23.1 The Solar System

Reading Focus

Key Concepts

- How do terrestrial planets differ from Jovian planets?
- How did the solar system form?

Vocabulary

- terrestrial planet
- Jovian planet
- nebula
- planetesimal

Reading Strategy

Relating Text and Diagrams As you read, refer to Figure 3 to complete the flowchart on the formation of the solar system.

Cloud of dust and gas began rotating. → a. ? → b. ? → c. ?

The sun is the hub of a huge rotating system of planets, their satellites, and numerous smaller bodies. An estimated 99.85 percent of the mass of our solar system is contained within the sun. The planets collectively make up most of the remaining 0.15 percent. As Figure 1 shows, the planets, traveling outward from the sun, are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

Guided by the sun's gravitational force, each planet moves in an elliptical orbit, and all travel in the same direction. The nearest planet to the sun—Mercury—has the fastest orbital motion at 48 kilometers per second, and it has the shortest period of revolution. By contrast, the most distant planet, Neptune, has an orbital speed of 5 kilometers per second, and it requires 165 Earth-years to complete one revolution.

Imagine a planet's orbit drawn on a flat sheet of paper. The paper represents the planet's orbital plane. The orbital planes of seven planets lie within 3 degrees of the plane of the sun's equator. Mercury's orbit is inclined by 7 degrees.

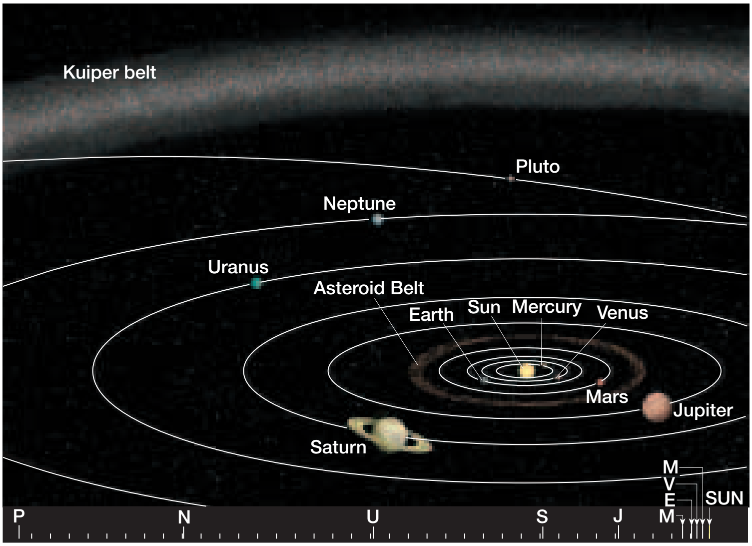

Figure 1 Orbits of the Planets and Pluto The positions of the planets and Pluto are shown to scale along the bottom of the diagram.

The Planets: An Overview

Careful examination of Table 1 shows that the planets fall quite nicely into two groups. The **terrestrial planets**—Mercury, Venus, Earth, and Mars—are relatively small and rocky. (*Terrestrial* = Earth-like.)The **Jovian planets**—Jupiter, Saturn, Uranus, and Neptune—are huge gas giants. (*Jovian* = Jupiter-like.)

Size is the most obvious difference between the terrestrial and the Jovian planets. The diameter of the largest terrestrial planet, Earth, is only one-quarter the diameter of the smallest Jovian planet, Neptune. Also, Earth's mass is only 1/17 as great as Neptune's. Hence, the Jovian planets are often called giants. Because of their distant locations from the sun, the four Jovian planets are also called the outer planets. The terrestrial planets are closer to the sun and are called the inner planets. As we shall see, there appears to be a correlation between the positions of these planets and their sizes.

Density, chemical makeup, and rate of rotation are other ways in which the two groups of planets differ. The densities of the terrestrial planets average about five times the density of water. The Jovian planets, however, have densities that average only 1.5 times the density of water. One of the outer planets, Saturn, has a density only 0.7 times that of water, which means that Saturn would float if placed in a large enough water tank. The different chemical compositions of the planets are largely responsible for these density differences.

Reading Checkpoint *Compare the densities of terrestrial planets and Jovian planets.*

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Table 1 Planetary Data

Planet	Average Distance from Sun AU	Millions of km	Period of Revolution	Orbital Velocity km/s	Period of Rotation	Diameter (km)	Relative Mass (Earth = 1)	Average Density (g/cm^3)	Number of Known Satellites*
Mercury	0.39	58	88^d	47.5	59^d	4878	0.06	5.4	0
Venus	0.72	108	225^d	35.0	244^d	12,104	0.82	5.2	0
Earth	1.00	150	365.25^d	29.8	$23^h\ 56^m\ 04^s$	12,756	1.00	5.5	1
Mars	1.52	228	687^d	24.1	$24^h\ 37^m\ 23^s$	6794	0.11	3.9	2
Jupiter	5.20	778	12^{yr}	13.1	$9^h\ 50^m$	143,884	317.87	1.3	63
Saturn	9.54	1427	29.5^{yr}	9.6	$10^h\ 14^m$	120,536	95.14	0.7	56
Uranus	19.18	2870	84^{yr}	6.8	$17^h\ 14^m$	51,118	14.56	1.2	27
Neptune	30.06	4497	165^{yr}	5.3	$16^h\ 03^m$	50,530	17.21	1.7	13
Pluto**	39.44	5900	248^{yr}	4.7	6.4^d	approx. 2300	0.002	1.8	3

*Includes all satellites discovered as of December 2006.

**Pluto is included for purposes of comparison.

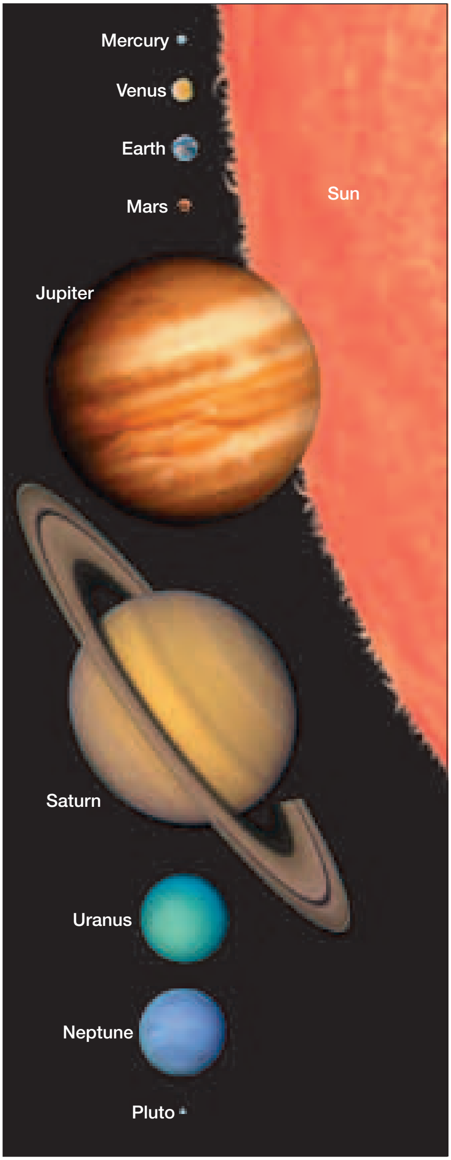


Figure 2 The planets and Pluto are drawn to scale.
Interpreting Diagrams ***How do the sizes of the terrestrial planets compare with the sizes of the Jovian planets?***

The Interiors of the Planets The planets (and Pluto) are shown to scale in Figure 2. The substances that make up the planets are divided into three groups: gases, rocks, and ices. The classification of these substances is based on their melting points.

1. The gases—hydrogen and helium—are those with melting points near absolute zero (−273°C or 0 kelvin).
2. The rocks are mainly silicate minerals and metallic iron, which have melting points above 700°C.
3. The ices include ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2), and water (H_2O). They have intermediate melting points. For example, H_2O has a melting point of 0°C.

The terrestrial planets are dense, consisting mostly of rocky and metallic substances, and only minor amounts of gases and ices. The Jovian planets, on the other hand, contain large amounts of gases (hydrogen and helium) and ices (mostly water, ammonia, and methane). This accounts for their low densities. The outer planets also contain substantial amounts of rocky and metallic materials, which are concentrated in their cores.

The Atmospheres of the Planets The Jovian planets have very thick atmospheres of hydrogen, helium, methane, and ammonia. By contrast, the terrestrial planets, including Earth, have meager atmospheres at best. A planet's ability to retain an atmosphere depends on its mass and temperature, which accounts for the difference between Jovian and terrestrial planets.

Simply stated, a gas molecule can escape from a planet if it reaches a speed known as the escape velocity. For Earth, this velocity is 11 kilometers per second. Any material, including a rocket, must reach this speed before it can escape Earth's gravity and go into space.

A comparatively warm body with a small surface gravity, such as our moon, cannot hold even heavy gases, like carbon dioxide and radon. Thus, the moon lacks an atmosphere. The more massive terrestrial planets of Earth, Venus, and Mars retain some heavy gases. Still, their atmospheres make up only a very small portion of their total mass.

In contrast, the Jovian planets have much greater surface gravities. This gives them escape velocities of 21 to 60 kilometers per second—much higher than the terrestrial planets. Consequently, it is more difficult for gases to escape from their gravitational pulls. Also, because the molecular motion of a gas depends upon temperature, at the low temperatures of the Jovian planets even the lightest gases are unlikely to acquire the speed needed to escape.

Formation of the Solar System

Between stars is "the vacuum of space." However, it is not a pure vacuum because it is populated with regions of dispersed dust and gases. A cloud of dust and gas in space is called a **nebula** (*nebula* = cloud; plural: *nebulae*). A nebula, shown in Figure 3A, often consists of 92 percent hydrogen, 7 percent helium, and less than 1 percent of the remaining heavier elements. For some reason not yet fully understood, these thin gaseous clouds begin to rotate slowly and contract gravitationally. As the clouds contract, they spin faster. For an analogy, think of ice skaters—their speed increases as they bring their arms near their bodies.

Nebular Theory

Scientific studies of nebulae have led to a theory concerning the origin of our solar system. **According to the nebular theory, the sun and planets formed from a rotating disk of dust and gases.** As the speed of rotation increased, the center of the disk began to flatten out, as shown in Figure 3B. Matter became more concentrated in this center, where the sun eventually formed.

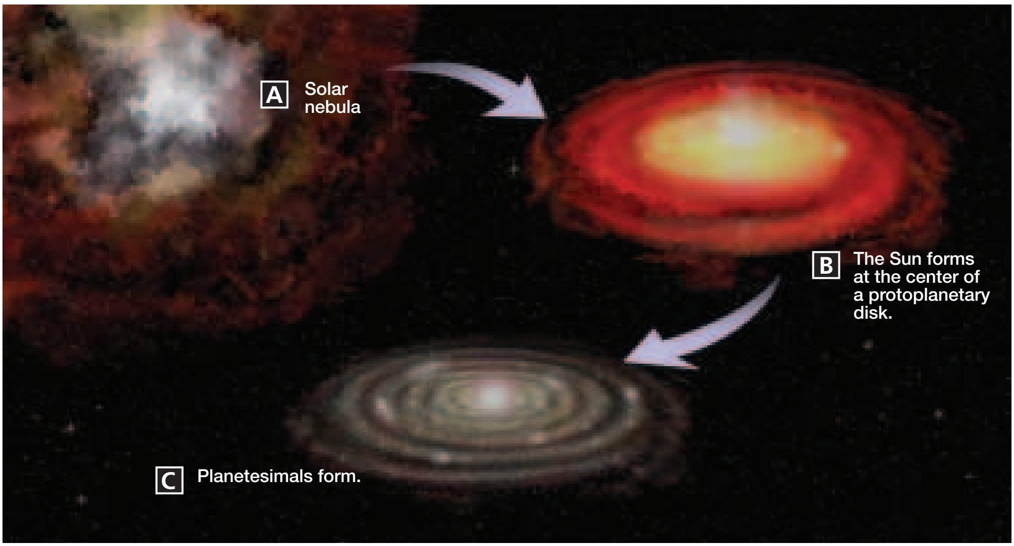


Figure 3 Formation of the Solar System A According to the nebular theory, the solar system formed from a rotating cloud of dust and gas. **B** The sun formed at the center of the rotating disk. **C** Planetesimals collided, eventually gaining enough mass to be planets.

Planetesimals The growth of planets began as solid bits of matter began to collide and clump together through a process known as accretion. The colliding matter formed small, irregularly shaped bodies called **planetesimals.** As the collisions continued, the planetesimals grew larger, as shown in Figure 3C on page 647. They acquired enough mass to exert a gravitational pull on surrounding objects. In this way, they added still more mass and grew into true planets.

In the inner solar system, close to the sun, temperatures were so high that only metals and silicate minerals could form solid grains. It was too hot for ices of water, carbon dioxide, and methane to form. As shown in Figure 4, the inner planets grew mainly from substances with high melting points.

In the frigid outer reaches of the solar system, on the other hand, it was cold enough for ices of water and other substances to form. Consequently, the Jovian planets grew not only from accumulations of solid bits of material but also from large quantities of ices. Eventually, the Jovian planets became large enough to gravitationally capture even the lightest gases, such as hydrogen and helium. This enabled them to grow into giants.

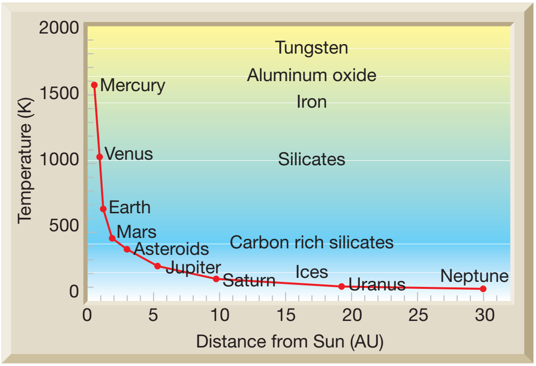


Figure 4 The terrestrial planets formed mainly from silicate minerals and metallic iron that have high melting points. The Jovian planets formed from large quantities of gases and ices.

Section 23.1 Assessment

Reviewing Concepts

1. Which planets are classified as terrestrial? Which planets are classified as Jovian?
2. List the planets in order, beginning with the planet closest to the sun.
3. How do the terrestrial planets differ from the Jovian planets?
4. What is a nebula?
5. How did distance from the sun affect the size and composition of the planets?

Critical Thinking

6. **Summarizing** Summarize the nebular theory of the formation of the solar system.
7. **Inferring** Among the planets in our solar system, Earth is unique because water exists in all three states—solid, liquid, and gas—on its surface. How would Earth's water cycle be different if its orbit was outside the orbit of Mars?

Math Practice

8. Jupiter is 6.3×10^8 (630 million kilometers) from Earth. Calculate how long it would take to reach Jupiter if you traveled at
1) 100 km/h (freeway speed);
2) 1,000 km/h (jetliner speed);
3) 40,000 km/h (rocket speed); and
4) 3.0×10^8 km/s (speed of light).

23.2 The Terrestrial Planets

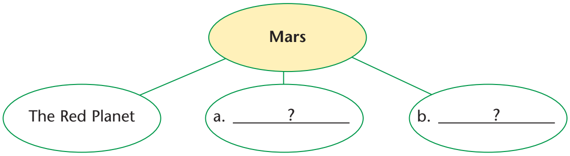
Reading Focus

Key Concepts

- What are the distinguishing characteristics of each terrestrial planet?

Reading Strategy

Using Prior Knowledge Copy the web diagram below. Before you read, add properties that you already know about Mars. Then add details about each property as you read. Make a similar web diagram for the other terrestrial planets.



In January 2004, the space rover, *Spirit,* bounced onto the rocky surface of Mars, known as the Red Planet. Shown in Figure 5, *Spirit* and its companion rover, *Opportunity,* were on the Red Planet to study minerals and geological processes, both past and present. They also searched for signs of the liquid water—such as eroded rocks or dry stream channels on Mars's surface. For the next few months, the rovers sent back to Earth numerous images and chemical analysis of Mars's surface. Much of what we learn about the planets has been gathered by rovers, such as *Spirit,* or space probes that travel to the far reaches of the solar system, such as *Voyager.* In this section, we'll explore three terrestrial planets—Mercury, Venus, and Mars—and see how they compare with Earth.

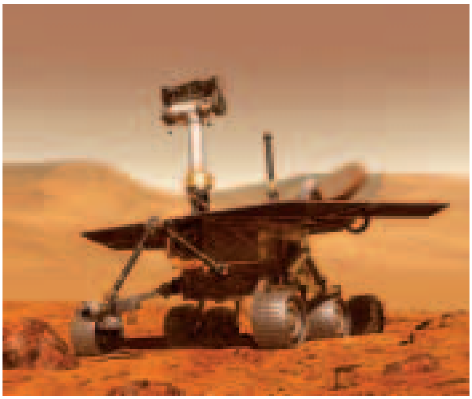


Figure 5 *Spirit* roved the surface of Mars and gathered data about the Red Planet's geologic past and present.

Mercury: The Innermost Planet

Mercury, the innermost and smallest planet, is hardly larger than Earth's moon and is smaller than three other moons in the solar system. Like our own moon, it absorbs most of the sunlight that strikes it and reflects only 6 percent of sunlight back into space. This low percentage of reflection is characteristic of terrestrial bodies that have no atmosphere. Earth, on the other hand, reflects about 30 percent of the light that strikes it. Most of this reflection is from clouds.

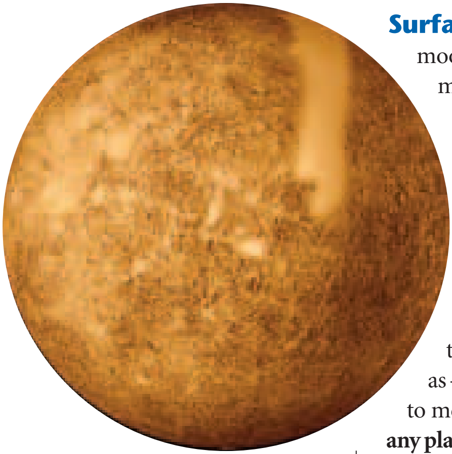


Figure 6 Mercury's surface looks somewhat similar to the far side of Earth's moon.

Surface Features Mercury has cratered highlands, much like the moon, and some smooth terrains that resemble maria. Unlike the moon, however, Mercury is a very dense planet, which implies that it contains a large iron core for its size. Also, Mercury has very long scarps (deep slopes) that cut across the plains and craters alike. These scarps may have resulted from crustal changes as the planet cooled and shrank.

Surface Temperature Mercury, shown in Figure 6, revolves around the sun quickly, but it rotates slowly. One full day-night cycle on Earth takes 24 hours. On Mercury, one rotation requires 59 Earth-days. Nighttime temperatures drop as low as –173°C, and noontime temperatures exceed 427°C—hot enough to melt lead. **Mercury has the greatest temperature extremes of any planet.** The odds of life as we know it existing on Mercury are almost nonexistent.

Reading Checkpoint *How does Mercury's period of rotation compare with Earth's?*

Venus: The Veiled Planet

Venus is second only to the moon in brilliance in the night sky. It orbits the sun once every 255 Earth-days. Venus is similar to Earth in size, density, mass, and location in the solar system. Thus, it has been referred to as "Earth's twin." Because of these similarities, it is hoped that a detailed study of Venus will provide geologists with a better understanding of Earth's history.

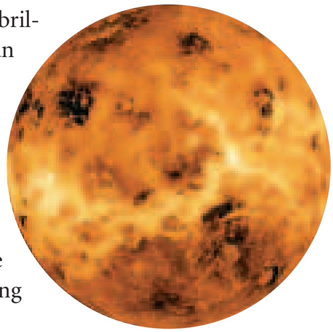


Figure 7 Venus This global view of the surface of Venus is computer generated from two years of Magellan Project radar mapping. The twisting bright features that cross the planet are highly fractured mountains and canyons of the eastern Aphrodite highland.

Surface Features Venus is covered in thick clouds that hide its surface from view. Nevertheless, radar mapping by the uncrewed *Magellan* spacecraft and by instruments on Earth have revealed a varied topography with features somewhat between those of Earth and Mars, as shown in Figure 7. To map Venus, radar pulses are sent toward the planet's surface, and the heights of plateaus and mountains are measured by timing the return of the radar echo. **Data have confirmed that basaltic volcanism and tectonic activity shape Venus's surface. Based on the low density of impact craters, these forces must have been very active during the recent geologic past.**

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About 80 percent of Venus's surface consists of plains covered by volcanic flows. Some lava channels extend hundreds of kilometers—one is 6800 kilometers long. Scientists have identified thousands of now inactive volcanic structures. Most are small shield volcanoes, although more than 1500 volcanoes greater than 20 kilometers across have been mapped. Figure 8 shows two of these volcanoes—one is Sapas Mons, 400 kilometers across and 1.5 kilometers high. Flows from this volcano mostly erupted from its flanks rather than its summit, in the manner of Hawaiian shield volcanoes.

Only 8 percent of Venus's surface consists of highlands that may be similar to continental areas on Earth. Tectonic activity on Venus seems to be driven by upwelling and downwelling of material in the planet's interior.

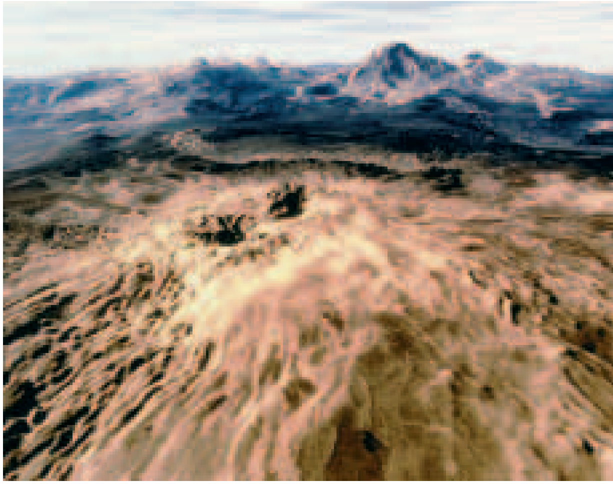


Figure 8 Sapas Mons and Maat Mons In this computer-generated image from Venus, Maat Mons, a large volcano, is near the horizon. Sapas Mons is the bright feature in the foreground.
Comparing and Contrasting ***What features on Venus are similar to those on Earth? What features are different?***

Surface Temperature On Venus, the greenhouse effect has heated the planet's atmosphere to 475°C. That's hot enough to melt lead! Several factors contribute to what scientists have called Venus's *runaway* greenhouse effect.

The main reason for the runaway greenhouse effect on Venus is that its atmosphere is 97 percent carbon dioxide, a greenhouse gas. Venus lacks oceans in which carbon dioxide gas could dissolve, thus removing it from the atmosphere. Scientists think that oceans on Venus may have evaporated early in its history. Water vapor in the atmosphere then accelerated the greenhouse effect. But the atmosphere eventually lost most of its water vapor. The sun's ultraviolet radiation broke down water molecules into hydrogen and oxygen. These gases then escaped into space.

Reading Checkpoint ***Describe the composition of Venus's atmosphere.***

Mars: The Red Planet

Mars has evoked great interest throughout history. Mars is easy to observe, which may explain why so many people are fascinated by it. Mars is known as the Red Planet because it appears as a reddish ball when viewed through a telescope. Mars also has some dark regions that change intensity during the Martian year. The most prominent telescopic features of Mars are its brilliant white polar caps.

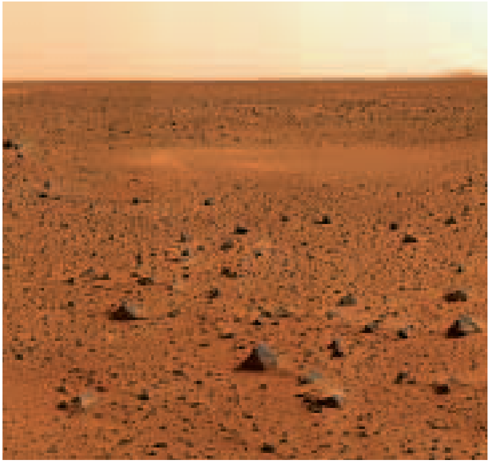


Figure 9 Many parts of Mars's landscape resemble desert areas on Earth.

The Martian Atmosphere

The Martian atmosphere has only 1 percent the density of Earth's. It is made up primarily of carbon dioxide with tiny amounts of water vapor. Data from Mars probes confirm that the polar caps of Mars are made of water ice, covered by a thin layer of frozen carbon dioxide. As winter nears in either hemisphere, temperatures drop to −125°C, and additional carbon dioxide is deposited. **Although the atmosphere of Mars is very thin, extensive dust storms occur and may cause the color changes observed from Earth. Hurricane-force winds up to 270 kilometers per hour can persist for weeks.** The composition of Mars's atmosphere is similar to that of Venus. But Mars is very cold. Why doesn't the greenhouse effect warm Mars's atmosphere? The reason is that Mars's atmosphere is extremely thin compared with the atmosphere of Venus (or Earth). Scientists think that, early in its history, Mars had a thick atmosphere warmed by the greenhouse effect. But Mars's gravity was too low for the planet to keep its atmosphere. Most of the gases escaped into space, and the planet cooled.

Surface Features

Mariner 9, the first spacecraft to orbit another planet, reached Mars in 1971 amid a raging dust storm. When the dust cleared, images of Mars' northern hemisphere revealed numerous large inactive volcanoes. The biggest, Olympus Mons, is the size of Ohio and is 23 kilometers high—over two and a half times higher than Mount Everest. This gigantic volcano and others resemble Hawaiian shield volcanoes on Earth.

Most Martian surface features are old by Earth standards. The highly cratered southern hemisphere is probably 3.5 billion to 4.5 billion years old. Even the relatively "fresh" volcanic features of the northern hemisphere may be older than 1 billion years.

Another surprising find made by *Mariner 9* was the existence of several canyons that are much larger than Earth's Grand Canyon. The largest, Valles Marineris, is shown in Figure 10. It is thought to have formed by slippage of material along huge faults in the crustal layer.

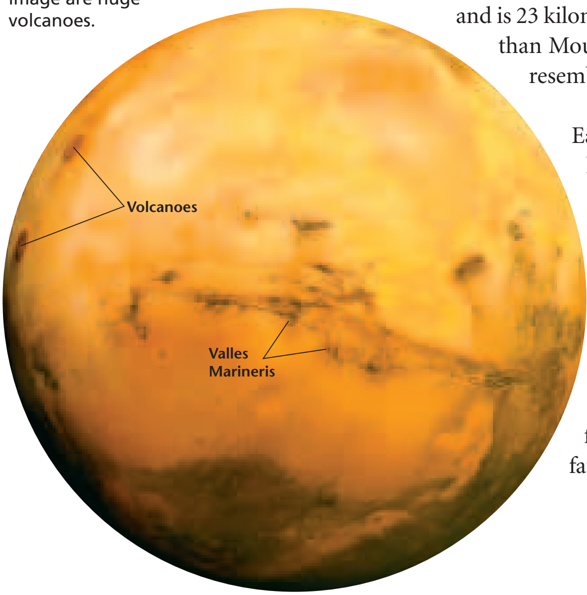


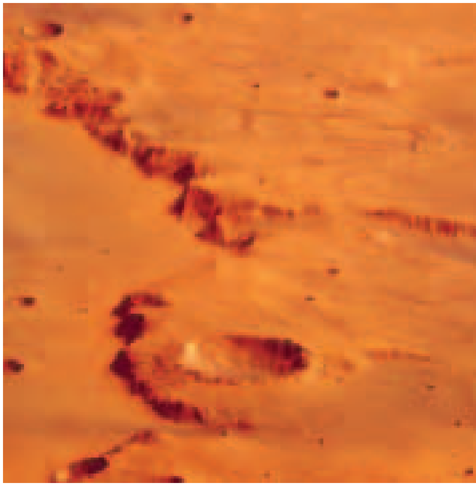
Figure 10 Valles Marineris Mars's Valles Marineris canyon system is more than 5000 kilometers long and up to 8 kilometers deep. The dark spots on the left edge of the image are huge volcanoes.

Water on Mars Some areas of Mars exhibit drainage patterns similar to those created by streams on Earth. The rover *Opportunity*, for example, found evidence of evaporite minerals and geologic formations associated with liquid water, as shown in Figure 11. In addition, *Viking* images have revealed ancient islands in what is now a dry streambed. When these streamlike channels were first discovered, some observers speculated that a thick water-laden atmosphere capable of generating torrential downpours once existed on Mars. If so, what happened to this water? The present Martian atmosphere contains only traces of water.

Images from the *Mars Global Surveyor* indicate that groundwater has recently migrated to the surface. These spring-like seeps have created gullies where they emerge from valley and crater walls. Some of the escaping water may have initially frozen due to the average Martian temperatures that range between −70°C and −100°C. Eventually, however, it seeped out as a slurry of sediment, ice, and liquid that formed the gullies.

Many scientists do not accept the theory that Mars once had an active water cycle similar to Earth's. Rather, they believe that most of the large stream-like valleys were created by the collapse of surface material caused by the slow melting of subsurface ice. Data from *Opportunity*, however, indicate that some areas were "drenched" in water. It will take scientists many months, if not years, to analyze the data gathered by the latest Mars mission. Because water is an essential ingredient for life, scientists and nonscientists alike are enthusiastic about exploring this phenomenon.

Figure 11 These channels show that liquid water once flowed on the surface of Mars.



Section 23.2 Assessment

Reviewing Concepts

1. Which inner planet is smallest?
2. How does Venus compare with Earth?
3. Identify one distinguishing characteristic of each inner planet.
4. What surface features does Mars have that are also common on Earth?

Critical Thinking

5. **Making Judgments** Besides Earth, which inner planet may have been most able to support life? Explain your answer.
6. **Relating Cause and Effect** Why are surface temperatures so high on Venus?

Writing in Science

Editorial A space mission to the moon or Mars often costs millions of dollars. Yet, it is hoped that space exploration can give us valuable knowledge about the solar system. Consider the pros and cons of space exploration. Then write an editorial stating whether or not you believe the costs are worth the potential benefits.

23.3 The Outer Planets (and Pluto)

Reading Focus

Key Concepts

- What characteristics distinguish each outer planet?
- Why is Pluto not considered a planet?

Vocabulary

- dwarf planet

Reading Strategy

Summarizing Make a table like the one shown that includes a row for each outer planet. Write a brief summary of the characteristics of each planet.

Outer Planets	Characteristics
Jupiter	largest; most mass, Great Red Spot
a. ___?___	b. ___?___
c. ___?___	d. ___?___

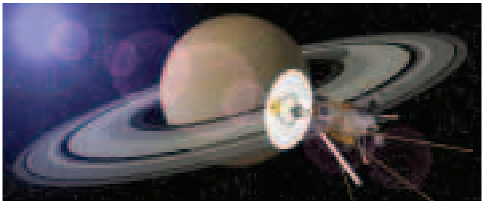


Figure 12 This artist's rendition shows *Cassini* approaching Saturn.

In 2004, the space probe *Cassini,* launched seven years earlier, finally reached the planet Saturn. The mission of *Cassini,* shown in Figure 12, was to explore Saturn's stunning ring system and its moons, including the unique moon Titan. In 2005, the *Huygens* probe, carried into space by the *Cassini* orbiter, descended to Titan's surface for further studies. In this section, we'll take a clue from *Cassini* and explore the outer planets—Jupiter, Saturn, Uranus, and Neptune.

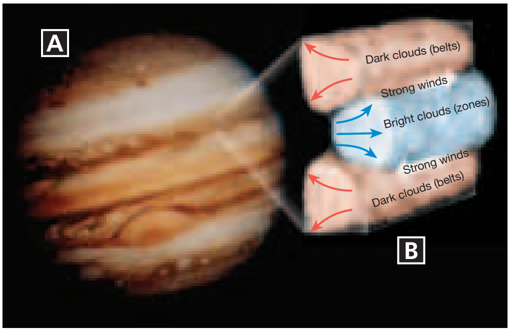


Figure 13 **A** When photographed by *Voyager 2,* the Great Red Spot was the size of two Earth-size circles placed side by side. **B** The dark clouds are regions where gases are sinking and cooling. The convection currents and the rapid rotation of the planet generate high-speed winds.

Jupiter: Giant Among Planets

Jupiter is only 1/800 as massive as the sun. Still, it is the largest planet by far. **Jupiter has a mass that is 2 1/2 times greater than the mass of all the other planets and moons combined.** In fact, had Jupiter been about 10 times larger, it would have evolved into a small star. Jupiter rotates more rapidly than any other planet, completing one rotation in slightly less than 10 Earth-hours.

When viewed through a telescope or binoculars, Jupiter appears to be covered with alternating bands of multicolored clouds that run parallel to its equator. The most striking feature is the Great Red Spot in the southern hemisphere, shown in Figure 13A. The Great Red Spot was first discovered more than three centuries ago by two astronomers, Giovanni Cassini (for whom the space probe was named) and Robert Hooke. When *Pioneer 11* moved within 42,000 kilometers of Jupiter's cloud tops, images from the orbiter indicated that the Great Red Spot is a cyclonic storm.

Structure of Jupiter Although Jupiter is called a gas giant, it is not simply a ball of gas. At 1000 kilometers below the clouds, the pressure is great enough to compress hydrogen gas into a liquid. Consequently, Jupiter is thought to be a gigantic ocean of liquid hydrogen. Less than halfway into Jupiter's interior, extreme pressures cause the liquid hydrogen to turn into liquid metallic hydrogen. Jupiter is also believed to have a rocky and metallic central core.

Jupiter's hydrogen-helium atmosphere is very active. It contains small amounts of methane, ammonia, water, and sulfur compounds. The wind systems, shown in Figure 13B, generate the light- and dark-colored bands that encircle this giant. Unlike the winds on Earth, which are driven by solar energy, Jupiter itself gives off nearly twice as much heat as it receives from the sun. Thus, the interior heat from Jupiter produces huge convection currents in the atmosphere.

Jupiter's Moons Jupiter's satellite system, consisting of 63 moons discovered so far, resembles a miniature solar system. The four largest moons, Io, Europa, Ganymede, and Callisto, were discovered by Galileo in 1610. Each of the four Galilean satellites is a unique geological world. The moons are shown in Figure 14. The innermost of the Galilean moons, Io, is one of four known volcanically active bodies in our solar system. The other volcanically active bodies are Earth, Saturn's moon Enceladus, and Neptune's moon Triton. The heat source for volcanic activity on Io is thought to be tidal energy generated by a relentless "tug of war" between Jupiter and the other Galilean moons. The gravitational power of Jupiter and nearby moons pulls and pushes on Io's tidal bulge as its orbit takes it alternately closer to and farther from Jupiter. This gravitational flexing of Io is transformed into frictional heat energy and results in Io's volcanic eruptions.

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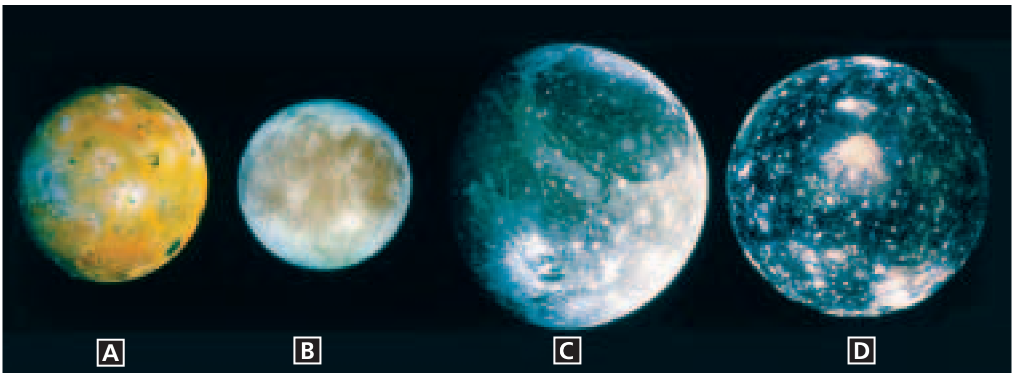
Figure 14 Jupiter's Moons
A Io is the innermost moon and is one of only four volcanically active bodies in the solar system. **B** Europa—the smallest of the Galilean moons—has an icy surface that is crossed by many linear features. **C** Ganymede is the largest Jovian moon, and it contains cratered areas, smooth regions, and areas covered by numerous parallel grooves. **D** Callisto—the outermost of the Galilean moons—is densely cratered, much like Earth's moon.



Jupiter's Rings Jupiter's ring system was one of the most unexpected discoveries made by *Voyager 1*. By analyzing how these rings scatter light, researchers concluded that the rings are composed of fine, dark particles, similar in size to smoke particles. The faint nature of the rings also indicates that these minute fragments are widely dispersed. The particles are thought to be fragments blasted by meteorite impacts from the surfaces of Metis and Adrastea, two small moons of Jupiter.

Reading Checkpoint *Which Galilean moon is volcanically active?*

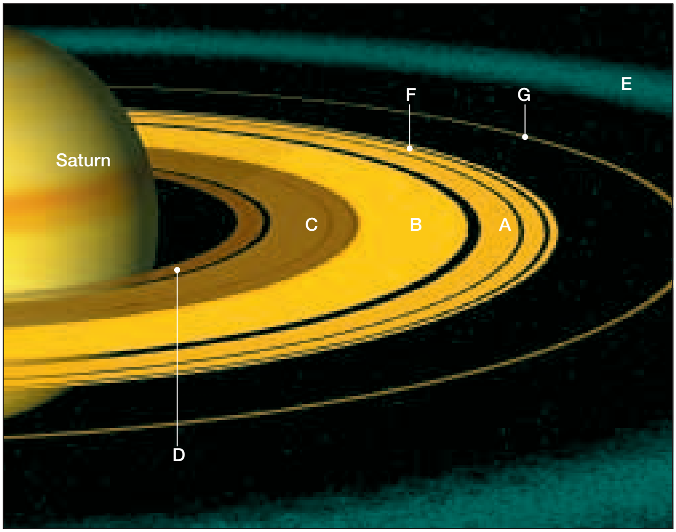


Figure 15 Saturn's Rings Saturn's rings fall into two categories based on particle density. The main rings (A and B) are densely packed. In contrast, the outer rings are composed of widely dispersed particles.

Saturn: The Elegant Planet

Requiring 29.46 Earth-years to make one revolution, Saturn is almost twice as far from the sun as Jupiter. However, its atmosphere, composition, and internal structure are thought to be remarkably similar to Jupiter's. **The most prominent feature of Saturn is its system of rings, shown in Figure 15.** In 1610, Galileo used a primitive telescope and first saw the structures that were later found to be the rings. They appeared as two small bodies adjacent to the planet. Their ring nature was explained 50 years later by the Dutch astronomer Christian Huygens.

Features of Saturn In 1980 and 1981, flyby missions of the *Voyagers 1* and *2* spacecraft came within 100,000 kilometers of Saturn. More information was gained in a few days than had been acquired since Galileo first viewed this elegant planet.

1. Saturn's atmosphere is very active, with winds roaring at up to 1500 kilometers per hour.
2. Large cyclonic "storms" similar to Jupiter's Great Red Spot, although smaller, occur in Saturn's atmosphere.
3. Eleven additional moons were discovered.
4. The rings of Saturn were found to be more complex than expected.

More recently, observations from ground-based telescopes, the Hubble Space Telescope, and *Cassini* have added to our knowledge of Saturn's ring and moon system. When the positions of Earth and Saturn allowed the rings to be viewed edge-on—thereby reducing the glare from the main rings—Saturn's faintest rings and satellites became visible.

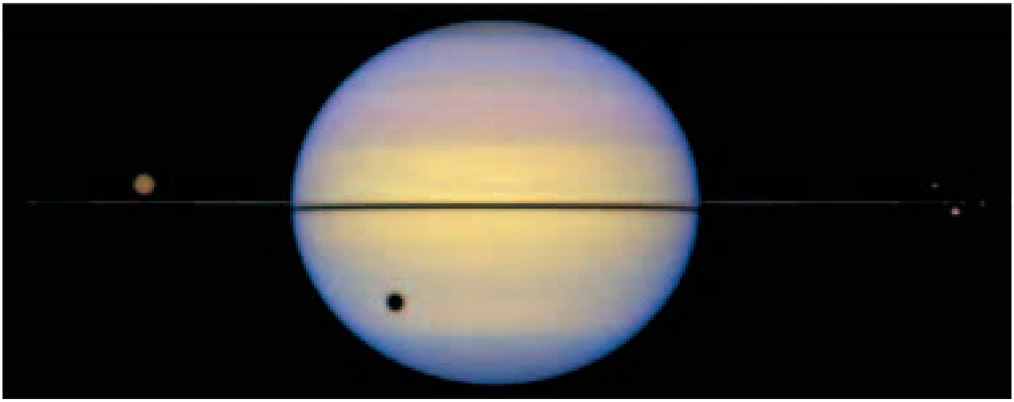


Figure 16 Saturn's Moons This image of Saturn shows several of its moons.

Saturn's Rings Until the discovery that Jupiter, Uranus, and Neptune also have ring systems, this phenomenon was thought to be unique to Saturn. Although the four known ring systems differ in detail, they share many attributes. They all consist of multiple concentric rings separated by gaps of various widths. In addition, each ring is composed of individual particles—"moonlets" of ice and rock—that circle the planet while regularly impacting one another.

Most rings fall into one of two categories based on particle density. Saturn's main rings, designated A and B in Figure 15, and the bright rings of Uranus are tightly packed and contain "moonlets" that range in size from a few centimeters to several meters. These particles are thought to collide frequently as they orbit the parent planet. Despite the fact that Saturn's dense rings stretch across several hundred kilometers, they are very thin, perhaps less than 100 meters from top to bottom.

At the other extreme, the faintest rings, such as Jupiter's ring system and Saturn's outermost rings, are composed of very fine particles that are widely dispersed. Saturn's outermost rings are designated E in Figure 15. In addition to having very low particle densities, these rings tend to be thicker than Saturn's bright rings.

Saturn's Moons Saturn's satellite system consists of 56 moons, some of which are shown in Figure 16. Titan is the largest moon and is bigger than Mercury. It is covered with rivers and oceans of liquid hydrocarbons. Titan and Neptune's Triton are the only moons in the solar system known to have substantial atmospheres. Because of its dense gaseous cover, the atmospheric pressure at Titan's surface is about 1.5 times that at Earth's surface. Another moon, Enceladus, is one of four known volcanically active bodies in our solar system. In 2006, the *Cassini* space probe discovered liquid water geysers in the moon's south polar region.

Reading Checkpoint ***How many moons of Saturn have been discovered thus far?***

Uranus: The Sideways Planet

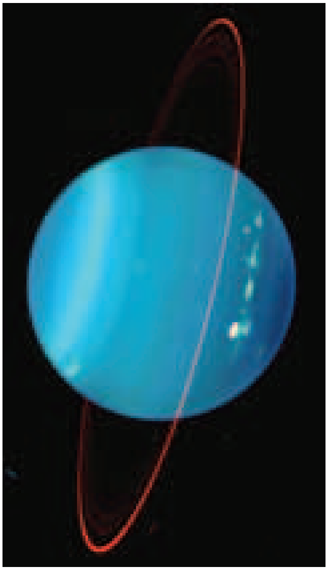


Figure 17 The axis of rotation of Uranus is nearly parallel with the plane of its orbit. This photo also shows the planet's ring system.

A unique feature of Uranus, shown in Figure 17, is that it rotates "on its side." **Instead of being generally perpendicular to the plane of its orbit like the other planets, Uranus's axis of rotation lies nearly parallel with the plane of its orbit.** Its rotational motion, therefore, has the appearance of rolling, rather than the top-like spinning of the other planets. Uranus's spin may have been altered by a giant impact.

A surprise discovery in 1977 revealed that Uranus has a ring system. This find occurred as Uranus passed in front of a distant star and blocked its view. Observers saw the star "wink" briefly both before and after Uranus passed by. Later studies indicate that Uranus has at least nine distinct ring belts.

The five largest moons of Uranus show varied terrain. Some of the moons have long, deep canyons and linear scars, whereas others possess large, smooth areas on otherwise crater-riddled surfaces. Miranda, the innermost of the five largest moons, has a greater variety of landforms than any body yet examined in the solar system.

Reading Checkpoint ***What is unique about Uranus's axis of rotation?***

Neptune: The Windy Planet

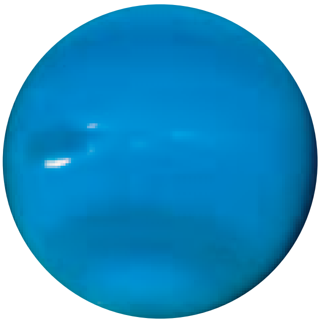


Figure 18 The Great Dark Spot of Neptune (photographed by *Voyager 2* in 1989) is visible in the center of the left of the image. Bright cirrus-like clouds that travel at high speeds around the planet are also visible.
Identifying ***What was the Great Dark Spot?***

As shown in Figure 18, Neptune has a dynamic atmosphere, much like those of Jupiter and Saturn. **Winds exceeding 1000 kilometers per hour encircle Neptune, making it one of the windiest places in the solar system.** It also had an Earth-size blemish called the Great Dark Spot that was reminiscent of Jupiter's Great Red Spot. The Great Dark Spot was assumed to be a large rotating storm. About five years after the Great Dark Spot was discovered, it vanished, only to be replaced by another dark spot in the planet's northern hemisphere, which also vanished within a few years.

Neptune has many surprising features. Perhaps most surprising are the cirrus-like clouds that occupy a layer about 50 kilometers above the main cloud deck. The clouds are most likely frozen methane. *Voyager* images revealed that the bluish planet also has a ring system.

Neptune has 13 known moons. Triton, Neptune's largest moon, is nearly the size of Earth's moon. Triton is the only large moon in the solar system that exhibits retrograde motion. This motion indicates that Triton formed independently of Neptune and was gravitationally captured.

Triton also has the lowest surface temperature yet measured on any body in the solar system at −200°C. Its atmosphere is mostly nitrogen with a little methane. Despite low surface temperatures, Triton displays volcanic-like activity.

Pluto: Dwarf Planet

Until 2006, Pluto was considered to be one of the nine planets. But in August of 2006, the International Astronomical Union (IAU) redefined the word "planet" in a way that excluded Pluto. **Pluto is not considered a planet, because it has not cleared the neighborhood around its orbit.**

Because Pluto was no longer a planet, the IAU also created a new term to describe it. A **dwarf planet** is a round object that orbits the sun but has not cleared the neighborhood around its orbit. A planet's gravity is strong enough for it to pull in smaller nearby bodies, thus clearing its orbital path. But a dwarf planet's gravity is too weak to attract all the debris nearby. Therefore, a dwarf planet orbits in a zone along with other small solar system bodies.

Pluto is the most well known of the dwarf planets. However, it is neither the largest nor the first to be discovered. The dwarf planet Ceres, which is in the asteroid belt, was discovered in 1801. And the dwarf planet Eris, just discovered in 2005, is slightly larger than Pluto. All dwarf planets likely contain a mixture of rock and ice, but can be found in very different parts of the solar system. Pluto is unusual in that it has a moon, Charon, which is more than half its size and may be considered a dwarf planet on its own. It is not yet known how many objects in the solar system will be considered dwarf planets. As new discoveries are made, this definition may be revisited.

Figure 19 This Hubble image shows Pluto and its moon Charon.

Section 23.3 Assessment

Reviewing Concepts

1. What is the largest planet? What is the smallest?
2. What is Jupiter's Great Red Spot?
3. Identify one distinguishing characteristic of each outer planet and Pluto.
4. How are Saturn's moon Titan and Neptune's Triton similar?
5. In what way is Io similar to Earth? What other body shows this similarity?

Critical Thinking

6. **Relating Cause and Effect** What may have caused Uranus's unique axis of rotation?
7. **Making Judgments** Should Pluto have been reclassified as a dwarf planet? Explain your answer.

Connecting Concepts

Convection Currents Write a brief paragraph comparing and contrasting atmospheric convection currents on Jupiter and Earth.

23.4 Minor Members of the Solar System

Reading Focus

Key Concepts

- Where are most asteroids located?
- What is the structure of a comet?
- What is the origin of most meteoroids?

Vocabulary

- asteroid
- comet
- coma
- meteoroid
- meteor
- meteorite

Reading Strategy

Building Vocabulary Copy the table below. Then as you read the section, write a definition for each vocabulary term in your own words.

Vocabulary	Definition
asteroid	a. ___?___
b. ___?___	c. ___?___
d. ___?___	e. ___?___

In February 2001 an American spacecraft, *NEAR Shoemaker,* finished its mission in spectacular fashion—it became the first visitor to an asteroid. This historic accomplishment was not part of *NEAR Shoemaker's* original goal, which was to orbit the asteroid, taking images and gathering data about these objects in space. With this mission accomplished, however, NASA engineers wanted to see if they could actually land a spacecraft on an asteroid. The data they would gather would be priceless. As an added benefit, NASA would gain valuable experience that might help in the future to deflect an asteroid on a collision course with Earth.

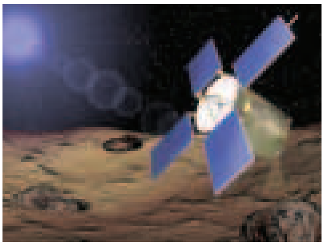


Figure 20 This artist's rendition shows *NEAR Shoemaker* touching down on the asteroid Eros.

Although it was not designed for landing, *NEAR Shoemaker*—shown in Figure 20—successfully touched down on the asteroid, Eros. It generated information that has planetary geologists both intrigued and perplexed. The spacecraft drifted toward the surface of Eros at the rate of 6 kilometers per hour. The images obtained revealed a barren, rocky surface composed of particles ranging in size from fine dust to boulders up to 8 meters across. Researchers unexpectedly discovered that fine debris is concentrated in the low areas that form flat deposits resembling ponds. Surrounding the low areas, the landscape is marked by an abundance of large boulders.

Seismic shaking is one of several hypotheses being considered as an explanation for the boulder-laden topography. This shaking would move the boulders upward. The larger materials rise to the top while the smaller materials settle to the bottom, which is similar to what happens when a can of mixed nuts is shaken.

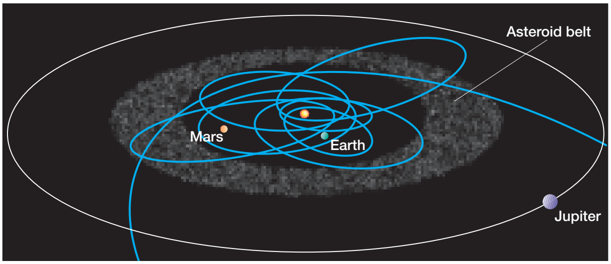


Figure 21 The orbits of most asteroids lie between Mars and Jupiter. Also shown are the orbits of a few near-Earth asteroids. Perhaps a thousand or more asteroids pass close to Earth. Luckily, only a few dozen of these are thought to be larger than 1 kilometer in diameter.

Asteroids

Asteroids are small rocky bodies that orbit the sun. The largest, the dwarf planet Ceres, is about 1000 kilometers in diameter, but more than a million are greater than 1 kilometer across. By definition, asteroids are larger than 10 meters in diameter. **Most asteroids lie in the asteroid belt between the orbits of Mars and Jupiter. They have orbital periods of three to six years.** Some asteroids have very elongated orbits and travel very near the sun, and a few larger ones regularly pass close to Earth and the moon as shown in Figure 21. Many of the most recent impact craters on the moon and Earth were probably caused by collisions with asteroids. Inevitably, future Earth–asteroid collisions will occur.

Many asteroids have irregular shapes, as shown in Figure 22. Because of this, planetary geologists first speculated that they might be fragments of a broken planet that once orbited between Mars and Jupiter. However, the total mass of the asteroids is estimated to be only 1/1000 that of Earth, which itself is not a large planet. What happened to the remainder of the original planet? Others have hypothesized that several larger bodies once coexisted in close proximity, and their collisions produced numerous smaller ones. The existence of several families of asteroids has been used to support this explanation. However, no conclusive evidence has been found for either hypothesis.

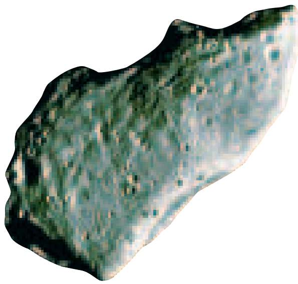


Figure 22 Asteroid 951, also called Gaspra, is probably the fragment of a larger body that was torn apart by a collision.

Reading Checkpoint *What is an asteroid?*

Comets

Comets are among the most interesting and unpredictable bodies in the solar system. **Comets** are pieces of rocky and metallic materials held together by frozen water, ammonia, methane, carbon dioxide, and carbon monoxide. Many comets travel in very elongated orbits that carry them far beyond Pluto. These comets take hundreds of thousands of years to complete a single orbit around the sun. However, a few have orbital periods of less than 200 years and make regular encounters with the inner solar system.

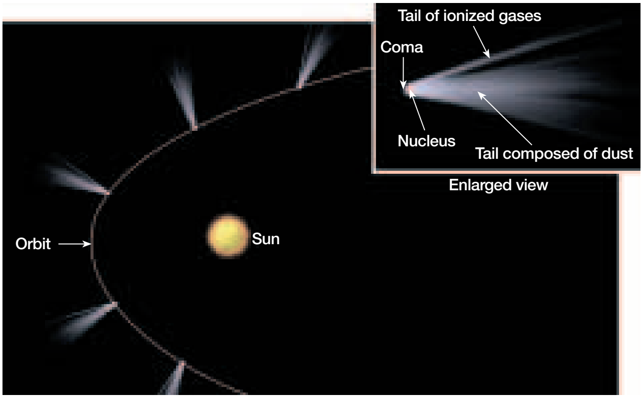


Figure 23 A comet's tail always points away from the sun.

Coma When first observed, a comet appears very small. But as it approaches the sun, solar energy begins to vaporize the frozen gases. This produces a glowing head called the **coma,** shown in Figure 23. **A small glowing nucleus with a diameter of only a few kilometers can sometimes be detected within a coma. As comets approach the sun, some, but not all, develop a tail that extends for millions of kilometers.**

The fact that the tail of a comet points away from the sun in a slightly curved manner led early astronomers to propose that the sun has a repulsive force that pushes the particles of the coma away, thus forming the tail. Today, two solar forces are known to contribute to this formation. One, radiation pressure, pushes dust particles away from the coma. The second, known as solar wind, is responsible for moving the ionized gases, particularly carbon monoxide. You'll learn more about solar wind in the next chapter. Sometimes a single tail composed of both dust and ionized gases is produced, but often two tails are observed.

As a comet moves away from the sun, the gases forming the coma recondense, the tail disappears, and the comet returns to cold storage. Material that was blown from the coma to form the tail is lost from the comet forever. Therefore it is believed that most comets cannot survive more than a few hundred close orbits of the sun. Once all the gases are expelled, the remaining material—a swarm of tiny metallic and stony particles—continues the orbit without a coma or a tail.

Kuiper Belt Comets apparently originate in two regions of the outer solar system. Those with short orbital periods are thought to orbit beyond Neptune in a region called the Kuiper belt. Like the asteroids in the inner solar system, most Kuiper belt comets move in nearly circular orbits that lie roughly in the same plane as the planets. A chance collision between two Kuiper belt comets, or the gravitational influence of one of the Jovian planets, may occasionally alter the orbit of a comet enough to send it to the inner solar system, and into our view.

Reading Checkpoint *In which direction does the tail of a comet point?*

Oort Cloud Unlike Kuiper belt comets, comets with long orbital periods aren't confined to the plane of the solar system. These comets appear to be distributed in all directions from the sun, forming a spherical shell around the solar system called the Oort cloud. The gravitational effect of another object in space is thought to send an occasional Oort cloud comet into a highly eccentric orbit that carries it toward the sun. However, only a tiny portion of the Oort cloud comets pass into the inner solar system.

Halley's Comet The most famous short-period comet is Halley's comet, shown in Figure 24. Its orbital period averages 76 years. When it passed near Earth in 1910, Halley's comet had developed a tail nearly 1.6 million kilometers long and was visible during the daylight hours.

In March 1986, the European probe *Giotto* approached to within 600 kilometers of the nucleus of Halley's comet and obtained the first images of this elusive structure. We now know that the nucleus is potato-shaped, 16 kilometers by 8 kilometers. The surface is irregular and full of craterlike pits. Gases and dust that vaporize from the nucleus to form the coma and tail appear to gush from parts of its surface as bright jets or streams.

Figure 24 Halley's Comet will return to the inner solar system in 2061.

Meteoroids

Nearly everyone has seen a "shooting star." This streak of light occurs when a meteoroid enters Earth's atmosphere. A **meteoroid** is a small solid particle that travels through space. **Most meteoroids originate from any one of the following three sources: (1) interplanetary debris that was not gravitationally swept up by the planets during the formation of the solar system, (2) material from the asteroid belt, or (3) the solid remains of comets that once traveled near Earth's orbit.** A few meteoroids are believed to be fragments of the moon, or possibly Mars, that were ejected when an asteroid impacted these bodies.

Some meteoroids are as large as asteroids. Most, however, are the size of sand grains. Consequently, they vaporize before reaching Earth's surface. Meteoroids that enter Earth's atmosphere and burn up are called **meteors.** The light that we see is caused by friction between the particle and the air, which produces heat.

Occasionally, meteor sightings can reach 60 or more per hour. These displays, called meteor showers, result when Earth encounters a swarm of meteoroids traveling in the same direction and at nearly the same speed as Earth. As shown in Table 2, some meteor showers are closely associated with the orbits of some comets, strongly suggesting that they are material lost by these comets. The Perseid meteor shower, which occurs each year around August 12, may be the remains of Comet 1862 III.

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Table 2 Major Meteor Showers		
Shower	Approximate Dates Each Year	Associated Comet
Quadrantids	Jan. 4–6	
Lyrids	Apr. 20–23	Comet 1861 I
Eta Aquarids	May 3–5	Halley's comet
Delta Aquarids	July 30	
Perseids	Aug. 12	Comet 1862 III
Draconids	Oct. 7–10	Comet Giacobini-Zinner
Orionids	Oct. 20	Halley's comet
Taurids	Nov. 3–13	Comet Encke
Andromedids	Nov. 14	Comet Biela
Leonids	Nov. 18	Comet 1866 I
Geminids	Dec. 4–16	

A meteoroid that actually reaches Earth's surface is called a **meteorite.** A few very large meteorites have blasted out craters on Earth's surface, similar to those on the moon. The most famous is Meteor Crater in Arizona. Prior to moon rocks brought back by astronauts, meteorites such as the one in Figure 25 were the only extraterrestrial materials that could be directly examined.

Meteorites and the Age of the Solar System

How did scientists determine the age of the solar system? They used evidence from meteorites, moon rocks, and Earth rocks. Radiometric dating of meteorites found on Earth shows that the oldest meteorites formed more than 4.57 billion years ago. These meteorites are the oldest-known materials in the solar system. Some are made mostly of iron. Others, called stony meteorites, contain silicates. Scientists think that the composition of meteorites is similar to the composition of other materials in the inner solar system during its formation.

Moon rocks from the lunar highlands have a composition similar to that of stony meteorites. These moon rocks date to about 4.5 billion years ago, almost as old as the oldest meteorites. From these facts, scientists infer that the moon must be just slightly younger than the formation of the solar system, which occured 4.567 billion years ago.

The ages of the oldest known Earth rocks are consistent with this conclusion. Scientists have dated rocks found in northwestern Canada at about 4 billion years old. These are the oldest rocks found on Earth so far. In addition, some tiny crystals of the mineral zircon found in sedimentary rocks in Australia are 4.4 billion years old.

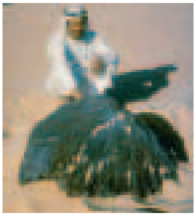


Figure 25 This meteorite is made up mostly of iron.

Section 23.4 Assessment

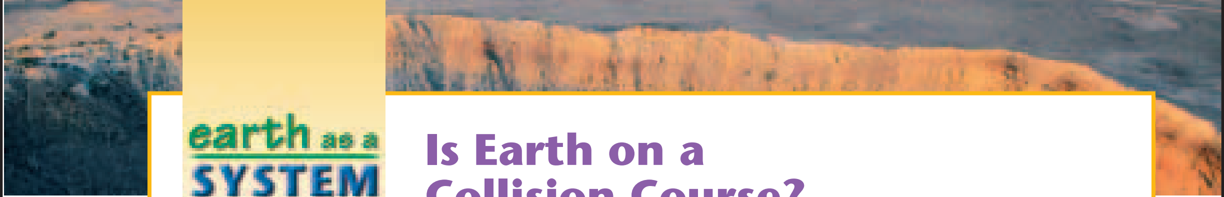
Reviewing Concepts

1. Where are most asteroids located?
2. Describe the structure of a comet.
3. Where do short-period comets come from? What about long-period comets?
4. Meteoroids originate from what three sources?

Critical Thinking

5. **Comparing and Contrasting** Compare and contrast a meteoroid, meteor, and meteorite.
6. **Predicting** What do you think would happen if Earth passed through the tail of a comet?

7. It has been estimated that Halley's comet has a mass of 1×10^{11} metric tons. This comet is estimated to lose 1×10^{8} metric tons of material each time its orbit brings it close to the sun. With an orbital period of 76 years, what is the maximum remaining life span of Halley's comet?



earth as a SYSTEM

Is Earth on a Collision Course?

The solar system is cluttered with meteoroids, asteroids, active comets, and extinct comets. These fragments travel at great speeds and can strike Earth with the explosive force of a powerful nuclear weapon.

Ancient Collisions

During the last few decades, it has become increasingly clear that comets and asteroids have collided with Earth far more frequently than was previously known. The evidence for these collisions is giant impact structures. See Figure 26. More than 100 impact structures have been identified as shown on the map in Figure 27. Most are so old that they no longer resemble impact craters. However, evidence of their intense impact remains. One notable exception is a very fresh-looking crater near Winslow, Arizona, known as Meteor Crater.

Evidence is mounting that about 65 million years ago a large asteroid about 10 kilometers in diameter collided with Earth. This impact may have caused the extinction of the dinosaurs, as well as nearly 50 percent of all plant and animal species.

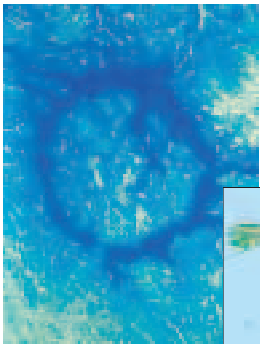


Figure 26 Manicouagan, Quebec, is a 200-million-year-old eroded impact structure. The lake outlines the crater remnant.

Close Calls

More recently, a spectacular explosion has been linked to the collision of our planet with a comet or asteroid. In 1908, in a remote region of Siberia, a "fireball" that appeared more brilliant than the sun exploded with a violent force. The shock waves rattled windows and triggered reverberations heard up to 1000 kilometers away. The "Tunguska event," as it is called, scorched, de-limbed, and flattened trees up to 30 kilometers from the epicenter. However, expeditions to the area did not find any evidence of an impact crater or metallic fragments. It is believed that the explosion—which equaled at least a 10-megaton nuclear bomb—occurred a few kilometers above the surface. It was most likely the end of a comet or perhaps a stony asteroid. The reason it exploded prior to impact remains unclear.

A reminder of the dangers of living with these small but deadly objects from space came in 1989 when an asteroid—nearly 1 kilometer across—shot past Earth. The asteroid came close to Earth, passing it by only twice the distance to the moon. It traveled at a speed of 70,000 kilometers per hour, and it could have made an impact crater 10 kilometers in diameter and perhaps 2 kilometers deep.

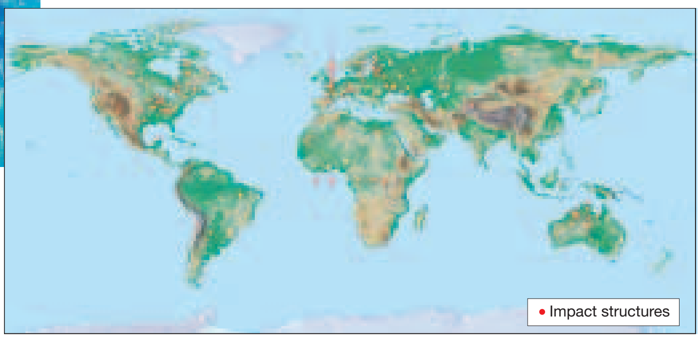


Figure 27 Major Impact Structures