that strike the Earth today were part of larger bodies for nearly all of their history and that these larger bodies were broken up to produce meteorite-sized objects only quite recently.

> Analysis of the radioactive elements in meteorites shows that most of them solidified about 4.6 billion years ago. The oldest lunar samples date back to about the same time. The cosmic ray exposure ages of meteorites show that they were located within larger bodies until only a few tens of millions of years ago.

Parent Bodies of Meteorites

Most meteorites are quite uniform in texture and mineral structure, which suggests that they remained at fairly constant temperatures of 1000 K or more for long periods of time. During that time they were cooked as though in a pressure cooker. This changed their textures and made their mineral structures uniform. Some meteorites, however, seem to have resulted from temperatures high enough to melt part of their parent bodies. Figure 15.10 shows one of the parent bodies before and after it melted. After melting, iron and other metals sank to the bottom and rocky material rose to the top of the melted zone. The remnants of these zones are the iron meteorites and the achondrites. The stony-irons may have formed from material that lay at the boundary between the molten metal core of a parent body and its outer layer of rock. There is little evidence, however, that carbonaceous chondrites were ever heated. Instead, they may have been at or near the original surface of the parent body or perhaps were never part of a parent body.

The sizes of the parent bodies can be estimated from the very slow rate at which iron meteorites cooled once they solidified. For the iron to remain hot for tens of millions of years, it must have been well insulated. Cooling at the required rate could have taken place only within bodies larger than approximately 100 km in diameter.

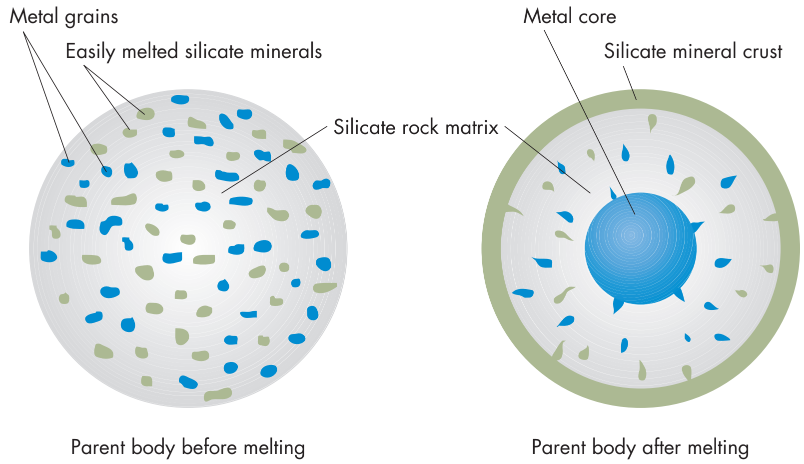


FIGURE 15.10
The Possible Evolution of a Parent Body of Meteorites
The parent body is shown in its original form on the left. It consisted of metal grains (shown as small blue regions) and easily melted silicate minerals (shown as green inclusions) in a matrix of silicate rock. When the parent body was heated, it partially melted. Molten metal sank to the center to form a core. Easily melted silicate minerals rose to form the crust.

Astronomers also have been able to learn something about where the parent bodies of the meteorites were located in the solar system and the kinds of orbits they had. A number of meteoroids have been tracked through the Earth's atmosphere accurately enough to determine that, before they hit the Earth, they were traveling on elliptical orbits with aphelia between the orbits of Mars and Jupiter.

Putting the clues together, we can conclude that the parent bodies of the meteorites must have ranged in size up to at least hundreds of kilometers in diameter. There must have been enough of them that they have been colliding with and fragmenting each other for as long as the solar system has existed. Finally, these bodies must have orbits that carry them into the region between Mars and Jupiter. We might expect to be able to find some evidence for the group of objects that produce meteorites. We do. These objects are asteroids.

Most meteorites were cooked at high temperatures over long periods of time. Also, the iron meteorites contain crystals that could have formed only if the iron had cooled from a molten state very slowly. To have cooled slowly enough, the parent bodies of the meteorites must have been at least 100 km in diameter. The orbits of meteoroids show that they came from bodies whose orbits carried them into the region between Mars and Jupiter.

15.3 ASTEROIDS

Asteroids are the multitude of rocky bodies that orbit the Sun within the planetary system and that range from a few kilometers in diameter up to nearly a thousand kilometers in diameter. These bodies are also called **minor planets.**

Discovery of Asteroids

The first asteroid was discovered by the Sicilian astronomer Giuseppe Piazzi on January 1, 1801. As he made routine observations of the positions of stars, Piazzi saw that one of the objects he thought to be a star moved with respect to the other stars. He observed the object long enough to determine that its orbit lay in the large gap between the orbits of Mars and Jupiter. Because many astronomers had speculated that there might be an undiscovered planet within that gap, Piazzi decided that he had found a new planet, which he named Ceres. The mathematician Carl Friedrich Gauss used Piazzi's observations to show that Ceres had an elliptical orbit with a semimajor axis of 2.77 AU and an orbital period of 4.62 years.

Ceres had escaped previous detection because it is too faint to be seen with the unaided eye. In fact, it is less than one one-thousandth as bright as Mars and Jupiter, the planets that orbit inside and outside its orbit. Piazzi's "planet" was certainly different from the other known planets. Ironically, Ceres, the first discovered asteroid, is now considered to be a dwarf planet because it is in orbit about the Sun, is not a satellite of a planet, and is massive enough that its gravity pulls it into a nearly spherical shape. Some important properties of Ceres are given in Table 15.2.

While looking for Ceres in 1802, Wilhelm Olbers found a second body, which he named Pallas, orbiting between Mars and Jupiter. Two more bodies with similar orbits were soon discovered—Juno in 1804 and Vesta in 1807. Now there was an abundance of bodies between Mars and Jupiter rather than a dearth. All of these bodies were so faint and so small that astronomers realized they represented a new kind of celestial object and began to refer to them as asteroids.

After the discovery of Vesta, nearly 40 years passed before another asteroid was discovered. However, when charts became available for stars below the limit of unaided vision, asteroids began to be discovered at a steady rate. One hundred ten asteroids had been found by 1870. In the 1890s, a new technique utilizing long-exposure photographs

Table 15.2
Dwarf Planet Data

Ceres

Orbital distance	2.77 AU
Orbital period	4.6 years
Mass	0.00016 M_{Earth} = 9.5 × 10^{20} kg
Diameter	0.074 D_{Earth} = 950 km
Density (relative to water)	2.1
Escape velocity	0.5 km/s
Surface gravity	0.03 g
Global temperature	170 K
Main atmospheric gases	None
Rotation period	9.1 hours
Axial tilt	4°
Known satellites	None
Distinguishing features	May contain more water (frozen) than is in Earth's oceans.

of starfields came into practice. Asteroids, which moved with respect to the stars, showed up as streaks on the images. By the turn of the century, the number of known asteroids had risen to 450.

Over the years, ever fainter and smaller asteroids have been discovered. There are now more than 300,000 asteroids that have been observed often enough that we know their orbits. Hundreds of thousands of other asteroids have been seen but have not been well enough observed for their orbits to be determined.

Asteroid Names If you discover an asteroid and determine its orbit, you get to name it. As a result, there is a wide variety of asteroid names. Many asteroids are named after characters from different mythological traditions (Aten, Frigga, Agamemnon). Others are named for observatories (Alleghenia), cities (Chicago), benefactors (Rockefellia), relatives (Winifred), operas (Turandot), and many other people and things.

Orbits of Asteroids

The orbits of asteroids vary in shape and size, but nearly all of them orbit the Sun in the same direction as the Earth does. Compared with the planets, however, asteroids tend to have more eccentric orbits that are more inclined to the ecliptic plane.

The Asteroid Belt The overwhelming majority of known asteroids are located in the **asteroid belt,** which lies between 2.1 and 3.3 AU from the Sun. Figure 15.11 shows the positions of more than 7000 asteroids on March 7, 1997. Notice that nearly all of them were located in the asteroid belt between the orbits of Mars and Jupiter. The

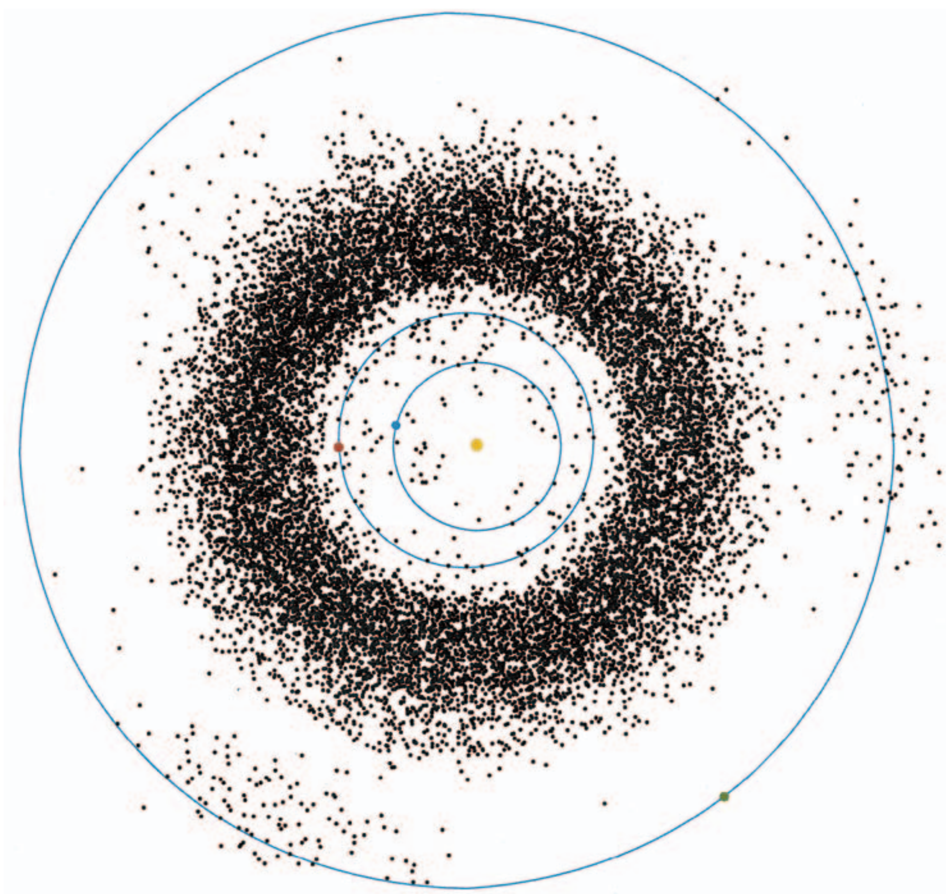
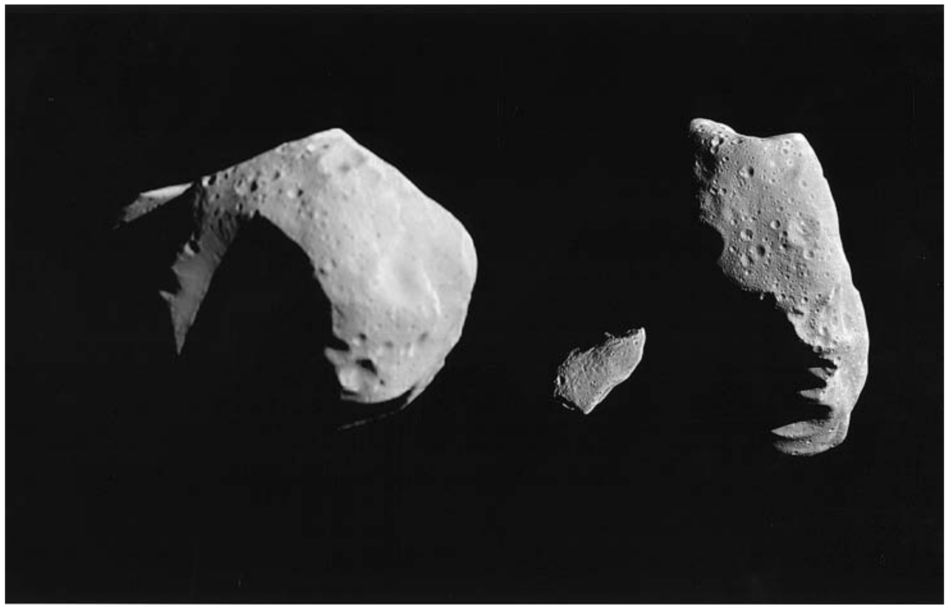


FIGURE 15.11
Asteroid Locations
The locations of more than 7000 asteroids on March 7, 1997, are shown along with the positions and orbits of the Earth, Mars, and Jupiter. Most asteroids orbit in the main belt, which lies between 2.1 and 3.3 AU. This is outside the orbit of Mars. Two clusters of asteroids, known as the Trojan asteroids, follow Jupiter's orbit but are 60° ahead of or behind Jupiter. Note that there are some asteroids inside the orbits of Mars and the Earth.

FIGURE 15.12
Asteroids Mathilde, Gaspra, and Ida
The asteroids are shown at the same scale in this composite image. Mathilde is about 60 km in diameter, Gaspra is about 12 by 20 by 11 km, and Ida is about 56 km long.



Mathilde Gaspra Ida

large number of asteroids orbiting within this region may give the impression that the asteroid belt is very crowded, with frequent collisions and near misses. Science fiction movies reinforce this impression when they portray asteroid belts as if they were as crowded and as hazardous as shopping mall parking lots. This picture is completely wrong, however. If there were a million asteroids in the asteroid belt, the average distance between nearest neighbors would be about 2 million km (more than five times the separation of the Earth and the Moon). You could spend your entire life on an asteroid without ever getting close enough to another asteroid to see it as anything larger than a point of light.

The largest known asteroids are in the asteroid belt. Pallas and Vesta are both a little larger than 500 km in diameter. Thousands of other asteroids in the main belt are larger than 10 km in diameter.

In the last decade, astronomers have obtained close-up images of three main-belt asteroids when spacecraft flew past them on their way to other destinations. Images of these asteroids are shown in Figure 15.12. Gaspra, which has an elongated shape that measures 20 by 12 by 11 km, resembles Mars's satellite Phobos in that it is pitted with craters and shows a series of cracks that apparently resulted from a particularly violent collision with another, smaller asteroid. Ida, about 56 km in length, is elongated and heavily cratered like Gaspra. Remarkably, Ida has a satellite of its own. Ida's satellite, shown in Figure 15.13, is about 1.5 km across and orbits Ida at a distance of about 100 km. Observations from Earth have identified over 50 other asteroids that have satellites. One asteroid, Sylvia, is orbited by two satellites. The third main-belt asteroid visited by spacecraft is Mathilde, a roughly round body about 60 km across. Figure 15.12 shows that Mathilde is pocked by craters, including one 30 km across and 10 km deep. Mathilde has an albedo of only 0.04, indicating that it reflects sunlight about as poorly as a chunk of coal. Its surface materials may be similar to those of carbonaceous chondrites. As the spacecraft passed Mathilde, it was deflected slightly by the asteroid's gravity. This made it possible for astronomers to calculate Mathilde's mass and density. Mathilde's density is less than 2000 kg/m^3—about half the density of carbonaceous chondrites or other rocky materials. This suggests that

FIGURE 15.13
The Asteroid Ida and Its Satellite, Dactyl
This picture of Ida and its satellite was obtained by the *Galileo* spacecraft when it passed Ida at a distance of 11,000 km in 1993. Ida is elongated and has a cratered surface. The small object to the right of Ida is its satellite, Dactyl, about 1.5 km across. The satellite appears to be very close to Ida, but this is because it is closer to the spacecraft than Ida is. The distance between Ida and the satellite is actually about 100 km, or twice the length of Ida.

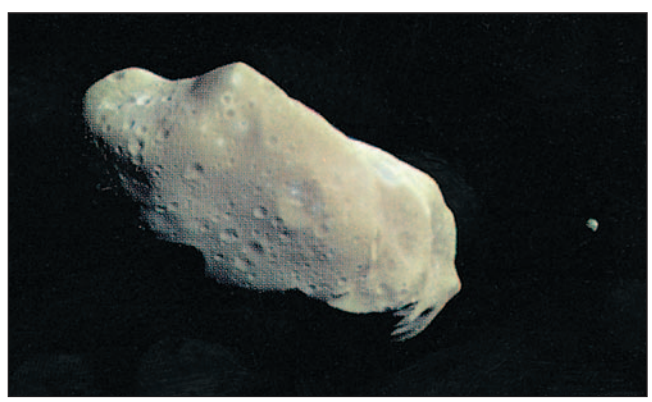
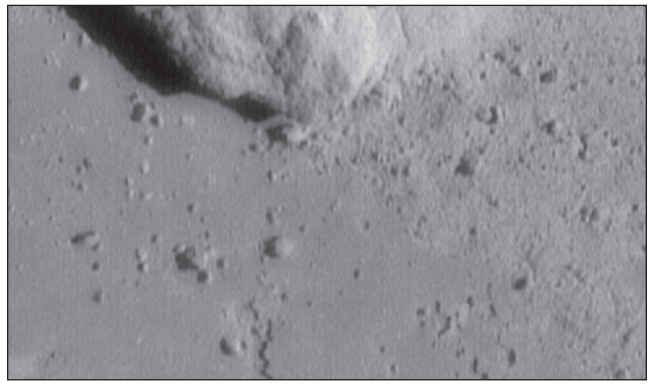


FIGURE 15.14
Asteroid Eros
This image of Eros is the result of many measurements by *NEAR Shoemaker*.

FIGURE 15.15
The Surface of Eros
This view of Eros was taken by *NEAR Shoemaker* from a distance of 50 km and shows the interior of one of Eros's largest craters. The view shows large boulders and numerous small craters. Much of the surface appears to be covered with a layer of brown dust.

FIGURE 15.16
A High-Resolution Image of Eros
This image was taken by *NEAR Shoemaker* from 130 m above the surface. The image shows a region only 6 m across. Details as small as 10 cm can be seen.



Mathilde is porous. It may be a "rubble pile" fragmented by the numerous impacts it has experienced.

The most detailed examination of an asteroid occurred when the *NEAR* (Near Earth Asteroid Rendezvous) *Shoemaker* spacecraft orbited Eros for nearly a year in 2000 and 2001. Figure 15.14 shows a composite image of Eros, which is an irregularly shaped body about 40 km long that orbits between the orbits of Earth and Mars. *NEAR Shoemaker* images showed many fine details, including grooves and ridges that suggest that Eros may be a collision fragment from a larger body. Figure 15.15 shows boulders as large as 40 m across that may be debris from impacts with other asteroids. On February 12, 2001, *NEAR Shoemaker* touched down on Eros. Just before it landed, *NEAR Shoemaker* returned an image shown in Figure 15.16, in which features as small as about 10 cm (4 inches) can be seen. After it landed, *NEAR Shoemaker* used gamma rays to determine the chemical composition of Eros. Eros's composition resembles that of chondrite meteorites, suggesting that, like the chondrites, the surface of Eros may be as old as the solar system.

Another close examination of an asteroid was carried out by the Japanese spacecraft *Hayabusa*, which landed on Itokawa in 2005. *Hayabusa* collected samples of Itokawa's surface materials that will eventually be returned to Earth for analysis.

Most of the known asteroids orbit the Sun in the asteroid belt, which lies between 2.1 and 3.3 AU from the Sun. Even though there are many asteroids, they are widely spread out in this immense region of space. Spacecraft encounters have provided us with our best views of asteroids.

Asteroids at Jupiter's Distance and Beyond In addition to asteroids in the asteroid belt, Figure 15.11 shows two swarms of asteroids that share Jupiter's orbit around the Sun. These are the **Trojan asteroids,** located 60° ahead of or behind Jupiter, where the gravitational attractions of Jupiter and the Sun combine to produce regions where small bodies can have stable orbits. The orbital periods of the Trojan asteroids are the same as Jupiter's, but they have a range of orbital eccentricities and inclinations. This means that they lie 60° from Jupiter, on average, but their individual orbits cause them to wander back and forth around their average positions.

Surveys of the Trojan asteroids are much less complete than surveys of main-belt asteroids. About 2400 Trojan asteroids are known. The largest measures about 150 by 300 km and has been named Hector. Estimates suggest that there may be nearly half as many Trojan asteroids (mostly undiscovered) as asteroids in the main belt. Although the Trojan asteroid swarms are usually portrayed as curiosities of our solar system, it is more appropriate to think of them as a second asteroid belt quite unexplored compared with the main belt.

Another group of asteroids, including Hidalgo and Chiron, have semimajor axes larger than the orbit of Jupiter. Hidalgo has a semimajor axis of 5.8 AU. Chiron, which has a semimajor axis of 13.7 AU, may be as large as 400 km in diameter. Chiron's orbit, strongly affected by Saturn, may be slowly growing smaller so that Chiron will eventually move into the inner part of the solar system. Occasionally, Chiron undergoes large increases in its brightness. These changes, in addition to the discovery that Chiron is surrounded by a large cloud of gas, suggest that Chiron may have much in common with comets.

Many asteroids are not found in the asteroid belt. The Trojan asteroids share Jupiter's orbit, leading or trailing Jupiter by 60°. Some asteroids, including Hidalgo and Chiron, have orbits larger than Jupiter's.

Earth-crossing Asteroids Just as some asteroids travel far beyond the main belt, others penetrate deeply into the inner solar system. The **Amor asteroids,** for example, pass inside Mars's orbit and approach the Earth without ever crossing the Earth's orbit. The **Aten asteroids,** on the other hand, have orbital semimajor axes smaller than 1 AU and cross the Earth's orbital distance when they are near aphelion. All of the **Apollo asteroids** have orbits with aphelia well beyond the Earth's orbit and perihelia inside the Earth's orbit, so they are sometimes referred to as Earth-crossing asteroids (although the Atens are Earth crossing as well).

So far, only about 5000 of these asteroids have been discovered. This is partly because they are so small. The largest known Amor asteroid is only 40 km in diameter, and the largest known Apollo asteroid is 8 km in diameter. Figure 15.17 compares the sizes of some of these asteroids with the altitude at which commercial jets fly.

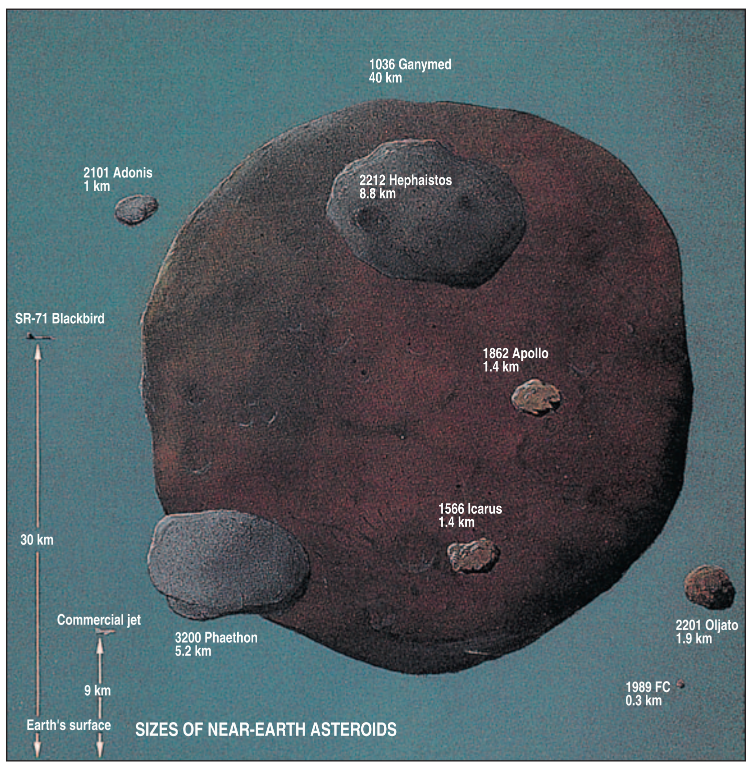


FIGURE 15.17
The Sizes of Near-Earth Asteroids
Although near-Earth asteroids are smaller than many of the asteroids in the asteroid belt, they are big compared with the altitudes at which jet airplanes fly in Earth's atmosphere.

Even though the Earth is a relatively small target, a large fraction of the Apollo asteroids will strike the Earth and be destroyed within the next few tens of millions of years. The consequences of such an encounter are described at the end of this chapter. Near misses occur quite frequently. In 2004, for example, asteroid 2004 FH came within 45,000 km (7 Earth radii) of the Earth. It was discovered only 2 days earlier, so there was essentially no warning.

The solar system has been in existence for much longer than tens of millions of years, so the Apollo asteroids would have all been destroyed long ago unless there was a source to resupply them. This source is the asteroid belt. Asteroids at some orbital distances can be influenced by Jupiter's gravity so that their orbits become more eccentric. Eventually, they pass close enough to Mars to be pulled even deeper into the solar system.

There are thousands of asteroids that have orbits that cross the Earth's orbit. A large fraction of the asteroids in Earth-crossing orbits will strike the Earth within a few tens of millions of years.

Classes of Asteroids

The asteroids have been grouped into different classes based on their **reflectance spectra,** which show how well they reflect light of different wavelengths. When sunlight falls on the surface of an asteroid, some is reflected and some is absorbed. For many minerals, the absorption of sunlight is much stronger at some wavelengths than at others. This makes the asteroid absorb well but reflect poorly at those wavelengths. The presence of an absorption feature of a particular mineral in the spectrum of an asteroid indicates that the surface layers of the asteroid contain that mineral.

About three-fourths of the asteroids are **C-type.** The C-type asteroids are very dark, so their reflectivities are only a few percent. Their spectra show no strong absorption features due to minerals. Most of the remaining asteroids are **S-type,** which show an absorption feature due to the mineral olivine. Many other classes exist, including the **M-type** asteroids, which have reflectance spectra like those of metallic iron and nickel, and the unique **V-type** asteroid Vesta, which shows a strong absorption feature due to pyroxene, a common mineral in basaltic lava flows.

Asteroids and Meteorites

Most of the meteorites that fall to the Earth are derived from main-belt asteroids. In some cases the immediate parent bodies of the meteorites are Earth-crossing asteroids that have been deflected from the asteroid belt. Most of the different classes of meteorites have reflectivity spectra that strongly resemble classes of asteroids. That is, the carbonaceous chondrites (as distinct from the much more common ordinary chondrites) look like smaller versions of the C-type asteroids, whereas the iron meteorites resemble the M-type asteroids.

There is one very important exception to the identification of asteroids as parent bodies of meteorites, however. Asteroids that look like ordinary chondrites, by far the most common kind of meteorite, seem to be rare among the large asteroids for which reflectivity spectra have been measured. Perhaps large asteroids were heated enough that the chondritic material near their surfaces was melted and ceased to be chondritic. If this is true, then only small asteroids, which were never heated very much, could retain their chondritic characteristics. Thus, smaller asteroids, for which reflectivity spectra have not yet been measured, may be the missing source of the ordinary chondrites.

One important thing to keep in mind when comparing asteroids and meteorites is that at any given time, the majority of meteorites may have come from only a few asteroids that happen to be in Earth-crossing orbits. This means that the kinds of meteorites that strike the Earth may change significantly over millions of years as the population of Earth-crossing asteroids changes. This idea is supported by the fact that there are significant differences between the Antarctic meteorites that fell to the Earth a million years ago and the ones that have fallen in the last few centuries. For instance, iron and stony-iron meteorites are approximately four times less common in Antarctic meteorites than in recent falls. This suggests that ordinary chondrite parent bodies may not be very common in the asteroid belt despite the fact that the majority of fragments striking the Earth today are chondrites. In the past and in the future, the most common kinds of meteorites may very well not be ordinary chondrites. Only if we could collect meteorites over many millions of years might we expect the collection to give a good representation of the kinds of objects in the asteroid belt.

The reflectance spectra of asteroids show that many of them resemble larger versions of different classes of meteorites. One problem for the identification of meteorites with asteroids is the absence or rarity of asteroids that resemble the ordinary chondrites, the most common kind of meteorite. It is possible that the kinds of meteorites that have fallen to Earth in the last few centuries reflect only the kinds of Earth-crossing asteroids that exist today and are not characteristic of the kinds of objects in the asteroid belt.

15.4 COMETS

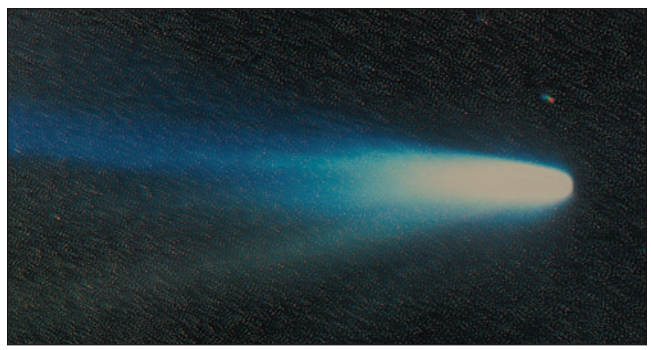
A **comet** is a small icy body in orbit about the Sun. When it passes near the Sun, a comet becomes much brighter and can produce a conspicuous tail. Records of observations of comets date back to the time of the Babylonians. During most of history, however, comets were believed to be phenomena within the Earth's atmosphere rather than celestial objects. At various times, comets were thought to be reflections from high clouds or violent, fiery winds. Aristotle's view—that comets were fiery phenomena in the atmosphere—was extremely influential and generally accepted until the sixteenth century.

Comets were also considered to be omens, sometimes good and sometimes bad. Suetonius, in his biography of Julius Caesar, said that on the first day of the games given in honor of the deification of Caesar, a comet appeared in the evening sky and was visible for a week. The comet was thought to be Caesar's soul, elevated to heaven. When Halley's comet appeared in April of 1066 (Figure 15.18), it was considered an ill omen for King Harold of England. This interpretation of the comet seemed to be confirmed when Harold was killed at the Battle of Hastings and England fell to the Norman invasion. Even in the twentieth century, the appearance of Halley's comet in 1910 was thought by many to be a sign that the world was about to end.

The modern view of comets as celestial bodies began to develop when Tycho Brahe made careful observations of the position and motion of the bright comet of 1577. He showed that the comet had to be at least six times as far away from the Earth as the Moon was. He suggested that comets revolved about the Sun, possibly on elongated orbits. More than a century later, in 1682, another bright comet captured the interest of Edmund Halley. He found that the comet had the same elliptical orbit as other comets seen in 1456, 1531, and 1607. Concluding that these were all appearances of a single comet with an average orbital period of 75 years, he predicted that the comet would be seen again in 1758 or 1759. The prediction came true when the comet, now known as Comet Halley, was seen by an amateur astronomer on Christmas Night in 1758.

FIGURE 15.18
Part of the Bayeux Tapestry
This tapestry was woven in about 1070 to commemorate the Norman conquest of England in 1066. Comet Halley can be seen at the top center of this section of the tapestry.

FIGURE 15.19
Comet Halley in March 1986
This picture, taken by astronomers at the European Southern Observatory in Chile, shows the comet about a month after it had passed perihelion. At that time, Comet Halley was bright and easily seen by viewers in the southern hemisphere but was difficult to observe for those in the northern hemisphere. The picture was taken in the same week that five spacecraft encountered the comet.



Anatomy of a Comet

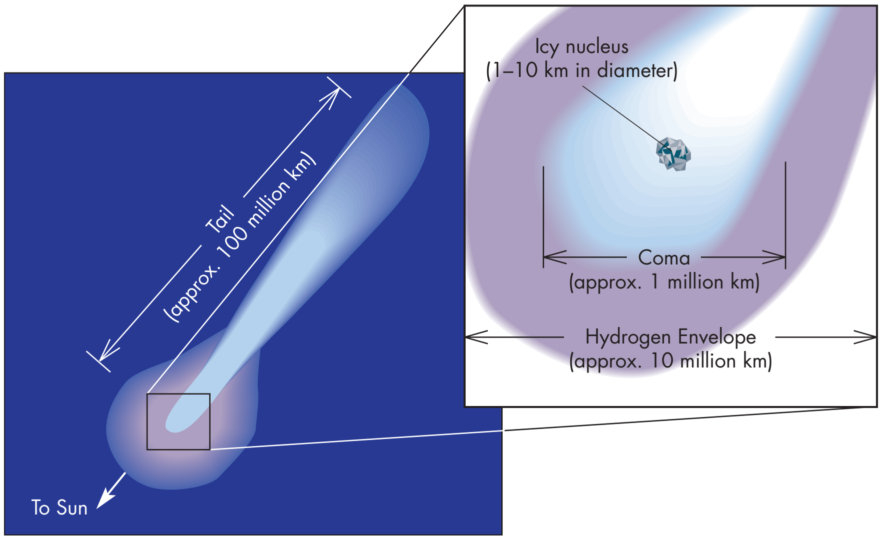
Figure 15.19 shows Comet Halley as most people picture comets. It is a spectacular sight with a bright head and tails stretching across the sky. For the great majority of their lives, however, comets are small, dim lumps of frozen ices.

Nucleus The only part of a comet present at all times is the **nucleus.** The nucleus of a comet is an irregularly shaped, loosely packed lump of dirty ice that measures between a few hundred meters and several kilometers across. Most of the ice is frozen water, but frozen carbon monoxide, carbon dioxide, and formaldehyde are present as well. Microscopic dust particles are also trapped within the mass of ice. In some respects, the nucleus of a comet resembles a larger version of the mounds of snow and dirt plowed into piles in shopping center parking lots. When the snow evaporates or melts, most of the dirt is left behind, forming a dirty crust that makes the pile very dark.

Like the shopping center snowpile, a comet nucleus begins to evaporate when solar energy warms it. Within about 3 AU of the Sun, water and other molecules within the comet nucleus evaporate and flow outward, carrying with them some of the dust mixed with the ice. Much of the escape of gas and dust seems to occur in spots where subsurface material can break through the crust of the nucleus to produce jets that stream outward. The gas and dust that escape from the nucleus form the coma and tails shown in Figure 15.20. Thus, the coma and tails exist only when the comet is near the Sun.

The nuclei of comets are far too small to be resolved by even the largest telescopes on Earth. They appear only as

FIGURE 15.20
The Parts of a Comet
The nucleus is so small that it appears pointlike from the Earth. Surrounding the nucleus is the coma, a spherical cloud of gas and dust that extends as far as a million kilometers from the nucleus. Around the coma is an invisible cloud of hydrogen that can be several million kilometers across. The tail or tails of the comet point away from the Sun and extend as much as 100 million km (nearly 1 AU) outward into the solar system.



points of light. To learn more about comets, space probes have been sent to encounter four comets as they passed through the inner solar system. The *Giotto* spacecraft obtained images of Comet Halley in 1986 and *Deep Space 1* imaged Comet Borelly in 2001. In 2004 the *Stardust* spacecraft imaged Comet Wild 2 as it flew within 250 km of the nucleus. *Stardust* collected dust samples from the coma of Wild 2 and returned them to Earth in 2006. The most detailed examination of a comet nucleus was accomplished by the *Deep Impact* spacecraft. In July 2005, *Deep Impact* released a 372-kg copper projectile, which impacted the surface of Comet Tempel 1 at a speed of 10 km/s. The projectile produced a crater about 100 m across and ejected 10 million kg of material into space. Light emitted by the ejected material was analyzed by *Deep Impact.* In addition to ice and silicate rock, the ejected material was found to have a substantial amount of organic molecules. This suggests that comets impacting the Earth early in its history may have brought organic compounds to Earth and may have played a role in the origin of life. Observations of the motion of the plume of material ejected by the impact yielded the gravity of the nucleus and showed that Tempel 1 has a density only 60% that of water ice and, thus, must be very porous. As it approached the nucleus, the projectile obtained a series of high-resolution images. A composite of the images is shown in Figure 15.21. The nuclei of Comets Halley, Borelly, Wild 2, and Tempel 1 are generally quite similar. Their surfaces are very irregular, with craters, mountains, and rolling terrain. The nucleus of Tempel 1 differs from those of Halley, Borelly, and Wild 2 in that it shows what appear to be impact craters. The image returned by *Giotto, Deep Space 1, Stardust,* and *Deep Impact* generally confirmed the ideas astronomers had developed about the nuclei of comets.

FIGURE 15.21
The Nucleus of Comet Tempel 1
This picture is a composite of high-resolution images. The images were obtained by a projectile released by the *Deep Impact* spacecraft just before the projectile struck the nucleus. The impact occurred between the two impact craters at the bottom of the image. The nucleus of Tempel 1 is 7.6 km long and 4.9 km wide. Unlike other comet nuclei for which images have been obtained, Tempel 1 shows a number of impact craters.

Coma The **coma** of a comet is a ball of outflowing gas and dust that surrounds the nucleus. A coma, which can be a million kilometers in diameter, is much bigger than the nucleus that produces it. Although there are probably only a few kinds of molecules released from the nucleus, these molecules are broken apart and ionized by solar radiation to produce a large variety of atoms, ions, and molecules within the coma. The coma appears bright because of a

FIGURE 15.22

The Dust and Plasma Tails of Comet West (1975)

The dust tail, on the left, is yellow and broader than the plasma tail. Plasma tails are blue and often much longer than dust tails. Plasma tails are very straight, whereas dust tails often appear as curving arcs.

combination of emission from the gas and sunlight reflected by the dust. The coma looks quite substantial, but this is very deceptive. All of the gas and dust in the coma comes from a thin outer layer of the nucleus. This small amount of material spreads out over an enormous volume of space to form the coma. The coma actually is a much better vacuum than we can make in laboratories on the Earth.

Tails Many comets show two tails. Figure 15.22 shows that one of these tails is blue, whereas the other appears white or yellow. The white or yellow tail is made of dust swept from the nucleus, so it is called the **dust tail.** A common misconception about comets is that their tails trail behind their nuclei like hair streaming behind a person who is running. Figure 15.23 shows that their tails actually point away from the Sun. The reason the dust tail points away from the Sun is that the force of sunlight pushes the dust particles outward.

The blue tail in Figure 15.22 is called the **plasma tail,** because it is made of ions and electrons. The color of the plasma tail is produced by ionized carbon monoxide, which emits strongly in the blue part of the spectrum. The plasma tails of comets interact strongly with the ionized gases in the solar wind. The interaction is so strong, in fact, that the solar wind can sweep the plasma tail outward to more than 1 AU in length.

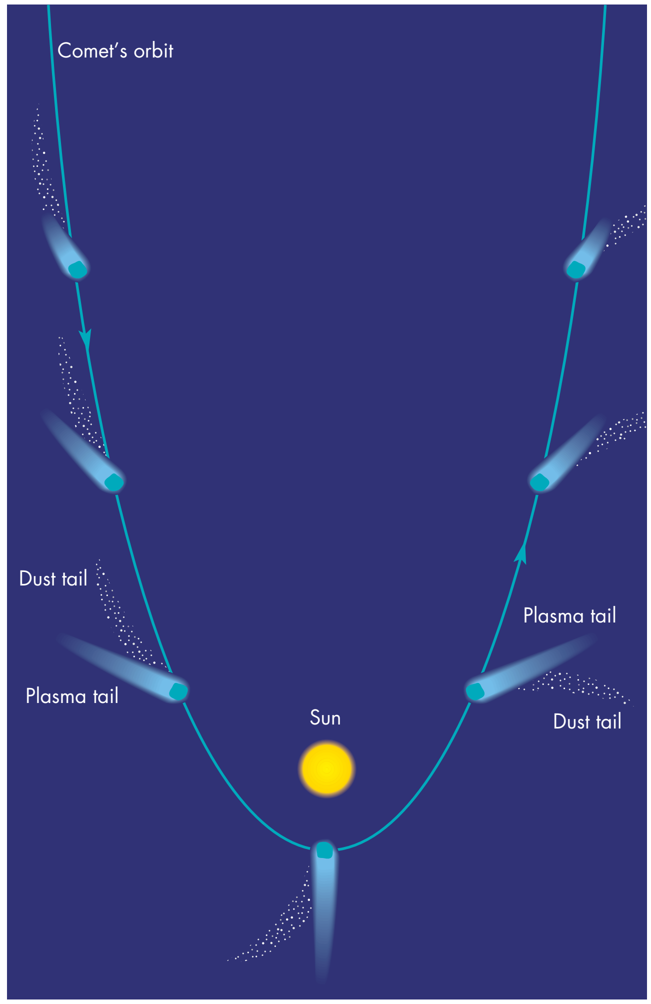
Solar warming diminishes as a comet recedes from the Sun, so the rate at which new gas and dust are supplied to the coma and tail diminishes as well. The coma and tail shrink and fade. By the time the comet reaches a distance

FIGURE 15.23

The Orientation of Comet Tails

Both the dust tail and the plasma tail of a comet point away from the Sun. This means that the tails sometimes follow the nucleus and coma and sometimes precede the nucleus and coma as the comet orbits the Sun.

ANIMATION *Orientation of comet tails*



of 3 AU on its way outward, it looks like a snowball again. It is somewhat smaller and dirtier than it was before approaching the Sun, but otherwise it is not seriously altered.

Far from the Sun, a comet consists only of a nucleus, a loosely packed chunk of water ice, other ices, and dust. The warmth of sunlight, however, drives gas and dust from the nucleus. These form the coma, the dust tail, and the plasma tail of the comet.

FIGURE 15.24
Comet Hale-Bopp
Comet Hale-Bopp was a spectacular sight during spring 1997, yet didn't pass very close to either the Earth or the Sun. If Hale-Bopp had passed through the inner solar system 4 months earlier it would have passed within 0.1 AU of Earth and would have been one of the brightest comets in history.
(© Wally Pacholka/AstroPics.com)

Comet Orbits

Since the Babylonians began keeping astronomical records, more than a thousand different comets have been observed. Only about 500 of these, however, have been observed well enough and often enough to determine their orbits with any accuracy. Astronomers use orbital information to divide comets into two groups, long-period and short-period. The **long-period comets** have orbital periods longer than 200 years, and the **short-period comets** have orbital periods shorter than 200 years. This is an arbitrary, but convenient, dividing point. Most short-period comets have periods much shorter than 200 years (in fact, half of them orbit the Sun in less than 6.5 years), and most long-period comets have periods much longer than 200 years. Comet Halley, with a period of 76 years, is a short-period comet, whereas Comet Hale-Bopp (shown in Figure 15.24), which passed through the inner solar system in 1997, is a long-period comet with a period of about 2400 years.

> Comets are divided into two groups, the long-period and short-period comets, based on the lengths of their orbital periods. The long-period comets have orbital periods longer than 200 years, whereas the short-period comets have orbital periods shorter than 200 years.

Long-period Comets and the Oort Cloud As a long-period comet enters the planetary system, its orbit is influenced by the gravitational pulls of the planets. Therefore, to find out where the comet came from, it is important to determine the orbit it was following before it entered the planetary system. For those comets for which this has been done, the orbits are extremely large. Almost half of them, in fact, have aphelia more than 10,000 AU from the Sun (about 250 times the orbital distance of Pluto). Some have aphelia as great as 100,000 AU from the Sun. At such a distance, a comet is more than one-third of the way to the nearest stars. Orbital periods for such large orbits are tens of millions of years.

Many of the long-period comets that we see are entering the inner solar system for the first time, so they are called **new comets.** Even though astronomers observe only a few new comets each year, it is thought that there is an enormous number of comets orbiting the Sun on large, elliptical orbits. For one thing, the long orbital periods of the new comets mean that each one is visible for only a small fraction of its orbital period (about 1 year out of perhaps 10 million). Thus, for every new comet that we see each year, there are millions moving on orbits that will eventually bring them near enough to the Sun to become visible from Earth. Also, only those comets that have perihelion distances within about 3 AU are likely to be detected. There must be many more that have perihelia at 10 or 100 or 10,000 AU and never develop highly visible comas and tails. As a result of these factors, the total number of long-period comets has been estimated to be at least a trillion. The total mass of the long-period comets is thought to be between 10 and 100 times the mass of the Earth. The swarm of comets shown orbiting the Sun on long-period orbits in Figure 15.25 is called the **Oort cloud** after Jan Oort, who first realized the significance

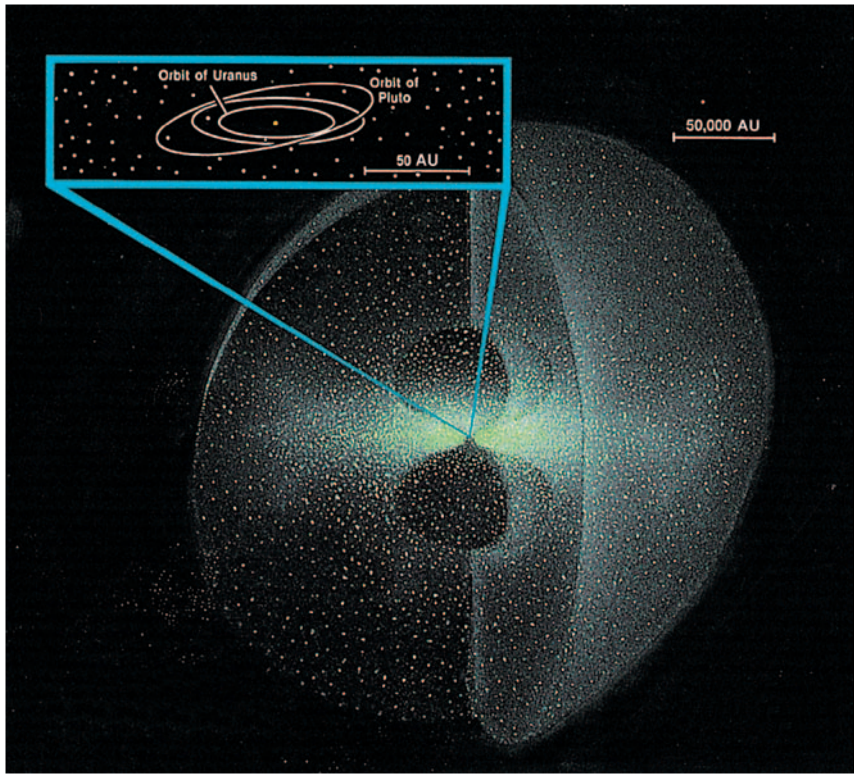


FIGURE 15.25
The Oort Cloud
The cloud of comets around the Sun extends about one-third of the way to the nearest stars. Although there may be as many as 1 trillion comets in the Oort cloud, the volume of space that the Oort cloud occupies is so immense that the comets are separated from one another by distances that are typically about 10 AU.

ANIMATION *Oort cloud and Kuiper belt*

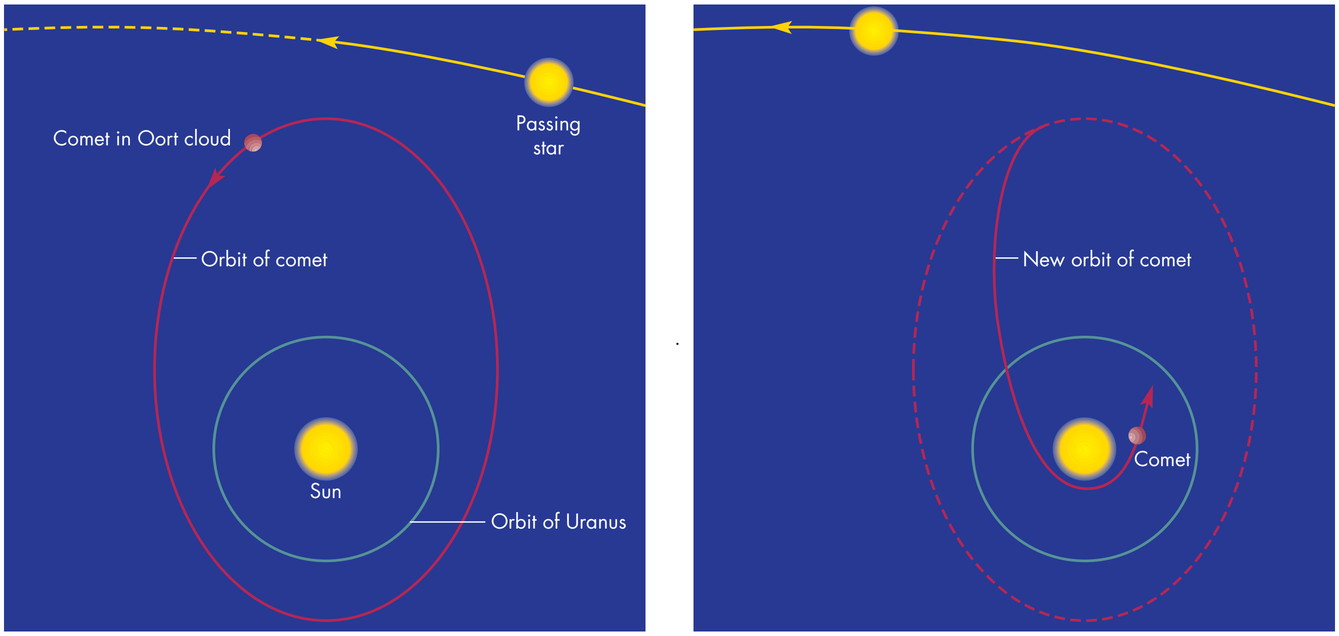
of the large aphelion distances of the new comets and deduced that the comet swarm exists. In 2004, astronomers discovered Sedna, a body about half the size of the Moon and 90 AU from the Sun. Sedna's elliptical orbit carries it as far as 900 AU from the Sun. Sedna is the most distant known solar system body and may be an inner Oort cloud comet.

Gravitational forces caused by the planets have a strong effect on the orbits of new comets. About half are accelerated to higher speeds and are ejected from the solar system on hyperbolic orbits. The other half lose speed and assume less eccentric orbits. These remain long-period comets, but with periods of thousands or tens of thousands of years rather than millions of years. In effect, all of the Oort cloud comets whose orbits carry them into the inner solar system are lost to the Oort cloud. The comets on such orbits when the solar system formed disappeared billions of years ago. So why do we continue to see new comets? The answer to this question depends on other stars and on the Milky Way galaxy.

As described in Chapter 16, the stars are in motion with respect to each other. Every million years or so, a few of them pass close enough to the Sun to penetrate or graze the Oort cloud. When this happens, the star's gravity alters the motions of the comets that it passes near. Some are speeded up and escape from the solar system. Others lose a little speed and, on their next orbit, pass closer to the Sun than they ever have before, as shown in Figure 15.26. These are the new comets, which are influenced by the planets and are either ejected from the solar system or have their orbital periods shortened to thousands of years. The theory of stellar encounters is difficult to check directly, because the stars that produced the new comets we see today passed near the solar system millions of years ago. Moving on their individual paths through space, they are no longer among the near or bright stars. The comets that are propelled toward the inner solar system by the stars near us now won't arrive for millions of years. Another force disturbing the Oort cloud is the tidal force due to the Milky Way galaxy. The galactic tide is always present and supplies new comets at a more or less steady rate.

The Origin of the Short-period Comets The short-period comets don't originate in the Oort cloud but rather in a flattened disk of comets called the **Kuiper belt,** named for Gerard Kuiper, who proposed the existence of the belt in 1951. The reason that the Kuiper belt is thought to be a flattened disk is that the short-period comets have orbits that lie much closer to the ecliptic plane than do the orbits of the long-period comets. The Kuiper belt begins at the orbit of Neptune and extends outward to about 50 AU. The reason the Kuiper belt ends at 50 AU isn't known. One possibility is that there are one or more additional planets remaining to be discovered beyond 50 AU. The Kuiper belt probably contains about 10 billion comets larger than 1 km in size. Although most of the comets in the Kuiper belt are probably small, some are quite large. Since 1990, astronomers have discovered over 1200 bodies with orbital distances beyond 30 AU and

FIGURE 15.26
Stellar Perturbations
A, The gravitational attraction of passing stars slows down some of the comets in the Oort cloud so that, **B,** their orbits carry them into the inner solar system for the first time. The orbits of Oort cloud comets are actually much larger and more elongated than shown here.



A Orbit of comet before it is slowed by passing star

B Comet enters inner solar system after being slowed by passing star

with diameters larger than about 50 km. The largest discovered so far, the dwarf planet Eris, is about 2400 km across. This makes it the largest known dwarf planet. It is about 5% larger than Pluto and 100 times the size of the nucleus of Comet Halley. Some important properties of Eris are given in Table 15.3. There are probably about 100,000 Kuiper-belt objects larger than 100 km. The Kuiper-belt objects experience gravitational perturbations due to the giant planets, and their orbits are sometimes altered enough to bring them close enough to the Sun to be seen as short-period comets.

Table 15.3
Dwarf Planet Data

Eris

Orbital distance	37.8 AU to 97.6 AU
Orbital period	560 years
Mass	0.00025 M_{Earth} = 1.5 × 10^{22} kg (estimated)
Diameter	0.19 D_{Earth} = 2400 km
Density (relative to water)	2 (estimated)
Escape velocity	1.3 km/s (estimated)
Surface gravity	0.06 g (estimated)
Global temperature	30 K
Main atmospheric gases	None
Rotation period	Unknown
Axial tilt	Unknown
Known satellites	1
Distinguishing features	Largest known body in Kuiper belt

The long-period comets have extremely elongated orbits that carry them as far as 100,000 AU from the Sun. It is estimated that 10 billion comets orbit the Sun on such orbits. This swarm of comets is called the Oort cloud. Passing stars disturb the orbits of some of the comets from the Oort cloud. These comets enter the planetary system for the first time and become visible as new comets. Short-period comets are thought to originate in the Kuiper belt, a flattened disk of comets lying outside the orbit of Neptune.

What Happens to Comets?

We have seen how the orbits of comets in the Oort cloud and Kuiper belt are modified so that they carry the comets into the inner planetary system. There must be processes that eliminate comets from the inner planetary system as

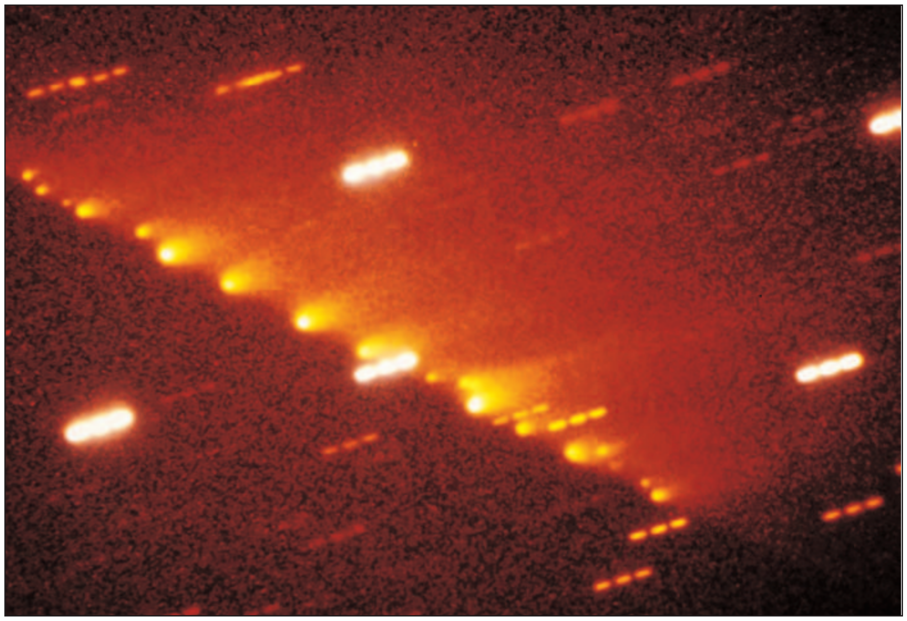


FIGURE 15.27
Fragments of a Comet
The glowing bodies aligned from lower right to upper left are the fragments of Comet Shoemaker-Levy 9, which was disrupted by Jupiter's gravity when it passed near that planet in 1992. The fragments struck Jupiter in July 1994.

well. Otherwise, the inner solar system would be clogged with them by now. In fact, at least three mechanisms exist that destroy comets. The first is a collision with one of the planets or the Sun. The second, erosion, is much more probable than a collision. On each passage near the Sun, a comet loses an outer layer of ice and dust. Therefore its size and perihelion distance determine how many orbits it will make before all of its icy material is gone. Comet Halley, for example, has been observed on each of the 30 times it has approached the Sun since 240 B.C., and there is reason to think that it made many more appearances before that. Although Comet Halley grows smaller on each trip near the Sun, it is large enough to survive many more orbits. The third way that a comet can be destroyed is by being broken into several pieces when it passes too near to the Sun or one of the planets. After a comet is broken into smaller pieces, erosion continues to wear away each piece until it is gone or until it strikes a planet or satellite.

Figure 15.27 shows a trail of at least 18 glowing objects—pieces of Comet Shoemaker-Levy 9, which was disrupted when it passed too close to Jupiter in 1992. The fragments of Comet Shoemaker-Levy 9 struck Jupiter and were destroyed in July 1994. The disruption of Comet Shoemaker-Levy 9 has led some astronomers to propose that the nucleus of a typical comet consists of a collection of smaller balls of ice held together by their mutual gravitational attraction. Near a planet, tidal forces pull the balls apart, forming a line of fragments. When the fragments strike a solid body, they may produce a chain of craters like the ones shown in Figure 15.28. Many crater chains have been found on the Moon, Ganymede, and Callisto.

The impacts of the fragments of Comet Shoemaker-Levy 9 on Jupiter's southern hemisphere gave astronomers their first direct glimpses of the violent collisions between planets and smaller bodies. Actually, the impacts took place just around the limb of Jupiter on the far side and were hidden from Earth. The impact sites could be seen by the *Galileo* spacecraft, which was approaching Jupiter.

FIGURE 15.28
A Crater Chain on Ganymede
This chain of craters stretches 150 km across the surface of Ganymede. The chain may have been formed when a line of comet fragments struck Ganymede. Similar crater chains are seen on the Moon and Callisto.

FIGURE 15.29

An Infrared Image of an Impact Fireball

At infrared wavelengths, the fireballs produced by some impacts of comet fragments were momentarily brighter than the disk of Jupiter. The glow of warm regions produced by earlier impacts can be seen to the right and above the fireball.

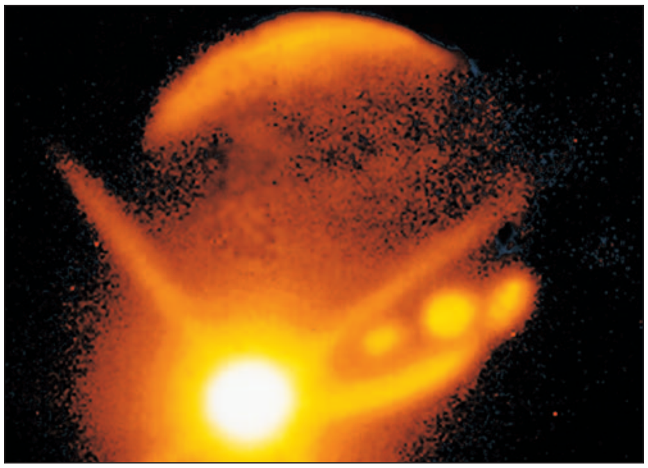


FIGURE 15.30

An Atmospheric Feature Produced by the Impact of a Comet Fragment on Jupiter

Debris from the impact of a fragment of Comet Shoemaker-Levy 9 formed a dark, multiringed feature high in the atmosphere of Jupiter. The feature was about twice as large as the Earth.

The first sign of an impact was the flash of a meteor as a fragment of the comet entered Jupiter's atmosphere. Within seconds the fragment exploded, producing a fireball hotter than the surface of the Sun as shown in Figure 15.29. Each time Jupiter's rotation brought a fresh impact site into view, astronomers saw a new multiringed cloud feature that, for some fragments, was as much as 25,000 km in diameter (twice the size of the Earth). One of the new cloud features is shown in Figure 15.30. Although Jupiter's winds quickly began to pull the new cloud features apart, they could be seen for more than a year after the impacts. The energy released by each fragment's impact was up to hundreds of times greater than the total energy of all of the Earth's nuclear bombs. If they had hit the Earth, the fragments would have left craters many tens of kilometers in diameter.

Meteoroid Swarms Once the icy material in the nucleus of a comet is used up, the nucleus can never produce a coma or a plasma tail again. However, even when the ice is gone, dust is left behind. The dust particles ejected from the nucleus of a comet (that form its dust tail) continue to follow the orbit of the comet for many years. If the orbit of the comet nearly crosses the orbit of the Earth, then the Earth can pass through the swarm of dust particles, or meteoroids, every year where the two orbits nearly intersect (see Figure 15.4). When this happens, a meteor shower occurs.

If the nucleus of the comet is also near the place where the two orbits cross, the meteor shower can be very intense. For example, the Draconid meteor shower occurs each October when the Earth passes close to the orbit of Comet Giacobini-Zinner. However, the Draconid shower varies greatly in intensity from year to year, depending on where the comet is situated in its 6.5-year orbit about the Sun. In 1946, for instance, the Earth crossed the orbit of Comet Giacobini-Zinner only 15 days after the comet had passed. The result was a spectacular meteor shower, in which 5000 meteors per hour were seen. In other years, when Comet Giacobini-Zinner was far away from the crossing point, only a few Draconid meteors per hour were seen.

Most meteor showers, however, aren't associated with any known comet. In those cases, it is thought that the meteoroid swarm was produced by a comet, but that the comet has used up all its ice and become invisible. It may be that all that is left is the swarm of dust particles. This may have happened in the case of Comet Biela, which was seen at several perihelion passages between 1826 and 1852. It was never seen again, but when the Earth crossed its orbit four times between 1872 and 1899, spectacular meteor showers (with rates as high as 50,000 per hour) were seen.

Only a small fraction of the dust particles produced by comet nuclei are destroyed by hitting the Earth or another planet. The rest eventually spread out from the comet orbit

FIGURE 15.31
The Zodiacal Light
Sunlight reflected from dust particles orbiting near the ecliptic can be seen on dark nights after sunset or before sunrise. The glow is usually very faint.

into the region near the ecliptic. Figure 15.31 shows that sunlight reflected from these dust particles produces a glow, called the **zodiacal light,** which can be seen above the horizon when the sky is dark after sunset or before sunrise.

Asteroids from Comets? It's possible that something in addition to dust particles is left behind when a comet uses up all of its ice. Some comets may have solid cores of rocky material that become asteroids when the comet's icy material is gone. The asteroids Chiron and Hidalgo, for example, have cometlike orbits. Chiron, which sometimes develops a gaseous coma, may be an extinct comet nucleus. On the other hand, Chiron is so far from the Sun (13.7 AU) that the evaporation of its ices is negligible. Therefore, Chiron may be mostly ice, so it might be better to think of Chiron as an inactive comet rather than an extinct comet nucleus. Three bodies in the asteroid belt have been found to have dust tails and may be comets rather than asteroids.

Repeated passages near the Sun eventually erode all of the icy material in the nucleus of a comet. When the ice is gone, a swarm of dust particles is left behind. These form the meteoroid swarms responsible for meteor showers. It is possible that some comet nuclei have rocky cores that become asteroids when all the ice is gone.

15.5 WHERE DID COMETS FORM?

Could the comets have originated beyond the solar system, elsewhere in the galaxy? This possibility can be ruled out by the orbits of the new comets. If comets came from interstellar space they would move on hyperbolic orbits and have speeds in excess of escape velocity. In fact, no comet has ever been found to have a hyperbolic orbit when it entered the planetary system. Thus, the comets formed within the solar system, probably at the same time that the Sun and the planets formed. The question, then, is where within the solar system did they form?

It is unlikely that comets formed in the Oort cloud itself. At such enormous distances from the Sun, the density of matter has probably never been high enough for bodies 1 km in diameter or larger to have accumulated. At the present time, it seems most likely that the comets formed near the orbit of Neptune. This hypothesis is supported by the similarity in composition between the comets and the icy satellites of the outer planets. Two different things could happen to comets orbiting near Neptune. Interactions with Neptune could reduce the size of the comet's orbit, bringing it into the inner solar system as a short-period comet. Alternatively, repeated interactions with Neptune and then Uranus could increase the speed of the comet, ejecting it from the solar system or sending it to the Oort cloud. Thus, icy bodies in the Kuiper belt near the edge of the planetary system could both resupply the Oort cloud and provide some of the short-period comets.

Wherever they formed, comets should have a distribution of sizes. Most of the comet nuclei should be only a few kilometers in diameter, but there should also be some comets much larger than that. The recently discovered objects beyond Neptune's orbit are some of the largest comets in the Kuiper belt. Chiron, also, may be a large comet nucleus. Perhaps even Pluto is a giant comet nucleus.

The comets probably formed at the outer edge of the planetary system, near Neptune. Many of them may still exist there as the Kuiper belt. There may be some very large comet nuclei, of which Chiron and Pluto may be examples.

15.6 COLLISIONS WITH EARTH

Given the presence of Earth-crossing asteroids and comet nuclei that cross the orbit of the Earth, it is certain that from time to time the Earth is struck by bodies several kilometers or more in diameter and moving at speeds as great as 70 km/s.

How Often Do Collisions Occur?

As a rule of thumb, a large meteoroid that strikes the Earth produces a crater with a diameter about 10 to 20 times larger than the meteoroid. With this information and our estimates of the numbers of Earth-crossing asteroids and comets of different sizes, we can estimate how often craters of different sizes should be formed on the Earth. The result is that a crater with a 10 km diameter should be produced, on average, about once every 100,000 years. A crater 50 km in diameter should be formed once every 5 million years and a crater 100 km in diameter once every 50 million years.

Record of Impacts

The Moon, Mars, Mercury, and other bodies preserve their impact scars for very long periods of time. On Earth, impact craters are destroyed or eroded relatively quickly. About two-thirds of all impact craters are formed on the ocean bottoms. Over the course of 100 million years, the ocean floor on which a crater lies is carried to a subduction zone by plate tectonics and disappears into the interior of the Earth. On the continents, erosion, the deposition of sediments, and glaciation smooth crater rims and fill in the crater itself.

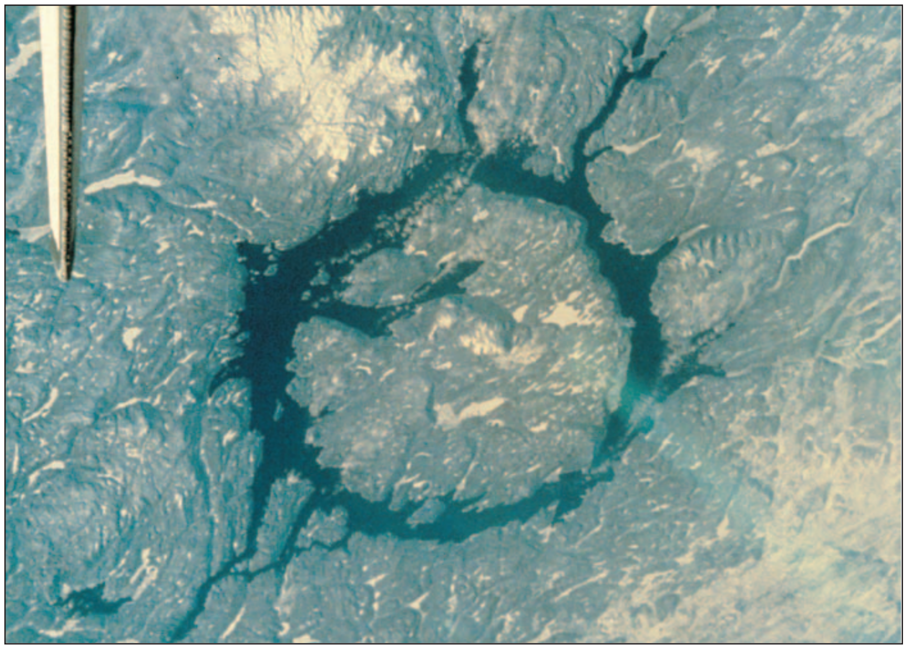
Only very young craters such as 50,000-year-old Meteor Crater in Arizona (Figure 15.32) are easy to recognize. Much older impact craters, such as 200 million-year-old Manicouagan in Canada (Figure 15.33), can sometimes be identified in photographs from aircraft or from space. Still other ancient craters are completely undetectable at the surface. They can only be discovered by studying the shattered, disturbed rock beneath the surface.

FIGURE 15.32
Meteor Crater
This impact crater in central Arizona was formed about 50,000 years ago. It is about 1 km in diameter and 200 m deep.

Consequences of an Impact

On the morning of June 30, 1908, a meteoroid about 50 m across exploded in Earth's atmosphere about 6 km above the ground near the Tunguska River in Siberia. The energy of the explosion has been estimated to be about the same as a very large hydrogen bomb. Because the event occurred in a remote area, it appears that only one person

FIGURE 15.33
The Manicouagan Impact Structure in Quebec
The structure is 70 km in diameter and formed about 200 million years ago. The circular lake lies just within the original walls of the crater, which eroded away long ago. The pencil-shaped object in the upper left is the tail of the space shuttle *Columbia,* from which this picture was taken in 1983.



was killed by the blast. However, perhaps 60 million trees were leveled over an area of about 2000 square km (a larger area than Washington, D.C.). At 60 km from the blast, people were knocked to the ground and windows were broken. People 500 km away heard loud explosions and saw a fiery cloud.

A meteoroid as large or larger than the one that caused the Tunguska event strikes the Earth every few centuries, most of the time over the oceans. A Tunguska-like impact near a population center would cause severe damage and loss of life. Yet we have reason to believe that the Earth is occasionally struck by far larger meteoroids that cause explosions of such power that the entire Earth is affectd.

The impact of an asteroid or comet 1 km in diameter or larger would have extremely serious local and global consequences. The impact would vaporize both the impacting body and a large volume of terrestrial rock. These hot gases would expand upward and outward, somewhat like a nuclear fireball, but rising as high as tens of kilometers into the atmosphere. Somewhat deeper rock would be melted rather than vaporized. The melted rock would be splashed outward on trajectories that would carry molten droplets as far as several thousand kilometers from the impact site. Still deeper rock would be smashed and thrown outward as a blanket of ejecta. If the impact took place on the ocean floor, enormous waves would sweep across the oceans.

The flash of light and heat accompanying the fireball would ignite vegetation near the impact, perhaps triggering vast forest fires. The shock wave from the impact would be capable of killing anyone within perhaps a thousand kilometers of the impact site and injuring those considerably farther away. The ejected molten and solid material, of course, would obliterate everything close to the impact.

The relative importance of several possible global consequences is still uncertain. After the hot gas from the vaporized material reached the upper atmosphere, it would cool to form dust particles that would remain suspended in the atmosphere for months or years. The dust would obscure sunlight, plunging the Earth into a period of darkness and cold. Just how much dust would be formed, how long it would last, and how serious the consequences for the climate would be are uncertain. Thick clouds of smoke from forest fires could also contribute to the darkening.

Another serious consequence would be that large quantities of atmospheric nitrogen would burn within the fireball, yielding the same kinds of nitrogen oxides that are partly responsible for acid rain. Following an impact, however, the amount of nitrogen oxides produced would far exceed those formed by industrial pollution. A possible result would be global rain with the acidity of strong laboratory acids. Such rain would have devastating consequences for life on land, in lakes, and in shallow ocean waters. Still another possibility is that ejected material, blasted to heights above the atmosphere, would heat the atmosphere upon reentry, producing a thermal pulse a few hours or days in duration that would roast any unsheltered plants and animals.

The impact of a large meteoroid on the Earth would have many severe consequences, both local and global. Some of the possible global consequences include prolonged darkness, very acidic rain, and temporary heating of the atmosphere. Molten and solid material ejected from the impact site would be propelled to great distances.

Has This Ever Happened?

We have ample evidence that large objects have struck the Earth. Is there any reason to think that such impacts have produced global disasters? In the last 30 years, evidence has accumulated that answers this question with a reasonably definite yes. The evidence shows that meteoroid (or comet) impacts are sometimes associated with dramatic changes in the nature of plant and animal life on Earth.

The first indication that impacts play a role in the evolution of life on the Earth came when Luis and Walter Alvarez examined a thin layer of clay, shown in Figure 15.34, that lies at the Cretaceous-Tertiary boundary. Cretaceous and Tertiary rocks, like other rocks, are identified by the life forms that existed during the time when the rocks were deposited. The Cretaceous period ended 65 million years ago and was followed by the Tertiary period, in which the life forms were distinctly different. Boundaries between geological periods are, almost by definition, times of wholesale extinction of species. At the end of the Cretaceous period, about 60% of all species of plants and animals became extinct. The end of the Cretaceous period brought the extinction of the dinosaurs and all species of land animals larger than goats. About half of all species of floating marine vegetation also died.

The Alvarezes and their colleagues discovered that the layer of clay at the Cretaceous-Tertiary boundary is about 30 times richer in the element iridium than in typical terrestrial rocks. This is significant because iridium is much more common in meteorites than it is in the Earth's crustal rocks. The Earth's supply of iridium is believed to have accompanied iron and other metals when they sank to form the Earth's core. The Alvarezes proposed that the iridium came from the vaporized material in a large meteoroid that struck the Earth. On impact, the iridium, the rest of the meteoroid, and some terrestrial rock were vaporized. They rose to the upper atmosphere, solidified to form dust, slowly settled, were washed from the atmosphere by rain,

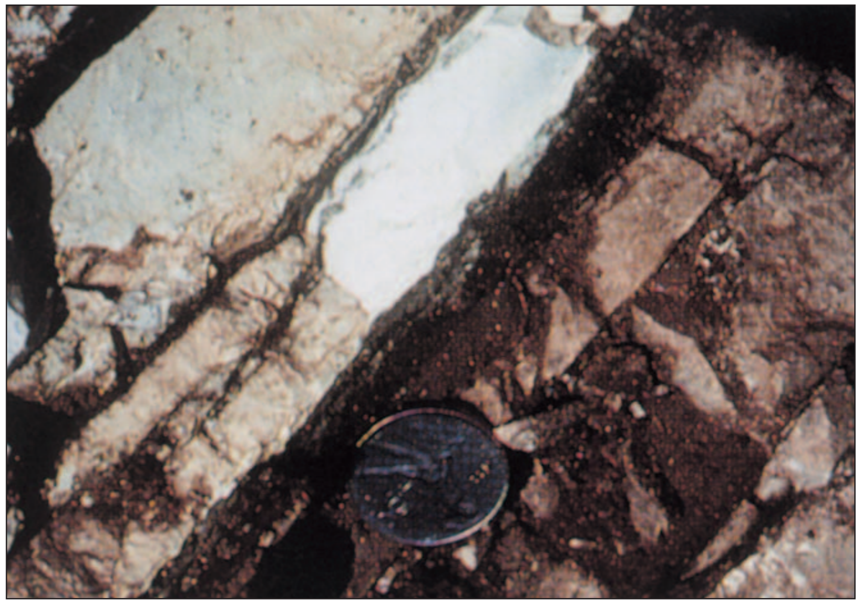


FIGURE 15.34
The Layer of Dark, Iridium-Rich Clay at the Cretaceous-Tertiary Boundary
The iridium in the clay may have resulted from the impact of an iridium-rich asteroid or comet with the Earth. Widespread extinction of life on Earth took place at the time that the layer was produced. The circle shown in the picture is a coin about as large as a quarter. The upper-left edge of the coin is touching the iridium-rich layer.

and were carried with the rainwater to form the sediments of the Cretaceous-Tertiary boundary. Shattered mineral grains and rock fragments in the boundary clay seem to be solid debris from the impact.

The Impact Site? Geologists have eagerly sought the site of the Cretaceous-Tertiary impact. One clue to its whereabouts is that although the shattered mineral grains are found around the world, they are most numerous in North America, suggesting that the impact may have occurred there. Currently, the best candidate is a crater centered near Chicxulub in northern Yucatán, Mexico. The location of the Chicxulub crater is shown in Figure 15.35. The Chicxulub crater has a diameter of 180 km, making it one of the largest craters on Earth, but it is buried beneath a kilometer of sedimentary rocks. The crater was formed 65 million years ago. Geological evidence from the region surrounding Chicxulub supports the idea that a violent impact occurred there. At the time of the impact, Yucatán lay beneath about 100 m of water in the Gulf of Mexico. It appears that the impact produced enormous waves. The waves swept over the coasts of the Gulf of Mexico, dragging rocks and vegetation back into the sea. This material settled to the bottom to form an unusual layer of sedimentary rock that has been found in several sites around the Gulf of Mexico. The disturbed sedimentary layers also include tiny spheres of glassy rock melted by the impact and hurled thousands of kilometers from the impact site. These glassy spheres are found as far away as Haiti.

Impacts and Extinctions We probably need to be cautious in concluding that large impacts lead to extinctions or that extinctions are caused by impacts. For one thing, the extinctions that took place at the end of the Cretaceous period were fairly gradual. The dinosaurs had been on the way out for millions of years. Perhaps the

FIGURE 15.35
The Chicxulub Impact Structure
The impact at Chicxulub took place 65 million years ago and produced a crater 180 km in diameter. The crater has been buried under a kilometer of sedimentary rock so that no trace of it can be seen at the surface. The impact at Chicxulub may have been responsible for the mass extinction that took place at the end of the Cretaceous period.

impact only accelerated the extinction of species that were doomed anyway. Also, although there is evidence that impacts may have triggered relatively minor extinctions several times in the past 100 million years, there have been other extinction events, some much more severe than the Cretaceous-Tertiary event, for which there isn't yet any compelling evidence of an impact.

Although the relationship between impacts and the extinction of species has not yet been completely worked out, it is becoming clear that the course of life on the Earth might have been quite different had it not been for the impacts of solar system debris.

The discovery that rocks formed at the end of the Cretaceous era (a time of mass extinction) were enriched in the element iridium suggests that the Earth was struck by an asteroid at that time. Although the impact may have played a role in the Cretaceous extinctions, the nature of that role and whether extinctions and impacts are generally related is not yet clear.

Chapter Summary

- A meteor occurs when a meteoroid enters the Earth's atmosphere and vaporizes, heating itself and atmospheric gases so that they glow. Most meteoroids are no more than 1 cm in diameter. (Section 15.1)
- High meteor rates occur during meteor showers, when the Earth runs into a swarm of meteoroids. Showers take place on or close to the same date each year, when the Earth crosses the common orbit of the meteoroids. (15.1)
- The number of recovered meteorites has risen dramatically with the discovery that Antarctic ice fields collect and preserve meteorites for millions of years. (15.2)
- Meteorites are classed as stones, irons, and stony-irons. Stones resemble Earth rocks and are the most common meteorites. Carbonaceous chondrites are a type of stony meteorite and may represent unaltered material from early in the history of the solar system. Irons are alloys of iron and nickel and stony-irons are mixtures of stone and metal. (15.2)
- The radioactive elements in meteorites show that most of them solidified at almost the same time as the oldest Moon rocks, about 4.6 billion years ago. (15.2)
- Many meteorites appear to have been kept at high temperatures for a long period of time or to have cooled very slowly. To cool slowly, they must have been part of a body at least 100 km in diameter. The orbits of meteorites show that the bodies from which they came had orbits that carried them into the region between Mars and Jupiter. (15.2)
- Most of the known asteroids orbit in a belt located between the orbits of Mars and Jupiter. These asteroids are very widely spread out. (15.3)
- Many asteroids are not found in the asteroid belt. The Trojan asteroids, for example, either trail or precede Jupiter in its orbit around the Sun. In addition, the asteroids Hidalgo and Chiron have orbits larger than Jupiter's. (15.3)
- Many asteroids have orbits that carry them inside the orbit of the Earth. Within tens of millions of years, these asteroids are likely to be destroyed by striking the Earth. (15.3)
- The reflectance spectra of many asteroids resemble those of various kinds of meteorites. However, asteroids that resemble ordinary chondrites, the most common kind of meteorite, are very scarce. (15.3)
- The nucleus of a comet is a low-density chunk of ice and dust. Upon coming within 3 AU of the Sun, however, the nucleus is warmed enough by sunlight to release gas and dust. These flow away from the nucleus to produce the coma and the dust and plasma tails. (15.4)
- Comets with orbital periods shorter than 200 years are called short-period comets. Comets with orbital periods longer than 200 years are called long-period comets. (15.4)
- The Sun is surrounded by the Oort cloud, a swarm of comets extending as far as 100,000 AU from the Sun. There may be as many as a trillion comets in the Oort cloud. Passing stars alter the orbits of Oort cloud comets, causing some of them to enter the planetary system and become visible as new comets. Short-period comets are thought to come from the Kuiper belt, a disk of comets just beyond the orbit of Neptune. (15.4)
- A comet loses icy material each time it passes the Sun. Eventually, the ice is entirely eroded. The dust particles left behind form meteoroid swarms that produce meteor showers. Some comet nuclei may have rock cores that become asteroids once the surrounding ice is gone. (15.4)
- Comets may have formed in a region near the orbit of Neptune. The bodies recently found beyond the orbit of Neptune may be among the largest comets that still remain in that region. (15.5)
- If a large meteoroid or comet struck the Earth, there would be serious local and global consequences.

The global consequences might include darkness for weeks or months, very acidic rain, and temporary heating of the atmosphere. (15.6)

- An excess of the element iridium, discovered in rocks formed at the end of the Cretaceous period 65 million years ago, suggests that an asteroid struck the Earth at that time. The consequences of the impact may have played a role in the Cretaceous extinctions. However, the way that the impact affected life on the Earth and the relationship between extinctions and impacts is not yet understood. (15.6)

Key Terms

achondrite *351*
Amor asteroid *357*
Apollo asteroid *357*
asteroid *353*
asteroid belt *354*
Aten asteroid *357*
carbonaceous chondrite *351*
chondrite *350*
chondrule *350*
coma *360*
comet *359*
cosmic ray *352*
cosmic ray exposure age *352*
C-type asteroid *358*
dust tail *361*
fireball *347*
iron meteorite *351*
Kuiper belt *363*
long-period comet *362*
meteor *346*
meteorite *347*
meteoroid *346*
meteor shower *347*
micrometeorite *349*
minor planet *353*
M-type asteroid *358*
new comet *362*
nucleus *359*
Oort cloud *362*
plasma tail *361*
radiant *348*
reflectance spectra *358*
short-period comet *362*
solidification age *352*
stony-iron meteorite *350*
stony meteorite *350*
S-type asteroid *358*
terminal velocity *347*
Trojan asteroid *357*
V-type asteroid *358*
zodiacal light *367*

Conceptual Questions

1. Distinguish between a meteoroid, a meteor, and a meteorite.
2. Tell what happens to meteoroids with diameters of (a) 10 millionths of a meter, (b) 1 centimeter, (c) 1 meter, and (d) 10 meters beginning from the time they enter the Earth's atmosphere.
3. Explain why the meteors in a given shower appear to be diverging from a fixed point in the sky.
4. Why do meteor showers recur on the same date each year?
5. Why are carbonaceous chondrites especially important for the study of the early solar system?
6. What is the significance of the large crystals contained in iron meteorites?
7. What does the cosmic ray exposure age tell us about the history of a meteorite?
8. How do we know that the parent bodies of the meteorites were larger than about 100 km in diameter?
9. Ceres, the first asteroid to be discovered, lies between Mars and Jupiter. Why was Ceres unknown to ancient astronomers?
10. What is the relationship between asteroids and meteorites?
11. Describe what happens to the nucleus of a comet as it moves from 10 AU from the Sun to 0.5 AU from the Sun.
12. Where does the gas and the dust in the coma of a comet come from?
13. Why do the dust tail and the plasma tail of a comet point away from the Sun?
14. What evidence is there that the Sun is surrounded by a vast cloud of comets known as the Oort cloud?
15. What causes Oort cloud comets to enter the inner solar system and become visible as new comets?
16. Where do short-period comets come from?
17. What is the eventual fate of most short-period and long-period comets?
18. What is the relationship between comets and meteor showers?
19. What evidence do we have that comets are permanent solar system members rather than interlopers from other parts of the galaxy?
20. Suppose the Earth were struck by an asteroid 10 km in diameter. Describe the local and global consequences of the impact.
21. What evidence do we have that the extinction of species at the end of the Cretaceous era was associated with an asteroid or comet striking the Earth?

Problems

1. Most asteroids are located in the asteroid belt that lies between 2.1 and 3.3 AU from the Sun. What orbital periods correspond to the inside and outside of the asteroid belt?
2. What is the orbital period of one of the Trojan asteroids?
3. Icarus, an Apollo asteroid, has a perihelion distance of 0.19 AU and an aphelion distance of 1.97 AU. How often does it cross the orbit of the Earth?
4. An Oort cloud comet has an orbital period of 5 million years. What is its average distance from the Sun?

Planetarium Activity

Turn off the daylight and horizon displays. Use the "Planet" Palette to center on Comet Halley and lock on Comet Halley. Use the "Settings" button to set Orientation to Equatorial. Use the "Zoom" button to zoom in until the field of view is 40°. Set the date to December 1, 2061. Set the time step to 1 day. Step ahead until you pass the time that the tail of Comet Halley seems to be the longest. Then step back and forth in time until you find the date that the tail is longest. Use the Angular Separation Tool to find the angular length of the tail of Comet Halley. Set the cursor on the nucleus of Comet Halley and find the distance of the comet from the Earth. Step forward in time and see how the distance of the comet changes with time. Find the date on which Comet Halley will be closest to the Earth and its distance on that date. Try to explain why Comet Halley isn't closest to the Earth on the date its tail is longest.

Group Activities

1. Travel with your group to a dark spot on a clear, moonless night. Divide the group into two or more subgroups and have each group sit facing a different direction. Each group should look about halfway from the horizon to the zenith and count the number of meteors each member of the group sees in 15 minutes. Average the number of meteors seen by each member of the group and multiply by four to get the meteor rate in number per hour. If possible, repeat the experiment during one of the meteor showers listed in Table 15.1. Compare the meteor rates of the two observations.
2. Go to the website http://cfa-www.harvard.edu/iau/lists/MPNames.html where you will find a list of asteroid names. Have each member of your group use the list to try to make up a sentence using only asteroid names. (For example: Rockefellia Neva Edda McDonalda Hamburga.) After you have an entry from each member of the group, have the group decide which is the best entry.

For More Information

Visit the text website at **www.mhhe.com/fix** for chapter quizzes, interactive learning exercises, and other study tools.