8 VAGABONDS OF THE SOLAR SYSTEM

IN THIS CHAPTER YOU WILL DISCOVER

- asteroids and meteoroids, pieces of interplanetary rock and metal
- comets, bodies containing large amounts of ice and rocky debris
- space debris that falls through the Earth's atmosphere
- that impacts from space 250 million and 65 million years ago caused mass extinctions of life on Earth
- that a wayward asteroid could again threaten life on Earth

WEB LINK 8.1

Comet Hyakutake
A comet is almost always named after the person who first sees it. The Japanese amateur astronomer Yuji Hyakutake first observed the comet named for him using binoculars on the morning of January 30, 1996. This photograph was taken two months later, in April 1996, when the comet extended more than 30° across the sky—more than 60 times the diameter of the full Moon as seen from Earth. Comet Hyakutake passed within 0.1 AU (15 million kilometers or 9 million miles) of Earth. (Jerry Lodriguss)

R I V U X G

WHAT DO YOU THINK?

1. Are the asteroids a planet that was somehow destroyed?
2. How far apart are the asteroids on average?
3. Why do comets have tails?
4. In which direction does a comet tail point?
5. What is a shooting star?

The formation of the solar system was not a tidy affair. Planetesimals collided by the billions to form the planets we see today and their moons. For nearly a billion years, pieces of smaller debris struck them often, scarring and shaping their surfaces. This era of frequent collisions ended some 3.8 billion years ago, but innumerable pieces of debris still orbits the Sun, and dramatic impacts continue today. Large, rocky bodies occasionally pass startlingly close to the Earth—closer even than the Moon. Myriad small ones penetrate the atmosphere daily. Comets weave glorious trails across the sky. Icy bodies such as these may once have provided Earth with water and other material essential to the evolution of life.

These leftovers, the vagabonds of the solar system, are the asteroids, meteoroids, and comets. We have already seen pieces of Comet Shoemaker-Levy 9 plunge into Jupiter. You may have spotted Comet Hale-Bopp during the summer of 1997. What do the characteristics of these interplanetary travelers reveal about the composition of the solar system and about how life began here?

ASTEROIDS

WEB LINK 8.2

We know that the solar system formed from a rotating disk of gas and dust. The matter that had too much angular momentum to fall onto the protosun coalesced at varying distances into planetesimals. Many of these chunks of rock and metal eventually collided, forming the planets and larger moons of the solar system. Others were captured whole by various planets as small, irregularly shaped moons, like Phobos and Deimos in orbit around Mars. However, many planetesimals still orbit the Sun today in splendid isolation. These are the **asteroids,** sometimes called *minor planets.*

8-1 Most asteroids orbit the Sun between Mars and Jupiter

On New Year's Day 1801, the Sicilian astronomer Giuseppe Piazzi was carefully mapping faint stars in the constellation of Taurus. He noticed a dim, previously uncharted "star" that shifted its position slightly over the next several nights. Uranus had been discovered that way by William Herschel just 20 years before. Was Piazzi's object another planet? The answer is no. His lucky sighting was too small to qualify as a full-fledged planet. Rather, he was the first to discover an asteroid.

Later that year, the orbit of this object was determined to lie between Mars and Jupiter. At Piazzi's request, the object was named Ceres (pronounced see-reez), after the patron goddess of Sicily. Ceres is spherical like the planets (Figure 8-1), but its diameter is a scant 940 km, only one-quarter the diameter of our Moon.

In 1802, the German astronomer Heinrich Olbers discovered another faint, starlike object that moved against the background stars. He called it Pallas, after the Greek goddess of wisdom. Like Ceres, Pallas orbits the Sun in a low eccentricity (nearly circular) orbit between the orbits of Mars and Jupiter. Pallas is even dimmer and smaller than Ceres, with a diameter of only 600 km.

Only two more of these minor planets—Juno and Vesta—were found until the mid-1800s, when telescopes improved. Astronomers then began to stumble across many more asteroids orbiting the Sun at distances from 2 and $3\frac{1}{2}$ AU, between the orbits of Mars and Jupiter. This region of the solar system is now called the **asteroid belt** (Figure 8-2). Asteroids whose orbits lie entirely within this region are called **belt asteroids.**

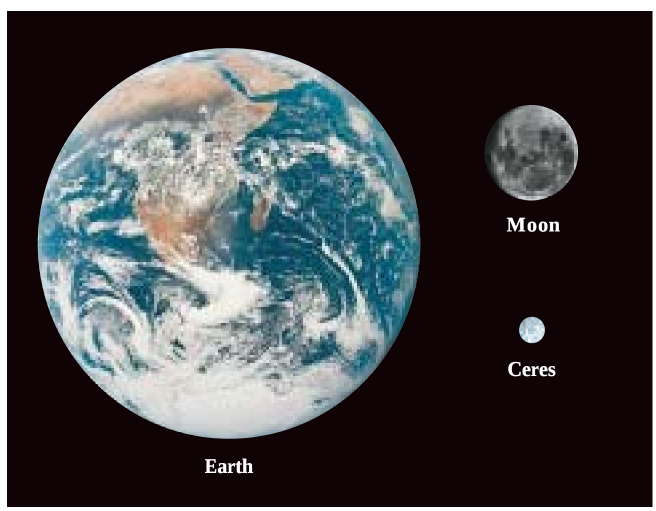

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FIGURE 8-1 Comparison of Ceres with the Moon and the Earth Ceres, the Moon, and the Earth are shown here to scale. Ceres, shown in this infrared photo (Earth and Moon appear in visible light) is the largest asteroid but is so small that it is not considered a planet. Because it does not orbit a body other than the Sun, it is also not classified as a moon. (NASA)

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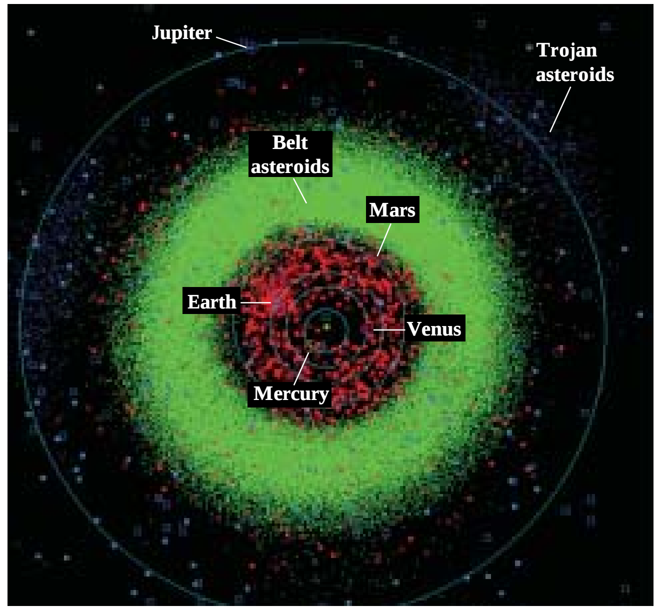

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FIGURE 8-2 Asteroid Orbits (a) An artist's rendition of some asteroids and their orbits. Most asteroids orbit the Sun in a 1½-AU-wide belt between the orbits of Mars and Jupiter. The orbits of belt asteroids Ceres, Pallas, and Juno are indicated to scale. Some asteroids, such as Apollo and Icarus, have highly eccentric paths that cross Earth's orbit. Others, called the Trojan asteroids, follow the same orbit as Jupiter. (b) Actual positions of all known asteroids at Jupiter's orbit or closer. The locations of the belt asteroids are indicated by green dots. Objects passing closer than 1.3 AU to the Sun are shown by red circles. Objects observed at more than one opposition are indicated by filled circles, objects seen at only one opposition are indicated by outline circles. Jupiter's Trojan asteroids are deep blue squares. Comets are filled and unfilled light-blue squares. (b: Minor Planet Center)

The next real breakthrough came in 1891, when the German astronomer Max Wolf applied photographic techniques to the search for asteroids. A total of 300 asteroids had been found up to that time, each painstakingly discovered by scrutinizing the skies for faint, uncharted "stars" whose positions shifted slowly from one night to the next. With the advent of astrophotography, however, the floodgates were opened. Astronomers could simply aim a camera-equipped telescope at the stars and take long exposures. If an asteroid happened to be in the field of view, it left a distinctive trail on the photographic plate (Figure 8-3). Using this technique, Wolf alone discovered 228 asteroids.

Insight into Science **Confirming Observations** New findings must be confirmed or replicated by other competent scientists before discoveries and observations are accepted by the scientific community. Therefore, asteroid observations need to be repeated and repeated in order to determine exact orbits and to eliminate the possibility that a sighting is of a known asteroid or other object.

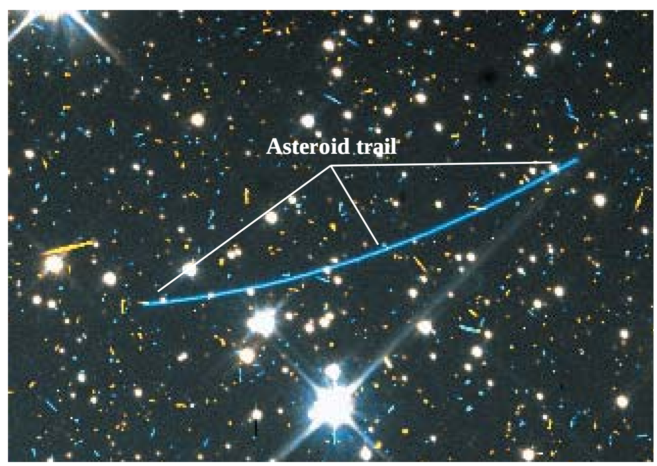

FIGURE 8-3 Discovering Asteroids In 1998, the Hubble Space Telescope found this asteroid while observing in the constellation Centaurus. The exposure, tracking stars, shows the asteroid as a 19 arcsecond streak. This asteroid is about 2 km in diameter and was located about 140 million km (87 million miles) from Earth. (R. Evans and K. Stapelfeldt, Jet Propulsion Laboratory and NASA)

Ceres, the largest asteroid, alone accounts for about 30% of the mass of all the known asteroids combined. Only three asteroids—Ceres, Pallas, and Vesta—have diameters greater than 300 km. Records of all objects smaller than planets in our solar system are kept by the Minor Planet Center in Cambridge, Massachusetts. The center reports that as of May 2002, 39,462 asteroids had been confirmed to exist, with more than 125,000 other observations awaiting confirmation as new asteroids. The number of asteroids increases dramatically with *decreasing size:* Only 30 asteroids have diameters between 200 and 300 km; 200 more are bigger than 100 km across; there are estimated to be millions that are less than 1 km across.

You may have heard the common belief that the aster-
1 oids were once a single planet that was somehow destroyed. It is much more likely that Jupiter's gravitational force pulling by differing amounts on the planetesimals in the region of the asteroid belt made it virtually impossible for large numbers of asteroids to meet, coalesce, and form a single object. (We consider Jupiter's gravitational effect in more detail in the next section.)

In fact, if all the asteroids had once been part of a single body, it would have had a diameter of only 1500 km, or 12% of the Earth's diameter. This is less than two-thirds the diameter of Pluto and half the diameter of our Moon. Because Pluto just barely makes it into the category of a planet, a single body containing the entire asteroid mass would not qualify as a planet.

8-2 Jupiter's gravity creates gaps in the asteroid belt

In 1867, the American astronomer Daniel Kirkwood called attention to gaps in the asteroid belt. These features, called **Kirkwood gaps,** show the influence of Jupiter's gravitational attraction, as best seen in a graph of asteroid orbital periods, like the one in Figure 8-4. Note the gaps at simple fractions ($^1/_3$, $^2/_5$, $^3/_7$, and $^1/_2$) of Jupiter's orbital period. The gravitational effect of Jupiter creating gaps in the asteroid belt resembles the gravitational *resonance* effect of Mimas creating the Cassini division in Saturn's rings (see Chapter 7).

MORE TO KNOW 8.1 Resonances

Although it is likely that the asteroid belt contains mil-
2 lions of asteroids, their typical separation is a staggering 10 million kilometers. This is quite unlike the image that has been created by innumerable science fiction movies of asteroids so close together that you must dodge them as you fly past.

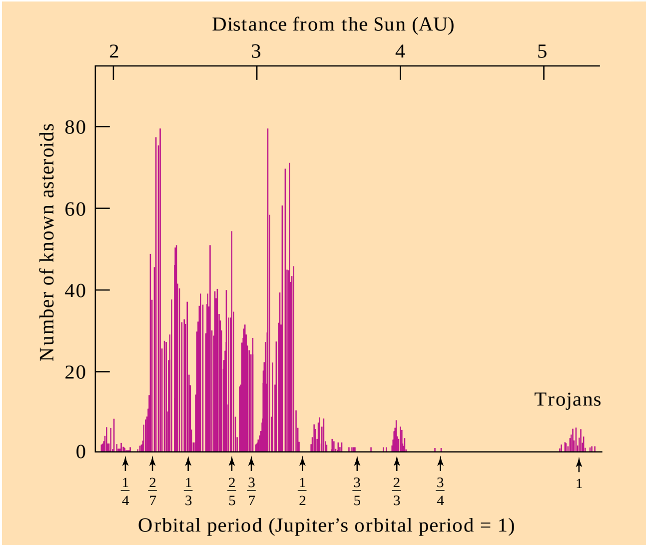

FIGURE 8-4 The Kirkwood Gaps This graph displays the number of asteroids at various distances from the Sun. Notice that few orbital periods of asteroids correspond to such simple fractions as $^1/_3$, $^2/_5$, $^3/_7$, and $^1/_2$ of Jupiter's orbital period. Repeated alignments with Jupiter have deflected asteroids away from these orbits. The Trojan asteroids accompany Jupiter as it orbits the Sun.

Insight into Science **Get Real** Scientists continually apply the "laws of nature" to new situations, problems, observations, and experiments, even to popular culture. For example, applying Newton's law of gravity to the asteroids reveals that they could never swarm, as science fiction movies suggest. At those close quarters, their gravity would cause them either to collide or to pass so close together that they would actually fly rapidly and permanently apart.

Despite the large average separation between asteroids, the gravitational influences of Mars and Jupiter have sent some asteroids caroming into each other at various times over the 4.6 billion years that the solar system has existed. In 1918, the Japanese astronomer Kiyotsugu Hirayama drew attention to groups of asteroids that share nearly identical orbits. These are fragments of parent asteroids.

A collision between kilometer-sized asteroids must be an awe-inspiring event. Typical collision velocities are estimated to be 3600 to 18,000 km/h (2000 to 11,000 mph), which is more than sufficient to shatter rock. In some collisions, the resulting fragments may not have enough speed to escape from each other's gravitational attraction, and they reassemble. Alternatively, several large fragments may end up orbiting or in contact with each other. The asteroid

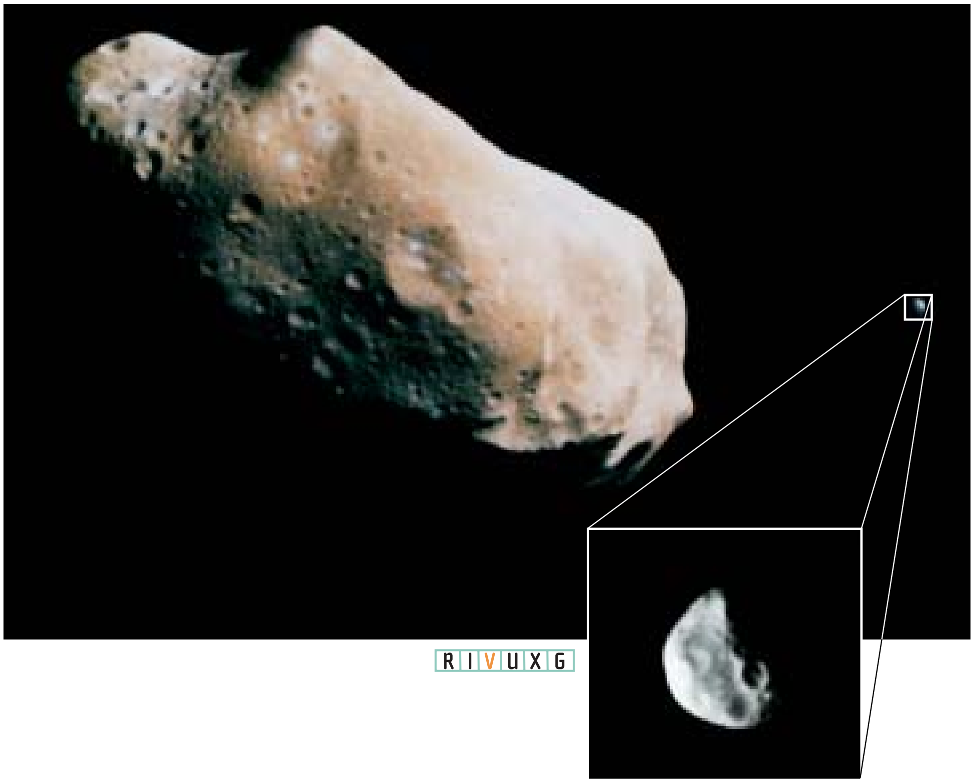

FIGURE 8-5 **Ida and Its Moon** The 55-km-long rocky asteroid Ida, shown here with its moon Dactyl, is about twice the size of the younger asteroid Gaspra (see Figure II-11). **Inset:** Dactyl is also heavily cratered. (NASA)

Toutatis appears to be composed of two comparably sized pieces connected to each other, as does the asteroid Castalia.

In the early 1990s, the Jupiter-bound *Galileo* spacecraft passed near two asteroids—Gaspra (see Figure II-11) and Ida (Figure 8-5)—and sent back close-up views. Both asteroids are probably fragments of larger parent bodies that were broken apart by catastrophic collisions. Because Ida's surface is more heavily cratered than Gaspra's, Ida is much older.

At least two asteroids have their own moons: Ida, accompanied by Dactyl, and Dionysus, whose moon has yet to be named. Dactyl is a pockmarked asteroid some 1.5 km in diameter that orbits Ida at a distance of 100 km. Dionysus's moon appears to be 0.5 km across, orbiting only a few kilometers from the larger body.

8-3 Asteroids exist outside the asteroid belt

While Jupiter's gravitational pull clears out certain orbits within the asteroid belt, it actually captures asteroids at two locations in the path of its own orbit. The gravitational forces of the Sun and Jupiter work together to hold asteroids in orbit at these locations, called **stable Lagrange points,** in honor of the French mathematician Joseph Lagrange, whose calculations explained them. One Lagrange point is located 60° ahead of Jupiter, and the other is 60° behind, as shown in Figure 8-6.

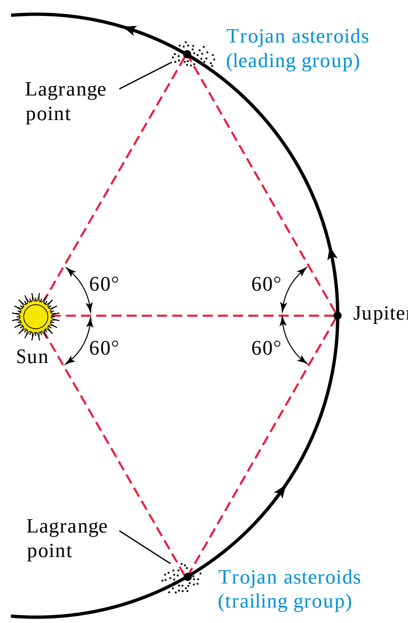

FIGURE 8-6 **Jupiter's Trojan Asteroids** Groups of asteroids orbit at the two stable Lagrange points along Jupiter's orbit, trapped by the combined gravitational forces of Jupiter and the Sun. Asteroids at these locations are named after Homeric heroes of the Trojan War. For more details of the location of Jupiter's Trojan asteroids, see Figure 8-2b.

The asteroids trapped at Jupiter's Lagrange points are called **Trojan asteroids,** each named after a hero of the Trojan War. As of May 2002, 1215 Trojan asteroids orbiting Jupiter have been catalogued (see Figure 8-2b). Closer to home, six asteroids have been discovered at one of Mars's Lagrange points, and asteroid number 3753 (Cruithne) orbits at one of Earth's Lagrange points.

WEB LINK 8.6

Some asteroids have highly elliptical orbits that bring them into the inner regions of the solar system (see Figure 8-2). Others have similarly elliptical orbits that extend from the asteroid belt out beyond the farthest reaches of Pluto's orbit. The *Amor asteroids,* cross Mars's orbit, while the **Apollo asteroids** even cross Earth's orbit.

The Apollo asteroid 433 Eros passed within 23 million kilometers of our planet in 1931. On October 30, 1937, the asteroid Hermes passed within 900,000 km of Earth—only a little more than twice the distance to the Moon. On June 14, 1968, asteroid Icarus passed Earth at a distance of only 6 million kilometers. In 1972, space debris was observed to skip off Earth's atmosphere and retreat back into space.

There were several close calls recently. On December 9, 1994, asteroid 1994 XM1 passed within 105,000 km of the Earth, and on January 8, 2002, an asteroid passed within 375,000 km. The former asteroid is about 10 m across—the size of a small bus (Figure 8-7). At least 1690 *Earth-crossing* asteroids are known.

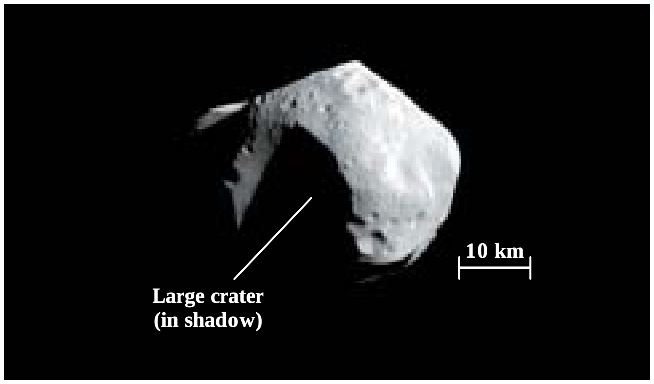

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FIGURE 8-8 Asteroid Mathilde Reflecting only half as much light as a charcoal briquette, Mathilde is half as dense as typical, stony asteroids. Slightly larger than Ida, irregularly shaped Mathilde measures 66 × 48 × 46 km, rotates once every 17.4 d, and has a mass equivalent to 110 trillion tons. The part of the asteroid shown is about 59 × 47 km. The large crater in shadow is about 20 km across. (Johns Hopkins University, Applied Physics Laboratory)

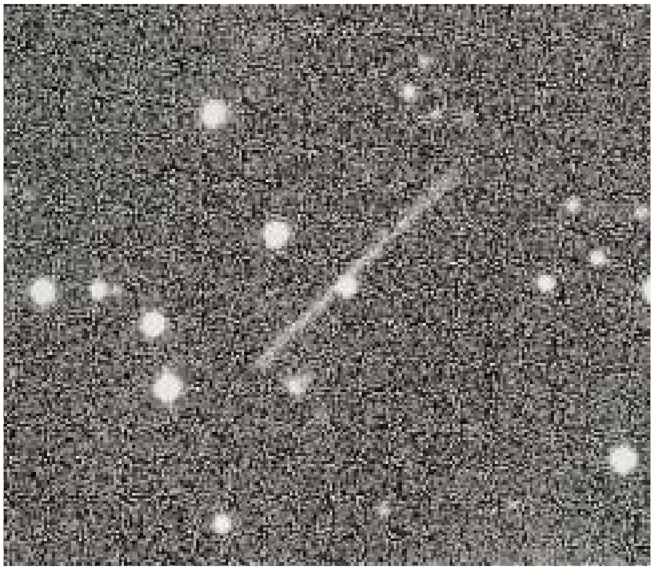

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FIGURE 8-7 Asteroid 1994 XM1 This image was obtained on December 9, 1994, shortly before the asteroid arrived in the Earth's vicinity. When it passed by the Earth just 12 hours later, asteroid 1994 XM1 was less than half the distance from the Earth to the Moon. (Jim Scotti, Spacematch on Kitt Peak)

During these close encounters, astronomers can examine the details of asteroids. For example, an asteroid's brightness often varies as it rotates because different surface features scatter different amounts of light. Such data show that typical rotation periods for asteroids are between 5 and 20 hours, although one asteroid, labeled 1998 KY26, rotates about once every 10.7 minutes. This is the fastest-rotating object known in the solar system.

The proximity of asteroids and the promise of learning more about these ancient and extremely varied members of our solar system prompted NASA to send the *Near Earth Asteroid Rendezvous* (*NEAR*) *Shoemaker* spacecraft to visit asteroids Mathilde (Figure 8-8) and Eros. *NEAR Shoemaker* revealed that Mathilde is only 1.3 times denser than water and has an albedo of 0.04, making it darker than charcoal. This heavily cratered, carbon-rich body therefore has only half the density of the other asteroids astronomers have studied, such as Ida. Eros is about 3 times as dense as water and rotates once every $5^{1}/_{4}$ hours. In February 2000, *NEAR Shoemaker* went into orbit around Eros, and for a year the spacecraft's cameras and other sensors sent back a wealth of information about the asteroid.

NEAR Shoemaker showed that Eros (Figure 8-9) is a solid chunk of rock and metal. Analyzing Eros's spectra reveals that it is probably much the same as it was when it coalesced 4.6 billion years ago. This means that it was never hot enough to differentiate (separate rock from metal). Infrared observations reveal that like our Moon, Eros has a regolith. It also has several substantial craters and is strewn

FIGURE 8-9 Eros (a) The *Near Earth Asteroid Rendezvous* (*NEAR*) *Shoemaker* spacecraft took this image of asteroid Eros in February 1999. The top of the figure is the asteroid's north polar region. Eros's dimensions are 33 × 13 × 13 km (21 × 8 × 8 mi) and it rotates every 5¼ hours. Its density is 2700 kg/m^3, close to the average density of the Earth's crust and twice as dense as asteroid Mathilde. (b) Looking into the large crater near the top of (a), which is 5.3 km (3.3 miles) across. (c) The penultimate image taken by *NEAR Shoemaker* before it was gently landed on Eros. Taken from an altitude of 250 m (820 ft), the image is only 12 meters across. You can see rocks and boulders buried to different depths in the regolith. (a, b & c: Johns Hopkins Applied Physics Laboratory)

with boulders (Figure 8-9c). On February 12, 2001, NASA engineers landed *NEAR Shoemaker* on Eros so gently that the spacecraft continued to transmit data after landing. Details of Eros as small as 1.4 meters across were imaged by *NEAR Shoemaker.*

Most of the Apollo asteroids will eventually strike a moon or planet—even the Earth. Some asteroids will end up heading straight into the Sun. However, the chance of the Earth being hit by an asteroid in the next few thousand years is remote. We will examine this possibility at the end of the chapter.

The Sun is not the only star with an asteroid belt. In 2001, astronomers discovered that the star Zeta Leporis, 70 light-years from Earth in the constellation Lepus (the hare), has a disk of debris that appears to contain asteroids. This star system is less than 0.5 billion years old and astronomers hope it will provide insights into the early evolution of the asteroids and other objects in the disk of gas and dust surrounding the early Sun.

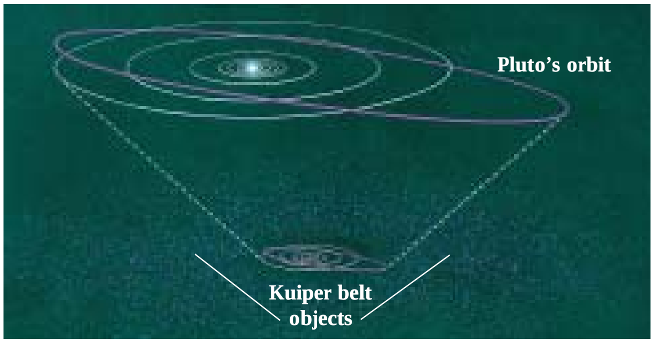
COMETS

While asteroids consist primarily of rock and metal, other pieces of space debris are composed of frozen water, along with rock, metal, and ices of other compounds. We have seen in earlier chapters that water ice, along with carbon dioxide, methane, and ammonia ices, was locked up in planets and moons. Ices in the young solar system also condensed with roughly equal amounts of small rocky and metallic debris into bodies that still remain in orbit around the Sun. These dirty icebergs in space are the **comets.** To better determine their composition, the *Stardust* probe is on its way to Comet Wild 2, where it will collect samples and return to Earth in 2006.

8-4 Comets come from far out in the solar system

In the first few hundred millions years of the solar system's existence, comets formed in its outer reaches at roughly the distances of Saturn, Uranus and Neptune. In that region, water was plentiful and the temperature low enough for the ices to condense into chunks several kilometers across. In 2001, astronomers were able to measure the temperature at which ammonia ice formed in the comet Linear, thereby determining that this comet formed between the orbits of Saturn and Uranus. Then, gravitational tugs from Uranus and Neptune flung the comets in every direction.

Today, the solar system is believed to contain two reservoirs of comets. Most comets that eventually return to the inner solar system and develop the long tails that we usually associate with them are believed to come from a doughnut-shaped region beyond the orbit of Pluto. This **Kuiper belt,** named after the American astronomer Gerard Kuiper, who first proposed its existence in 1951, is centered on the plane of the ecliptic and extends out some 500 AU from the Sun (Figure 8-10).



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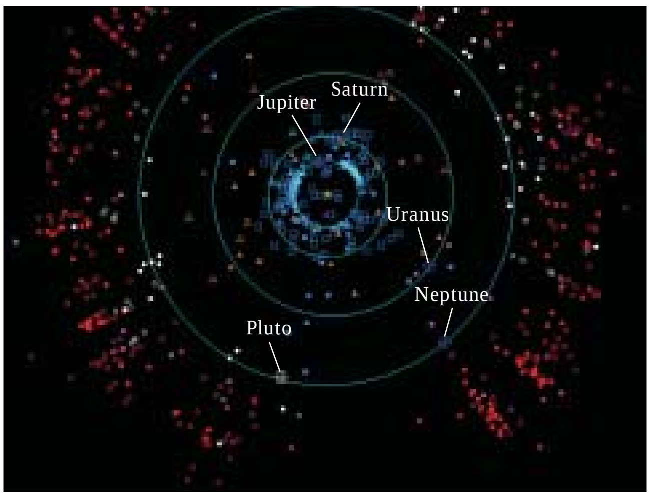

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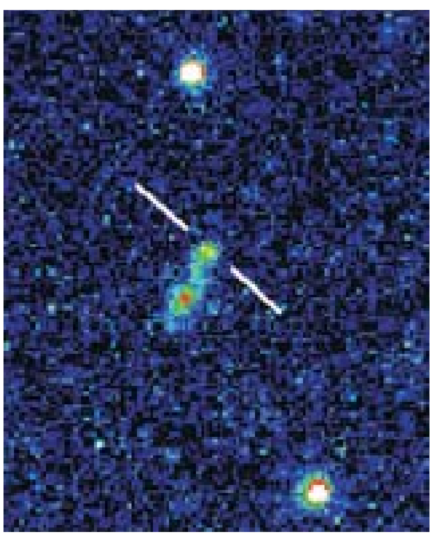
FIGURE 8-10 The Kuiper Belt (a) The Kuiper belt of comets spreads from Pluto out 500 AU from the Sun, as depicted in this artist's conception. Most of the estimated 200 million belt comets are believed to orbit in or near the plane of the ecliptic. More than 530 of these objects have been located; the largest is 320 km across. Some astronomers believe that Pluto and Charon are members of the Kuiper belt. (b) The current positions of the minor bodies in the outer solar system are shown in this diagram. Unusual high eccentricity objects are shown as cyan triangles. Objects roaming among the outer planets, called Centaur objects, are orange triangles. Plutinos are white circles. Miscellaneous objects are magenta circles and "classical" or "main-belt" objects as red circles. Objects observed at only one opposition are denoted by open symbols, objects with multiple-opposition orbits are denoted by filled symbols. Comets are filled and unfilled light-blue squares. (b: Minor Planet Center)

More than 530 Kuiper belt objects have been observed (Figure 8-11). At least one of them, named 1998 WW31, has a moon of its own (Figure 8-11c). Another, 2000 WR106, is between one quarter and one half the size of Pluto. At least 40 Kuiper belt objects orbit the Sun in the same region as Pluto. Because these latter bodies are smaller than Pluto, they are called *Plutinos.* Given the number and locations of these objects, astronomers estimate that the Kuiper belt contains at least 200 million comets.



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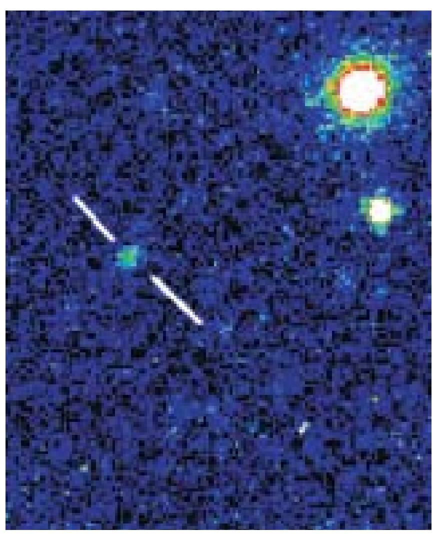

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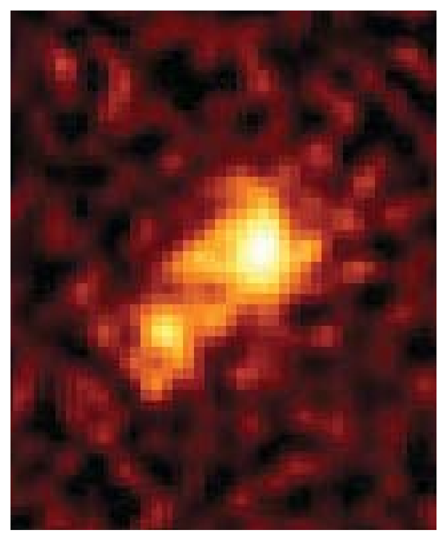

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FIGURE 8-11 Kuiper Belt Objects (a) and (b) These 1993 images show the discovery (white lines) of one of more than 530 known Kuiper belt objects. These two images of Kuiper belt object 1993 SC were taken 4.6 hours apart, during which time the object moved from (a) to (b) against the background stars. (c) The Kuiper belt object 1998 WW31 and its moon (lower left). (a & b: Alan Fitzsimmons, Queen's University of Belfast; c: C. Veillet/CFHT)

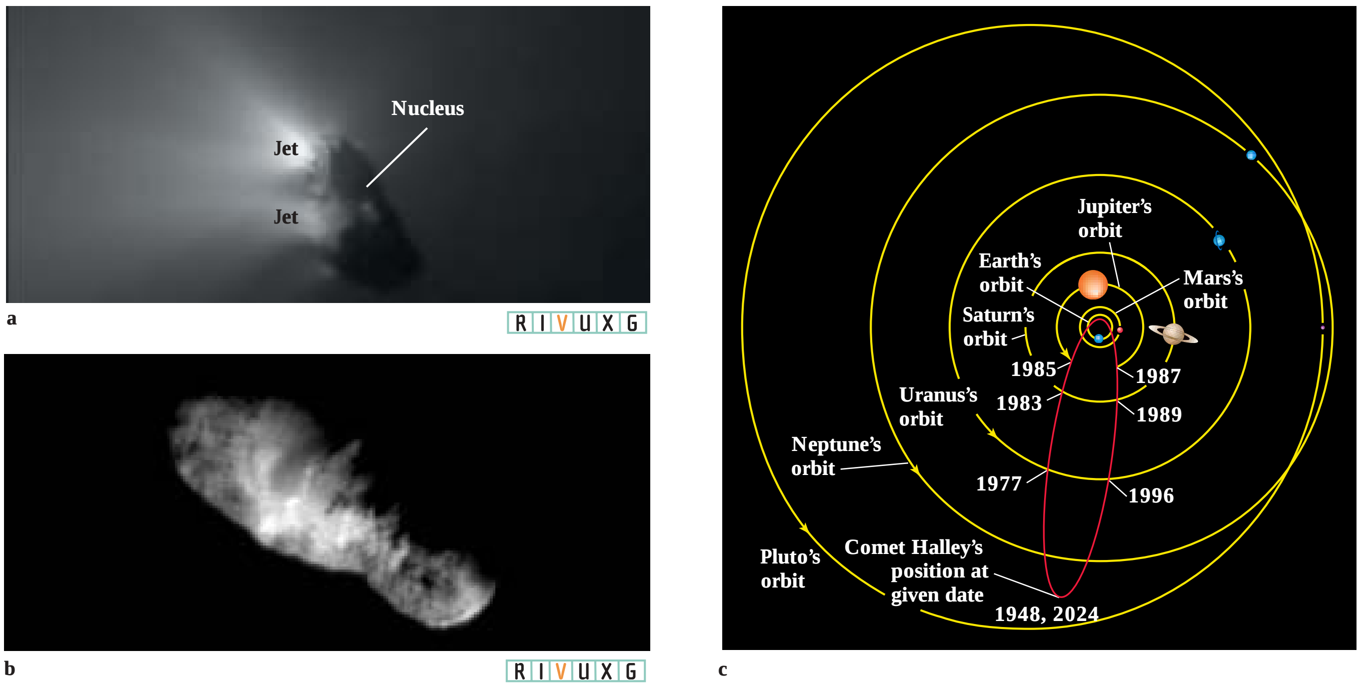


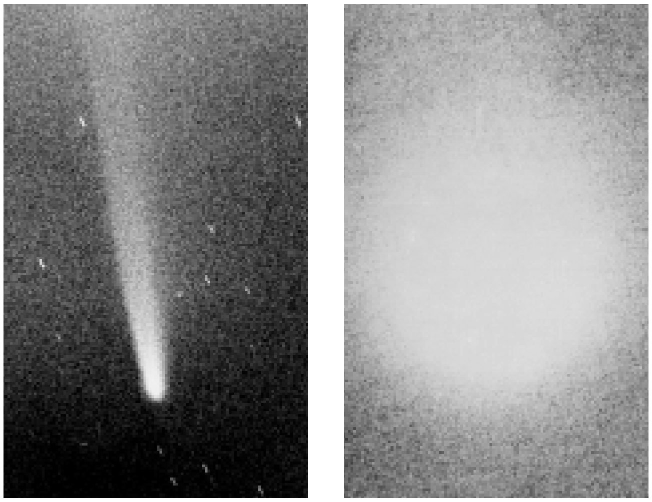
FIGURE 8-12 Comet Nuclei (a) The nucleus of Comet Halley. This image, taken by the *Giotto* spacecraft, shows the potato-shaped nucleus of the comet. Its dark nucleus measures 15 km in its longest dimension and about 8 km in its shortest. The Sun illuminates the comet from the left. The numerous bright areas on the nucleus are icy outcroppings that reflect more sunlight than surrounding areas of the comet. Two jets of gas can be seen emanating from the left side of the nucleus. (b) The nucleus of Comet Borrelly. Taken by *Deep Space 1,* this image has resolution of 45 m (150 ft). The nucleus is 8 km (5 mi) long, and the image was taken from 3417 km (about 2000 mi) away. (c) Comet Halley's orbit. Its highly eccentric orbit takes Halley out beyond Neptune with a period of about 76 years. (a: Max-Planck-Institut für Aeronomie; b: Deep Space 1 Team, JPL, NASA)

The vast majority of the several billion comets estimated to exist are believed to lie even farther from the Sun. Unlike the Kuiper belt comets and the rest of the solar system, these comets are believed to have a spherical distribution around the Sun called the **Oort cloud,** named after the Dutch astronomer Jan Oort, who first proposed its existence in the 1950s. Astronomers calculate that the Oort cloud extends out at least 50,000 AU, one-fifth the distance to the nearest stars. Most of these comets have orbits so nearly circular that they never even get as close as Pluto is to the Sun. However, occasionally a passing star's gravitational force nudges a distant comet toward the inner solar system. As a result of its inward plunge, comets from the Oort comet cloud, like Hale-Bopp and Hyakutake, have highly elliptical orbits. Often comets also have orbits that are highly tilted, even perpendicular, to the plane of the ecliptic.

Because the comets in the Kuiper belt and Oort cloud are far from the Sun, they are completely frozen. Solid comet bodies, called **nuclei** (*singular* **nucleus**), are typically 20 kilometers across. The first pictures of a comet's nucleus were obtained when a fleet of spacecraft flew past Comet Halley in 1986 (Figure 8-12a). Halley's potato-shaped nucleus is darker than coal, probably because of carbon-rich compounds left behind after its ice evaporated. In 2001, the *Deep Space 1* spacecraft took the highest resolution image ever of a comet nucleus (Figure 8-12b). The ends of the comet are very rugged, while the center has long, rolling plains, from which jets of gas appear to originate.

As a comet nucleus comes within 20 AU of the Sun, solar radiation begins to vaporize the ices on its surface. The liberated gases form an atmosphere, or **coma,** around the nucleus. Because the coma scatters sunlight, it appears as a fuzzy, luminous ball. The largest coma ever measured was more than a million kilometers across—nearly as large as the Sun. Not visible to the human eye is the **hydrogen envelope,** a sphere of tenuous gas surrounding the comet's nucleus and measuring as much as 20 million kilometers in diameter (Figure 8-13).

Of course, the most visible and inspiring features of comets are their long, flowing, diaphanous **tails** (Figure 8-14). 3
Comet tails develop from coma gases and dust pushed outward from the Sun. This means that comet tails do not trail 4
behind the nucleus, as the exhaust from a jet plane does in the



a R I V U X G b R I V U X G

FIGURE 8-13 Comet Kohoutek and Its Hydrogen Envelope Comet Kohoutek as seen in visible light (a) and to the same scale at ultraviolet wavelengths (b). The ultraviolet picture reveals a huge hydrogen cloud surrounding the comet's nucleus. (a & b: Johns Hopkins University and Naval Research Laboratory)

R I V U X G

FIGURE 8-14 Comet West Astronomer Richard M. West first noticed this comet on a photograph taken with a telescope in 1975. After passing near the Sun, Comet West became one of the brightest comets of the 1970s. This photograph shows the comet in the predawn sky in March 1976. (Hans Vehrenberg)

Earth's atmosphere. Rather, *at the comet's nucleus, the tails always point away from the Sun* (Figure 8-15), regardless of the direction of the comet's motion. The implication that something from the Sun was "blowing" the comet's gases radially outward led Ludwig Biermann to predict the existence of the solar wind (see Chapters 5 and 9). This stream of particles from the Sun was actually discovered in 1962, a full decade later, by instruments on the spacecraft *Mariner 2*.

Insight into Science **Working in Reverse** Science often advances by working from observations and experiments that require scientific explanations. For example, seeing comet tails and how they behave led Biermann to wonder what caused them. The simplest physical explanation is that matter from each comet body is being evaporated and pushed upon by something from the sun, the solar wind. Remember Occam's razor.

The Sun's radiation usually produces two comet tails: a **gas** (or **ion**) **tail** and a **dust tail** (Figure 8-16). Positively charged ions (atoms missing one or more electrons) from the coma are swept directly away from the Sun by the solar wind to form the gas tail. This tail often appears blue, because of blue light emitted by carbon monoxide ions in it. Ions typically leave the coma at speeds of 1.4 million

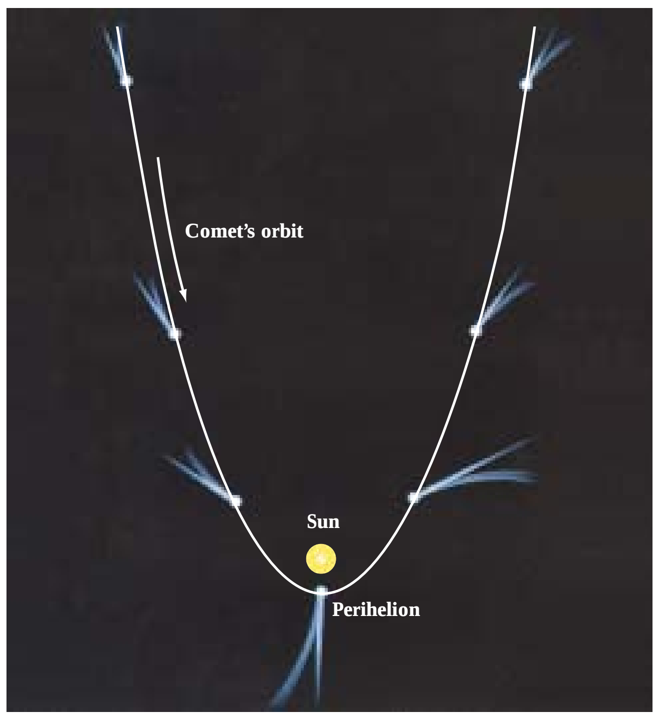


FIGURE 8-15 The Orbit and Tails of a Comet The solar wind and sunlight blow a comet's dust particles and ionized atoms away from the Sun. Consequently, comets' tails always point away from the Sun.

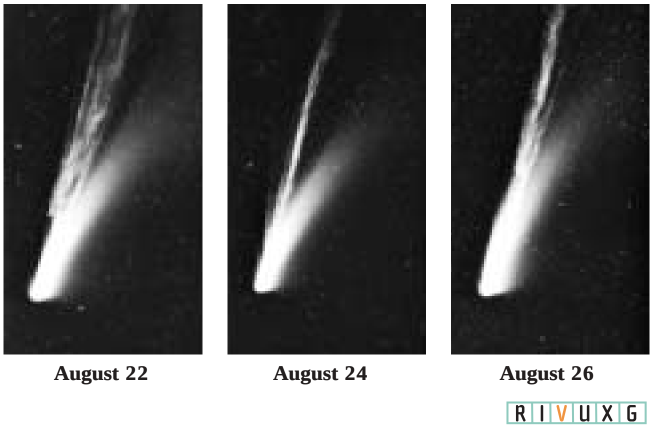


FIGURE 8-16 The Two Tails of Comet Mrkos Comet Mrkos dominated the evening sky in August 1957. These three views, taken at two-day intervals, show dramatic changes in the comet's gas tail. In contrast, the slightly curved dust tail remained fuzzy and featureless. (Palomar Observatory)

kilometers per hour. The relatively straight gas tail can change dramatically from night to night (see Figure 8-16).

The dust tail is formed when photons strike dust particles that have been freed from the comet's evaporating nucleus. Light exerts pressure on any object that absorbs or scatters it. While this pressure, called **radiation pressure** or **photon pressure,** is quite weak, fine-grained dust particles in a comet's coma are sufficiently light to be blown away from the comet, thus producing a dust tail. The dust tail often is the color of sunlight. The dust particles are massive enough not to flow straight away from the Sun, rather, the dust tail arches in a path that lies between the gas tail and the direction from which the comet came (Figures 8-15 and 8-17).

Figure 8-17 outlines the structure of a comet. Some, like the comet shown in Figure 8-18, have a large, bright coma but short, stubby tails. Others have an inconspicuous coma but one or more tails of astonishing length. The gas tail in Figure 8-19 stretches more than 150 million kilometers (1 AU) in length.

8-5 Comets do not last forever

MORE TO KNOW 8.2 Discovering Comets

Astronomers, many of them amateurs, typically discover at least a dozen new comets each year. Falling Sunward from the Kuiper belt or Oort cloud, most are **long-period comets,** which have such eccentric orbits that they leave the inner solar system after one pass by the Sun and typically take 1 million to 30 million years to return.

However, sometimes a comet passes so close to a planet that the planet's gravitational force changes the comet's orbit, slowing it down and trapping it in the inner solar sys-

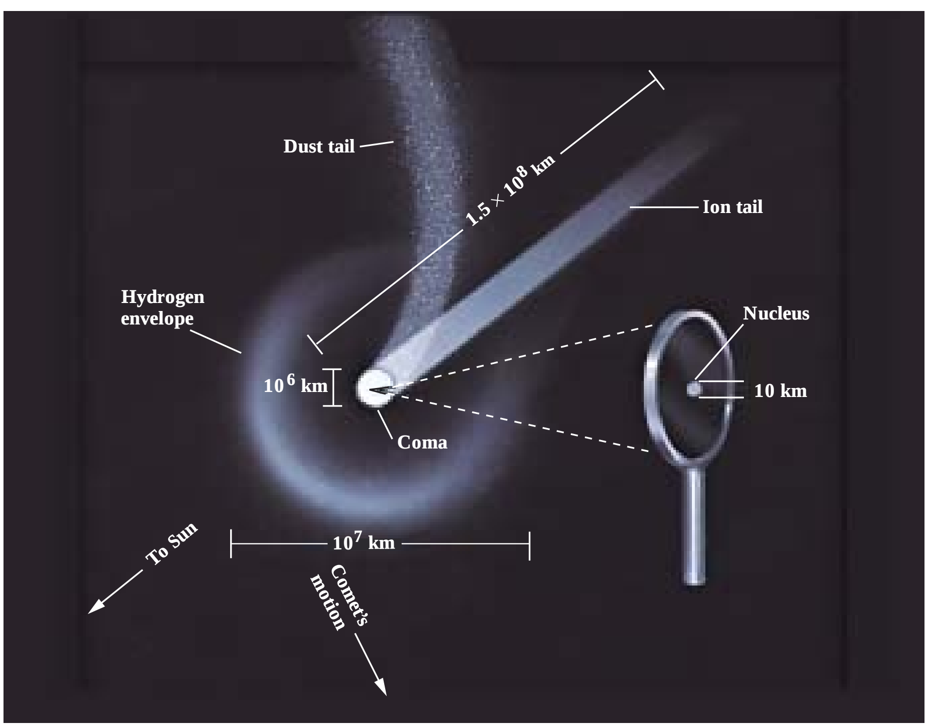


FIGURE 8-17 The Structure of a Comet The solid part of a typical comet (the nucleus) is roughly 10 km in diameter. The coma can be as large as 10^5 to 10^6 km across, and the hydrogen envelope is typically 10^7 km in diameter. A comet's tail can be enormous—as long as 1 AU. (This drawing is not to scale.)

FIGURE 8-18 The Head of Comet Brooks This comet, named after its discoverer, had an exceptionally large, bright coma. It dominated the night skies in October 1911. (UCO/Lick Observatory)

FIGURE 8-19 The Tail of Comet Ikeya-Seki Named after its codiscoverers in Japan, this comet dominated the predawn skies in late October 1965. Although its coma was tiny, its tail spanned 1 AU. (C. R. Lynds/Kitt Peak National Observatory/Tucson, AZ)

tem (Figure 8-20). The comet then becomes a **short-period comet,** orbiting the Sun in fewer than 200 years. Like Comet Halley, short-period comets appear again and again at predictable intervals. If you missed Halley's comet in its 1985 visit, your next chance to see it is in 2061.

Comets cannot survive an infinite number of passages near the Sun. A typical comet is estimated to lose between 1/60th and 1/100th of its mass at each perihelion (closest approach to the Sun). Therefore, a typical comet survives at most 100 close passes to the Sun before its ices evaporate completely. It is likely, then, that Comet Halley, which has been seen at least 27 times, will survive for fewer than 5600 more years. Figure 8-21 shows the nucleus of a comet breaking up shortly after it passed perihelion. Soon thereafter, its remaining dust and rock fragments spread out in a loose collection of debris that continues to circle the Sun along the comet's orbital path.

A comet can also be torn apart when it comes too close to a planet, or it can be destroyed completely by striking a planet, a moon, or the Sun. A spectacular example was Comet Shoemaker-Levy 9. As discussed in Chapter 7, that comet fragmented under the tidal force from Jupiter in 1992. Two years later, with the world's astronomers watching carefully, the pieces returned and struck the planet (see Figures 7-8 and 7-9).

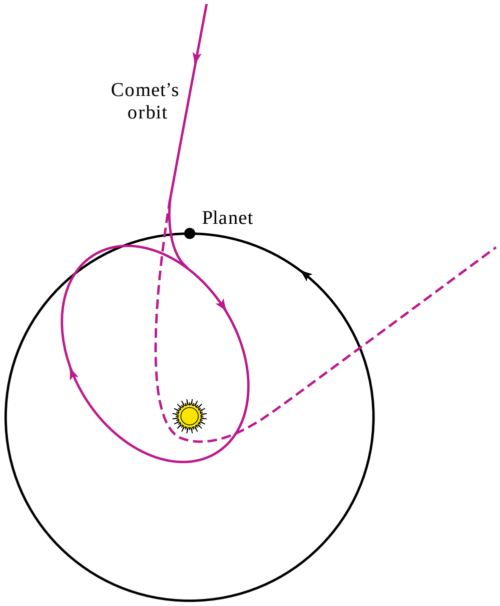


FIGURE 8-20 Transforming a Long-Period Comet into a Short-Period Comet The gravitational force of a planet can change a comet's orbit. Initially, on highly elliptical orbits, comets are sometimes deflected into more circular paths that keep them in the inner solar system.

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WEB LINK 8.12

FIGURE 8-21 The Fragmentation of Comet LINEAR On July 26, 2000, Comet LINEAR passed its perihelion 0.74 AU from the Sun. Within days, the comet was observed to have fragmented, like comets Shoemaker-Levy 9 and West (among many others) before it. (European Southern Observatory)

The comet's disintegration provided an important clue to its structure. For Shoemaker-Levy 9 to break up in the first place tells astronomers that its nucleus must have been held together very weakly. It may actually have been composed of separate pieces that had stuck together until Jupiter's tidal force pulled them apart. Since then, astronomers have observed at least three other comets break up, in 1999, 2000 (Comet LINEAR) and 2001. These observations suggest that this structure may be typical of other comets as well.

Comets occasionally lose mass quickly by ejecting it in bursts. Several times, starting in September 1995, astronomers observed Comet Hale-Bopp eject 7 to 10 times more mass than usual (Figure 8-22). Astronomers believe that this event resulted from surface ice and dust being heated by the Sun and then being rapidly ejected from a local region on the comet's surface called a *vent.* Hale-Bopp rotates with a period of about 12 hours. The ejected matter therefore formed a pinwheel-shaped distribution spiraling from the comet's nucleus at a speed of 109 km/hr (68 mph). While the ejected matter did not represent a significant fraction of the comet's mass, its light-reflecting dust made it look like a huge comet fragment.

MOVIE MISCONCEPTIONS

Asteroid (NBC Television Miniseries, 1998)
(© H. Mikuz)

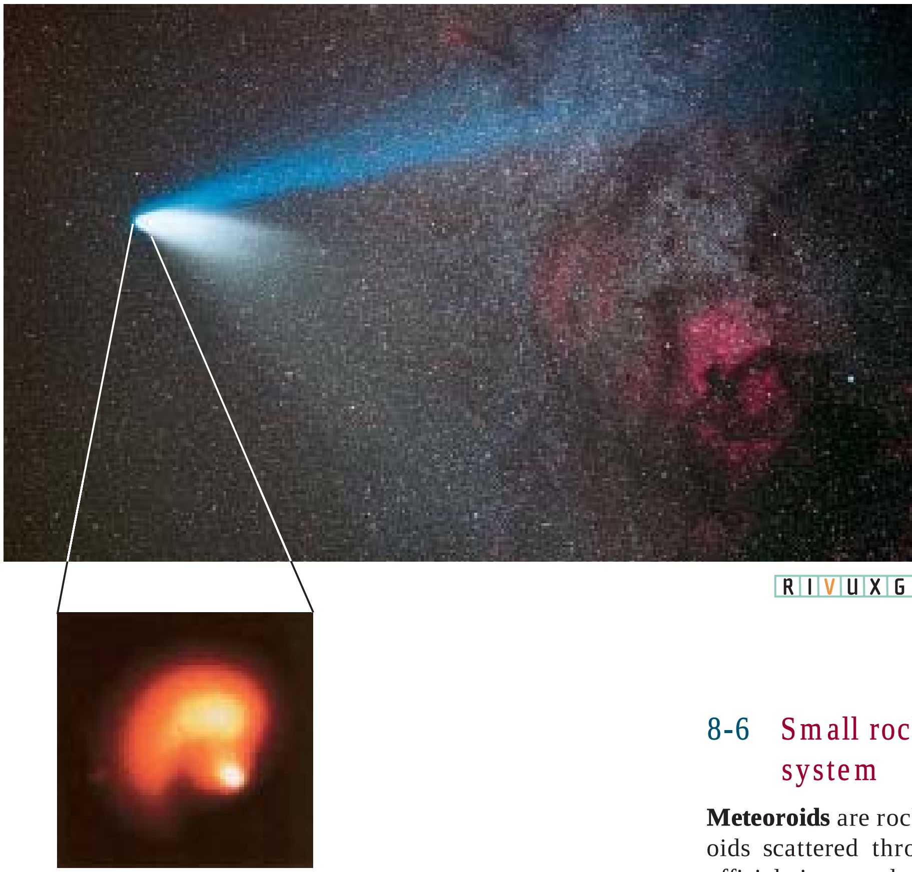
The made-for-TV movie *Asteroid* opens with a comet flying through a field of asteroids. This is the same comet the main character, Dr. Lily McKeen, an astronomer from Colorado, has been studying as it makes its trip through the solar system. Dr. McKeen discovers that as the comet passed through the asteroid belt it struck and dislodged two asteroids from their harmless orbits, sending them Earthward. The small one will create an explosion more powerful than the atomic bomb dropped on Hiroshima and the bigger one could send the Earth into another ice age. Dr. McKeen decides it is time to notify Washington of the impending catastrophe.

In the movie, the comet was completely unscathed by the encounters and continues on its original orbit. There are several scientific inaccuracies with this scene. Describe the errors. *Hint:* consider, among other things, the sizes and chemical compositions of comets and asteroids.

If this type of interaction were possible, then the likelihood of asteroids coming earthward would be quite high, because each year several comets actually pass through the asteroid belt. Movie plots like the one presented in *Asteroid* create fear that the Earth is in imminent danger of a life-threatening impact. Such concerns can be used to justify spending billions of dollars for a system to detect these bodies and defend the Earth from them. Is this concern justified? You may find a search of the Web useful in answering this question, but be careful to check the credentials of the sources you use and cite.

Near the end of the movie *Asteroid,* there is a scene showing the audience the original comet flying briskly across the sky with its tail trailing behind it. What two aspects of this scene are unrealistic?

(Answers appear at the end of the book.)



WEB LINK 8.13 **FIGURE 8-22** Comet Hale-Bopp Discovered on July 23, 1995, this comet was at its breathtaking best in mid-1997. Did you see it? Inset: Jets of gas and debris were observed shooting out from Comet Hale-Bopp several times. This image shows the comet nucleus (lower bright region), an ejected piece of the comet's surface (upper bright region), and a spiral tail. The ejected piece eventually disintegrated, following the same spiral pattern as the tail. (Tony and Daphne Hallas, Astrophotos)

The Sun is not the only star around which comets orbit. A star labeled CW Leonis, about 500 light-years from Earth, is presently enlarging in size and vaporizing billions of comets around it. The spectra of the water vapor from these bodies has been observed.

METEOROIDS, METEORS, AND METEORITES

WEB LINK 8.14 As noted earlier, asteroids occasionally collide with each other, sending fragments into interplanetary space. These smaller pieces, along with rocky and metallic fragments from evaporating comets, and debris that never coalesced with larger bodies, are still strewn throughout the solar system. Indeed, by studying the chemistry of various asteroids, astronomers are now beginning to identify which asteroids were the origins for others. For example, asteroid Braille (named in honor of Louis Braille, developer of the alphabet for the blind), is a piece of debris 2 km long blasted off the 500-km-diameter asteroid Vesta.

8-6 Small rocky debris peppers the solar system

Meteoroids are rocky and metallic debris smaller than asteroids scattered throughout the solar system. Although no official size standard distinguishes the two, meteoroids are no more than a few tens of meters across, and the vast majority are smaller than a millimeter.

Meteoroids are often pulled by gravity into the Earth's atmosphere. Air friction generates so much heat that a meteoroid's outer layer begins to vaporize. (The same process creates the heat on the hull of the Space Shuttle as it reenters our atmosphere.) As the meteoroid penetrates farther into the air, leaving behind a trail of dusty gas, it becomes a **meteor** (Figure 8-23). Common names for these dramatic streaks of light flashing across the sky include *shooting stars*, *fireballs*, and *bolides*. Fireballs are meteors at least as bright as Venus; bolides are bright meteors that explode in the air. Therefore, "shooting stars" are not stars of any kind, nor are they dying stars. 5

8-7 Impact craters and meteor showers mark remnants of space debris on Earth

Most meteors vaporize completely before they can strike the Earth. Their dust settles to the ground, often carried by raindrops. (This is not the source of acid rain, however, which comes from natural and human-made gases ejected into the atmosphere.) Any part of a meteor that survives its fiery descent to Earth may leave an **impact crater.** Weather and

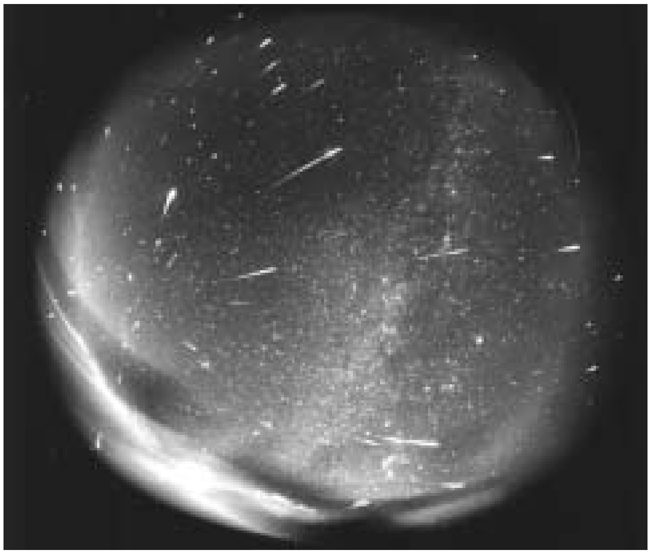


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FIGURE 8-23 Meteors A streak of light is produced when a piece of interplanetary rock or dust strikes the Earth's atmosphere at high speed. Seen through a fisheye lens, this image of the 2001 Leonids meteor shower shows at least a doxen meteors. (Juraj Toth/Comenius U. Bratislava/Modra Observatory/NASA)

FIGURE 8-24 The Barringer Crater An iron meteoroid measuring 50 m across struck the ground in Arizona 50,000 years ago. The result was this beautifully symmetric impact crater. (D. J. Roddy & K. Zeller/USGS)

water erosion are wearing away all of the 200 or so impact craters now known on the Earth, and thousands more have long since been drawn into the Earth by the motion of its tectonic plates. Indeed, those known today are all less than 500 million years old because of forces reshaping the Earth's surface.

One of Earth's best-preserved impact craters is the famous Barringer (or Meteor) Crater near Winslow, Arizona (Figure 8-24). Measuring 1.2 km across and 200 m deep, it formed 50,000 years ago when an iron-rich meteoroid some 50 m across (about half the length of a football field) struck the ground at 40,000 km/h (25,000 mph). The blast was like the detonation of a 20-megaton hydrogen bomb.

On a typical clear night, you can expect to see a meteor about every 10 minutes. However, at predictable times throughout each year, the Earth is inundated with them. These **meteor showers** occur when the Earth moves through the orbit of debris left behind by a comet (Figures 8-23, 8-25, and 8-26).

Some 30 meteor showers can be seen each year. Because the meteors in each shower appear to come from a fixed region of the sky, they are named after the constellation from which the meteors appear to radiate (Figure 8-26). For example, meteors in the Perseid shower appear to originate in the constellation Perseus. More than one meteor can be seen each minute at the peaks of such prodi-

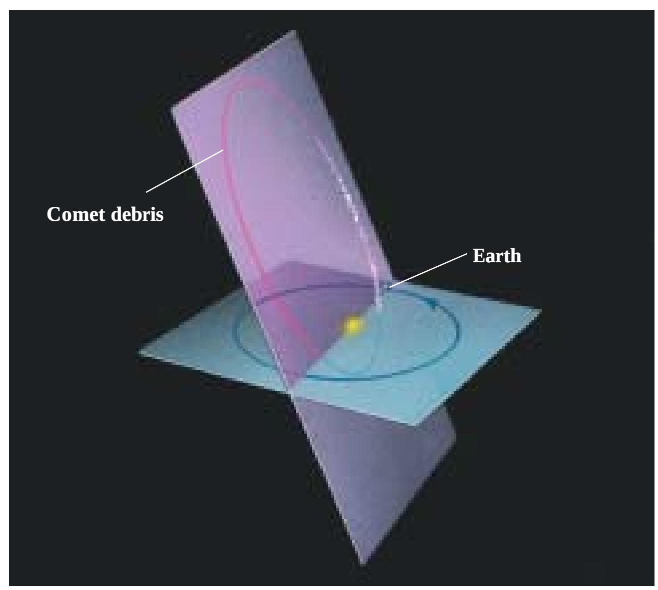
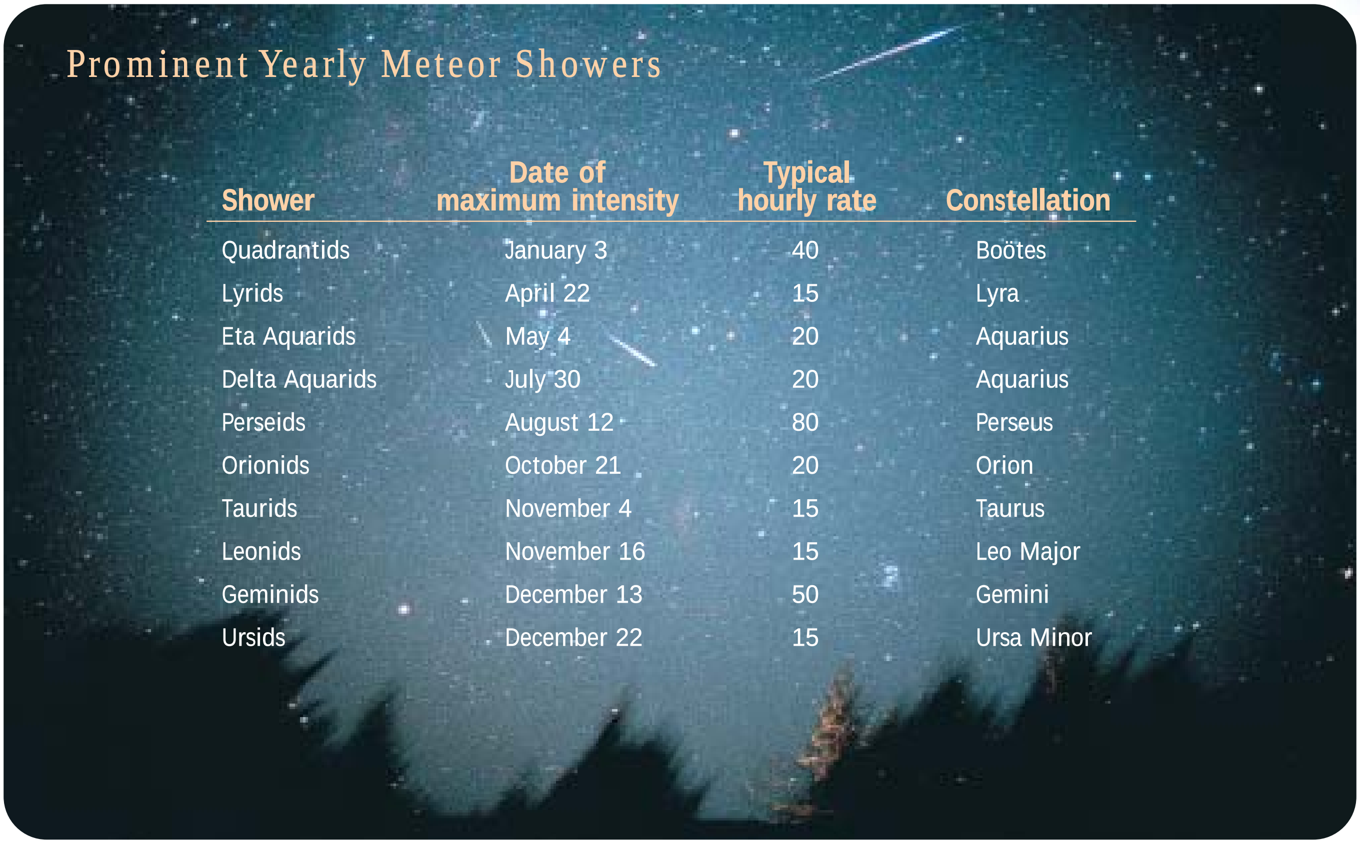


FIGURE 8-25 The Origin of Meteor Showers As comets dissipate, they leave debris behind that spreads out along their orbit. When the Earth plows through such material, many meteors can be seen emanating from the same place within a very short time—a meteor shower. As shown in this diagram, many comets have high orbital inclinations.



Prominent Yearly Meteor Showers

Shower	Date of maximum intensity	Typical hourly rate	Constellation
Quadrantids	January 3	40	Boötes
Lyrids	April 22	15	Lyra
Eta Aquarids	May 4	20	Aquarius
Delta Aquarids	July 30	20	Aquarius
Perseids	August 12	80	Perseus
Orionids	October 21	20	Orion
Taurids	November 4	15	Taurus
Leonids	November 16	15	Leo Major
Geminids	December 13	50	Gemini
Ursids	December 22	15	Ursa Minor

FIGURE 8-26 **Meteor Streaks Seen during a Meteor Shower** This table lists highly active, yearly meteor showers, which last for several days. The time exposure behind the table shows meteors streaking away from one place in the sky, in the constellation Perseus, during the Perseid meteor shower. (Akira Fujii, Chiro Astronomical Observatory, Koriyama, Japan) R I V U X G

gious meteor showers as the Perseids, which take place in the summertime and are among the best light shows in astronomy. Except for the Lyrids, these showers are best seen after midnight.

MORE TO KNOW 8-3 Meteors

8-8 Meteorites are space debris that land intact

Although most meteors completely vaporize in the atmosphere, some reach the ground before totally disintegrating. Such debris are called **meteorites,** and they come from a variety of sources: Many are believed to have been broken off from asteroids by collisions; some are debris that were never part of larger bodies; still others come from the Moon, Mars, and comets. We saw in Chapter 6, for example, how SNC meteorites offer clues to the chemistry of Mars.

Meteorites tell us the age of the solar system. Measuring the various radioactive elements in meteorites allows astronomers to determine how long ago they formed (see An Astronomer's Toolbox 4-2). The oldest known meteorites became solid bodies about 4.57 billion years ago.

People have been picking up debris from space for thousands of years. The descriptions of meteorites in historical Chinese, Indian, Islamic, Greek, and Roman literature show that early peoples placed special significance on these "rocks from heaven." They also have a practical "impact": Infalling space debris is increasing the Earth's mass by more than 300 tons per day on average.

FIGURE 8-27 A Stony Meteorite Most meteorites that fall to Earth are stones. Many freshly discovered specimens, like the one shown here, are coated with thin, dark crusts. This stony meteorite fell in Texas. (R. A. Oriti)

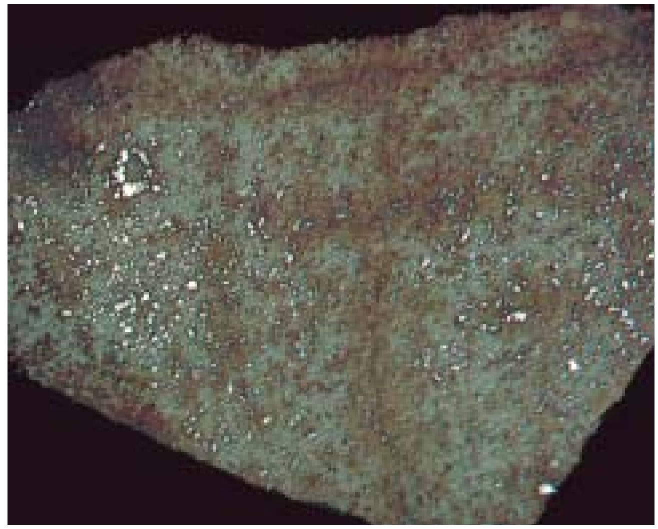


FIGURE 8-28 A Cut and Polished Stone Some stony meteorites contain tiny specks of iron, which can be seen when the stones are cut and polished. This specimen was discovered in California. (R. A. Oriti)

Meteorites are classified as stones, stony-irons, and irons. Most **stony meteorites** look much like ordinary rocks, although some are covered with a dark *fusion crust,* created when the meteorite's outer layer melts during its fiery descent through the atmosphere (Figure 8-27). When a stony meteorite is cut in two and polished, tiny flecks of iron are sometimes found in the rock (Figure 8-28).

Meteorites with a high iron content can be located with a metal detector. They also look unusual and hence are more likely to be noticed. Consequently, the easily found iron and stony-iron meteorites dominate most museum collections. Nevertheless, stony meteorites account for about 95% of all meteoritic material that falls on the Earth.

Iron meteorites (Figure 8-29) may also contain from 10% to 20% nickel by weight. Iron is moderately abundant in the universe as well as being one of the most common rock-forming elements, so it is not surprising that iron is an important constituent of asteroids and meteoroids. Another element, iridium, is common in the iron-rich minerals of meteorites but rare in ordinary rocks because most iridium settled deep into the Earth eons ago. Measurements of iridium in the Earth's crust can thus tell us the rate at which meteoritic material has been deposited on the Earth over the ages.

In 1808, Count Alois von Widmanstätten, director of the Imperial Porcelain Works in Vienna, discovered a conclusive test for the most common type of iron meteorite. Most irons have a unique structure of long nickel-iron crystals called **Widmanstätten patterns,** which become visible when the meteorites are cut, polished, and briefly dipped into a dilute solution of acid (Figure 8-30). Because nickel-iron crystals can grow to lengths of several centimeters only if the molten metal cools slowly over many millions of years,

FIGURE 8-29 An Iron Meteorite Irons are composed almost entirely of iron-nickel minerals. The surface of a typical iron is covered with thumbprintlike depressions created as the meteorite's outer layers vaporized during its high-speed descent through the atmosphere. This specimen was found in Australia. (R. A. Oriti)

FIGURE 8-30 Widmanstätten Patterns When cut, polished, and etched with a weak acid solution, most iron meteorites exhibit interlocking crystals in designs called Widmanstätten patterns. This meteorite was found in Australia. (R. A. Oriti)

FIGURE 8-31 A Stony-Iron Meteorite Stony-irons account for about 1% of all meteorites that fall to Earth. This specimen, a variety of stony-iron called a pallasite, was found in Chile. (Chip Clark)

Widmanstätten patterns are never found in counterfeit meteorites, or "meteorwrongs."

The final category of meteorites, the **stony-irons,** consists of roughly equal amounts of rock and iron. Figure 8-31, for example, shows the greenish mineral olivine suspended in a matrix of iron.

To understand why different types of meteorites exist, we consider their formation. Most meteorites were once pieces of asteroids. Heat from the rapid decay of radioactive isotopes melted newly formed asteroid interiors. Over the next few million years, differentiation occurred, just as in the young Earth. Iron sank toward the asteroid's center, while lighter rock floated up to the asteroid's surface. Iron meteorites are fragments of asteroid cores, and stones are samples of their crusts. Stony-irons are believed to come from the boundary regions between the iron cores and stony crusts.

A class of rare stony meteorites, **carbonaceous chondrites,** shows no evidence of ever having been melted as parts of asteroids. These rarities may therefore be primordial material from which our solar system was created. Carbonaceous chondrites contain complex carbon compounds and as much as 20% water bound into their minerals. The organic compounds would have been broken down and the water driven out if these meteorites had been significantly heated. Asteroid Mathilde, shown in Figure 8-8, has a very dark gray color and virtually the same spectrum as a carbonaceous chondrite meteorite, so it is likely composed of primordial material.

Amino acids, the building blocks of proteins upon which terrestrial life is based, are among the organic compounds occasionally found inside carbonaceous chondrites, although these may be contaminants acquired after the meteoroids entered the Earth's atmosphere. Nevertheless, some scientists suspect that carbonaceous chondrites may have played a role in the origin of life on Earth.

8-9 The Tunguska mystery and the Allende meteorite provide evidence of catastrophic collisions

At 7:14 A.M. local time on June 30, 1908, a spectacular explosion occurred over the Tunguska region of Siberia. The blast, comparable to a nuclear detonation of several megatons, knocked a man off his porch some 60 km away and was audible more than 1000 km away. Millions of tons of dust were injected into the atmosphere, darkening the air as far away as California.

Preoccupied with wars, along with political and economic upheaval, neither Russia nor its successor, the former Soviet Union, sent a scientific expedition to the site until 1927. At that time, Soviet researchers found that trees had been seared and felled radially outward in an area about 30 km in diameter (Figure 8-32). There was no clear evidence of a crater. In fact, the trees at "ground zero" were left standing upright, although they were completely stripped of branches and leaves. Because no significant meteorite samples were found, for many years scientists assumed that a small comet had struck the Earth.

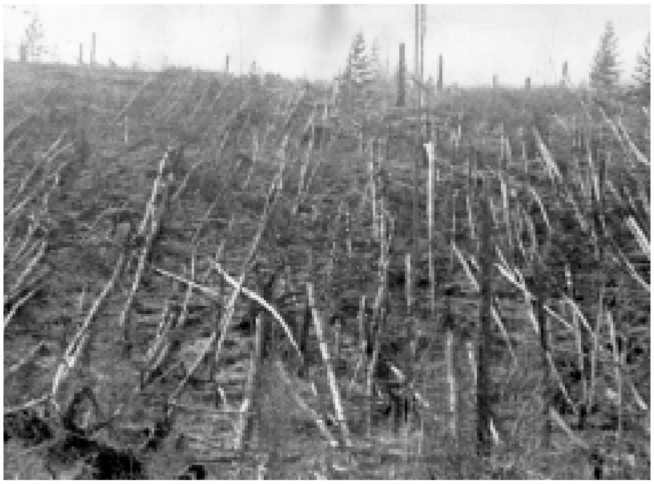


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FIGURE 8-32 Aftermath of the Tunguska Event In 1908 a stony asteroid traveling at supersonic speed struck the Earth's atmosphere and exploded over the Tunguska region of Siberia. Trees were blown down for many kilometers in all directions from the impact site. (SOVFOTO)

Recently, however, several teams of astronomers have argued that a small comet, composed primarily of light elements and ice, breaks up too high in the atmosphere to cause significant damage on the ground. They argue that the Tunguska explosion was actually caused by a small asteroid or large meteoroid traveling at supersonic speed. The Tunguska event is consistent with an explosion of an asteroid about 80 m (260 ft) in diameter entering the Earth's atmosphere at 79,000 km/h (50,000 mph) and exploding in the air as a result of becoming exceedingly hot.

A chance to study debris immediately after impact came shortly after midnight on February 8, 1969, when a brilliant, blue-white light shot across the night sky around Chihuahua, Mexico. Hundreds of people witnessed the dazzling display. The light disappeared in a spectacular, noisy explosion that dropped thousands of rocks and pebbles over the terrified onlookers. Within hours, teams of scientists were on their way to collect specimens of carbonaceous chondrites, collectively named the *Allende meteorite*, after the locality in which they fell (Figure 8-33).

One of the most significant discoveries to come from the Allende meteorite was evidence of the detonation of a nearby supernova 4.6 billion years ago. Among nature's most violent and spectacular phenomena, a *supernova explosion* occurs when a massive star dies. A massive star blows apart in a cataclysm that hurls matter outward at tremendous speeds, as we will see in Chapter 12. During this detonation, violent collisions between atomic nuclei produce a host of radioactive elements, including a short-lived radioactive isotope of aluminum. Based on its decay products, scientists found unmistakable evidence that this isotope once lay within the Allende meteorite. Some astronomers interpret this as evidence for a supernova in our vicinity at about the time the Sun was born. By compressing interstellar gas and dust, the supernova's shock wave may have helped stimulate the birth of our solar system.

8-10 An asteroid's impact with Earth apparently killed off the dinosaurs

In the late 1970s, the geologist Walter Alvarez and his father, physicist Luis Alvarez, discovered a different sort of shock wave closer to home. Working at a site of exposed marine limestone in the Apennine Mountains in Italy that had been on the Earth's surface 65 million years ago, the Alvarez team discovered an exceptionally high abundance of iridium in a dark-colored layer of clay between limestone strata (Figure 8-34).

Since this discovery was announced in 1979, a comparable layer of iridium-rich material has been uncovered at numerous sites around the world. In every case, geologic dating reveals that this apparently worldwide iridium-rich layer was deposited about 65 million years ago. Paleontologists were quick to realize the significance of this date, because it was 65 million years ago when all the dinosaurs rather suddenly became extinct. In fact, two-thirds of all the species on Earth disappeared within a brief span of time back then.

The Alvarez discovery suggests a startling explanation for the dramatic extinction of so much of the life that once inhabited our planet—an asteroid impact. An asteroid 10 km in diameter slamming into the Earth at high speed could have

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FIGURE 8-33 A Piece of the Allende Meteorite This carbonaceous chondrite fell near Chihuahua, Mexico, in February 1969. Note the meteorite's dark color, caused by a high abundance of carbon. Geologists believe that this meteorite is a specimen of primitive planetary material. The ruler is 15 cm long. (J. A. Wood)

FIGURE 8-34 Iridium-Rich Layer of Clay This photograph of strata in the Apennine Mountains of Italy shows a dark-colored layer of iridium-rich clay sandwiched between white limestone (below) from the late Mesozoic era and grayish limestone (above) from the early Cenozoic era. The coin is the size of a U.S. quarter. (W. Alvarez)

thrown enough dust into the atmosphere to block out sunlight for several years. As the temperature dropped drastically and plants died for lack of sunshine, the dinosaurs would have perished, along with many other creatures in the food chain that were highly dependent on vegetation. The dust eventually settled, depositing an iridium-rich layer over the Earth. Tiny, rodentlike creatures capable of ferreting out seeds and nuts were among the animals that managed to survive this holocaust, setting the stage for the rise of mammals and, consequently, the evolution of humans.

In 1992, a team of geologists suggested that the hypothesized asteroid crashed into a site in Mexico. They based this conclusion on glassy debris and violently shocked grains of rock ejected from the multiringed, 195-km-diameter Chicxulub Crater buried under the Yucatán Peninsula in Mexico (Figure 8-35). From the known rate at which radioactive potassium decays, the scientists have pinpointed the date when the asteroid struck—64.98 million years ago. In 1998, geologists digging on the Pacific Ocean floor discovered a piece of meteoritic debris with precisely the same age, apparently a piece of the offending asteroid. Other geologists and paleontologists are not yet convinced that an asteroid impact

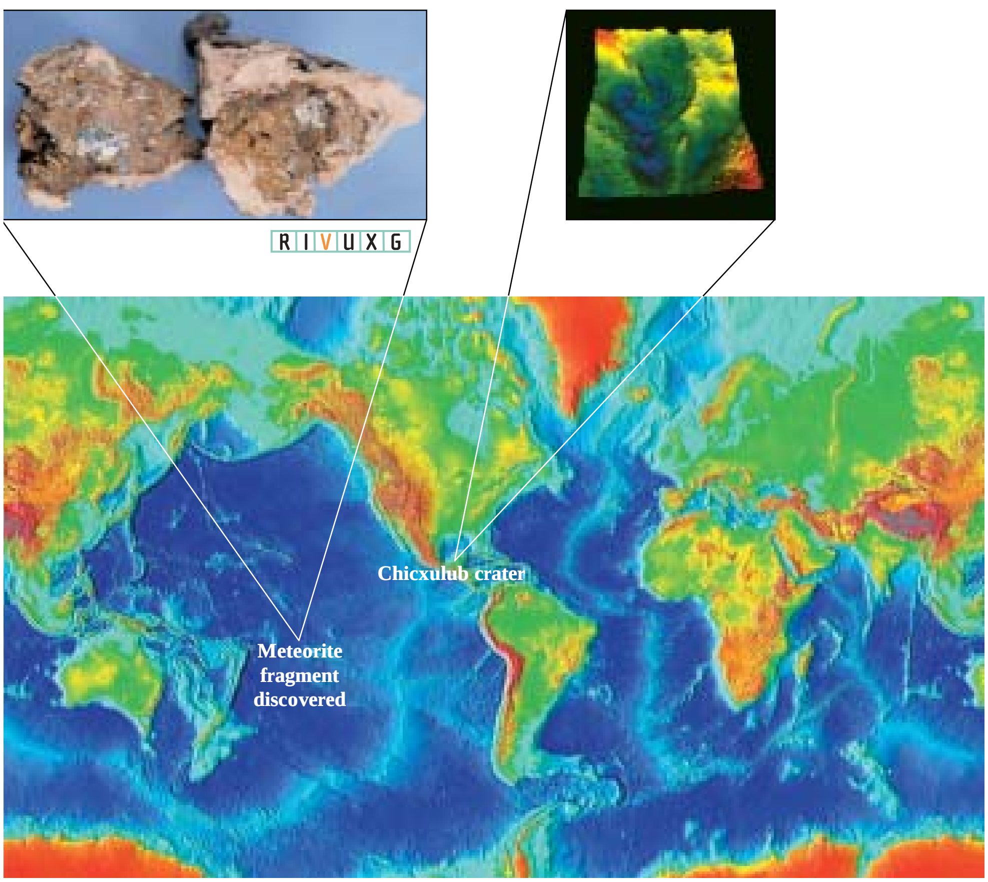

FIGURE 8-35 Confirming an Extinction-Level Impact Site Right inset: By measuring slight variations in the gravitational attraction of different materials under the Earth's surface, geologists create images of underground features. Concentric rings of the underground Chicxulub Crater, shown here, lie under a portion of the Yucatán Peninsula. This crater has been dated to 65 million years ago and is believed to be the site of the impact that led to the extinction of the dinosaurs. Left inset: A piece of 65-million-year-old meteorite discovered in the middle of the Pacific Ocean in 1998 and believed to be a fragment of the meteorite that struck the Yucatán Peninsula. The fragment, about a tenth of an inch long, was cut into two pieces, shown here. (Top left inset: Frank T. Kyte, UCLA; Top right inset: Virgil L. Sharpton, Lunar and Planetary Institute; Digital image by Peter W. Sloss, NOAA-NESDIS-NGDCD)

led to the extinction of the dinosaurs, but most agree that this hypothesis fits the available evidence better than any other explanation that has been offered so far.

The end of the dinosaurs' reign was not the only mass extinction caused by impacts from space. In 2001, evidence came to light from the Permian/Triassic boundary 250 million years ago that points to another devastating impact. This one wiped out 70 percent of the species of life living on land and 90 percent of those living in the oceans. Rocks from that time discovered in places from Japan to Hungary show evidence of coming from space in the form of fullerenes, soccer-ball-shaped molecules containing at least 60 carbon atoms. Trapped inside these fullerenes were gases that could only have been forced into them from stars. This signature of gas-filled fullerenes from space has also now been discovered in the layer of rock existing on the Earth's surface 65 million years ago.

Could such a catastrophic event happen again? So many asteroids cross the Earth's path that scientists agree that it is a matter of "when" rather than "if." The good news is that studies of craters show that larger asteroids strike the Earth significantly less often than do smaller ones. While asteroids large enough to create the Barringer Crater strike the Earth about once every 10,000 years, killer asteroids, like the one that struck the Yucatán, collide with Earth only once every 100 million years. The threat of a catastrophic impact by an asteroid or comet in our lifetimes, thankfully, is remote.

8-11 Frontiers yet to be discovered

The years of the *Pioneer* and *Voyager* spacecraft were the first golden era of solar system research. We are now in another such period, with spacecraft either in development or already going to planets, asteroids, comets, and even, as we will see shortly, out observing the weather in space. From the solar system debris astronomers hope to learn whether life on Earth was brought here from elsewhere by asteroid or meteoroid impacts. They also hope to answer such questions as the evolutionary history of the space debris, how much of Earth's water came here during the planet's formation and how much landed afterward from comet impacts, whether the asteroids have sufficiently valuable compositions to justify mining them, whether comets can be harvested to supply water and other materials for people colonizing the solar system, whether the Oort cloud really exists, and whether Pluto should be considered a Kuiper belt object.

Further Reading on These Topics

WHAT DID YOU KNOW?

1 *Are the asteroids a planet that was somehow destroyed?* No. The gravitational pull from Jupiter prevented a planet from ever forming in the asteroid belt. Also, the total mass of the asteroids is much less than even the mass of tiny Pluto, the smallest planet.

2 *How far apart are the asteroids on average?* The distance between asteroids averages 10 million kilometers.

3 *Why do comets have tails?* Gas and dust that evaporate from the comet nucleus are pushed away from the Sun by sunlight and the solar wind. We see the tails by the sunlight they scatter in our direction.

4 *In what direction does a comet tail point?* Comets' gas tails point directly away from the Sun; their dust tails make arcs pointing away from the Sun.

5 *What is a shooting star?* A shooting star is a piece of space debris plunging through the Earth's atmosphere—a meteor. It is not a star.

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KEY IDEAS

Asteroids

• Tens of thousands of belt asteroids with diameters larger than a kilometer are known to orbit the Sun between the orbits of Mars and Jupiter. The gravitational attraction of Jupiter depletes certain orbits within the asteroid belt. The resulting gaps, called Kirkwood gaps, occur at simple fractions of Jupiter's orbital period.

• Jupiter's and the Sun's gravity combine to capture Trojan asteroids in two locations, called stable Lagrange points, along Jupiter's orbit.

• The Apollo asteroids move in highly elliptical orbits that cross the orbits of Mars and Earth. Many of these asteroids will eventually strike one of the inner planets.

Comets

• Comets are fragments of ice and rock that generally move in highly elliptical orbits about the Sun often at a great inclination to the plane of the ecliptic.

• As a comet approaches the Sun, its icy nucleus develops a luminous coma surrounded by a vast hydrogen envelope. A gas (or ion) tail and a dust tail extend from the comet, pushed away from the Sun by the solar wind and radiation pressure.

• Many comets orbit the Sun in the Kuiper belt, a doughnut-shaped region beyond Pluto. Billions of cometary nuclei are also believed to exist in the spherical Oort cloud located far beyond Pluto.

Meteoroids, Meteors, and Meteorites

• Boulders and smaller rocks in space are called meteoroids. When a meteoroid enters the Earth's atmosphere, it produces a fiery trail, and it is then called a meteor. If part of the object survives the fall, the fragment that reaches the Earth's surface is called a meteorite.

• Meteorites are grouped in three major classes according to their composition: iron, stony-iron, and stony meteorites. Rare stony meteorites called carbonaceous chondrites may be relatively unmodified material from the primitive solar nebula. These meteorites often contain organic hydrocarbon compounds, including amino acids.

• Fragments of rock from "burned-out" comets produce meteor showers.

• An analysis of the Allende meteorite suggests that a nearby supernova explosion may have been involved in the formation of the solar system some 4.6 billion years ago.

• An asteroid that struck the Earth 65 million years ago probably contributed to the extinction of the dinosaurs and many other species. Such devastating impacts occur on average every 100 million years.

REVIEW QUESTIONS

1 Why are asteroids, meteoroids, and comets of special interest to astronomers who want to understand the early history of the solar system?

2 Describe the asteroid belt.

3 To test your understanding of the asteroid belt, do Interactive Exercise 8-1 on the Web or on the CD-ROM. You can print out your results, if required.

4 Why are there many small asteroids but only a few very large ones?

5 Does each comet always maintain its tails? Explain.

6 What are Kirkwood gaps and what causes them?

7 What are the Trojan asteroids, and where are they located?

8 Describe the three main classifications of meteorites. How do astronomers believe these different types of meteorites originated?

9 Suppose you found a rock that you suspect to be a meteorite. Describe some of the things you could do to see if it were a meteorite or a "meteorwrong."

10 Why do astronomers believe that many meteoroids come from asteroids, whereas the debris that creates meteor showers is related to comets?

11 Make a drawing that describes the structure of a comet.

12 To test your understanding of comets, do Interactive Exercise 8-2 on the Web or on the CD-ROM. You can print out your results, if required.

13 Why is the phrase "dirty snowball" an appropriate characterization of a comet's nucleus?

14 What is the Kuiper belt, and how is it related to debris left over from the formation of the solar system?

15 Why do scientists think the Tunguska event was caused by a large meteoroid and not a comet?

16 Which tail in Figure 8-22 is the gas tail and which is the dust tail? Justify your answers.

ADVANCED QUESTIONS

The answers to computational problems, which are preceded by an asterisk (*), appear at the end of the book.

17 How did the regolith on Eros form?

18 Why are comets generally brighter after passing perihelion (closest approach to the Sun) than before reaching perihelion?

19 Can you think of another place in the solar system where a phenomenon similar to the Kirkwood gaps in the asteroid belt exists? Explain.

20 Where on Earth might you find large numbers of stony meteorites that have not been significantly changed by weathering?

*21 Assuming a constant rate of meteor infall, how much mass has the Earth gained in the past 4.6 billion years?

DISCUSSION QUESTIONS

22 Suppose it was discovered that the asteroid Hermes had been perturbed in such a way as to put it on a collision course with Earth. Describe what you would do to counter such a catastrophe using present technology.

23 From the abundance of craters on the Moon and Mercury, we know that numerous asteroids and meteoroids struck the inner planets during the early history of the solar system. Is it reasonable to suppose that numerous comets also pelted the planets 4.0 to 4.5 billion years ago? Speculate about the effects of such a cometary bombardment, especially with regard to the evolution of the primordial atmospheres of the terrestrial planets and oceans on Earth.

WHAT IF …

24 An ocean on Earth were struck by a comet nucleus several kilometers across? What physical effects would occur to the Earth?

25 We passed through the tail of a comet? What would happen to the Earth and life on it?

26 As some astronomers have recently argued, passage of the solar system through an interstellar cloud of gas could perturb the Oort cloud, causing many comets to deviate slightly from their original orbits? What might be the consequences for Earth?

27 All the space debris (asteroids, meteoroids, and comets) had been cleared out of the solar system 3.8 billion years ago? What would have been different in the history of the Earth and in the history of life on the Earth?

WEB/CD-ROM QUESTIONS

28 Search the Web to find out why some scientists disagree with the idea that a tremendous impact led to the demise of the dinosaurs. (They do not dispute that the impact occurred, only what its consequences were.) What are their arguments? From what you learn, what is your opinion?

29 Several scientific research programs are dedicated to the search for near-Earth objects (NEOs), especially those that might someday strike our planet. Search the Web for information about at least one of these programs. How does the program search for NEOs? How many NEOs are known and how many has this program found? Will any of these NEOs pose a threat in your lifetime?

30 Search the Web to learn if there are any comets visible at present. List them. What constellations are they presently in? Are any visible to the naked eye? (Recall that the unaided human eye sees objects brighter than about sixth magnitude.)

OBSERVING PROJECTS

31 Make arrangements to view an asteroid. At opposition, some of the largest asteroids are bright enough to be seen through a modest telescope. Check the "Minor Planets" section of the current issue of the *Astronomical Almanac* to see if any bright asteroids are near opposition. If so, check the current issue as well as the most recent January issue of *Sky & Telescope* for a star chart showing the asteroid's path among the constellations. You will need such a chart to distinguish the asteroid from background stars. Observe the asteroid on at least two occasions separated by a few days. On each night, draw a star chart of the objects in your telescope's field of view. Has the position of one starlike object shifted between observing sessions? Does the position of the moving object agree with the path plotted on published star charts? Do you feel confident that you have in fact observed an asteroid?

32 Make arrangements to view a comet through a telescope. Because astronomers discover roughly a dozen comets each year, a comet is usually visible somewhere in the sky. Unfortunately, because most comets are quite dim, you will need access to a moderately large telescope. Consult the Web or recent issues of the *IAU Circular,* published by the International Astronomical Union's Central Bureau for Astronomical Telegrams, which contains predicted positions and the anticipated brightness of comets in the sky. Also, if there is an especially bright comet in the sky, the latest issue of *Sky & Telescope* might contain useful information. Is a comet visible and do you have a telescope at your disposal? If so, can you distinguish the comet from background stars? Can you see its coma? How many tails do you see?

33 Make arrangements to view a meteor shower. The date of maximum intensity in Figure 8-26 is the best time to observe a particular shower, although good displays can often be seen a day or two before and after the maximum. In order to see a fine meteor display, you need a clear, moonless sky. The Moon's presence above the horizon can significantly detract from the number of faint meteors you will be able to see.

STARRY NIGHT

34 Use *Starry Night Backyard*™ software to observe several comets. (a) Set the program to Atlas mode (*Go/Atlas*). Turn off the planets and Sun (*Sky/Planets/Sun*). Set the date to 3/22/97. Go to either +90° or –90° latitude (north or south pole). Choose Comet Hale-Bopp from the Planet list window (*Windows/Planet List/Comets*) by double-clicking on Hale-Bopp. Zoom in until you can see the comet and its tail. Predict in what direction the Sun is located relative to the comet and explain how you made your prediction. To verify that you are correct, zoom out to 90°, turn on the planets and Sun (*Sky/Planets/Sun*) to locate the Sun. If necessary use the hand cursor to move the sky in the direction of your prediction toward the Sun. Were you correct? (b) Using the Planet List, double-click on the name of another comet to center on it, but do not zoom in. Then move the sky with the hand cursor and locate the Sun. From your observations, predict the direction of the comet's tail on the sky, and explain how you made your prediction. Center again on the comet and zoom in until you can see its tail. Was your prediction correct?