25 Meteorites, Asteroids, and Comets

Comet McNaught was bright in the sky as seen from the southern hemisphere in January and February 2007. Streamers in the tail are produced by variations in the release of gas and dust from the nucleus. (Peter Daalder)

Guidepost

Compared with planets, the comets and asteroids are unevolved objects much as they were when they formed 4.6 billion years ago. The fragments of these objects that fall to Earth, the meteors and meteorites, will give you a close look at these ancient planetesimals. As you explore, you will find answers to four essential questions:

- **Where do meteors and meteorites come from?**
- **What are the asteroids?**
- **Where do comets come from?**
- **What happens when an asteroid or comet hits Earth?**

The subjects of this chapter are often faint and hard to find. As you study them, you will answer an important question concerning the design of scientific experiments:

- How Do We Know? **How can what scientists notice bias their conclusions?**

When you finish this chapter, you will have an astronomer's insight into your place in nature. You live on the surface of a planet. There are other planets. Are they inhabited too? That is the subject of the next chapter.

When they shall cry "PEACE, PEACE" then cometh sudden destruction!

COMET'S CHAOS?—What Terrible events will the Comet bring?

FROM A RELIGIOUS PAMPHLET PREDICTING THE END OF THE WORLD BECAUSE OF THE APPEARANCE OF COMET KOHOUTEK, 1973

YOU ARE NOT AFRAID of comets, of course; but not long ago, people viewed them with terror. A few centuries ago, comets were thought to predict the deaths of kings or the arrival of plague. Even in 1910, when Earth passed through the tail of Comet Halley, millions of people panicked, thinking the world would be destroyed. Householders in Chicago stuffed rags around doors and windows to keep out poisonous gas, and con artists in Texas sold comet pills and inhalers to ward off the fumes.

Should we snicker at our silly ancestors? Today we see comets as graceful and beautiful visitors to our skies (■ Figure 25-1). Astronomers understand that comets and their rocky cousins the asteroids are ancient bodies that carry precious clues to the birth of the planets 4.6 billion years ago. But the evidence also shows that comets and asteroids do hit Earth now and then, and such an impact could cause a civilization-ending catastrophe. Perhaps comets and asteroids deserve our attention and cautious respect.

Unfortunately, comets and asteroids are far beyond your reach, so they are a challenge to study. You can begin with the fragments of these bodies that fall to Earth—the meteorites.

25-1 Meteorites

IN THE AFTERNOON OF NOVEMBER 30, 1954, Mrs. E. Hulitt Hodges of Sylacauga, Alabama, lay napping on her living room couch. An explosion and a sharp pain jolted her awake, and she found that a meteorite had smashed through the ceiling and

■ **Figure 25-1**

Comet Hyakutake swept through the inner solar system in 1996 and was dramatic in the northern sky. Seen here from Kitt Peak National Observatory, the comet passed close to the north celestial pole (behind the observatory dome in this photo). Notice the Big Dipper below and to the left of the head of the comet. (Courtesy Tod Lauer) bruised her left leg. Mrs. Hodges is the only person known to have been injured by a meteorite. Coincidentally, Mrs. Hodges lived right across the street from the Comet Drive-In Theater.

Meteorite impacts on homes are not common, but they do happen. Statistical calculations show that a meteorite should damage a building somewhere in the world about once every 16 months. About two meteorites large enough to produce visible impacts strike somewhere on Earth each day, but most meteors are small particles ranging from a few centimeters down to microscopic dust. Earth gains about 40,000 tons of mass per year from meteorites of all sizes. That seems like a lot, but it is less than a thousandth of a trillionth of Earth's total mass.

Recall from Chapter 19 that astronomers distinguish between the words *meteoroid, meteor,* and *meteorite.* A small body in space is a meteoroid, but once it begins to vaporize in Earth's atmosphere it is called a meteor. If it survives to strike the ground, it is called a meteorite.

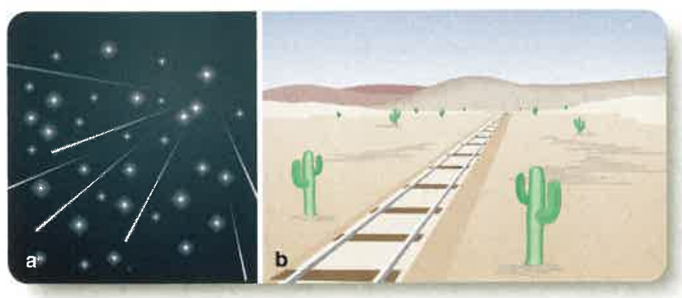
You should have two main questions concerning meteorites: Where in the solar system do these objects come from, and what can meteorites tell you about the origin of the solar system? To answer these questions, you must consider the orbits of meteoroids and the minerals found in meteorites.

Meteoroid Orbits

Meteoroids are much too small to be visible through even the largest telescope. They are visible only when they fall into Earth's atmosphere at 10 to 30 km/s, roughly 30 times faster than a rifle bullet, and are vaporized by friction with the air. The average meteoroid is about the mass of a paper clip and vaporizes at an altitude of about 80 km above Earth's surface. In doing so it produces a bright streak of fire that you see as a meteor. The trail of a meteor points back along the path of the meteoroid, so if you could study the direction and speed of meteors, you could get clues to their orbits.

One way to backtrack meteor trails is to observe meteor showers. On any clear night, you can see 3 to 15 meteors an hour, but on some nights you can see a shower of dozens of meteors an hour that are obviously related to each other. To confirm this, try observing a meteor shower. Pick a shower from ■ Table 25-1 and on the appropriate night stretch out in a lawn chair and watch a large area of the sky. When you see a meteor, sketch its path on the appropriate sky chart from the back of this book. In just an hour or so you will discover that most of the meteors you see seem to come from a single area of the sky, the **radiant** of the shower (■ Figure 25-2a). In fact, meteor showers are named after the constellation from which they seem to radiate. The Perseid shower radiates from the constellation Perseus in mid-August.

Observing a meteor shower is a natural fireworks show, but it is even more exciting when you understand what a meteor shower tells you. The fact that the meteors in a shower appear to come from a single point in the sky, the radiant, means that the meteoroids were traveling through space along parallel paths. When they encounter Earth and are vaporized in the upper atmosphere, you see their fiery tracks in perspective; so they appear



■ **Figure 25-2**

(a) Meteors in a meteor shower enter Earth's atmosphere along parallel paths, but perspective makes them appear to diverge from a radiant point. (b) Similarly, parallel railroad tracks appear to diverge from a point on the horizon.

■ **Table 25-1 | Meteor Showers**

Shower	Dates	Hourly Rate	Radiant* R. A.	Radiant* Dec.	Associated Comet
Quadrantids	Jan. 2–4	30	15^h24^m	50°	
Lyrids	April 20–22	8	18^h4^m	33°	1861 I
η Aquarids	May 2–7	10	22^h24^m	0°	Halley?
δ Aquarids	July 26–31	15	22^h36^m	−10°	
Perseids	Aug. 10–14	40	3^h4^m	58°	1982 III
Orionids	Oct. 18–23	15	6^h20^m	15°	Halley?
Taurids	Nov. 1–7	8	3^h40^m	17°	Encke
Leonids	Nov. 14–19	6	10^h12^m	22°	1866 I Temp
Geminids	Dec. 10–13	50	7^h28^m	32°	

*R. A. and Dec. give the celestial coordinates (right ascension and declination) of the radiant of each shower.

to come from a single radiant point, just as railroad tracks seem to come from a single point on the horizon (Figure 25-2b).

Studies of meteor-shower radiants reveal that these meteors are produced by bits of matter orbiting the sun along the paths of comets. The vaporizing head of the comet releases bits of rock that become spread along its entire orbit (■ Figure 25-3). When Earth passes through this stream of material, you see a meteor shower. In some cases the comet has wasted away and is no longer visible, but in other cases the comet is still prominent though somewhere else along its orbit. For example, in May Earth comes near the orbit of Comet Halley, and Earthlings see the Eta Aquarids shower. Around October 20, Earth passes near the other side of the orbit of Comet Halley, and you can see the Orionids shower. Evidently at least some meteoroids come from comets.

Even when there is no shower, you will still see meteors, which are called **sporadic meteors** because they are not part of specific showers. Many of these are produced by stray bits of matter that were released long ago by comets. Such comet debris gets spread throughout the inner solar system, and bits fall into Earth's atmosphere even when there is no shower.

Another way to backtrack meteor trails is to photograph the same meteor from two locations on Earth a few miles apart. Then astronomers can use triangulation to find the altitude, speed, and direction of the meteor as it moves through the atmosphere and work backward to find out what its orbit looked like before it entered Earth's atmosphere. Not surprisingly, these studies confirm that meteors belonging to showers and some sporadic meteors have orbits that are similar to the orbits of comets. A few sporadic meteors, however, have orbits that lead back to the asteroid belt between Mars and Jupiter. From this you can conclude that meteors have a dual source: Many come from comets, but some come from the asteroid belt. To learn more about meteors, you need to examine those that make it to Earth's surface, the meteorites. You can begin with their dramatic arrivals.

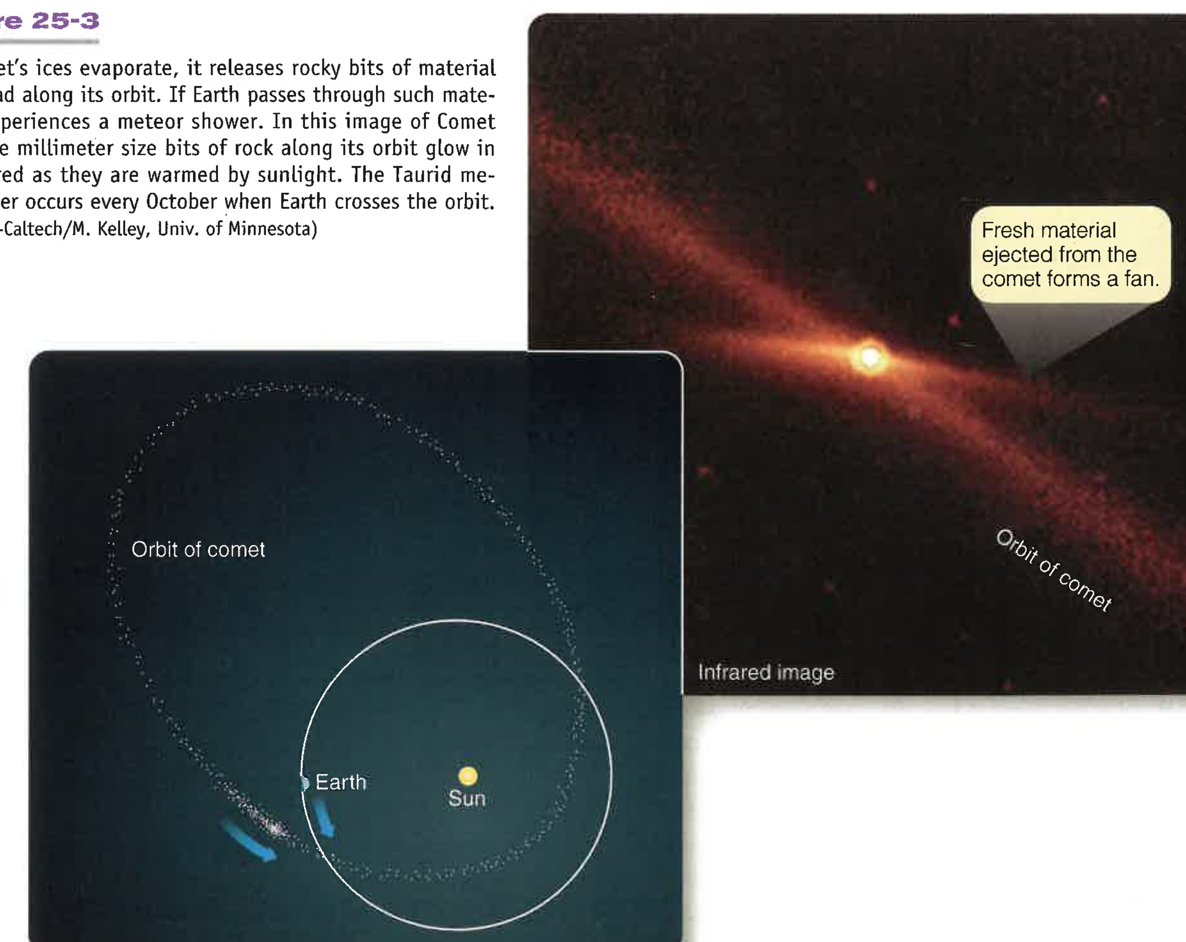
Meteorite Impacts on Earth

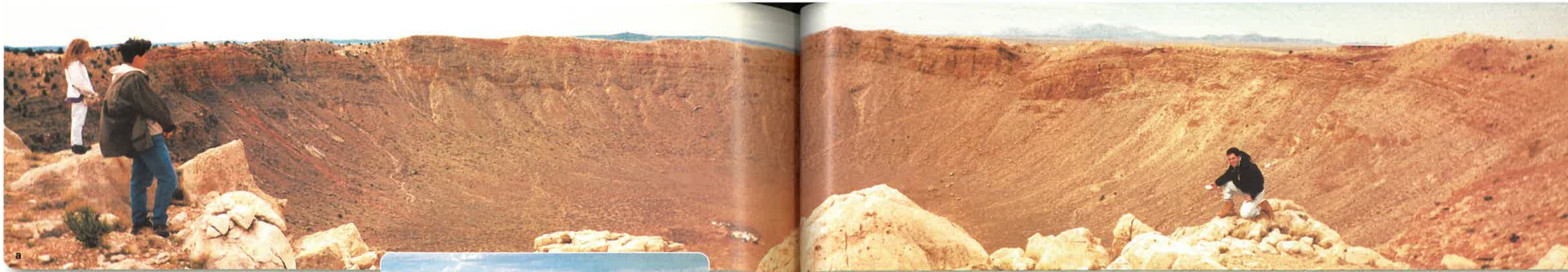
When a meteor is massive enough and strong enough to survive its plunge through Earth's atmosphere and reach Earth's surface, it is called a meteorite. A large meteorite hitting Earth might dig an impact crater much like those on the moon (see page 464).

Over 150 impact craters have been found on Earth. The Barringer Meteorite Crater near Flagstaff, Arizona, is a good example (■ Figure 25-4). It was created about 50,000 years ago by a meteorite about as large as a big building (40 m) that hit at a

■ **Figure 25-3**

As a comet's ices evaporate, it releases rocky bits of material that spread along its orbit. If Earth passes through such material, it experiences a meteor shower. In this image of Comet Encke, the millimeter size bits of rock along its orbit glow in the infrared as they are warmed by sunlight. The Taurid meteor shower occurs every October when Earth crosses the orbit. (NASA/JPL-Caltech/M. Kelley, Univ. of Minnesota)





Active Figure 25-4

(a) The Barringer Meteorite Crater (near Flagstaff, Arizona) is nearly a mile in diameter and was formed about 50,000 years ago by the impact of an iron meteorite roughly 40 m in diameter. It hit with energy equivalent to that of a 3-megaton hydrogen bomb. Notice the raised and deformed rock strata all around the crater. For scale, locate the brick building on the far rim at right. (M. Seeds) (b) Like all larger-impact features, the Barringer Meteorite Crater has a raised rim and scattered ejecta. (USGS)

speed of 11 km/s and released as much energy as a large thermonuclear bomb. Debris at the site shows that the meteorite was composed of iron.

The Barringer crater is 1.2 km in diameter and 200 m deep. It seems large when you stand on the edge, and the hike around it, though beautiful, is long and dry. Nevertheless, the crater is actually small compared with some other impact features on Earth. About 65 million years ago, an impact in the northern Yucatán of Central America produced a crater, now covered by sediment, that was between 180 and 300 km in diameter, almost as big as the state of Ohio. This impact has been blamed for changing Earth's climate and causing the extinction of the dinosaurs. Later in this chapter, you can come back to this Earth-shaking event.

Large meteorites can produce large craters, but most meteorites are small and don't create significant craters. Also, craters erode rapidly on Earth, so most meteorites are found without associated craters. The best place to look for meteorites turns out to be certain areas of Antarctica—not because more meteorites fall there but because they are easy to recognize on the icy terrain. Most meteorites look like Earth rocks, but on the ice of Antarctica there are no natural rocks. Also, the slow creep of the ice toward the sea concentrates the meteorites in certain areas where the ice runs into mountain ranges, slows down, and evaporates. Teams of scientists travel to Antarctica and ride snowmobiles in systematic sweeps across the ice to recover meteorites (■ Figure 25-5).

Meteorites that are seen to fall are called **falls;** a fall is known to have occurred at a given time and place, and thus the meteorite is well documented. A meteorite that is discovered but was not seen to fall is called a **find.** Such a meteorite could have fallen thousands of years ago. The distinction between falls and finds will be important as you analyze the different kinds of meteorites.

An Analysis of Meteorites

Meteorites can be divided into three broad categories: *Iron* meteorites are solid chunks of iron and nickel, *stony* meteorites are silicate masses that resemble Earth rocks, and *stony-iron* meteorites are mixtures of iron and stone. These types are illustrated in ■ Figure 25-6.

Iron meteorites are easy to recognize because they are heavy, dense lumps of iron-nickel steel—a magnet will stick to them. That explains an important bit of statistics. Iron meteorites make up 66 percent of finds (■ Table 25-2) but only 6 percent of falls. Why? Because an iron meteorite does not look like a rock. If you trip over one on a hike, you are more likely to recognize it as something odd, carry it home, and show it to your local museum. Also, some stony meteorites deteriorate rapidly when exposed to weather; irons survive longer. That means there is a **selection effect** that makes it more likely that iron meteorites will be found (How Do We Know? 25-1). That only 6 percent of falls are irons shows that iron meteorites are fairly rare.

Figure 25-5

Braving bitter cold and high winds, teams of scientists riding snowmobiles search for meteorites that fell long ago in Antarctica and are exposed as the ice evaporates. Thousands of these meteorites have been collected including rare meteorites from the moon and Mars. (Courtesy Monika Kress)

When iron meteorites are sliced open, polished, and etched with nitric acid, they reveal regular bands called **Widmanstätten patterns** (Figure 25-6). These patterns are caused by alloys of iron and nickel called kamacite and taenite that formed crystals billions of years ago as the molten iron cooled and solidified. The size and shape of the bands indicate that the molten metal cooled very slowly, no faster than 20 K per million years.

A lump of molten metal floating in space would cool very quickly. The Widmanstätten pattern tells you that the molten metal must have been well insulated to have cooled so slowly. Such slow cooling is typical of the interiors of bodies at least 30 to 50 km in diameter. On the other hand, the iron meteorites show no effects of the very high pressures that would exist inside larger bodies. Evidently, the iron meteorites

■ **Figure 25-6**

The three main types of meteorites, irons, stones, and stony-iron, have distinctive characteristics. (Lab photos courtesy of Russell Kempton, New England Meteoritical Services)

■ **Table 25-2 | Proportions of Meteorites**

Type	Falls (%)	Finds (%)
Stony	92	26
Iron	6	66
Stony-iron	2	8

formed from the cooling interiors of planetesimal-sized objects.

In contrast to irons, **stony meteorites** are relatively common. Among falls, 92 percent are stones. Although there are many different types of stony meteorites, you can classify them into two main categories depending on their physical and chemical content—chondrites and achondrites.

Roughly 80 percent of all meteorite falls are stony meteorites called **chondrites,** which look like dark gray, granular rocks. The chemical composition of chondrites is the same as that of a sample of matter from the sun with the most volatile gases removed. The classification of meteorites has become quite sophisticated, and there are many types of chondrites, but in general they appear to be samples of the original material that condensed from the solar nebula. Some have slight mineral differences, showing that the solar nebula was not totally uniform when this material condensed.

Most types of chondrites contain **chondrules,** round bits of glassy rock no larger than 5 mm across (Figure 25-6). To be glassy rather than crystalline, the chondrules must have cooled from a molten state quickly, within a few hours, but their origin is not clear. One theory is that they are bits of matter that were suddenly melted by shock waves spreading through the solar nebula. Whatever their origin, they are very old.

All of the different types of chondrites contain some volatiles such as water, and this shows that the meteoroids were never heated to high temperatures. Differences among the many types of chondrites are a result of their condensation in different parts of the solar nebula and from processes that altered their composition after they formed. Some, for example, appear to have been altered by the presence of water released by the melting of ice.

Among the chondrites, the **carbonaceous chondrites** are rare, only about 5.7 percent of falls. These dark gray, rocky meteorites contain volatiles including water and carbon compounds that would have been driven off if the meteoroid had been heated much above room temperature. It has been common for astronomers to think of the carbonaceous chondrites as the least altered of the chondrites and therefore the most likely objects to provide clues to the nature of the solar nebula. But many types of chondrites are also essentially unaltered samples of the solar nebula. A carbonaceous chondrite is shown in Figure 25-6.

How Do We Know? | 25-1

Selection Effects

How is a red insect like a red car? Scientists must plan ahead and design their research projects with great care. Biologists studying insects in the rain forest, for example, must choose which ones to catch. They can't catch every insect they see, so they might decide to catch and study any insect that is red. If they are not careful, a selection effect could bias their data and lead them to incorrect conclusions without their ever knowing it.

For example, suppose you needed to measure the speed of cars on a highway. There are too many cars to measure every one, so you might reduce the workload and measure only red cars. It is quite possible that this selection criterion will mislead you because people who buy red cars may be more likely to be younger and drive faster. Should you measure only brown cars? No, because older, more sedate people might tend to buy brown cars. Only by very carefully designing your experiment can you be certain that the cars you measure are traveling at representative speeds.

Astronomers understand that what you see through a telescope depends on what you notice, and that is powerfully influenced by selection effects. The biologists in the rain forest, for example, should not catch and study only red insects. Often, the most brightly colored insects are poisonous or at least taste bad to predators. Catching only red insects could produce a result highly biased by a selection effect.

Things that are bright and beautiful, such as spiral galaxies, may attract a disproportionate amount of attention. Scientists must be aware of such selection effects. (Hubble Heritage Team/STScI/AURA/NASA)

One of the most important meteorites ever recovered was a carbonaceous chondrite that was seen falling on the night of February 8, 1969, near the Mexican village of Pueblito de Allende. The brilliant fireball was accompanied by tremendous sonic booms and showered an area about 50 km by 10 km with over 4 tons of fragments. About 2 tons were recovered.

Studies of the Allende meteorite disclosed that it contained—besides volatiles and chondrules—small, irregular inclusions rich in calcium, aluminum, and titanium. Now called **CAIs,** for calcium–aluminum-rich inclusions, these bits of matter are highly refractory (■ Figure 25-7); that is, they can survive very high temperatures. If you could scoop out a ton of the sun's surface matter and cool it, the CAIs would be the first particles to form. As the temperature fell, other materials would condense in accord with the condensation sequence described in Chapter 19. When the material finally reached room temperature, you would find that all of the hydrogen, helium, and a few other gases like argon and neon had escaped and that the remaining lump, weighing about 18 kg (40 lb), had almost the same composition as the Allende meteorite, including CAIs. The Allende meteorite seems to be a very old sample of the solar nebula.

Unlike the chondrites, stony meteorites called **achondrites** (7.1 percent of falls) are highly modified. They contain no chondrules and no volatiles. This suggests that they have been hot enough to melt chondrules and drive off volatiles, leaving behind rock with compositions similar to Earth's basalts.

■ **Figure 25-7**

A sliced portion of the Allende meteorite showing round chondrules and irregularly shaped white inclusions called CAIs. (NASA)

Iron meteorites and stony meteorites make up most falls, but 2 percent of falls are meteorites that are made up of mixed iron and stone. These **stony-iron meteorites** appear to have solidified from a region of molten iron and rock—the kind of environment you might expect to find deep inside a planetesimal with a molten iron core and a rock mantle.

The Origin of Meteorites

Where do meteorites come from? Even though the iron, stony, and stony-iron meteorites seem very different from each other, their properties show that they all formed from the solar nebula. Some appear not to have been modified since they formed, but others have been heated slightly or even melted sometime after formation.

Meteorites almost certainly do not come from comets. Most cometary particles are very small specks of low-density, almost fluffy, material. When these specks enter Earth's atmosphere, you see them incinerated as meteors. Most meteors are produced by this cometary debris, but such meteors are small and weak and do not survive to reach the ground. Although most meteors come from comets, most meteorites are stronger, denser chunks of matter—more like fragments of asteroids.

Meteorites must have come not from cometlike planetesimals rich in ices but instead from asteroid-like planetesimals rich in metals and rock, which have evolved in complicated ways and eventually were broken during collisions. You already know that the solar nebula was full of rocky planetesimals, but you must be wondering about two things: How did these planetesimals evolve to produce both iron and stony meteorites? And when did these planetesimals break up?

At least some of the planetesimals must have melted and differentiated to produce the iron and achondritic meteorites, but what produced this heat? Planets the size of Earth can accumulate a great deal of heat from the slow decay of radioactive atoms such as uranium, thorium, and the radioactive isotope of potassium. The heat is trapped deep underground by thousands of kilometers of insulating rock. But in a small planetesimal, the insulating layers are not as thick, and the heat leaks out into space as fast as the slowly decaying atoms can produce it. If a small planetesimal is to melt, it must have a more rapidly decaying heat source.

Modern studies have shown that some meteorites must have contained the radioactive element aluminum-26. Aluminum-26 decays to form magnesium-26 with a half-life of only 715,000 years, so all of the aluminum-26 is now gone. But the magnesium-26 can be detected in the laboratory, and that shows that aluminum-26 was once present. Aluminum-26 decays so rapidly the heat could have melted the center of a planetesimal as small as 20 km in diameter.

The origin of the aluminum-26 has interesting implications for the solar system. Supernova explosions can manufacture aluminum-26. If the solar nebula was enriched in aluminum-26 from a nearby supernova explosion, the explosion must have occurred just before the formation of our solar system. In fact, some astronomers wonder if it was shock waves from the supernova explosion that compressed gas clouds and triggered the formation of the sun and planets.

The melting of a planetesimal's interior would allow differentiation as heavy metals sank to the center to form a molten metal core and the less-dense silicates floated upward to form a stony mantle. Once the aluminum-26 had decayed away, the planetesimal would slowly cool and solidify. If such a planetesimal were broken up (■ Figure 25-8), fragments from the center would look like iron meteorites with their Widmanstätten patterns.

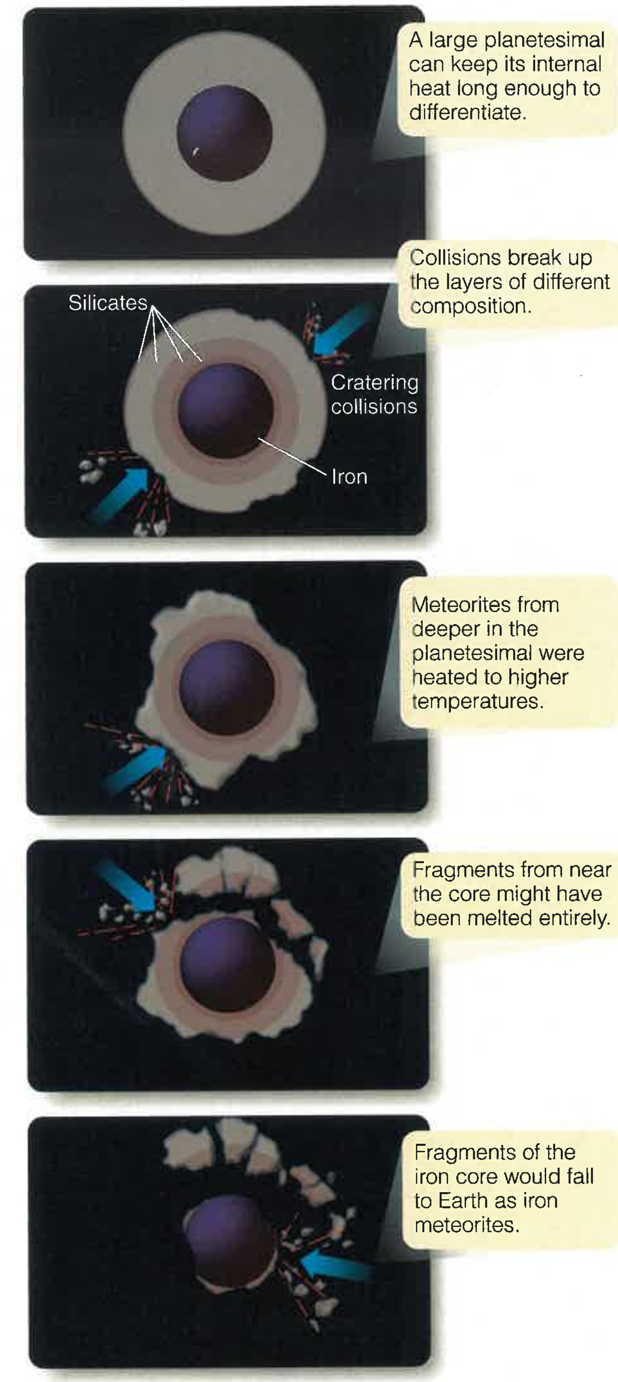
The achondrites, which have been strongly heated or melted, appear to come from the mantles and surfaces of differentiated planetesimals. The stony-iron meteorites probably come from the core–mantle boundaries where iron and stone were mixed. But the chondrites are probably fragments of smaller bodies that never melted. Volatile-rich meteorites such as the carbonaceous chondrites may have been part of smaller bodies that formed farther from the sun where temperatures were lower.

There is even more evidence that the meteorites are the result of the breaking up of larger bodies. For example, some meteorites are breccias—collections of stony fragments cemented together. Breccias are found on Earth and are very common on the moon, but studies of the meteoric breccias show that they were produced by impacts. A collision between planetesimals would produce fragments, and the slower-moving particles would fall back to the surface of the planetesimal to form a regolith, a soil of broken rock fragments. Later impacts may add to this regolith and stir it. Still later, an impact may be violent enough that the fragments are pressed together so hard they momentarily melt where they touch. Almost instantly, the material cools, and the fragments weld themselves together to form a breccia. Much later, as the planetesimals were broken up by collisions, the layers of breccia were exposed, shattered, and became brecciated meteoroids.

When did these planetesimals break up? Recall from Chapter 19 that radioactive dating shows that meteorites formed about 4.6 billion years ago. But that age tells you only when the parent bodies formed, melted, differentiated, and cooled. The collisions that broke up the planetesimals could not have happened that long ago, because small meteoroids would have been swept up by the planets in a billion years or less. Also, cosmic rays that strike meteoroids in space produce isotopes such as helium-3, neon-20, and argon-38. Studies of these atoms in meteorites show that most meteorites have not been exposed to cosmic rays for more than a few tens of millions of years. That means that the thousands of meteorites now in museums around the world must have been broken from planetesimals somewhere in our solar system within the last billion years or less. Where are those planetesimals?

To answer that question, you need only recall that many meteoroid orbits lead back to the asteroid belt. The asteroids are evidently the planetesimals from which meteorites are born.

The Origin of Meteorites



■ **Figure 25-8**

Planetesimals formed when the solar system was forming may have melted and separated into layers of different density and composition. The fragmentation of such a body could produce many types of meteorites. (Adapted from a diagram by C. R. Chapman)

◄ SCIENTIFIC ARGUMENT ►

How can meteors come from comets, but meteorites come from asteroids?

This is a revealing argument because it contains a warning that seeing is not enough in science; thinking about seeing is critical. A selection effect can determine what you notice when you observe nature, and a very strong selection effect prevents people from finding meteorites that originated in comets. Cometary particles are physically weak, and they vaporize in Earth's atmosphere easily. Very few ever reach the ground, and people are unlikely to find them. Furthermore, even if a cometary particle reached the ground, it would be so fragile that it would weather away rapidly, and, again, people would be unlikely to find it. Asteroidal particles, however, are made from rock and metal and so are stronger. They are more likely to survive their plunge through the atmosphere and more likely to survive erosion on the ground. Meteors from the asteroid belt are rare. Almost all of the meteors you see come from comets, but not a single meteorite is known to be cometary.

The meteorites are valuable because they provide hints about the process of planet building in the solar nebula. Build a new argument but, as always, think carefully about what you see. **Why are most falls stony, but most finds are irons?**

◄ ►

25-2 Asteroids

UNTIL RECENTLY, FEW ASTRONOMERS KNEW or cared much about asteroids. They were small chunks of rock drifting between the orbits of Mars and Jupiter that occasionally marred long-exposure photographs by drifting past more interesting objects. Asteroids were more irritation than fascination.

Now you know differently. The evidence from meteorites shows that the asteroids are the last remains of the rocky planetesimals that built the planets 4.6 billion years ago. The study of the asteroids gives you a way to explore the ancient past of our planetary system.

Properties of Asteroids

In Chapter 19, you learned that most of the asteroids orbit between Mars and Jupiter and that images recorded by passing spacecraft reveal them to be small, complex worlds with irregular shapes and heavily cratered surfaces (Figure 19-3).

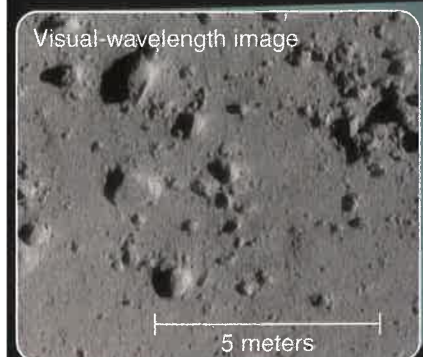
Study **Observations of Asteroids** on pages 578–579 and notice four important points:

1. Most asteroids are irregular in shape and battered by impact cratering. In fact, some appear to be rubble piles of broken fragments.
2. Some asteroids are double objects or have small moons in orbit around them. This is further evidence of collisions among the asteroids.
3. A few larger asteroids show signs of geological activity on their surfaces that may have been caused by volcanic activity when the asteroid was young.
4. Asteroids can be classified by their albedo and color to reveal clues to their compositions.

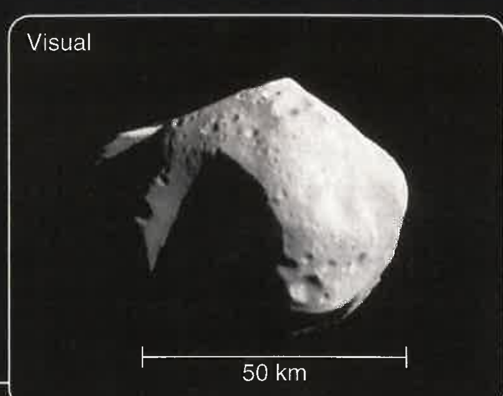
Observations of Asteroids

1 Seen from Earth, asteroids look like faint points of light moving in front of distant stars. Not many years ago they were known mostly for drifting slowly through the field of view and spoiling long time exposures. Some astronomers referred to them as "the vermin of the sky." Spacecraft have now visited asteroids, and the images radioed back to Earth show that the asteroids are mostly small, gray, irregular worlds heavily cratered by impacts.

The Near Earth Asteroid Rendezvous (NEAR) spacecraft visited the asteroid Eros in 2000 and found it to be heavily cratered by collisions and covered by a layer of crushed rock ranging from dust to large boulders. The NEAR spacecraft eventually landed on Eros.



Most asteroids are too small for their gravity to pull them into a spherical shape. Impacts break them into irregularly shaped fragments.



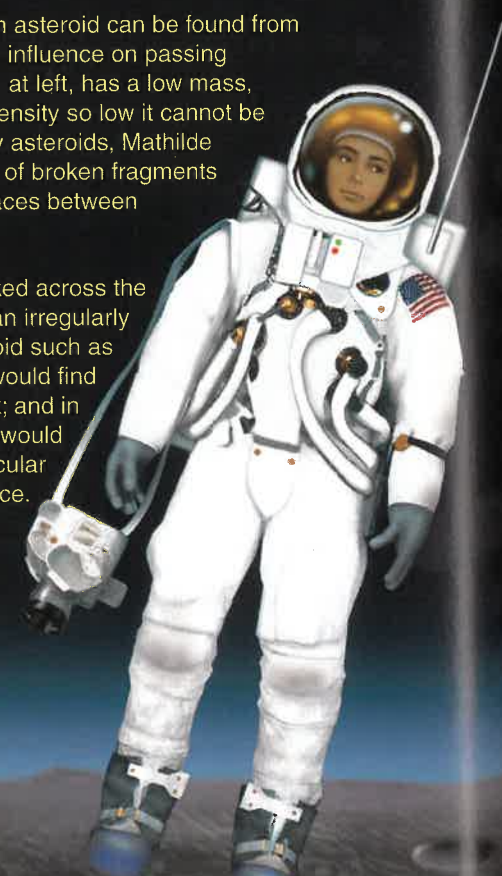
The surface of Mathilde is very dark rock.

1a The mass of an asteroid can be found from its gravitational influence on passing spacecraft. Mathilde, at left, has a low mass, and that makes its density so low it cannot be solid rock. Like many asteroids, Mathilde may be a rubble pile of broken fragments with large empty spaces between fragments.

Enhanced visual image

Like most asteroids, Gaspra would look gray to your eyes; but, in this enhanced image at left, color differences probably indicate difference in mineralogy.

If you walked across the surface of an irregularly shaped asteroid such as Eros, you would find gravity very weak; and in many places, it would not be perpendicular to the surface.



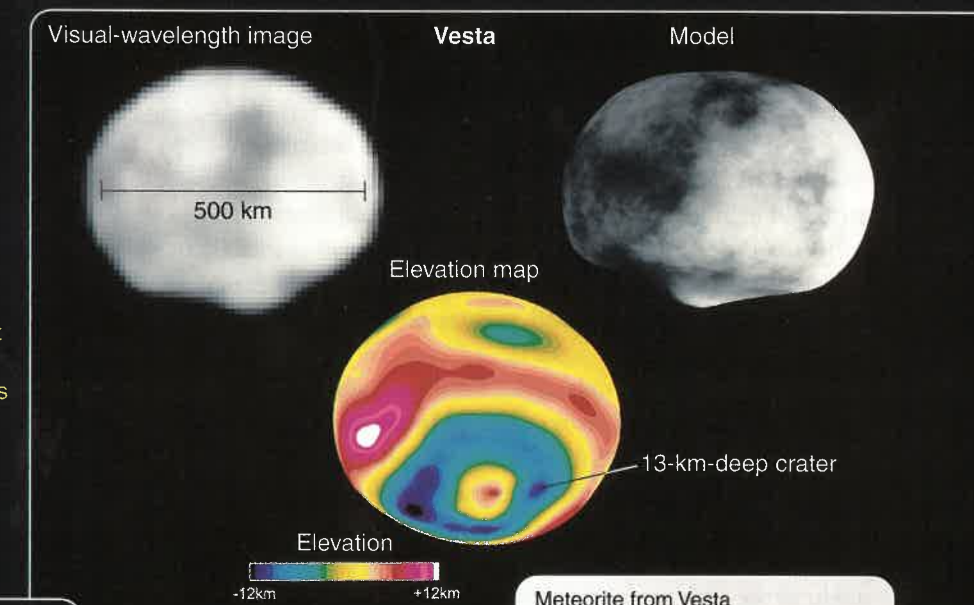
2 Asteroids that pass near Earth can be imaged by radar. The asteroid Toutatis is revealed to be a double object—two objects orbiting close to each other or actually in contact.

Enhanced visual + infrared

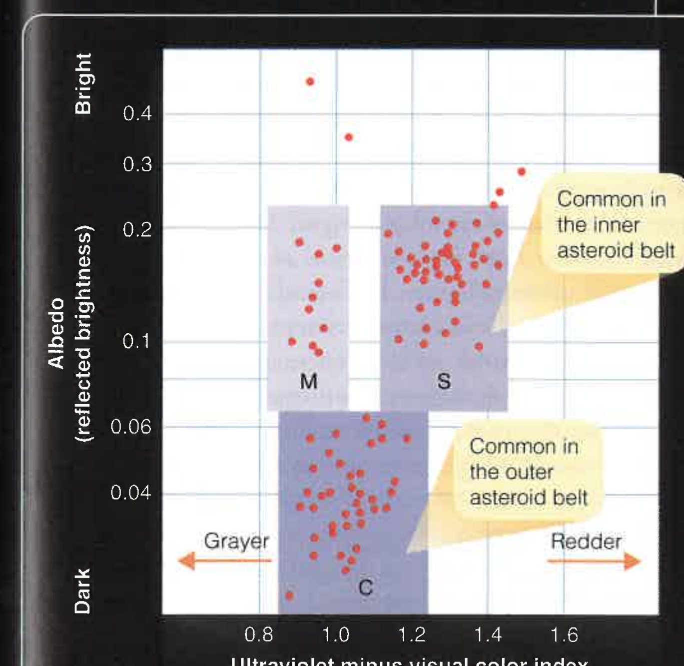
Double asteroids are more common than was once thought, reflecting a history of collisions and fragmentation. The asteroid Ida is orbited by a moon Dactyl only about 1.5 km in diameter.

Occasional collisions among the asteroids release fragments, and Jupiter's gravity scatters them into the inner solar system as a continuous supply of meteorites.

3 The large asteroid Vesta, as shown at right, provides evidence that some have suffered geological activity. No spacecraft has visited it, but its spectrum resembles that of solidified lava. Images made by the Hubble Space Telescope allow the creation of a model of its shape. It has a huge crater at its south pole. A family of small asteroids is evidently composed of fragments from Vesta, and a certain class of meteorites, spectroscopically identical to Vesta, are believed to be fragments from the asteroid. The meteorites appear to be solidified basalt.



3a Vesta appears to have had internal heat at some point in its history, perhaps due to the decay of radioactive minerals. Lava flows have covered at least some of its surface.



4 Although asteroids would look gray to your eyes, they can be classified according to their albedos (reflected brightness) and spectroscopic colors. As shown at left, S-types are brighter and tend to be reddish. They are the most common kind of asteroid and appear to be the source of the most common chondrites.

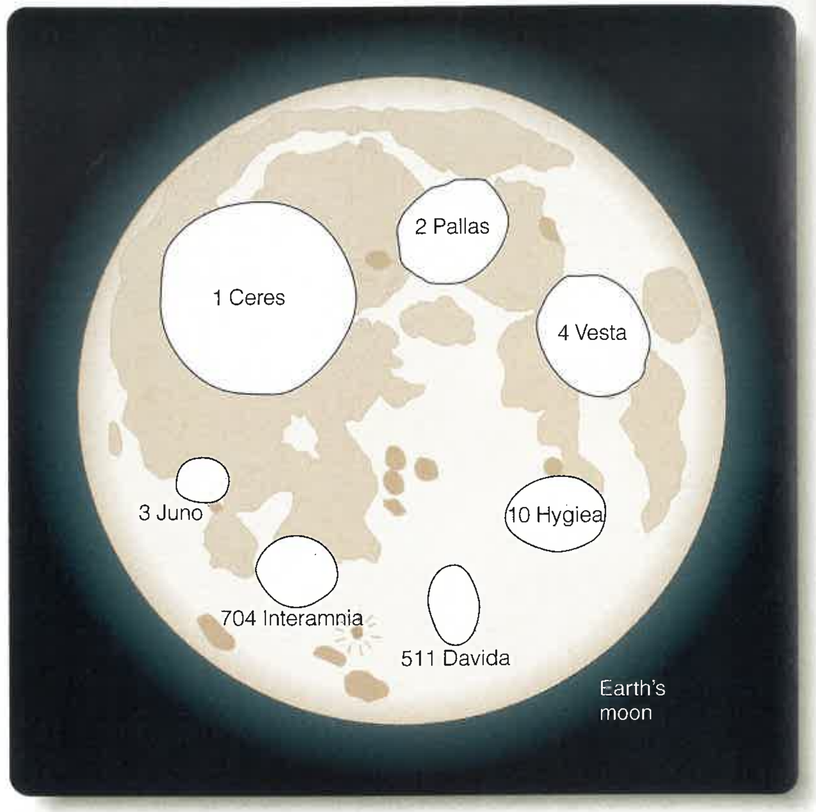
M-type asteroids are not too dark but are also not very red. They may be mostly iron-nickel alloys.

C-type asteroids are as dark as lumps of sooty coal and appear to be carbonaceous.

Collisions among asteroids must have been occurring since the formation of the solar system, and astronomers have found evidence of catastrophic impacts powerful enough to shatter an asteroid. Early in the 20th century, Japanese astronomer Kiyotsugu Hirayama discovered that some groups of asteroids share similar orbits. Each group is distinct from other groups, but asteroids within a group have the same average distance from the sun, the same eccentricity, and the same inclination. Up to 20 of these **Hirayama families** are known, and modern observations show that the asteroids in a family typically share similar spectroscopic characteristics. Evidently, a family is produced by a catastrophic collision that breaks a single asteroid into a family of fragments that continue traveling along similar orbits around the sun. Evidence shows that one family was produced only 5.8 million years ago in a collision between asteroids 3 km and 16 km in diameter traveling at about 5 km/s (11,000 mph), a typical speed for asteroid collisions. Evidently the fragmentation of asteroids is a continuing process.

In 1983, the Infrared Astronomy Satellite detected the infrared glow of sun-warmed dust scattered in bands throughout the asteroid belt. These dust bands appear to be the products of past collisions. The dust will eventually be blown away, but because collisions occur constantly in the asteroid belt, new dust bands will presumably be produced as the present bands dissipate.

What are the asteroids? Where did they come from? There are clues hidden among their orbits, and you can begin that story at its beginning.



■ **Figure 25-9**

The relative size and approximate shape of the larger asteroids are shown here compared with the size of Earth's moon. Smaller asteroids can be highly irregular in shape.

The Asteroid Belt

The first asteroid was discovered on January 1, 1801 (the first night of the 19th century), by the Sicilian monk Giuseppe Piazzi. It was later named Ceres after the Roman goddess of the harvest (thus our word *cereal*).

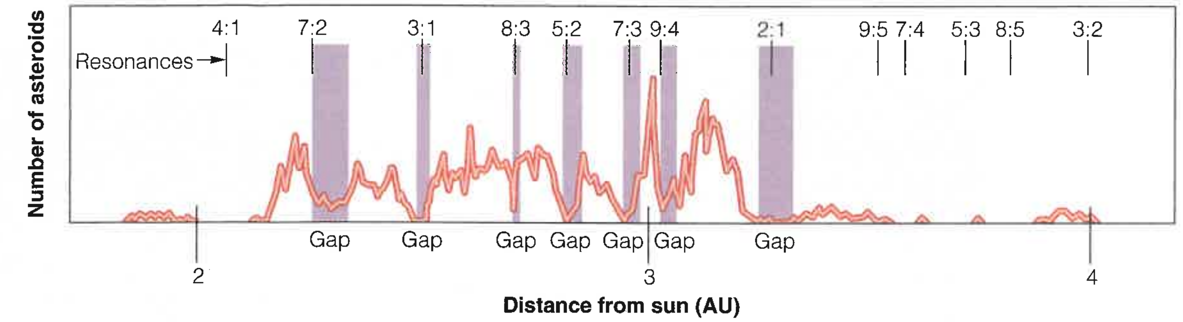
Astronomers were excited by Piazzi's discovery because there seemed to be a gap where a planet might exist between Mars and Jupiter at an average distance from the sun of 2.8 AU. Ceres fit right in; its average distance from the sun is 2.766 AU. But it was a bit small to be a planet, and three more objects—Pallas, Juno, and Vesta—were discovered in the following years, so astronomers realized that Ceres and the other asteroids were not true planets.

Today over 100,000 asteroids have well-charted orbits. Many more are as yet undiscovered, but they are all small bodies. All of the larger asteroids in the asteroid belt have been found. Only three are larger than 400 km in diameter, and most are much smaller (■ Figure 25-9).

If you discovered an asteroid, you would be allowed to choose a name for it, and asteroids have been named for spouses, lovers, dogs, Greek gods, politicians, and others.* Once an orbit has been calculated, the asteroid is assigned a number listing its position in the catalog known as the *Ephemerides of Minor Planets*. Thus, Ceres is known as 1 Ceres, Pallas as 2 Pallas, and so on.

Although a few asteroids follow orbits that bring them into the inner solar system or outward among the Jovian planets, most orbit in the asteroid belt between Mars and Jupiter, and you might suspect that massive Jupiter was responsible for their origin. Certainly the distribution of asteroids in the belt is strongly affected by Jupiter's gravitation. Certain regions of the belt, called **Kirkwood's gaps** after their discoverer, Daniel Kirkwood (1814–1895), are almost free of asteroids (■ Figure 25-10). These gaps lie at certain distances from the sun where an asteroid would find itself in resonance with Jupiter. For example, if an asteroid lay 3.28 AU from the sun, it would orbit twice around the sun in the time it took Jupiter to orbit once. On alternate orbits, the asteroid would find Jupiter at the same place in space tugging outward. The cumulative perturbations would rapidly change the asteroid's orbit until it was no longer in resonance with Jupiter. This example is a 2:1 resonance, but gaps occur in the asteroid belt at many resonances, including 3:1, 5:2, and 7:3. You will recognize that Kirkwood's gaps in the asteroid belt are produced in the same way as some of the gaps in Saturn's rings. Both sets of gaps were discovered by Daniel Kirkwood (Chapter 23).

*Some sample asteroid names: Olga, Chicago, Vaticana, Noel, Ohio, Tea, Gaby, Fidelio, Hagar, Geisha, Dudu, Tata, Mimi, Dulu, Tito, Zulu, Beer, and Zappafrank (after the late musician Frank Zappa).



■ **Figure 25-10**

Here the red curve shows the number of asteroids at different distances from the sun. Purple bars mark Kirkwood's gaps, where there are few asteroids. Note that these gaps match resonances with the orbital motion of Jupiter.

Modern research shows that the motion of asteroids in Kirkwood's gaps is described by a theory in mathematics that deals with chaotic behavior. As an example, consider how the smooth motion of water sliding over the edge of a waterfall decays rapidly into a chaotic jumble. The same theory of chaos that describes the motion of the water shows how the slowly changing orbit of an asteroid within one of Kirkwood's gaps can suddenly become a long, elliptical orbit that carries the asteroid into the inner solar system, where it is likely to be removed by a collision with Mars, Earth, or Venus. In this way, Jupiter's gravity can throw many meteoroids from the asteroid belt into the inner solar system.

Nonbelt Asteroids

You don't have to go all the way to the asteroid belt if you want to visit an asteroid. Some of the most interesting follow orbits that cross the orbits of the terrestrial planets or wander among the Jovian worlds. In fact, some asteroids even share orbits with the larger planets.

The **Apollo–Amor objects** are asteroids whose orbits carry them into the inner solar system. The Amor objects follow orbits that cross the orbit of Mars but don't reach the orbit of Earth. The Apollo objects have Earth-crossing orbits. These Apollo–Amor objects are dangerous. Jupiter's influence makes their orbits precess. About one-third will be thrown into the sun, and a few will be ejected from the solar system, but many of these objects are doomed to collide with a planet—perhaps ours. Earth is hit by an Apollo object once every 250,000 years, on average. With a diameter of up to 2 km, they hit with the power of a 100,000-megaton bomb and can dig craters 20 km in diameter.

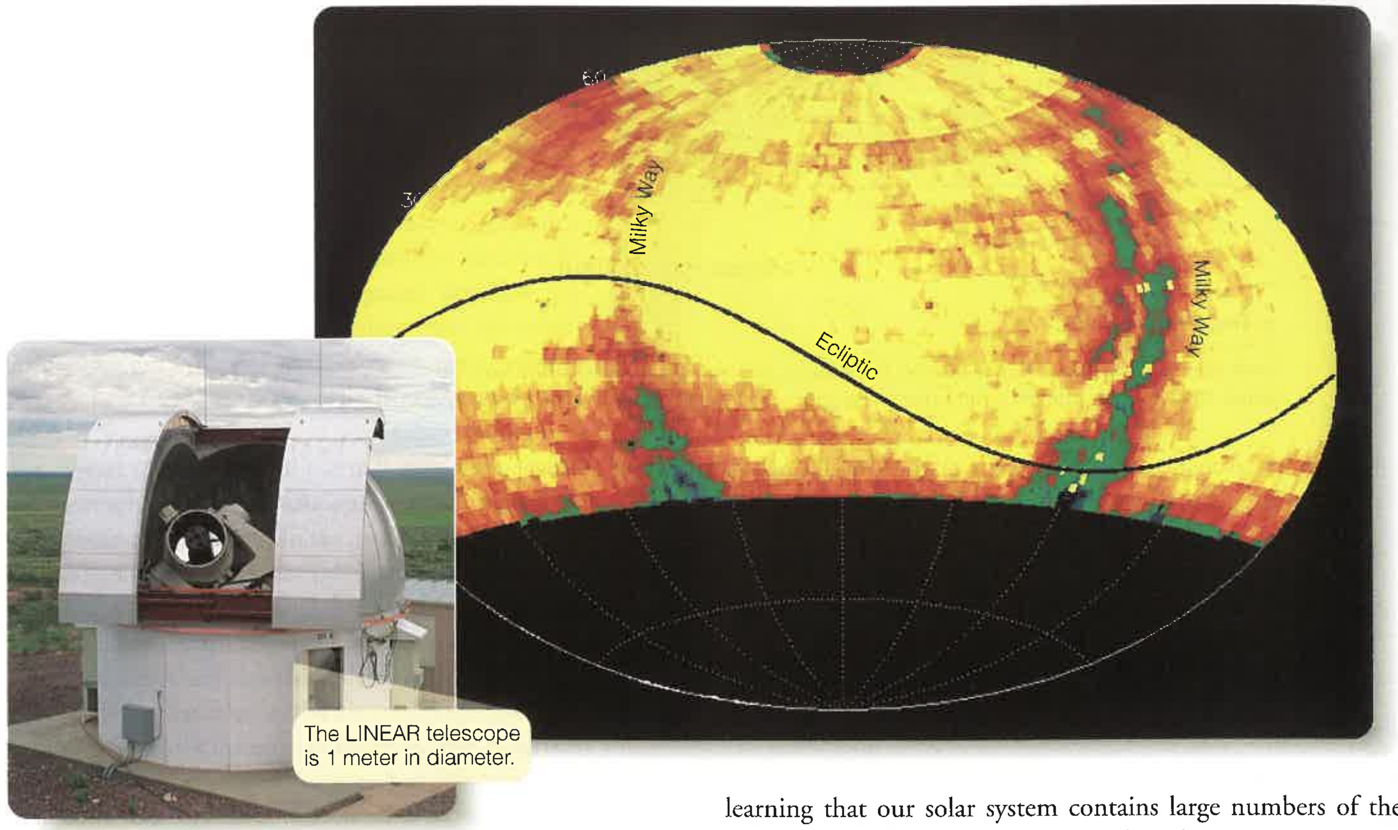
Over 2300 Apollo objects are known, and none of those will hit Earth in the foreseeable future. The bad news is that there are about 1000 of these near-Earth Objects (NEOs) larger than 1 km in diameter, the minimum size of an impactor that could cause global effects on Earth. More than half a dozen teams are now searching for these NEOs. For example, LONEOS (Lowell Observatory Near Earth Object Search) is searching the entire sky visible from Lowell Observatory once a month. The LINEAR (Lincoln Near-Earth Asteroid Research) telescope in New Mexico has been very successful in finding NEOs and in finding new main-belt asteroids (■ Figure 25-11). The combined searches should be able to locate all of the largest NEOs by 2010.

This is a serious issue because even a small asteroid could do serious damage. For example, in late December 2004, an asteroid was discovered that was predicted to have a 2.6 percent chance of striking Earth on April 13, 2029. The object is large enough to do significant damage over a wide area but is not large enough to alter Earth's climate. Fortunately, further observations revealed that the object will not hit Earth in 2029.

Objects a few tens of meters or less in diameter fragment and explode in Earth's atmosphere, but the shock waves from their explosions could still cause serious damage on Earth's surface. Declassified data from military satellites show that Earth is hit about once a week by meter-size asteroids. Larger impacts produce more damage but are much less common.

It is easy to assume that the Apollo–Amor objects are rocky asteroids that have been thrown into their extreme orbits by events in the main asteroid belt. At least some of these objects, however, may be comets that have exhausted their ices and become trapped in short orbits that keep them in the inner solar system. You will see later in this chapter that the distinction between comets and asteroids is not totally clear.

There are also nonbelt asteroids in the outer solar system. These objects, being farther from the sun, move more slowly. The object Chiron, found in 1977, appears to be about 170 km in diameter. Its orbit carries it from just inside the orbit of Uranus to just inside the orbit of Saturn. Although it was first classified as an asteroid, its status is now less certain. Ten years after its discovery, Chiron surprised astronomers by suddenly brightening as it releasing jets of vapor and dust much like a comet.



■ **Figure 25-11**

The LINEAR telescope searches for asteroids every clear night when the moon is not bright. The diagram shows the thoroughness of its search over the entire sky for one year. Asteroids are hard to discover in front of the starry Milky Way. (MIT/Lincoln Labs)

Studies of older photographs showed that Chiron had done this before sometimes when it was even farther from the sun. Astronomers now suspect that it may have a rocky crust covering deposits of ices such as solid nitrogen, methane, and carbon monoxide. Thus, Chiron may be more comet than asteroid, and it serves as a warning that the distinction is not clear-cut.

Jupiter ushers two groups of asteroids around its own orbit. These nonbelt asteroids have become trapped in the Lagrangian points along Jupiter's orbit. (See Figure 13-5.) These points lie 60° ahead of and 60° behind the planet and are regions where the gravitation of the sun and Jupiter combine to trap small bodies (■ Figure 25-12). Like cosmic sinkholes, the Lagrangian points have trapped chunks of debris now called **Trojan asteroids.** Individual asteroids are named after the heroes of the Trojan War (588 Achilles, 624 Hektor, 659 Nestor, and 1143 Odysseus, for example). Slightly over 1000 Trojan asteroids are known, but only the brightest have been given names.

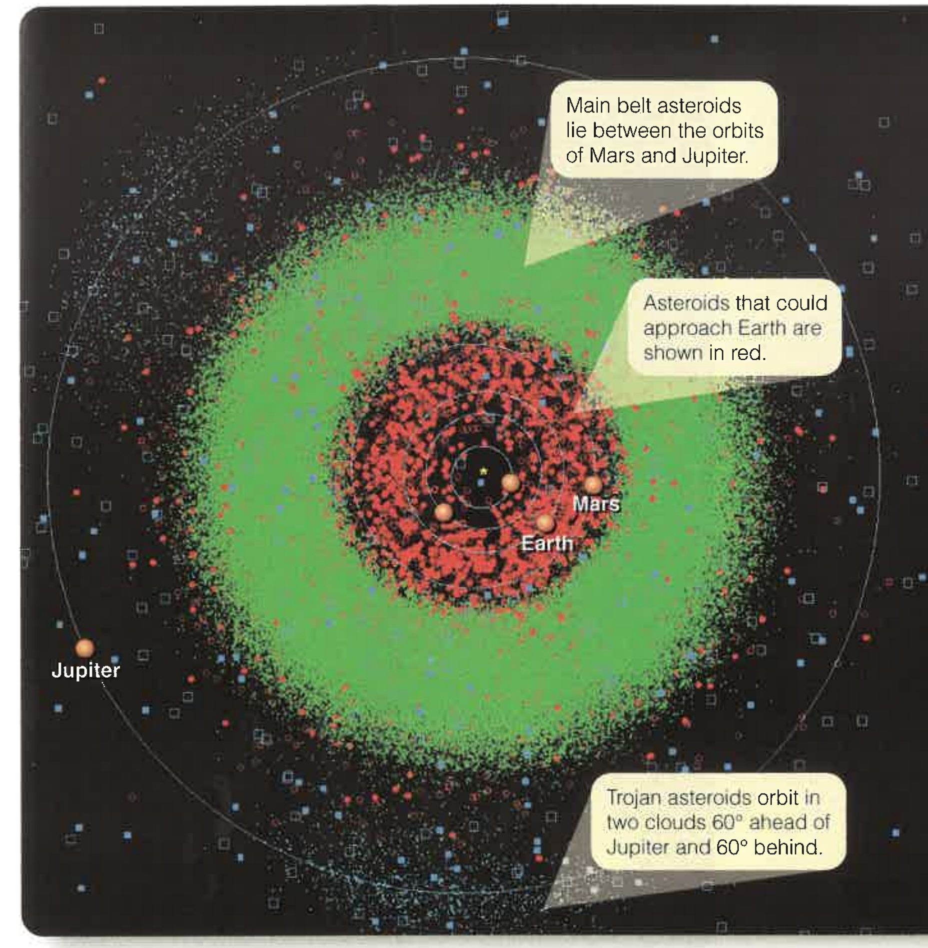
Astronomers have also found a few objects in the Lagrangian points of the orbits of Mars and Neptune. Other planets, including Earth, may have Trojan asteroids trapped in their orbits. As technology allows astronomers to detect smaller objects, they are learning that our solar system contains large numbers of these small bodies. The challenge is to explain their origin.

The Origin of the Asteroids

You have concluded your study of each planet by trying to summarize its history. Can you tell the story of the asteroids? Begin with an idea that didn't work out.

An old theory held that the asteroids are the remains of a planet that broke up. Modern astronomers discount that idea, but it survives as a **Common Misconception.** Once formed, a planet is very difficult to tear apart. Rather, astronomers now understand that the asteroids are the remains of planetesimals that were unable to form a planet. Jupiter's gravity stirred the planetesimals just inside its orbit and caused collisions at unusually high velocities. These impacts tended to break up the planetesimals rather than assemble them into a planet. Orbital resonances helped to eject material, and by now most of the planetesimal objects have been lost—swept up by planets, consumed by the sun, captured as satellites, or ejected from the solar system. The asteroid belt today contains hardly 4 percent the mass of Earth's moon.

Even though most of the planetesimals have been lost, the objects left behind carry clues to their origin. The C-type asteroids have albedos smaller than 0.06 and would look very dark to your eyes. They are probably made of carbon-rich material similar to that in carbonaceous chondrites. The S-type asteroids have albedos of 0.1 to 0.2, so they would look brighter and spectroscopically redder. The M-type asteroids are bright but not as red.



■ **Figure 25-12**

This diagram plots the position of known asteroids inside or near the orbit of Jupiter on a specific day. Squares, filled or empty, show the location of known comets. Although asteroids and comets are small bodies and lie far apart, there are a great many of them in the inner solar system. (Minor Planet Center)

S-type asteroids are believed to be rocky, but M-type asteroids appear to be metal rich and may be the iron cores of fragmented asteroids.

Although S-type asteroids are very common in the inner asteroid belt, their spectroscopic colors are different from the chondrites—the most common kind of meteorite. New evidence from the analysis of moon rocks and from observations of Eros, an S-type asteroid, shows that bombardment by micrometeorites can redden and darken S-type asteroids. Therefore, it seems that the most common kind of meteorites comes from the most common kind of asteroid.

A few other types of asteroids are known, and a number of individual asteroids have been found that are unique, but these three classes contain a majority of the known asteroids.

How did these three types originate? A clue lies in their distribution in the asteroid belt. The S-type asteroids are much more common in the inner belt, but there is almost none beyond a distance of about 3.45 AU. In contrast, the C types are rather rare in the inner belt but are very common in the outer belt. This distribution reflects differences in the temperature of the solar nebula during the formation of the planetesimals. It was cooler in the outer belt, so the planetesimals that formed there tended to be volatile-rich carbonaceous chondrites. In the warmer regions of the inner belt, the composition of the growing planetesimals was more like that of the chondrites.

Earlier you saw evidence that Vesta has at some time in the past been at least partly resurfaced by lava flowing up from its interior. How could a small asteroid be heated enough to produce lava flows? One source of heat in newly formed asteroids could be the decay of short-lived radioactive elements such as aluminum-26. The smallest asteroids lose their heat too fast to melt, but aluminum-26 decays fast enough to melt the interiors of bodies larger than a few dozen kilometers in diameter. Thus it is not so surprising that Vesta and some other asteroids larger than about 100 km in diameter were modified by lava flows.

In contrast, the largest main-belt asteroid, Ceres, is now recognized as a dwarf planet (Chapter 24). It is spherical, about 900 km in diameter, but does not seem to have been modified by internal heating. The light reflected from its surface suggests a claylike material related to carbonaceous chondrites. This is surprising, because clays form when minerals are exposed to water. In fact, spectroscopic observations reveal water ice on Ceres. Evidently some asteroids may have had significant amounts of water bound into their crusts when they were young.

All of this evidence suggests that the asteroids are the broken remains of planetesimals that formed in the solar nebula as planet building began. The largest remaining asteroids, such as Ceres and Vesta, may be largely unbroken planetesimals, and some of these may have experienced some surface evolution due to internal heat or the presence of water. Nevertheless, the vast majority of the asteroids are fragments, and many may consist of bodies that were shattered and then re-formed as gravity pulled the fragments back together. Compositional differences between asteroids seem to be due to temperature differences in the ancient solar nebula from which the planetesimals formed. The presence of massive Jupiter orbiting nearby prevented the original planetesimals from accreting to build a planet. Instead, collisions fragmented them, and nearly all of the material has been lost.

◄ SCIENTIFIC ARGUMENT ►

What evidence makes you think that the asteroids have been fragmented?

Some of the best scientific arguments test the interpretation of evidence. If you understand the evidence, you hold the key to the science. To begin, you might note that the solar nebula theory of the formation of the solar system predicts that planetesimals collided and either stuck together or fragmented. This is suggestive, but it is not evidence. A theory can never be used as evidence to support some other theory or hypothesis. Evidence takes the form of observations or experimental results, so you need to turn to observations of asteroids. Spacecraft photographs of asteroids such as Ida, Gaspra, and Eros show irregularly shaped little worlds heavily scarred by impact craters. In fact, observations of some asteroids show what may be pairs of bodies in contact, and the Galileo image of Ida reveals its small satellite, Dactyl. Furthermore, some meteorites appear to come from the asteroid belt, and a few have been linked to specific asteroids such as Vesta. There are even families of asteroids that seem to be fragments from a single collision. All of this evidence suggests that the asteroids have been broken up by violent impacts.

The impact fragmentation of asteroids has been important, but it has not erased all traces of the original planetesimals from which the asteroids formed. Build another argument based on evidence. **What evidence can you cite that reveals what those planetesimals were like?**

◄ ►

25-3 Comets

FEW THINGS IN ASTRONOMY ARE MORE BEAUTIFUL than a bright comet hanging in the night sky (■ Figure 25-13). It is a Common Misconception that comets whiz rapidly across the sky. Meteors shoot across the sky like demented fireflies, but a comet moves with the stately grace of a great ship at sea, its motion hardly apparent. Night by night it shifts slightly against the stars and may remain visible for weeks. Faint comets are common; a number are discovered every year. But a truly bright comet appears about once a decade. Comet Hyakutake in 1996 (Figure 25-1) and Comet Hale–Bopp in 1997 were both dramatic, but the later comet was so bright that you might class it with the great comets such as Comet Halley in 1910. A patient person might see half a dozen or more bright comets in a lifetime.

While everyone enjoys the beauty of comets, astronomers study them for their cargo of clues to the origin of our solar system.

Properties of Comets

As always, you should begin your study of a new kind of object by summarizing its observational properties. What do comets look like, and how do they behave? The observations are the evidence that reveals the secrets of the comets.

Study **Comet Observations** on pages 586–587 and notice three important properties of comets and three new terms:

■ **Figure 25-13**

Comet Hale–Bopp was very bright in the sky in 1997. A comet can remain bright in the sky for weeks as it sweeps along its orbit through the inner solar system. (Dean Ketelsen)

1. Comets have two kinds of tails shaped by the solar wind and solar radiation. Gas and dust released by a comet's icy nucleus produces a head or *coma* and is then blown outward. The gas produces a *type I,* or *gas, tail,* and the dust produces a *type II,* or *dust, tail.*
2. Notice the importance of dust in comets. It not only produces dust tails but spreads throughout the solar system.
3. Evidence shows that comet nuclei are fragile and can break into pieces.

Astronomers can put these and other observations together to study the structure of comet nuclei.

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The Geology of Comet Nuclei

The nuclei of comets are quite small and cannot be studied in detail using Earth-based telescopes. Nevertheless, astronomers are beginning to understand the geology of these peculiar objects.

Comet nuclei contain ices of water and other volatile compounds such as carbon dioxide, carbon monoxide, methane, ammonia, and so on. These are the kinds of compounds that should have condensed from the outer solar nebula, and that makes astronomers think that comets are ancient samples of the gases and dust from which the planets formed.

When comet nuclei approach the sun, the ices absorb energy from sunlight and sublime—change from a solid directly into a gas—producing the observed tails. As the gases break down and combine chemically, they produce the many compounds found in comet tails. Vast clouds of hydrogen gas observed around the heads of comets are derived from the breakup of molecules from the ices.

Five spacecraft flew past the nucleus of Comet Halley when it visited the inner solar system in 1985 and 1986. Other spacecraft flew past the nuclei of Comet Borrelly in 2001 and Comet Wild 2 in 2004. The Deep Impact probe hit Comet Tempel 1 in 2005. Photos show that these comet nuclei are irregular in shape and very dark, with jets of gas and dust spewing from active regions (■ Figure 25-14). In general, these nuclei are darker than a lump of coal, which suggests the composition of the carbon-rich meteorites called carbonaceous chondrites.

From the gravitational influence of a nucleus on a passing spacecraft, astronomers can calculate the mass and density of the nucleus. Comet nuclei appear to have densities of 0.1 to 0.25 g/cm^3, much less than the density of ice. Comet nuclei are evidently not solid balls of ice but must be fluffy mixtures of ices and rocky dust with significant amounts of empty space.

Photographs of the comae (plural of *coma*) of comets often show jets springing from the nucleus and being swept back by the pressure of sunlight and by the solar wind to form the tail (Figure 25-14). Studies of the motions of these jets as the nucleus rotates reveal that the jets originate from active regions that may be faults or vents. As the rotation of a cometary nucleus carries an active region into sunlight, it begins venting gas and dust, and as it rotates into darkness it shuts down. The nuclei of comets appear to have a crust of rocky dust left behind when the ices vaporize. Breaks in that crust can expose ices to sunlight, and vents can occur in those regions. It also seems that some comets have pockets of volatiles buried below the crust. When one of those pockets is exposed and begins to vaporize, the comet can suffer a dramatic outburst.

■ **Figure 25-14**

Visual-wavelength images made by spacecraft and by the Hubble Space Telescope show how the nucleus of a comet produces jets of gases from regions where sunlight vaporizes ices. (Halley nucleus: © 1986 Max-Planck Institute; Halley coma: Steven Larson; Comets Borrelly, Hale–Bopp and Wild 2: NASA)