6

Formation of Planetary Systems

Our Solar System and Beyond

learning goals

6.1 A Brief Tour of the Solar System
- What does the solar system look like?

6.2 Clues to the Formation of Our Solar System
- What features of our solar system provide clues to how it formed?
- What theory best explains the features of our solar system?

6.3 The Birth of the Solar System
- Where did the solar system come from?
- What caused the orderly patterns of motion in our solar system?

6.4 The Formation of Planets
- Why are there two major types of planets?
- Where did asteroids and comets come from?
- How do we explain the existence of our Moon and other exceptions to the rules?
- When did the planets form?

6.5 Other Planetary Systems
- How do we detect planets around other stars?
- How do extrasolar planets compare with planets in our solar system?
- Do we need to modify our theory of solar system formation?

Now that we have discussed some of the key laws that govern nature, we can apply these laws to the study of objects throughout our universe. We will begin with our solar system in this and the next three chapters, and later study stars, galaxies, and the universe.

In this chapter, we'll explore the nature of our solar system and current scientific ideas about its birth. After a brief overview of the solar system and its individual worlds, we'll focus on characteristics of the solar system that offer key clues about how it formed. Finally, we'll learn how astronomers have discovered planets around other stars, and how these other planetary systems are helping us understand our own.

essential preparation

1. What is our place in the universe? **[Section 1.1]**
2. How did we come to be? **[Section 1.1]**
3. How big is Earth compared to our solar system? **[Section 1.2]**
4. What keeps a planet rotating and orbiting the Sun? **[Section 4.3]**
5. How does light tell us the speed of a distant object? **[Section 5.2]**

MA Scale of the Universe Tutorial, Lesson 1

6.1 A Brief Tour of the Solar System

Our ancestors long ago recognized the motions of the planets through the sky, but it has been only a few hundred years since we learned that Earth is also a planet that orbits the Sun. Even then, we knew little about the other planets until the development of large telescopes. More recently, space exploration has brought us far greater understanding of other worlds. We've lived in this solar system all along, but only now are we getting to know it. Let's begin with a quick tour of our planetary system, which will provide context for the more detailed study that will follow.

• What does the solar system look like?

The first step in getting to know our solar system is to visualize what it looks like as a whole. Imagine viewing the solar system from beyond the orbits of the planets. What would we see?

Without a telescope, the answer would be "not much." Remember that the Sun and planets are all quite small compared to the distances between them **[Section 1.2]**—so small that if we viewed them from the outskirts of our solar system, the planets would be only pinpoints of light, and even the Sun would be just a small bright dot in the sky. But if we magnify the sizes of the planets by about a million times compared to their distances from the Sun and show their orbital paths, we get the central picture in Figure 6.1 (pages 144–145).

The ten pages that follow Figure 6.1 offer a brief tour through our solar system, beginning at the Sun and continuing to each of the planets. The tour highlights a few of the most important features of each world we visit—just enough information so that you'll be ready for the comparative study we'll undertake in later chapters. The side of each page shows the planets to scale, using the 1-to-10-billion scale introduced in Chapter 1. The map along the bottom of each page shows the locations of the Sun and each of the planets in the Voyage scale model solar system (see Figures 1.5 and 1.6) so that you can see relative distances from the Sun. Table 6.1, which follows the tour, summarizes key planetary data.

As you study Figure 6.1, the tour pages, and Table 6.1, you'll quickly see that our solar system is *not* a random collection of worlds. Figure 6.1 shows that all the planets orbit the Sun in the same direction and in nearly the same plane, while the figure and tour show that the four inner planets are quite different in character from the next four planets.

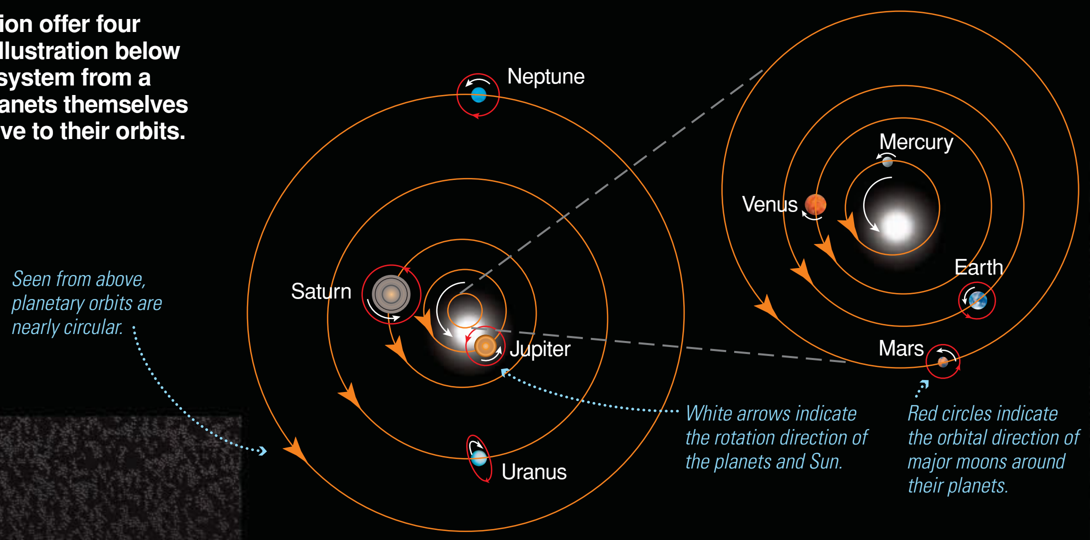
(main text continued on page 157)

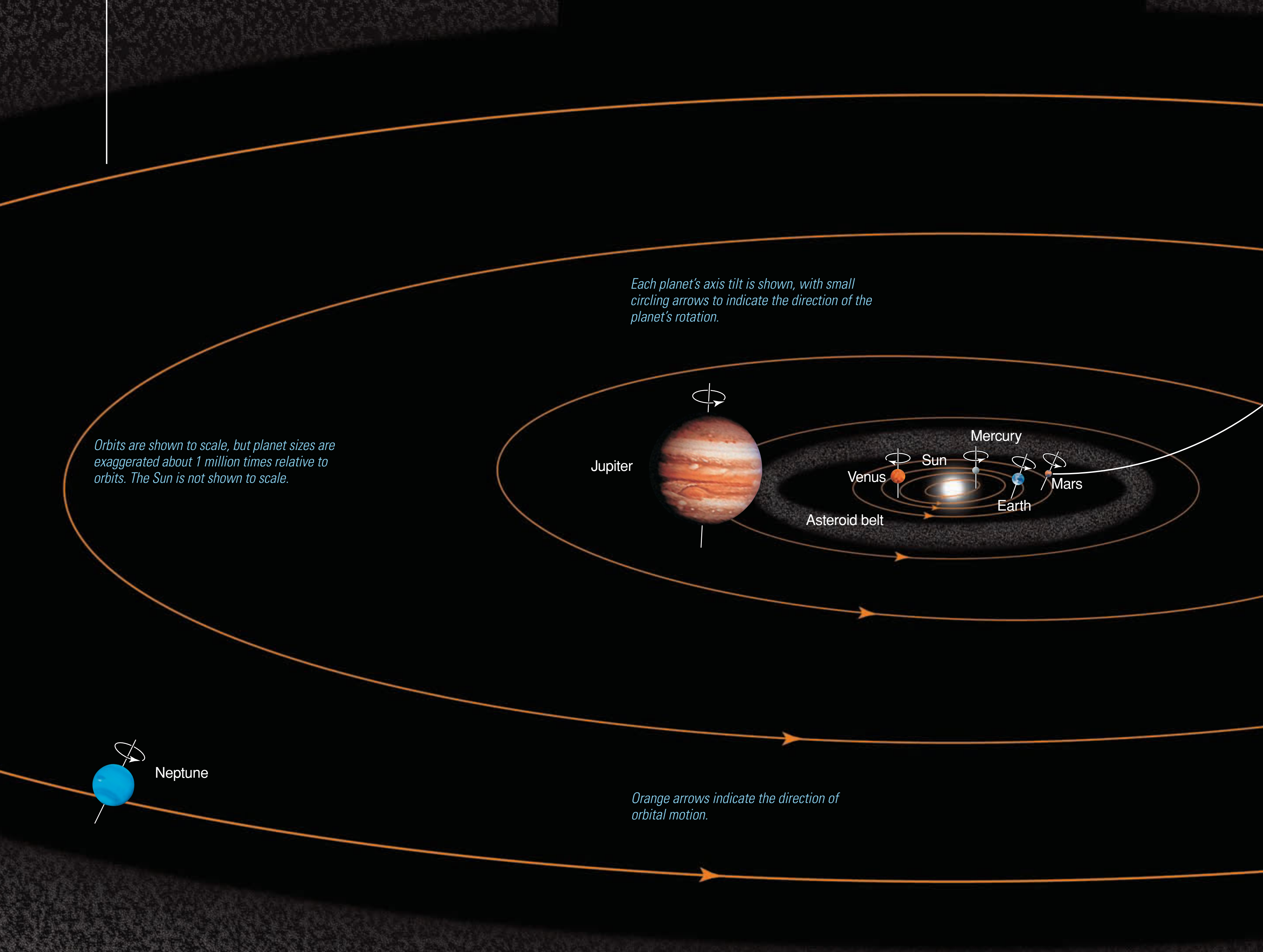
cosmic Context • Figure 6.1. The Solar System

MA interactive figure

The solar system's layout and composition offer four major clues to how it formed. The main illustration below shows the orbits of planets in the solar system from a perspective beyond Neptune, with the planets themselves magnified by about a million times relative to their orbits.

1. **Large bodies in the solar system have orderly motions.** All planets have nearly circular orbits going in the same direction in nearly the same plane. Most large moons orbit their planets in this same direction, which is also the direction of the Sun's rotation.





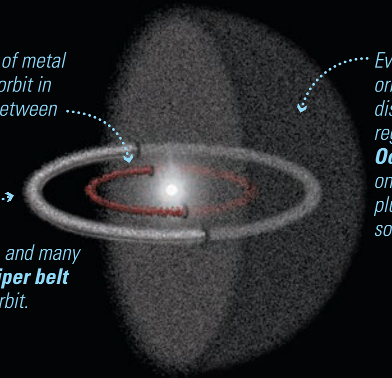
2 Planets fall into two major categories: Small, rocky terrestrial planets and large, hydrogen-rich jovian planets.

Terrestrial Planets:
- *small in mass and size*
- *close to the Sun*
- *made of metal and rock*
- *few moons and no rings*

Jovian Planets:
- *large mass and size*
- *far from the Sun*
- *made of H, He, and hydrogen compounds*
- *rings and many moons*

3 Swarms of asteroids and comets populate the solar system. Vast numbers of rocky asteroids and icy comets are found throughout the solar system, but are concentrated in three distinct regions.

Asteroids are made of metal and rock, and most orbit in the ***asteroid belt*** *between Mars and Jupiter.*

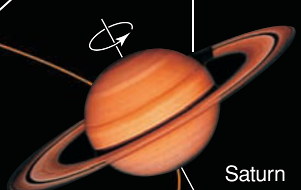


Comets are ice-rich, and many are found in the ***Kuiper belt*** *beyond Neptune's orbit.*

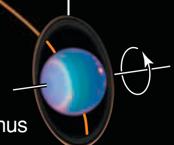
Even more comets orbit the Sun in the distant, spherical region called the ***Oort cloud****, and only a rare few ever plunge into the inner solar system.*

Kuiper belt

4 Several notable exceptions to these trends stand out. Some planets have unusual axis tilts, unusually large moons, or moons with unusual orbits.



Uranus's odd tilt



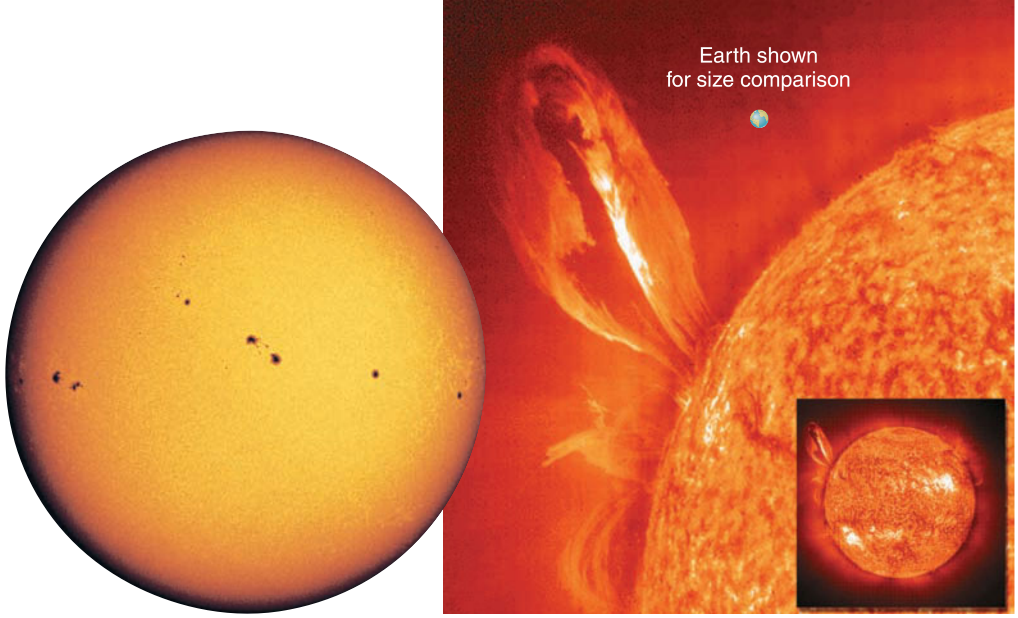
Uranus rotates nearly on its side compared to its orbit, and its rings and major moons share this "sideways" orientation.

Earth's relatively large moon

Our own Moon is much closer in size to Earth than most other moons in comparison to their planets.

Figure 6.2

The Sun contains more than 99.8% of the total mass in our solar system.



a A visible-light photograph of the Sun's surface. The dark splotches are sunspots—each large enough to swallow several Earths.

b This ultraviolet photograph, from the *SOHO* spacecraft, shows a huge streamer of hot gas on the Sun.

• The Sun

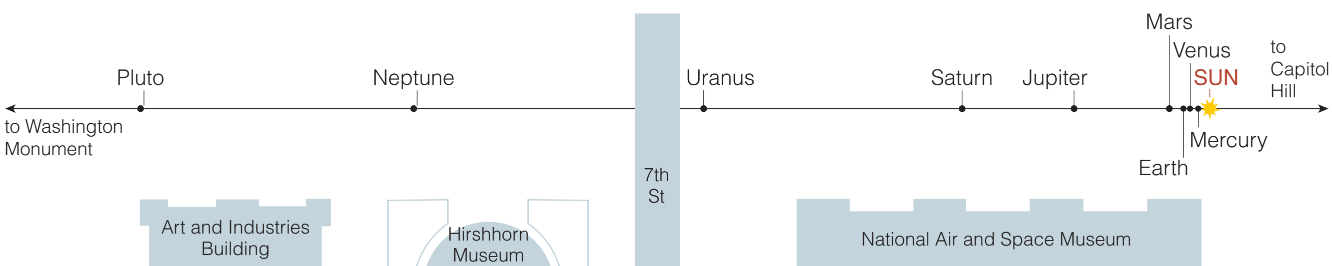
- Radius: 696,000 km $= 108R_{\text{Earth}}$
- Mass: $333{,}000M_{\text{Earth}}$
- Composition (by mass): 98% hydrogen and helium, 2% other elements

The Sun is by far the largest and brightest object in our solar system. It contains more than 99.8% of the solar system's total mass, making it more than a thousand times as massive as everything else in the solar system combined.

The Sun's surface looks solid in photographs (Figure 6.2), but it is actually a roiling sea of hot (about 5800 K, or 5500°C or 10,000°F) hydrogen and helium gas. The surface is speckled with sunspots that appear dark in photographs only because they are slightly cooler than their surroundings. Solar storms sometimes send streamers of hot gas soaring far above the surface.

The Sun is gaseous throughout, and the temperature and pressure both increase with depth. The source of the Sun's energy lies deep in its core, where the temperatures and pressures are so high that the Sun is a nuclear fusion power plant. Each second, fusion transforms about 600 million tons of the Sun's hydrogen into 596 million tons of helium. The "missing" 4 million tons becomes energy in accord with Einstein's famous formula, $E = mc^2$ **[Section 4.3]**. Despite losing 4 million tons of mass each second, the Sun contains so much hydrogen that it has already shone steadily for almost 5 billion years and will continue to shine for another 5 billion years.

The Sun is the most influential object in our solar system. Its gravity governs the orbits of the planets. Its heat is the primary influence on the temperatures of planetary surfaces and atmospheres. It is the source of virtually all the visible light in our solar system—the Moon and planets shine only by virtue of the sunlight they reflect. In addition, charged particles flowing outward from the Sun (the *solar wind*) help shape planetary magnetic fields and can influence planetary atmospheres. Nevertheless, we can understand almost all the present characteristics of the planets without knowing much more about the Sun than what we have just discussed. We'll save more detailed study of the Sun for Chapter 10, where we will study it as our prototype for understanding other stars.



The Voyage scale model solar system represents sizes and distances in our solar system at one ten-billionth of their actual values (see Figure 1.6). The strip along the side of the page shows the sizes of the Sun and planets on this scale, and the map above shows their locations in the Voyage model on the National Mall in Washington, D.C. The Sun is about the size of a large grapefruit on this scale.

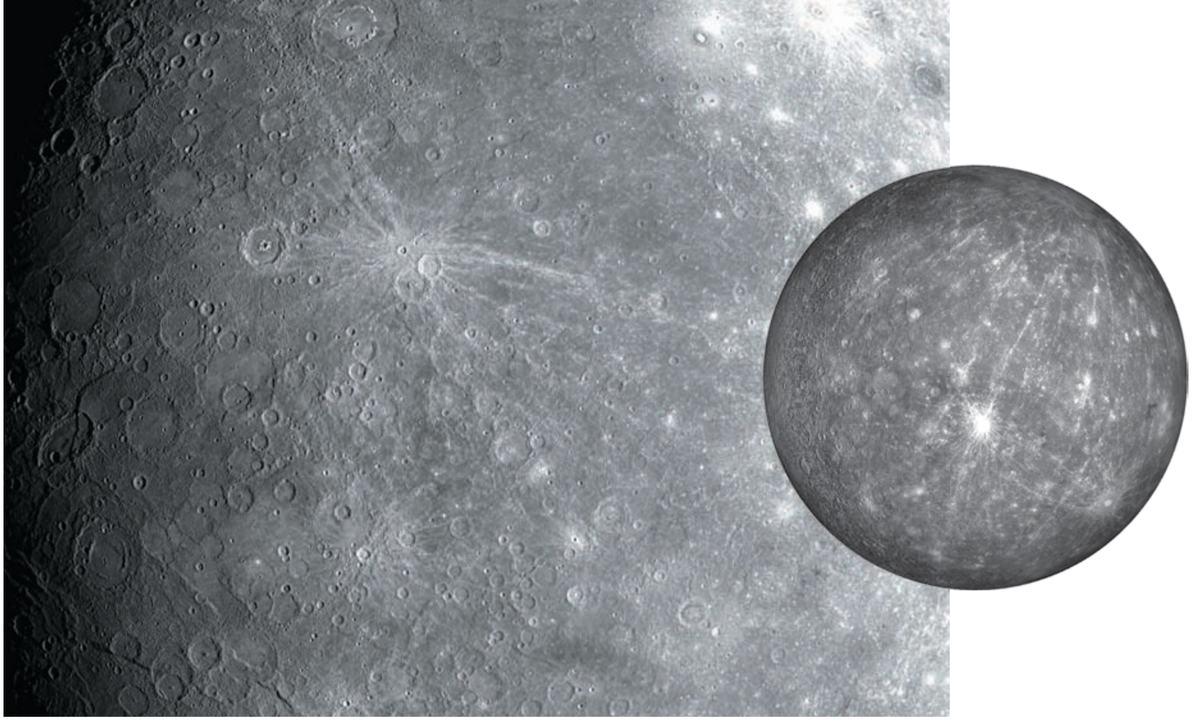


Figure 6.3

The main image, taken by the *MESSENGER* spacecraft, shows that Mercury's surface is heavily cratered but also has smooth volcanic plains and long, steep cliffs. The inset shows a nearly global composite image from *MESSENGER*.

Mercury

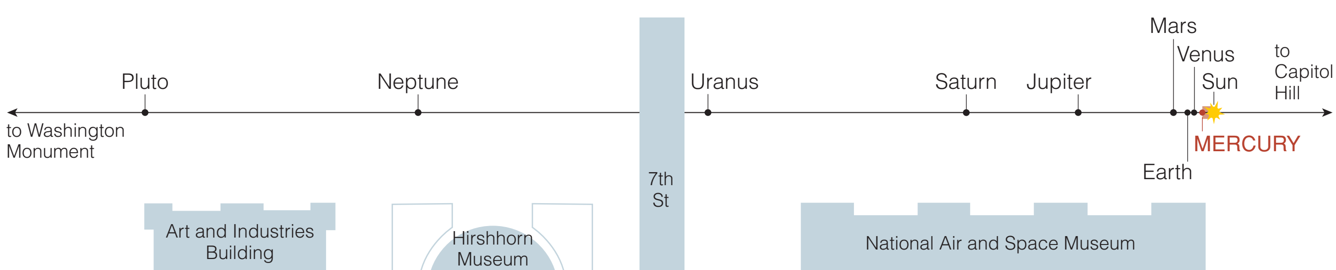
- Average distance from the Sun: 0.39 AU
- Radius: 2440 km = $0.38R_{\text{Earth}}$
- Mass: $0.055M_{\text{Earth}}$
- Average density: 5.43 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 700 K (day), 100 K (night)
- Moons: 0

Mercury is the innermost planet of our solar system, and the smallest of the eight official planets. It is a desolate, cratered world with no active volcanoes, no wind, no rain, and no life. Because there is virtually no air to scatter sunlight or color the sky, you could see stars even in the daytime if you stood on Mercury with your back toward the Sun.

You might expect Mercury to be very hot because of its closeness to the Sun, but in fact it is a world of both hot and cold extremes. Tidal forces from the Sun have forced Mercury into an unusual rotation pattern: Its 58.6-day rotation period means it rotates exactly three times for every two of its 87.9-day orbits of the Sun. This combination of rotation and orbit gives Mercury days and nights that last about 3 Earth months each. Daytime temperatures reach 425°C—nearly as hot as hot coals. At night or in shadow, the temperature falls below −150°C—far colder than Antarctica in winter.

Mercury's surface is heavily cratered, much like the surface of our Moon (Figure 6.3). But it also shows evidence of past geological activity, such as plains created by ancient lava flows and tall, steep cliffs that run hundreds of kilometers in length. These cliffs may be wrinkles from an episode of "planetary shrinking" early in Mercury's history. Mercury's high density (calculated from its mass and volume) indicates that it has a very large iron core, perhaps because it once suffered a huge impact that blasted its outer layers away.

Mercury is the least studied of the inner planets, in part because its proximity to the Sun makes it difficult to observe through telescopes. We are on the brink of a new wave of exploration, with NASA's *MESSENGER* mission reaching Mercury orbit in 2011 (after three earlier flybys) and ESA's *Bepi Colombo* mission launching in 2013.



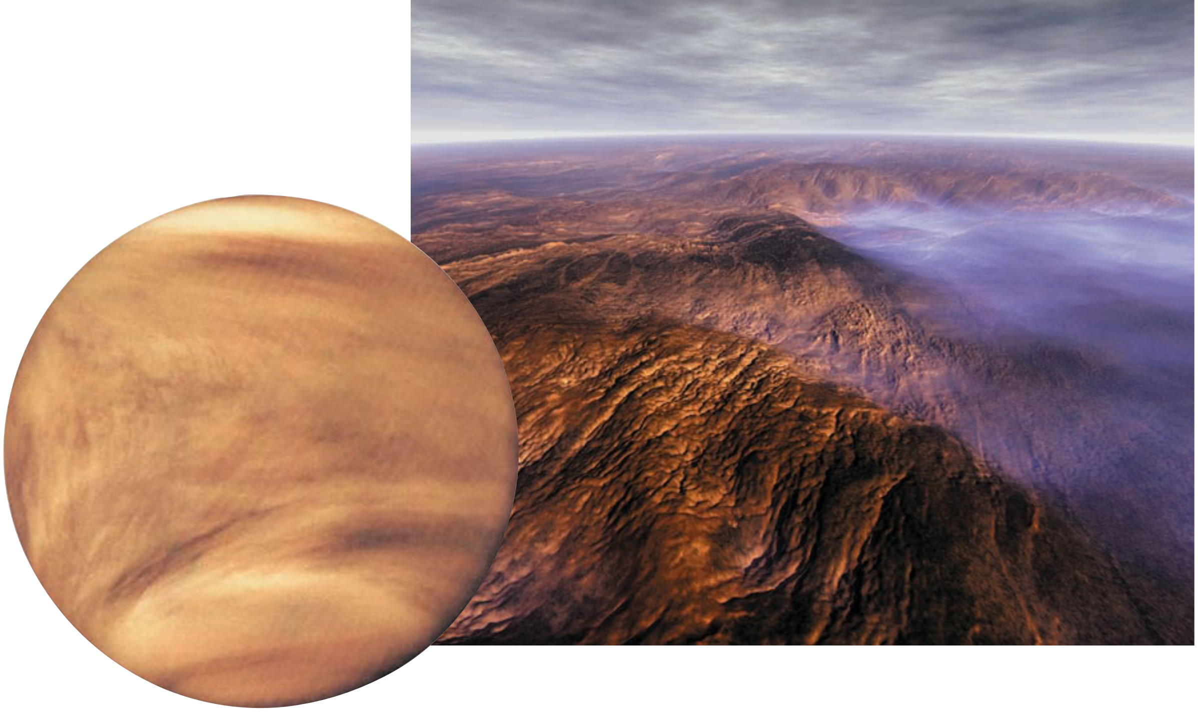


Figure 6.4

The image above shows an artistic rendition of the surface of Venus as scientists think it would appear to our eyes. The surface topography is based on data from NASA's *Magellan* spacecraft. The inset (left) shows the full disk of Venus photographed by NASA's *Pioneer Venus Orbiter* with cameras sensitive to ultraviolet light. With visible light, cloud features cannot be distinguished from the general haze. (Image above from the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image by David P. Anderson, Southern Methodist University © 2001.)

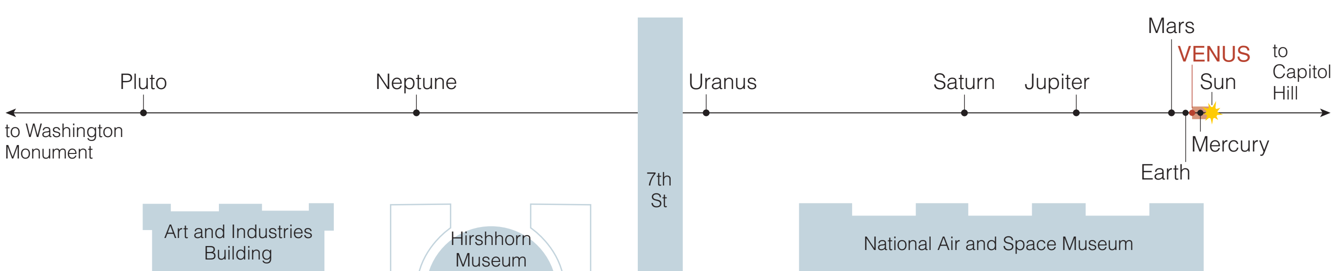
Venus

- Average distance from the Sun: 0.72 AU
- Radius: 6051 km = $0.95R_{\text{Earth}}$
- Mass: $0.82M_{\text{Earth}}$
- Average density: 5.24 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 740 K
- Moons: 0

Venus, the second planet from the Sun, is nearly identical in size to Earth. Before the era of spacecraft visits, Venus stood out largely for its strange rotation: It rotates on its axis very slowly and in the opposite direction of Earth, so days and nights are very long and the Sun rises in the west and sets in the east instead of rising in the east and setting in the west. Its surface is completely hidden from view by dense clouds, so we knew little about it until a few decades ago, when spacecraft began to map Venus with cloud-penetrating radar (Figure 6.4). Because we knew so little about it, some science fiction writers used its Earth-like size, thick atmosphere, and closer distance to the Sun to speculate that it might be a lush, tropical paradise—a "sister planet" to Earth.

The reality is far different. We now know that an extreme *greenhouse effect* bakes Venus's surface to an incredible 470°C (about 880°F), trapping heat so effectively that nighttime offers no relief. Day and night, Venus is hotter than a pizza oven, and the thick atmosphere bears down on the surface with a pressure equivalent to that nearly a kilometer (0.6 mile) beneath the ocean's surface on Earth. Far from being a beautiful sister planet to Earth, Venus resembles a traditional view of hell.

Venus has mountains, valleys, and craters, and shows many signs of past or present volcanic activity. But Venus also has geological features unlike any on Earth, and we see no evidence of Earth-like plate tectonics. We are learning more about Venus through studies by the European Space Agency's *Venus Express* spacecraft, orbiting Venus since 2006, and Japan's Venus Climate Orbiter *Akatsuki*, orbiting since late 2010.



a This image (left), computer generated from satellite data, shows the striking contrast between the daylight and nighttime hemispheres of Earth. The day side reveals little evidence of human presence, but at night our presence is revealed by the lights of human activity. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

b Earth and the Moon, shown to scale. The Moon's diameter is about one-fourth of Earth's diameter, and its mass is about 1/80 of Earth's mass. If you wanted to show the distance between Earth and Moon on the same scale, you'd need to hold these two photographs about 1 meter (3 feet) apart.

Figure 6.5

Earth, our home planet.

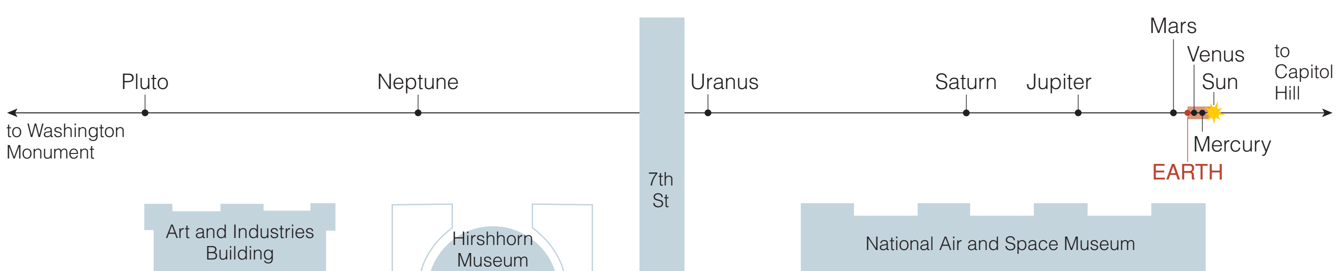
Earth

- Average distance from the Sun: 1.00 AU
- Radius: 6378 km = $1R_{Earth}$
- Mass: $1.00M_{Earth}$
- Average density: 5.52 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 290 K
- Moons: 1

Beyond Venus, we next encounter our home planet, Earth, the only known oasis of life in our solar system. Earth is also the only planet in our solar system with oxygen to breathe, ozone to shield the surface from deadly solar radiation, and abundant surface water to nurture life. Temperatures are pleasant because Earth's atmosphere contains just enough carbon dioxide and water vapor to maintain a moderate greenhouse effect.

Despite Earth's small size, its beauty is striking (Figure 6.5a). Blue oceans cover nearly three-fourths of the surface, broken by the continental land masses and scattered islands. The polar caps are white with snow and ice, and white clouds are scattered above the surface. At night, the glow of artificial lights reveals the presence of an intelligent civilization.

Earth is the first planet on our tour with a moon. The Moon is surprisingly large compared with Earth (Figure 6.5b), although it is not the largest moon in the solar system; almost all other moons are much smaller relative to the planets they orbit. As we'll discuss later in this chapter, the leading hypothesis holds that the Moon formed as a result of a giant impact early in Earth's history.



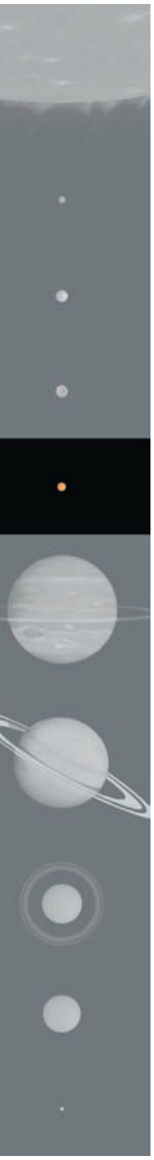
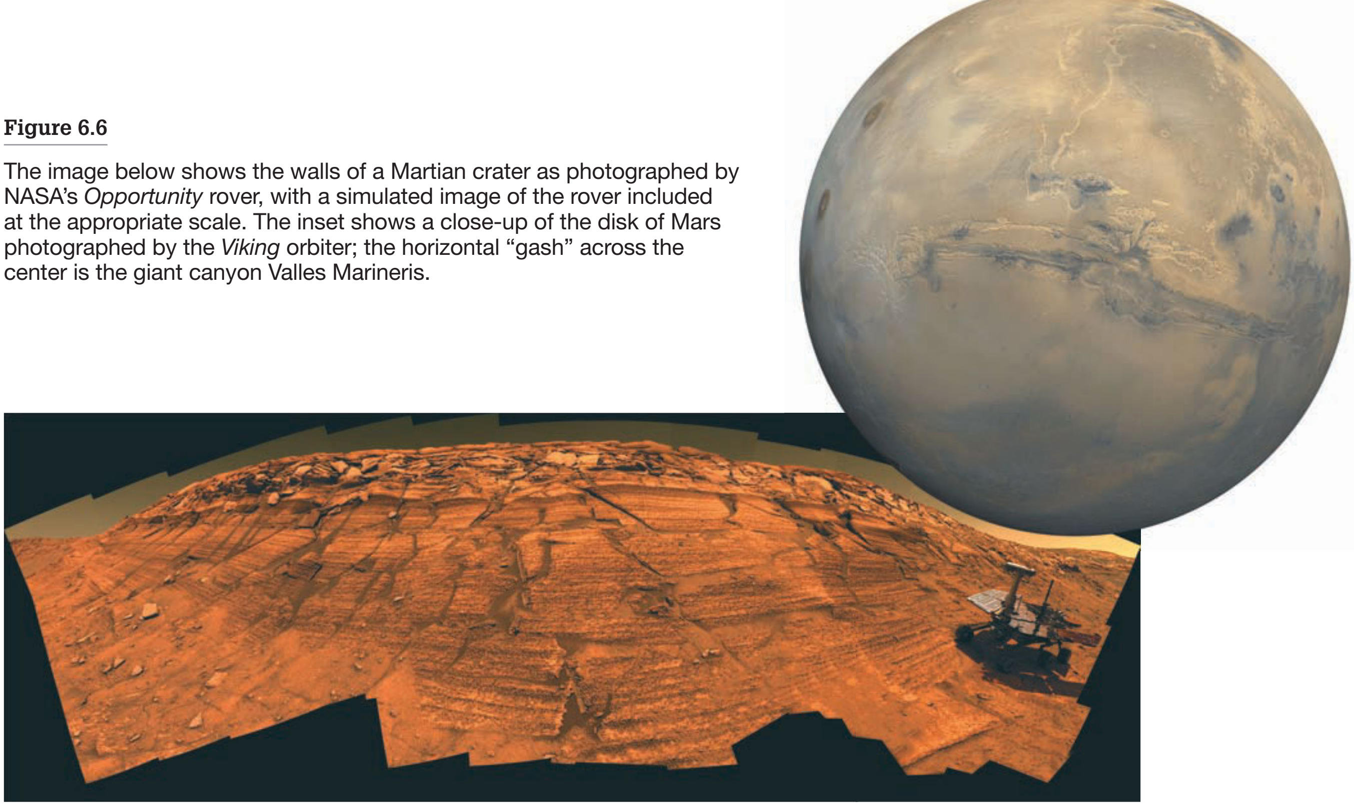


Figure 6.6

The image below shows the walls of a Martian crater as photographed by NASA's *Opportunity* rover, with a simulated image of the rover included at the appropriate scale. The inset shows a close-up of the disk of Mars photographed by the *Viking* orbiter; the horizontal "gash" across the center is the giant canyon Valles Marineris.



Mars

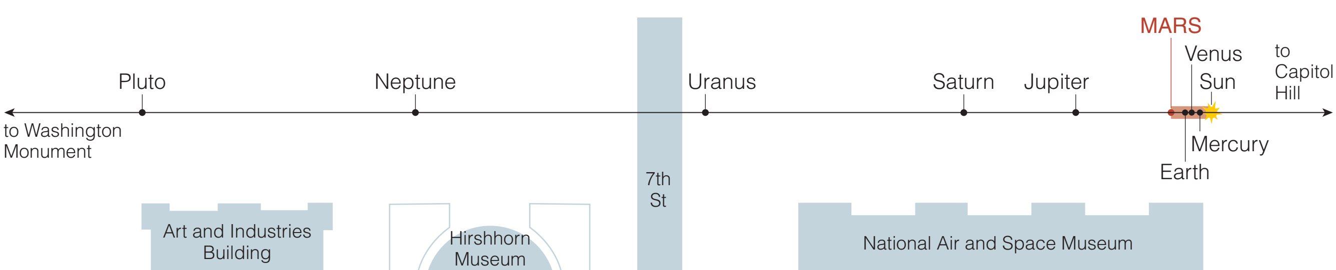
- Average distance from the Sun: 1.52 AU
- Radius: 3397 km = $0.53 R_{Earth}$
- Mass: $0.11 M_{Earth}$
- Average density: 3.93 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 220 K
- Moons: 2 (very small)

The next planet on our tour is Mars, the last of the four inner planets of our solar system (Figure 6.6). Mars is larger than Mercury and the Moon but only about half Earth's size in diameter; its mass is about 10% that of Earth. Mars has two tiny moons, Phobos and Deimos, that probably once were asteroids that were captured into Martian orbit early in the solar system's history.

Mars is a world of wonders, with ancient volcanoes that dwarf the largest mountains on Earth, a great canyon that runs nearly one-fifth of the way around the planet, and polar caps made of frozen carbon dioxide ("dry ice") and water. Although Mars is frozen today, the presence of dried-up riverbeds, rock-strewn floodplains, and minerals that form in water offers clear evidence that Mars had at least some warm and wet periods in the past. Major flows of liquid water probably ceased at least 3 billion years ago, but some liquid water could persist underground, perhaps flowing to the surface on occasion.

Mars's surface looks almost Earth-like, but you wouldn't want to visit without a space suit. The air pressure is far less than that on top of Mount Everest, the temperature is usually well below freezing, the trace amounts of oxygen would not be nearly enough to breathe, and the lack of atmospheric ozone would leave you exposed to deadly ultraviolet radiation from the Sun.

Mars is the most studied planet besides Earth. More than a dozen spacecraft have flown past, orbited, or landed on Mars, and plans are in the works for many more missions. We may even send humans to Mars within the next few decades. By overturning rocks in ancient riverbeds or chipping away at ice in the polar caps, explorers will help us learn whether Mars has ever been home to life.



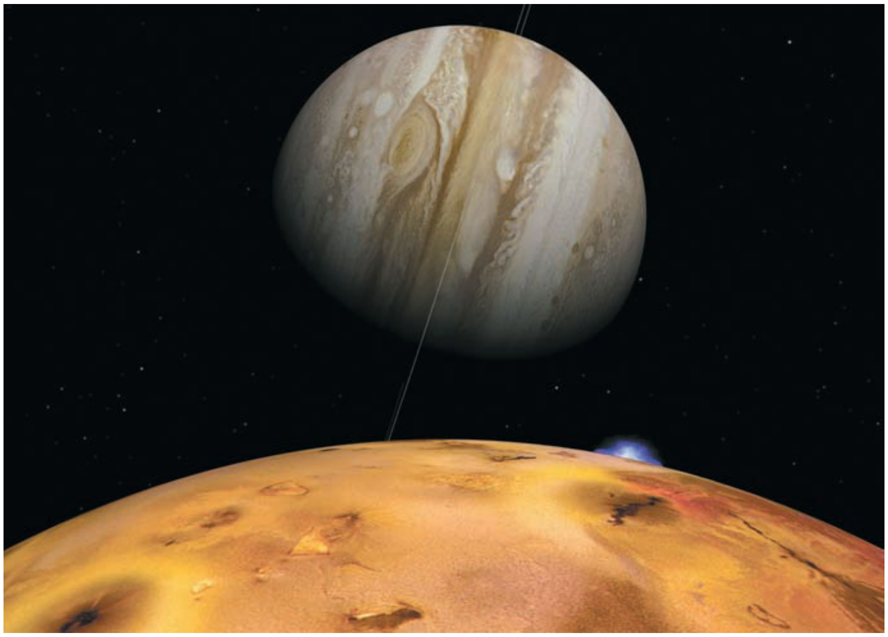


Figure 6.7

This image shows what it would look like to be orbiting near Jupiter's moon Io as Jupiter comes into view. Notice the Great Red Spot to the left of Jupiter's center. The extraordinarily dark rings discovered during the *Voyager* missions are exaggerated to make them visible. This computer visualization was created using data from both NASA's *Voyager* and *Galileo* missions. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

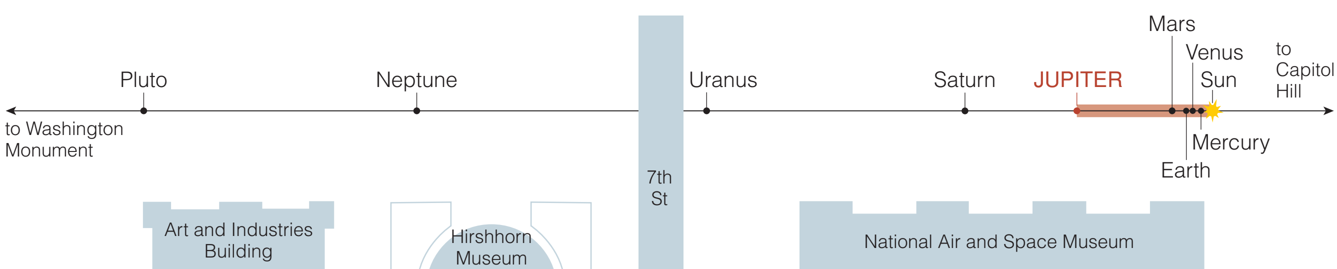
Jupiter

- Average distance from the Sun: 5.20 AU
- Radius 71,492 km = $11.2R_{\text{Earth}}$
- Mass: $318M_{\text{Earth}}$
- Average density: 1.33 g/cm^3
- Composition: mostly hydrogen and helium
- Cloud-top temperature: 125 K
- Moons: at least 63

To reach the orbit of Jupiter from Mars, we must traverse a distance that is more than double the total distance from the Sun to Mars, passing through the asteroid belt along the way. Upon our arrival, we find a planet much larger than any we have seen so far (Figure 6.7).

Jupiter is so different from the planets of the inner solar system that we must adopt an entirely new mental image of the term *planet.* Its mass is more than 300 times that of Earth, and its volume is more than 1000 times that of Earth. Its most famous feature—a long-lived storm called the Great Red Spot—is itself large enough to swallow two or three Earths. Like the Sun, Jupiter is made primarily of hydrogen and helium and has no solid surface. If we plunged deep into Jupiter, the increasing gas pressure would crush us long before we ever reached its core.

Jupiter reigns over dozens of moons and a thin set of rings (too faint to be seen in most photographs). Most of the moons are very small, but four are large enough that we'd probably consider them planets if they orbited the Sun independently. These four moons—Io, Europa, Ganymede, and Callisto—are often called the *Galilean moons,* because Galileo discovered them shortly after he first turned his telescope toward the heavens **[Section 3.3]**. They are also planetlike in having varied and interesting geology. Io is the most volcanically active world in the solar system. Europa has an icy crust that may hide a subsurface ocean of liquid water, making it a promising place to search for life. Ganymede and Callisto may also have subsurface oceans, and their surfaces have many features that remain mysterious.



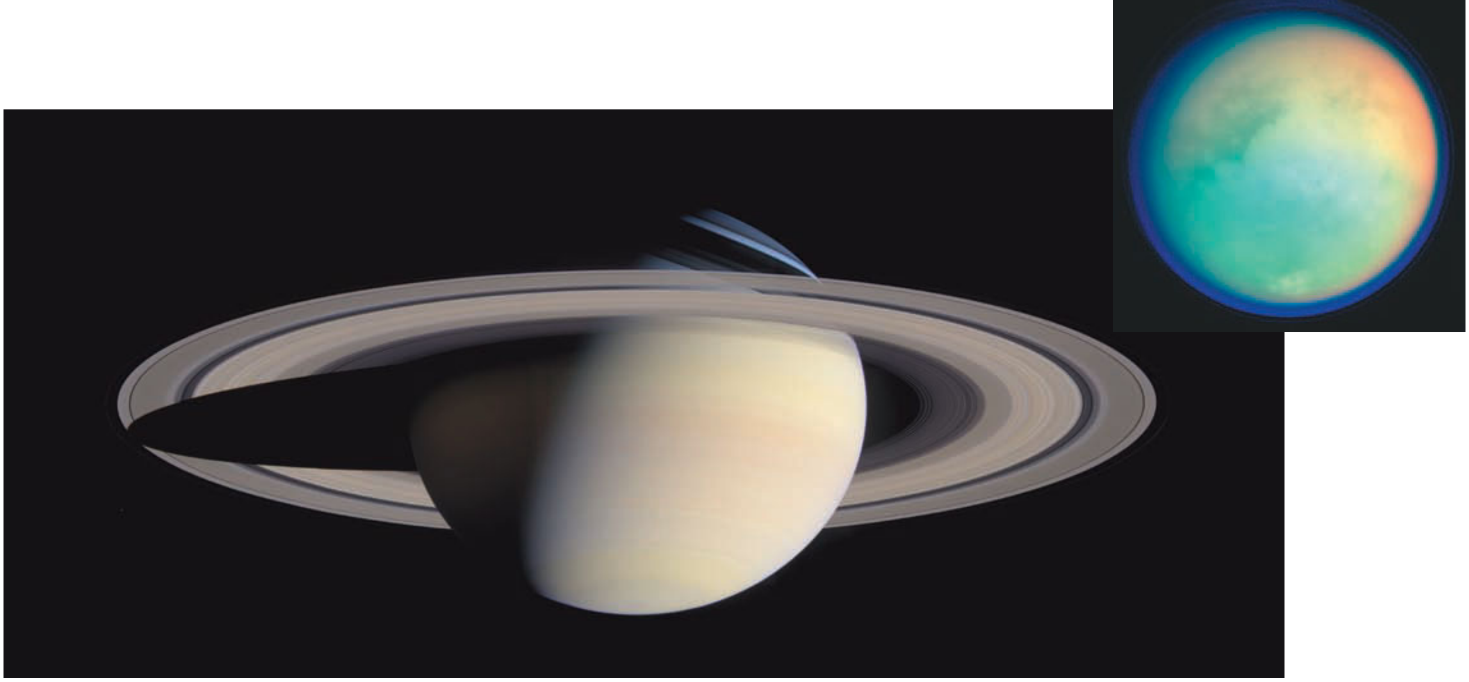


Figure 6.8

Cassini's view of Saturn. We see the shadow of the rings on Saturn's sunlit face, and the rings become lost in Saturn's shadow on the night side. The inset shows an infrared view of Titan, Saturn's large moon, shrouded in a thick, cloudy atmosphere.

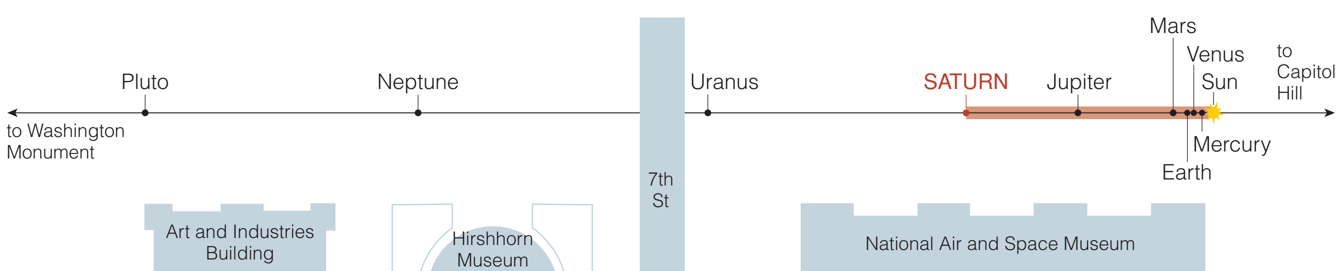
Saturn

- Average distance from the Sun: 9.54 AU
- Radius: 60,268 km = $9.4R_{Earth}$
- Mass: $95.2M_{Earth}$
- Average density: 0.70 g/cm^3
- Composition: mostly hydrogen and helium
- Cloud-top temperature: 95 K
- Moons: at least 60

The journey from Jupiter to Saturn is a long one: Saturn orbits nearly twice as far from the Sun as Jupiter. Saturn, the second-largest planet in our solar system, is only slightly smaller than Jupiter in diameter, but its lower density makes it considerably less massive (about one-third of Jupiter's mass). Like Jupiter, Saturn is made mostly of hydrogen and helium and has no solid surface.

Saturn is famous for its spectacular rings (Figure 6.8). Although all four of the giant outer planets have rings, only Saturn's rings can be seen easily through a small telescope. The rings may look solid from a distance, but in reality they are made of countless small particles, each of which orbits Saturn like a tiny moon. If you could wander into the rings, you'd find yourself surrounded by chunks of rock and ice that range in size from dust grains to city blocks. We are rapidly learning more about Saturn and its rings through observations made by the *Cassini* spacecraft, which has orbited Saturn since 2004.

Cassini has also taught us more about Saturn's moons, and has revealed that at least two are geologically active today: Enceladus, which has ice fountains spraying out from its southern hemisphere, and Titan, the only moon in the solar system with a thick atmosphere. Saturn and its moons are so far from the Sun that Titan's surface temperature is a frigid −180°C, making it far too cold for liquid water to exist. However, studies by *Cassini* and its *Huygens* probe, which landed on Titan in 2005, have revealed an erosion-carved landscape that looks remarkably Earth-like, except that it has been shaped by extremely cold liquid methane or ethane rather than liquid water. *Cassini* has even detected vast lakes of liquid methane or ethane on Titan's surface.



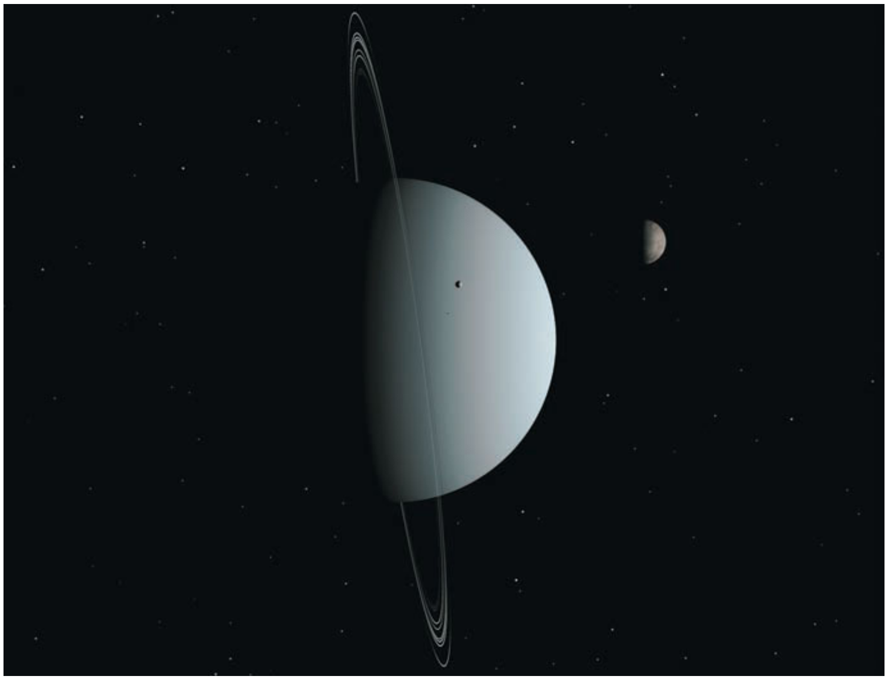


Figure 6.9

This image shows a view of Uranus from high above its moon Ariel. The ring system is shown, although it would actually be too dark to see from this vantage point. This computer simulation is based on data from NASA's *Voyager 2* mission. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

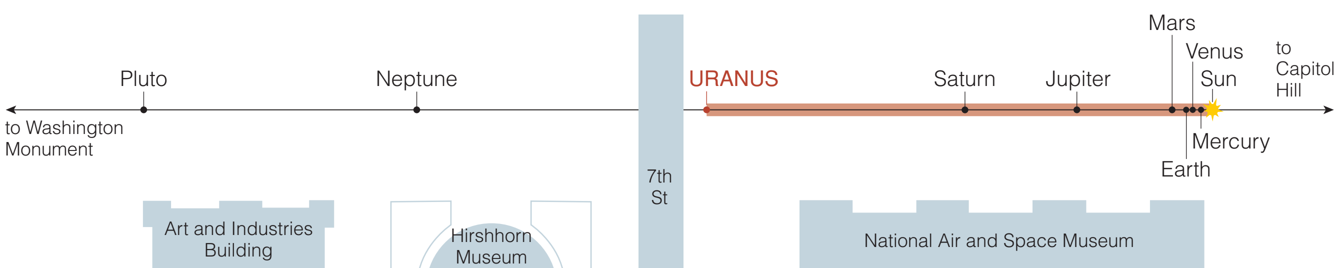
Uranus

- Average distance from the Sun: 19.2 AU
- Radius: 25,559 km = $4.0R_{Earth}$
- Mass: $14.5M_{Earth}$
- Average density: 1.32 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Cloud-top temperature: 60 K
- Moons: at least 27

It's another long journey to our next stop on the tour, as Uranus lies twice as far from the Sun as Saturn. Uranus (normally pronounced *YUR-uh-nus*) is much smaller than either Jupiter or Saturn but much larger than Earth. It is made largely of hydrogen, helium, and *hydrogen compounds* such as water (H_2O), ammonia (NH_3), and methane (CH_4). Methane gas gives Uranus its pale blue-green color (Figure 6.9). Like the other giants of the outer solar system, Uranus lacks a solid surface. More than two dozen moons orbit Uranus, along with a set of rings somewhat similar to those of Saturn but much darker and more difficult to see.

The entire Uranus system—planet, rings, and moon orbits—is tipped on its side compared to the rest of the planets. This extreme axis tilt may be the result of a cataclysmic collision that Uranus suffered as it was forming, and it gives Uranus the most extreme seasonal variations of any planet in our solar system. If you lived on a platform floating in Uranus's atmosphere near its north pole, you'd have continuous daylight for half of each orbit, or 42 years. Then, after a very gradual sunset, you'd enter into a 42-year-long night.

Only one spacecraft has visited Uranus: *Voyager 2*, which flew past all four of the giant outer planets before heading out of the solar system. Much of our current understanding of Uranus comes from that mission, though powerful new telescopes are also capable of studying it. Scientists would love an opportunity to study Uranus and its rings and moons in greater detail, but no missions to Uranus are currently under development.



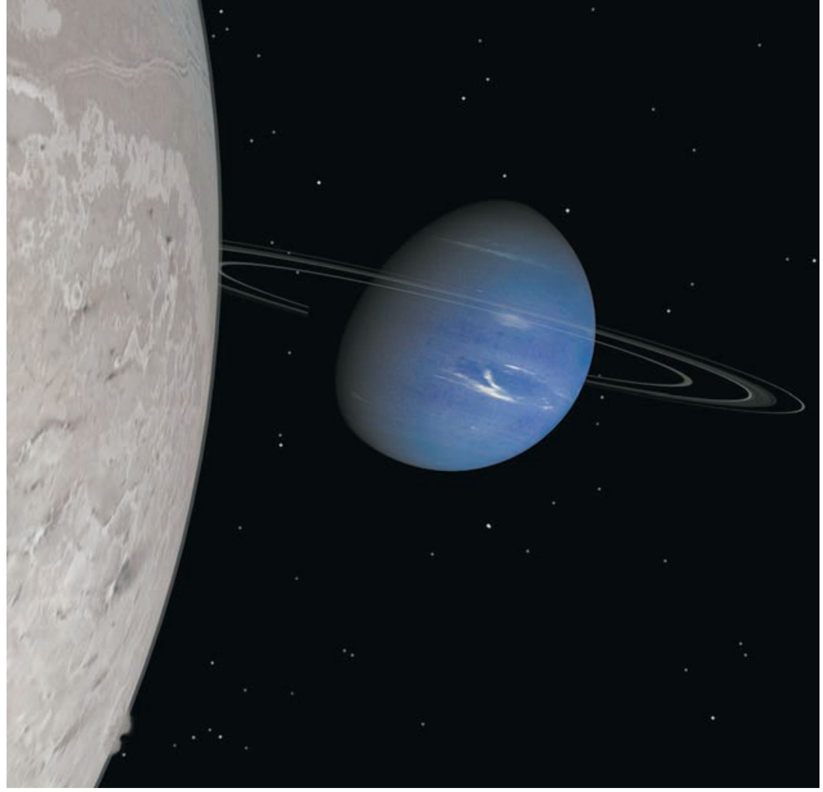


Figure 6.10

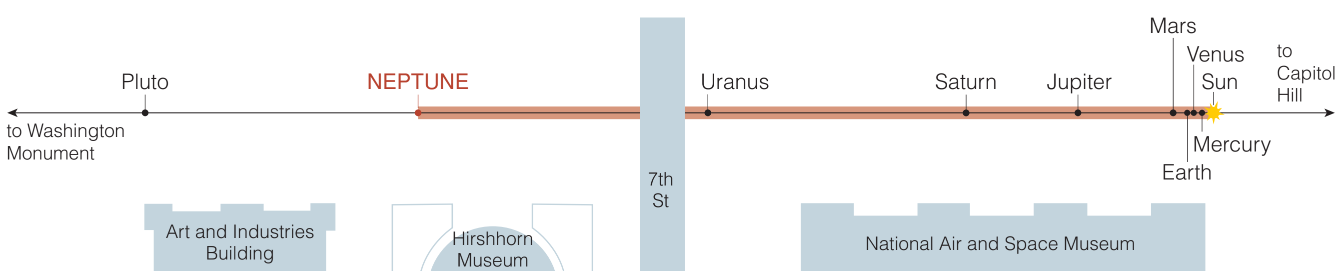
This image shows what it would look like to be orbiting Neptune's moon Triton as Neptune itself comes into view. The dark rings are exaggerated to make them visible in this computer simulation using data from NASA's *Voyager 2* mission. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

• Neptune

- Average distance from the Sun: 30.1 AU
- Radius 24,764 km = $3.9R_{\text{Earth}}$
- Mass: $17.1M_{\text{Earth}}$
- Average density: 1.64 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Cloud-top temperature: 60 K
- Moons: at least 13

The journey from the orbit of Uranus to the orbit of Neptune is the longest yet in our tour, calling attention to the vast emptiness of the outer solar system. Nevertheless, Neptune looks nearly like a twin of Uranus, although it is more strikingly blue (Figure 6.10). It is slightly smaller than Uranus in size, but a higher density makes it slightly more massive even though the two planets share very similar compositions. Like Uranus, Neptune has been visited only by the *Voyager 2* spacecraft, and no additional missions are currently planned.

Neptune has rings and numerous moons. Its largest moon, Triton, is larger than Pluto and is one of the most fascinating moons in the solar system. Triton's icy surface has features that appear to be somewhat like geysers, although they spew nitrogen gas rather than water into the sky **[Section 8.2]**. Even more surprisingly, Triton is the only large moon in the solar system that orbits its planet "backward"—that is, in a direction opposite to the direction in which Neptune rotates. This backward orbit makes it a near certainty that Triton once orbited the Sun independently before somehow being captured into Neptune's orbit.



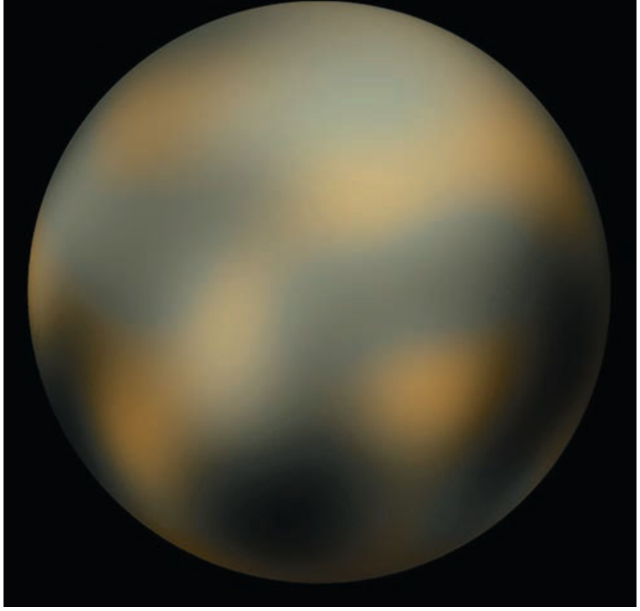


Figure 6.11

Pluto, as photographed by the Hubble Space Telescope.

• Pluto (and Other Dwarf Planets)

- Pluto's average distance from the Sun: 39.5 AU
- Radius: 1160 km = $0.18R_{\text{Earth}}$
- Mass: $0.0022M_{\text{Earth}}$
- Average density: 2.0 g/cm^3
- Composition: ices, rock
- Average surface temperature: 40 K
- Moons: 3

We conclude our tour at Pluto, which reigned for some 75 years as the ninth and last planet in our solar system. Pluto's average distance from the Sun lies as far beyond Neptune as Neptune lies beyond Uranus. Its great distance makes Pluto cold and dark. From Pluto, the Sun would be little more than a bright light among the stars. Pluto's largest moon, Charon, is locked together with it in synchronous rotation **[Section 4.4]**, so Charon would dominate the sky on one side of Pluto but never be seen from the other side.

We've known for decades that Pluto is much smaller and less massive than any of the other planets, and its orbit is much more eccentric and inclined to the ecliptic plane. Its composition of ice and rock is also quite different from that of any of those planets, although it is virtually identical to that of many known comets. Moreover, astronomers have discovered more than 1000 objects of similar composition orbiting in Pluto's general neighborhood, which is the region of our solar system known as the *Kuiper belt*. Pluto is not even the largest of these Kuiper belt objects: Eris, discovered in 2005, is slightly larger than Pluto.

Scientifically, these facts leave no room for doubt that both Pluto and Eris belong to a different class of objects than the first eight planets. They are just the largest known of hundreds of large iceballs—essentially large comets—located in the Kuiper belt. The only question has been one of words: Should Pluto and Eris be called "planets" or something else? In 2006, the International Astronomical Union (IAU) voted to classify Pluto and Eris as *dwarf planets*. The IAU definition (see Special Topic, page 12) also classifies several more objects as dwarf planets, including the largest asteroid, Ceres, and other objects that share the Kuiper belt with Pluto and Eris.

The great distances and small sizes of Pluto and other dwarf planets make them difficult to study, regardless of whether they are located in the asteroid belt or the Kuiper belt. As you can see in Figure 6.11, even the best telescopic views of Pluto reveal little detail. Better information should be coming soon. A spacecraft called *New Horizons,* launched in 2006, will fly past Pluto in mid-2015 and may then visit other objects of the Kuiper belt. Meanwhile, the *Dawn* spacecraft, launched in 2007, should give us our first good views of large asteroids in the asteroid belt beginning in about 2011, with a pass by Ceres in 2015 that will closely coincide with *New Horizons'* pass by Pluto.

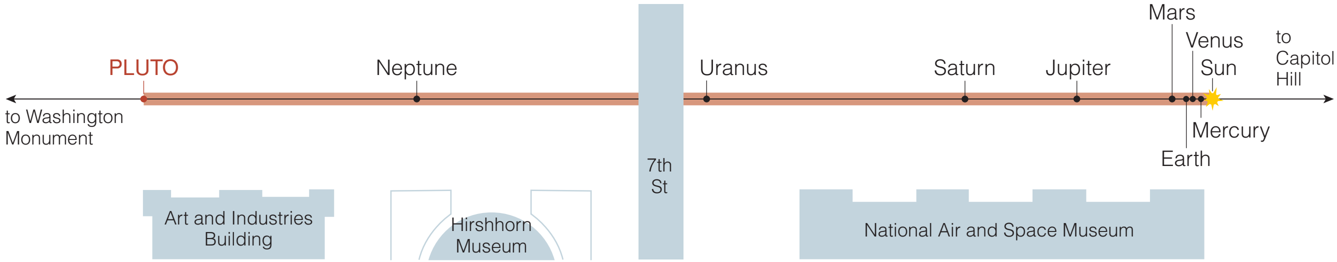
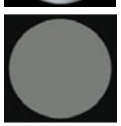


Table 6.1 *Planetary Data**

Photo	Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/m^3)	Orbital Period	Rotation Period	Axis Tilt	Average Surface (or Cloud-Top) Temperature†	Composition	Known Moons (2010)	Rings?
	Mercury		0.387	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night)	Rocks, metals	0	No
	Venus		0.723	6051	0.82	5.24	225 days	243 days	177.3°	740 K	Rocks, metals	0	No
	Earth		1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
	Mars		1.52	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
	Jupiter		5.20	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds§	63	Yes
	Saturn		9.54	60,268	95.2	0.70	29.4 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds§	60	Yes
	Uranus		19.2	25,559	14.5	1.32	83.8 years	17.2 hours	97.9°	60 K	H, He, hydrogen compounds§	27	Yes
	Neptune		30.1	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds§	13	Yes
	Pluto		39.5	1160	0.0022	2.0	248 years	6.39 days	112.5°	40 K	Ices, rock	3	No
	Eris		67.7	1200	0.0028	2.3	557 years	1.08 days	78°	30 K	Ices, rock	1	?

*Including the dwarf planets Pluto and Eris; Appendix E gives a more complete list of planetary properties.

†Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed.

§Includes water (H_2O), methane (CH_4), and ammonia (NH_3).

(continued from page 143)

In science, we always seek explanations for the existence of patterns like those evident in Figure 6.1 and the planetary tour. We will therefore devote most of this chapter to learning how our modern theory of solar system formation explains these and other features of the solar system. We will then see how recent discoveries of other planetary systems fit in with this theory, even as they have led us to refine some of its details.

The planets are tiny compared to the distances between them, but they exhibit clear patterns of composition and motion.

MA Orbits and Kepler's Laws Tutorial, Lessons 2–4

6.2 Clues to the Formation of Our Solar System

Let's begin by taking a more in-depth look at the general features of our solar system that must be explained by any successful theory of its origin. We can then discuss what theory best describes the major characteristics of our solar system and accounts for how it formed.

• What features of our solar system provide clues to how it formed?

We have already seen that our solar system is not a random collection of worlds but rather a family of worlds exhibiting many traits that would be difficult to attribute to coincidence. A valid theory of our solar system's formation must successfully account for these common traits. We could make a long list of such traits, but it is easier to develop a scientific theory by focusing on the more general structure of our solar system. For our purposes, four major features stand out:

1. **Patterns of motion among large bodies.** The Sun, planets, and large moons generally orbit and rotate in a very organized way.
2. **Two major types of planets.** The eight planets divide clearly into two groups: the small, rocky planets that are close together and close to the Sun, and the large, gas-rich planets that are farther apart and farther from the Sun.
3. **Asteroids and comets.** Between and beyond the planets, vast numbers of asteroids and comets orbit the Sun; some are large enough to qualify as dwarf planets. The locations, orbits, and compositions of these asteroids and comets follow distinct patterns.
4. **Exceptions to the rules.** The generally orderly solar system also has some notable exceptions. For example, only Earth has a large moon among the inner planets, and Uranus is tipped on its side. A successful theory must make allowances for exceptions even as it explains the general rules.

Because these four features are so important to our study of the solar system, let's investigate each of them in a little more detail.

Feature 1: Patterns of Motion Among Large Bodies If you look back at Figure 6.1, you'll notice several clear patterns of motion among the large bodies of our solar system. (In this context, a "body" is simply an individual object such as the Sun, a planet, or a moon.) For example:

- All planetary orbits are nearly circular and lie nearly in the same plane.
- All planets orbit the Sun in the same direction: counterclockwise as viewed from high above Earth's North Pole.
- Most planets rotate in the same direction in which they orbit, with fairly small axis tilts. The Sun also rotates in this direction.
- Most of the solar system's large moons exhibit similar properties in their orbits around their planets, such as orbiting in their planet's equatorial plane in the same direction that the planet rotates.

The Sun, planets, and large moons orbit and rotate in an organized way.

We consider these orderly patterns together as the first major feature of our solar system. As we'll see shortly, our theory of solar system formation explains these patterns as consequences of processes that occurred during the early stages of the birth of our solar system.

Feature 2: The Existence of Two Types of Planets Our brief planetary tour showed that the four inner planets are quite different from the four large outer planets. We say that these two groups represent two distinct planetary classes: *terrestrial* and *jovian.*

***Terrestrial planets* are small, rocky, and close to the Sun. *Jovian planets* are large, gas-rich, and far from the Sun.**

The **terrestrial planets** are the four planets of the inner solar system: Mercury, Venus, Earth, and Mars. (*Terrestrial* means "Earth-like.") These planets are relatively small and dense, with rocky surfaces and an abundance of metals deep in their interiors. They have few moons, if any, and no rings. We often count our Moon as a fifth terrestrial world, because its history has been shaped by the same processes that have shaped the terrestrial planets.

The **jovian planets** are the four large planets of the outer solar system: Jupiter, Saturn, Uranus, and Neptune. (*Jovian* means "Jupiter-like.") The jovian planets are much larger in size and lower in average density than the terrestrial planets, and they have rings and many moons. They lack solid surfaces and are made mostly of hydrogen, helium, and **hydrogen compounds**—compounds containing hydrogen, such as water (H_2O), ammonia (NH_3), and methane (CH_4). Because these substances are gases under earthly conditions, the jovian planets are sometimes called "gas giants." Table 6.2 contrasts the general traits of the terrestrial and jovian planets.

Table 6.2 *Comparison of Terrestrial and Jovian Planets*

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density	Lower density
Made mostly of rock and metal	Made mostly of hydrogen, helium, and hydrogen compounds
Solid surface	No solid surface
Few (if any) moons and no rings	Rings and many moons
Closer to the Sun (and closer together), with warmer surfaces	Farther from the Sun (and farther apart), with cool temperatures at cloud tops

Feature 3: Asteroids and Comets The third major feature of the solar system is the existence of vast numbers of small objects orbiting the Sun. These objects fall into two major groups: asteroids and comets.

Rocky asteroids and icy comets far outnumber the planets and their moons.

Asteroids are rocky bodies that orbit the Sun much like planets, but they are much smaller (Figure 6.12). Even the largest asteroids are much smaller than our Moon. Most known asteroids are found within the **asteroid belt** between the orbits of Mars and Jupiter (see Figure 6.1).

Figure 6.12

The asteroid Eros (photographed from the *NEAR* spacecraft). Its appearance is probably typical of most asteroids. Eros is about 40 kilometers in length, and like other small objects in the solar system, it is not spherical.

Comets are also small objects that orbit the Sun, but they are made largely of ices (such as water ice, ammonia ice, and methane ice) mixed with rock. You are probably familiar with the occasional appearance of comets in the inner solar system, where they may become visible to the naked eye with long, beautiful tails (Figure 6.13). These visitors, which may delight sky watchers for a few weeks or months, are actually quite rare among comets.

The vast majority of comets never visit the inner solar system. Instead, they orbit the Sun in one of the two distinct regions shown as Feature 3 in Figure 6.1. The first is a donut-shaped region beyond the orbit of Neptune that we call the **Kuiper belt** (*Kuiper* rhymes with *piper*). The Kuiper belt contains at least 100,000 icy objects, of which Pluto and Eris are the largest known. The second cometary region, called the **Oort cloud** (*Oort* rhymes with *court*), is much farther from the Sun and may contain a trillion comets. These comets have orbits randomly inclined to the ecliptic plane, giving the Oort cloud a roughly spherical shape.

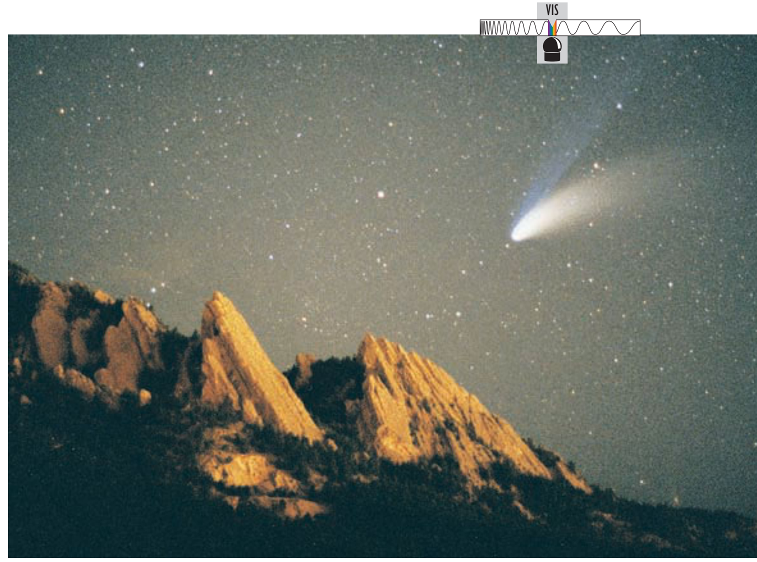


Figure 6.13

Comet Hale–Bopp, photographed over Boulder, Colorado, during its appearance in 1997.

Feature 4: Exceptions to the Rules The fourth key feature of our solar system is that there are a few notable exceptions to the general rules. Two such exceptions are the rotations of Uranus and Venus: While most of the planets rotate in the same direction as they orbit, Uranus rotates nearly on its side and Venus rotates "backward" (clockwise as viewed from high above Earth's North Pole). Similarly, while most large moons orbit their planets in the same direction as their planets rotate, many small moons have much more unusual orbits.

A successful theory of solar system formation must allow for exceptions to the general rules.

One of the most interesting exceptions concerns our own Moon. While the other terrestrial planets have either no moons (Mercury and Venus) or very tiny moons (Mars), Earth has one of the largest moons in the solar system.

• What theory best explains the features of our solar system?

After the Copernican revolution, many scientists speculated about the origin of the solar system. However, we generally credit two 18th-century scientists with proposing the hypothesis that ultimately blossomed into our modern scientific theory of the origin of the solar system. Around 1755, German philosopher Immanuel Kant proposed that our solar system formed from the gravitational collapse of an interstellar cloud of gas. About 40 years later, French mathematician Pierre-Simon Laplace put forth the same idea independently. Because an interstellar cloud is usually called a *nebula* (Latin for "cloud"), their idea became known as the *nebular hypothesis.*

The nebular hypothesis remained popular throughout the 19th century. By the early 20th century, however, scientists had found a few aspects of our solar system that the nebular hypothesis did not seem to explain well—at least in its original form as described by Kant and Laplace. While some scientists sought to modify the nebular hypothesis, others looked for entirely different explanations for how the solar system might have formed.

During the first half of the 20th century, the nebular hypothesis faced stiff competition from a hypothesis proposing that the planets represent debris from a near-collision between the Sun and another star. According to this *close encounter hypothesis,* the planets formed from blobs of gas that had been gravitationally pulled out of the Sun during the near-collision.

Today, the close encounter hypothesis has been discarded. It began to lose favor when calculations showed that it could not account for either the observed orbital motions of the planets or the neat division of the planets into two major categories (terrestrial and jovian). Moreover, the close encounter hypothesis required a highly improbable event: a near-collision between our Sun and another star. Given the vast separation between star systems in our region of the galaxy, the chance of such an encounter is so small that it would be difficult to imagine it happening even in the one case needed to make our own solar system. It certainly could not account for the many other planetary systems that we have discovered in recent years.

The nebular theory holds that our solar system formed from the gravitational collapse of a great cloud of gas, and it explains all the general features of our solar system.

While the close encounter hypothesis was losing favor, new discoveries about the physics of planet formation led to modifications of the nebular hypothesis. Using more sophisticated models of the processes that occur in a collapsing cloud of gas, scientists realized that the nebular hypothesis offered natural explanations for all four general features of our solar system. Indeed, so much evidence has accumulated in favor of the nebular hypothesis that it has achieved the status of a scientific *theory* **[Section 3.4]**—the **nebular theory** of our solar system's birth.

MA Formation of the Solar System Tutorial, Lessons 1–2

6.3 The Birth of the Solar System

We are now ready to examine the nebular theory in more depth. In this section, we'll see how it explains the first general feature of our solar system—orderly patterns of motion—and discuss why we expect similar patterns in other planetary systems.

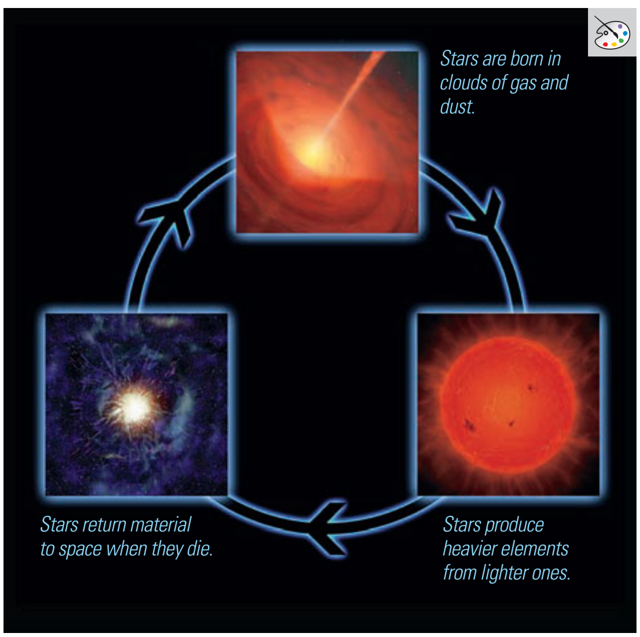


Figure 6.14 MA interactive figure

This figure (which is a portion of Figure 1.2) summarizes the galactic recycling process.

• Where did the solar system come from?

The nebular theory begins with the idea that our solar system was born from a cloud of gas, called the **solar nebula,** that collapsed under its own gravity. But where did this gas come from?

Recall that the universe as a whole is thought to have been born in the Big Bang **[Section 1.1]**, which essentially produced only two chemical elements **[Section 1.1]**: hydrogen and helium. Heavier elements were produced later by massive stars and released into space when the stars died. The heavy elements then mixed with other interstellar gas to form new generations of stars (Figure 6.14).

The gas that made up the solar nebula contained hydrogen and helium from the Big Bang and heavier elements produced by stars.

Despite billions of years of heavy element creation by stars, the overall chemical composition of the galaxy remains predominantly hydrogen and helium. By studying the composition of the Sun, of other stars of the same age, and of interstellar gas clouds, we have learned that the gas that made up the solar nebula contained (by mass) about 98% hydrogen and helium and 2% all other elements combined. The Sun still has this basic composition, while the planets tend to have higher proportions of heavy elements (for reasons we will discuss in Section 6.4).

think about it Could a solar system like ours have formed with the first generation of stars after the Big Bang? Explain.

Strong observational evidence supports this scenario. With telescopes we can witness stars in the process of formation today, and these forming stars are always found within interstellar clouds **[Section 12.1]**. Moreover, careful studies of gas in the Milky Way Galaxy have allowed us to put together a clear picture of the entire galactic recycling process **[Section 14.2]**, leaving little doubt that new stars are born from gas that has been recycled from prior generations of stars. As we saw in Chapter 1, we are "star stuff," because we and our planet are made of elements forged in stars that lived and died long ago.

• What caused the orderly patterns of motion in our solar system?

The solar nebula probably began as a large and roughly spherical cloud of very cold, low-density gas. Initially, this gas was so spread out—perhaps over a region a few light-years in diameter—that gravity alone may not have been strong enough to pull it together and start its collapse. Instead, the collapse may have been triggered by a cataclysmic event, such as the impact of a shock wave from the explosion of a nearby star (a supernova).

Once the collapse started, the law of gravity ensured that it would continue. Remember that the strength of gravity follows an inverse square law with distance **[Section 4.4]**. Because the mass of the cloud remained the same as it shrank, the strength of gravity increased as the diameter of the cloud decreased. For example, when the diameter decreased by half, the force of gravity increased by a factor of four.

Because gravity pulls inward in all directions, you might at first guess that the solar nebula would have remained spherical as it shrank. Indeed, the idea that gravity pulls in all directions explains why the Sun and the planets are spherical. However, we must also consider other physical laws that apply to a collapsing gas cloud in order to understand how orderly motions arose in the solar nebula.

Heating, Spinning, and Flattening As the solar nebula shrank in size, three important processes altered its density, temperature, and shape, changing it from a large, diffuse (spread-out) cloud to a much smaller spinning disk (Figure 6.15):

- **Heating.** The temperature of the solar nebula increased as it collapsed. Such heating represents energy conservation in action **[Section 4.3]**. As the cloud shrank, its gravitational potential energy was converted to the kinetic energy of individual gas particles falling inward. These particles crashed into one another, converting the kinetic energy of their inward fall to the random motions of thermal energy (see Figure 4.12b). The Sun formed in the center, where temperatures and densities were highest.
- **Spinning.** Like an ice skater pulling in her arms as she spins, the solar nebula rotated faster and faster as it shrank in radius. This increase in rotation rate represents conservation of angular momentum in action **[Section 4.3]**. The rotation of the cloud may have been imperceptibly slow before its collapse began, but the cloud's shrinkage made fast rotation inevitable. The rapid rotation

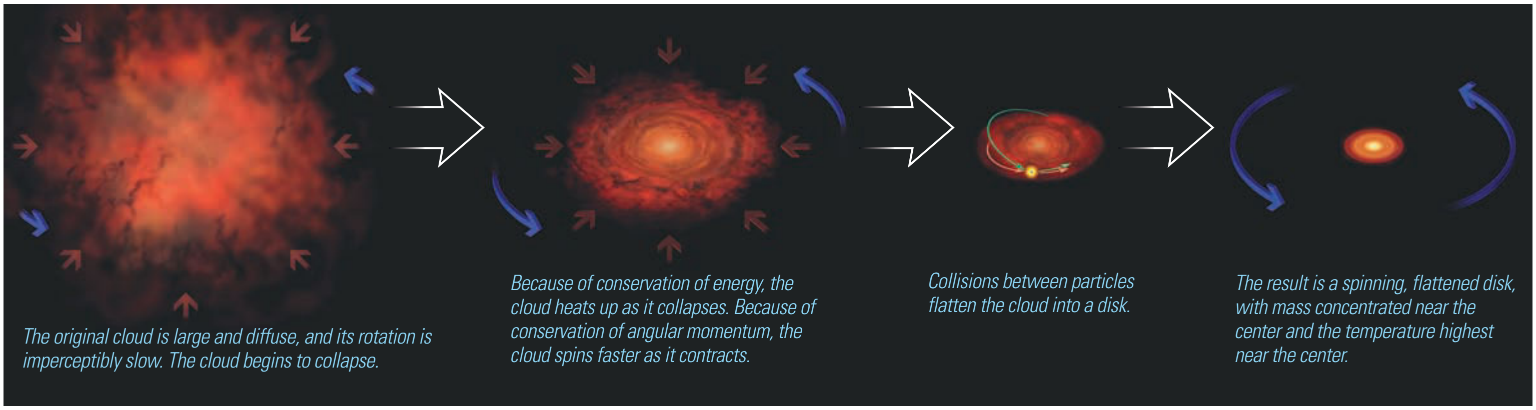


Figure 6.15 MA interactive figure

This sequence of illustrations shows how the gravitational collapse of a large cloud of gas causes it to become a spinning disk of matter. The hot, dense central bulge becomes a star, while planets can form in the surrounding disk.

helped ensure that not all the material in the solar nebula collapsed into the center: The greater the angular momentum of a rotating cloud, the more spread out it will be.

- **Flattening.** The solar nebula flattened into a disk. This flattening is a natural consequence of collisions between particles in a spinning cloud. A cloud may start with any size or shape, and different clumps of gas within the cloud may be moving in random directions at random speeds. These clumps collide and merge as the cloud collapses, and each new clump has the average velocity of the clumps that formed it. The random motions of the original cloud therefore become more orderly as the cloud collapses, changing the cloud's original lumpy shape into a rotating, flattened disk. Similarly, collisions between clumps of material in highly elliptical orbits reduce their eccentricities, making their orbits more circular.

The formation of the spinning disk explains the orderly motions of our solar system today. The planets all orbit the Sun in nearly the same plane because they formed in the flat disk. The direction in which the disk was spinning became the direction of the Sun's rotation and the orbits of the planets. Computer models show that planets would have tended to rotate in the same direction as they formed—which is why most planets rotate the same way—though the small sizes of planets compared to the entire disk allowed some exceptions to arise. The fact that collisions in the disk tended to make orbits more circular explains why most planets have nearly circular orbits.

The orderly motions of our solar system today are a direct result of the solar system's birth in a spinning, flattened cloud of gas.

see it for yourself You can demonstrate the development of orderly motion, much as it occurred in the solar system, by sprinkling pepper into a bowl of water and stirring it quickly in random directions. The water molecules constantly collide with one another, so the motion of the pepper grains will tend to settle into a slow rotation representing the average of the original, random velocities. Try the experiment several times, stirring the water differently each time. Do the random motions ever cancel out exactly, resulting in no rotation at all? Describe what occurs, and explain how this is similar to what took place in the solar nebula.

Testing the Model Because the same processes should affect other collapsing gas clouds, we can test our model by searching for disks around other forming stars. Observational evidence does indeed support our model of spinning, heating, and flattening.

The heating that occurs in a collapsing cloud of gas means the gas should emit thermal radiation **[Section 5.2]**, primarily in the infrared. We've detected infrared radiation from many nebulae where star systems appear to be forming. More direct evidence comes from flattened, spinning disks around other stars (Figure 6.16), some of which appear to be ejecting jets of material perpendicular to their disks **[Section 12.1]**. These jets are thought to result from the flow of material from the disk onto the forming star.

Other support for the model comes from computer simulations of the formation process. A simulation begins with a set of data representing the conditions we observe in interstellar clouds. Then, with the aid of a computer, we apply the laws of physics to predict the changes that should occur over time. These computer simulations successfully reproduce most of the general characteristics of motion in our solar system, suggesting that the nebular theory is on the right track.

Observations of disks around other stars support the idea that our own solar system was once a spinning disk of gas.

Additional evidence that our ideas about the formation of flattened disks are correct comes from many other structures in the universe. We expect flattening to occur anywhere that orbiting particles can collide, which explains why we find so many cases of flat disks, including the disks of spiral galaxies like the Milky Way, the disks of planetary rings, and the *accretion disks* that surround neutron stars and black holes in close binary star systems **[Section 13.3]**.

MA Formation of the Solar System Tutorial, Lesson 3

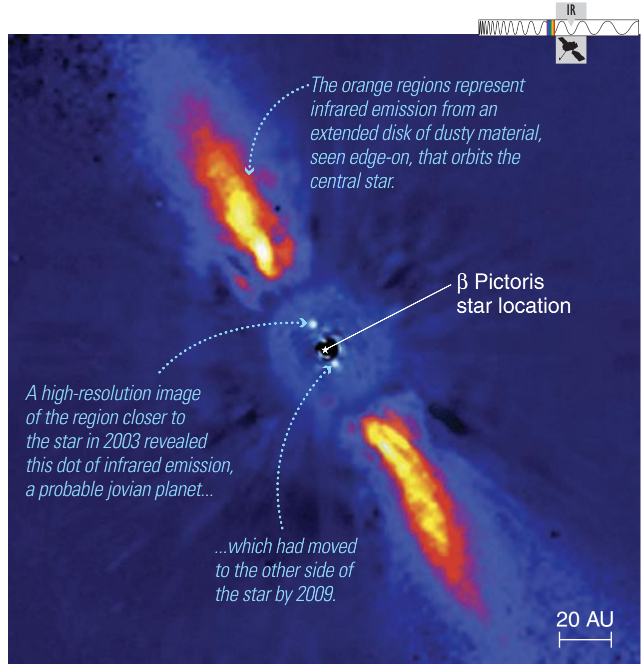
6.4 The Formation of Planets

The planets began to form after the solar nebula had collapsed into a flattened disk of perhaps 200 AU in diameter (about twice the present-day diameter of Pluto's orbit). In this section, we'll discuss planetary formation and address three major features of our solar system that we have not yet explained: the existence of two types of planets, the existence of asteroids and comets, and the exceptions to the rules.

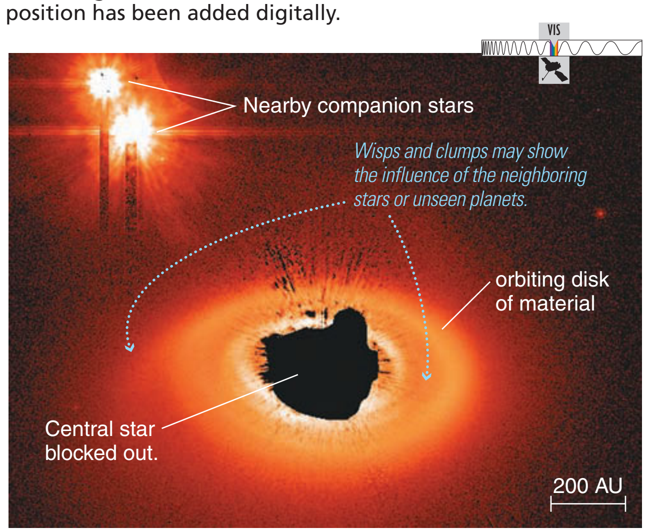
• Why are there two major types of planets?

The churning and mixing of gas in the solar nebula should have ensured that the nebula had the same composition throughout, so how did the terrestrial planets end up being so different in composition from the jovian planets? The key clue comes from their locations: The terrestrial planets formed in the warm, inner regions of the swirling disk, and the jovian planets formed in the colder, outer regions.

Condensation: Sowing the Seeds of Planets In the center of the collapsing solar nebula, gravity drew together enough material to form the Sun. In the surrounding disk, however, the gaseous material was too



a This infrared image composite from the European Southern Observatory shows a large debris disk orbiting the star Beta Pictoris and a probable jovian planet that has formed from the disk. Images were taken with the star itself blocked; the star's position has been added digitally.



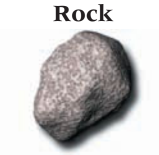
b This Hubble Space Telescope photo shows a disk around the star HD141569A. The colors are not real; a black-and-white image has been tinted red to bring out faint detail.

Figure 6.16

These photos show flattened, spinning disks of material around other stars.

Table 6.3 *Materials in the Solar Nebula*

A summary of the four types of materials present in the solar nebula. The squares represent the relative proportions of each type (by mass).

	Examples	*Typical condensation temperature*	*Relative abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1300 K	0.4%
Metals 	iron, nickel, aluminum	1000–1600 K	0.2%

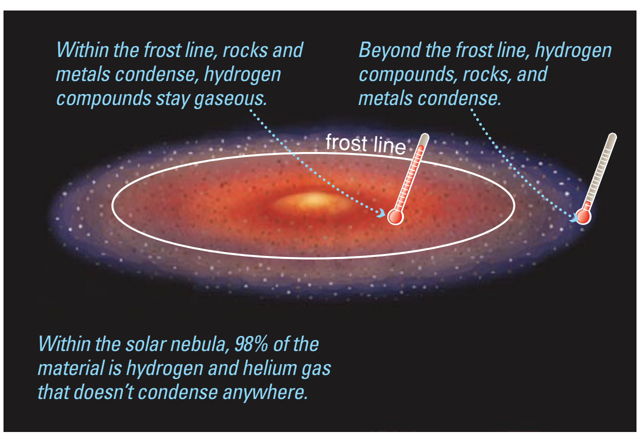


Figure 6.17 MA **interactive figure**

Temperature differences in the solar nebula led to different kinds of condensed materials, sowing the seeds for two different kinds of planets.

spread out for gravity alone to clump it together. Instead, material had to begin clumping in some other way and to grow in size until gravity could start pulling it together into planets. In essence, planet formation required the presence of "seeds"—solid bits of matter around which gravity could ultimately build planets.

Planet formation began around tiny "seeds" of solid metal, rock, or ice.

The basic process of seed formation was probably much like the formation of snowflakes in clouds on Earth: When the temperature is low enough, some atoms or molecules in a gas may bond and solidify. The general process in which solid (or liquid) particles form in a gas is called **condensation**—we say that the particles *condense* out of the gas. These particles start out microscopic in size, but they can grow larger with time.

Different materials condense at different temperatures. As summarized in Table 6.3, the ingredients of the solar nebula fell into four major categories:

- **Hydrogen and helium gas (98% of the solar nebula).** These gases never condense under the conditions present in a nebula.
- **Hydrogen compounds (1.4% of the solar nebula).** Materials such as water (H_2O), methane (CH_4), and ammonia (NH_3) can solidify into **ices** at low temperatures (below about 150 K under the low pressure of the solar nebula).
- **Rock (0.4% of the solar nebula).** Rocky material is gaseous at high temperatures but condenses into solid form at temperatures between about 500 K and 1300 K, depending on the type of rock.
- **Metals (0.2% of the solar nebula).** Metals such as iron, nickel, and aluminum are also gaseous at very high temperatures but condense into solid form at temperatures higher than rock—typically in the range of 1000 K to 1600 K.

Because hydrogen and helium gas made up 98% of the solar nebula's mass and did not condense, the vast majority of the nebula remained gaseous at all times. However, other materials could condense wherever the temperature allowed (Figure 6.17). Close to the forming Sun, where the temperature was above 1600 K, it was too hot for any material to condense. Near what is now Mercury's orbit, the temperature was low enough for metals and some types of rock to condense into tiny solid particles, but other types of rock and all the hydrogen compounds remained gaseous. More types of rock could condense, along with the metals, at the distances from the Sun where Venus, Earth, and Mars would form. In the region where the asteroid belt would eventually be located, temperatures were low enough to allow dark, carbon-rich minerals to condense, along with minerals containing small amounts of water. Hydrogen compounds could condense into ices only beyond the **frost line**—the minimum distance at which it was cold enough for ice to condense—which lay between the present-day orbits of Mars and Jupiter.

think about it Consider a region of the solar nebula in which the temperature was about 1300 K. Based on the data in Table 6.3, what fraction of the material in this region was gaseous? What were the solid particles in this region made of? Answer the same questions for a region with a temperature of 100 K. Would the 100 K region be closer to or farther from the Sun? Explain.

The frost line marked the key transition between the warm inner regions of the solar system where terrestrial planets formed and the cool outer regions where jovian planets formed. Inside the frost line, only metal and rock could condense into solid "seeds," which is why the terrestrial planets ended up being made of metal and rock. Beyond the frost line, where it was cold enough for hydrogen compounds to condense into ices, the solid seeds were built of ice along with metal and rock. Moreover, because hydrogen compounds were nearly three times as abundant in the nebula as metal and rock combined (see Table 6.3), the total amount of solid material was far greater beyond the frost line than within it. The stage was set for the birth of two types of planets: planets born from seeds of metal and rock in the inner solar system and planets born from seeds of ice (as well as metal and rock) in the outer solar system.

The solid seeds in the inner solar system were made only of metal and rock, but in the outer solar system they included the more abundant ices.

Building the Terrestrial Planets From this point, the story of the inner solar system seems fairly clear: The solid seeds of metal and rock in the inner solar system ultimately grew into the terrestrial planets we see today, but these planets ended up relatively small in size because rock and metal made up such a small amount of the material in the solar nebula.

The process by which small "seeds" grew into planets is called **accretion** (Figure 6.18). Accretion began with the microscopic solid particles that condensed from the gas of the solar nebula. These particles orbited the forming Sun with the same orderly, circular paths as the gas from which they condensed. Individual particles therefore moved at nearly the same speed as neighboring particles, so "collisions" were more like gentle touches. Although the particles were far too small to attract each other gravitationally at this point, they were able to stick together through electrostatic forces—the same "static electricity" that makes hair stick to a comb. Small particles thereby began to combine into larger ones. As the particles grew in mass, gravity began to aid in

common Misconceptions

Solar Gravity and the Density of Planets

You might think that it was the Sun's gravity that pulled the dense rocky and metallic materials to the inner part of the solar nebula, or that gases escaped from the inner nebula because gravity couldn't hold them. But this is not the case—all the ingredients were orbiting the Sun together under the influence of the Sun's gravity. The orbit of a particle or a planet does not depend on its size or density, so the Sun's gravity cannot be the cause of the different kinds of planets. Rather, the different temperatures in the solar nebula are the cause.

Figure 6.18

These diagrams show how planetesimals gradually accrete into terrestrial planets.

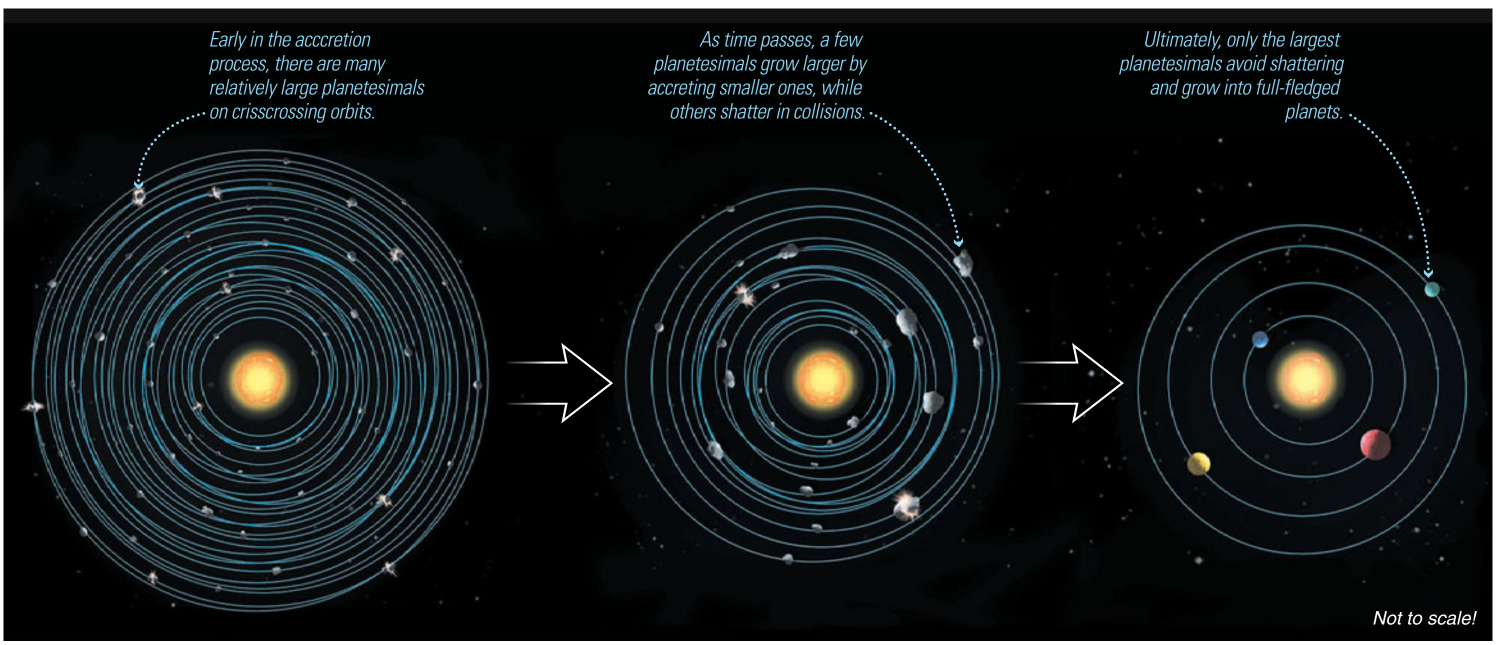


Figure 6.19

Shiny flakes of metal are clearly visible in this slice through a meteorite (a few centimeters across), mixed in among the rocky material. Such metallic flakes are just what we would expect to find if condensation really occurred in the solar nebula as described by the nebular theory.

the accretion process, accelerating their growth into boulders large enough to count as **planetesimals**, which means "pieces of planets."

The terrestrial planets were made from the solid bits of metal and rock that condensed in the inner solar system.

The planetesimals grew rapidly at first. As they grew larger, they had both more surface area to make contact with other planetesimals and more gravity to attract them. Some planetesimals probably grew to hundreds of kilometers in size in only a few million years—a long time in human terms, but only about $\frac{1}{1000}$ the present age of the solar system. However, once the planetesimals reached these relatively large sizes, further growth became more difficult.

Gravitational encounters **[Section 4.4]** between planetesimals tended to alter their orbits, particularly those of the smaller planetesimals. With different orbits crossing each other, collisions between planetesimals tended to occur at higher speeds and hence became more destructive. Such collisions tended to shatter planetesimals rather than help them grow. Only the largest planetesimals avoided being shattered and could grow into full-fledged planets.

Theoretical evidence in support of this model comes from computer simulations of the accretion process. Observational evidence comes from meteorites that appear to be surviving fragments from the period of condensation **[Section 9.1]**. These meteorites contain metallic grains embedded in rocky minerals (Figure 6.19), just as we would expect if metal and rock condensed in the inner solar system. Meteorites thought to come from the outskirts of the asteroid belt contain abundant carbon-rich materials, and some contain water—again, as we would expect for material that condensed in that region.

Making the Jovian Planets Accretion should have occurred similarly in the outer solar system, but condensation of ices meant both that there was more solid material and that this material contained ice in addition to metal and rock. The solid objects that reside in the outer solar system today, such as comets and the moons of the jovian planets, still show this ice-rich composition. However, the growth of icy planetesimals cannot be the whole story of jovian planet formation, because the jovian planets contain large amounts of hydrogen and helium gas.

The leading model for jovian planet formation holds that these planets formed as gravity drew gas around ice-rich planetesimals much more massive than Earth. Because of their large masses, these planetesimals had gravity strong enough to capture some of the hydrogen and helium gas that made up the vast majority of the surrounding solar nebula. This added gas made their gravity even stronger, allowing them to capture even more gas. Ultimately, the jovian planets accreted so much gas that they bore little resemblance to the icy seeds from which they started.

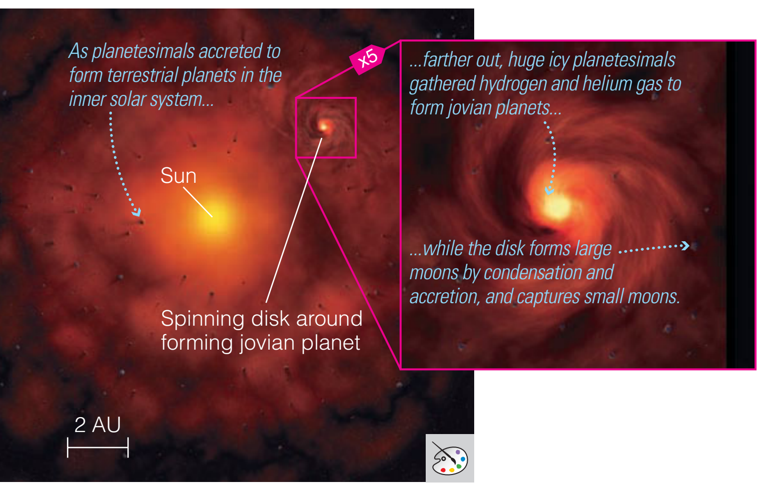


Figure 6.20

The forming jovian planets were surrounded by disks of gas, much like the disk of the entire solar nebula but smaller in size. According to the leading model, the planets grew as large, icy planetesimals that captured hydrogen and helium gas from the solar nebula. This painting shows the gas and planetesimals surrounding one jovian planet in the larger solar nebula.

The jovian planets began as large, icy planetesimals, which then captured hydrogen and helium gas from the solar nebula.

This model also explains most of the large moons of the jovian planets. The same processes of heating, spinning, and flattening that made the disk of the solar nebula should also have affected the gas drawn by gravity to the young jovian planets. Each jovian planet came to be surrounded by its own disk of gas, spinning in the same direction as the planet rotated (Figure 6.20). Moons that accreted from icy planetesimals within these disks therefore ended up with nearly circular orbits going in the same direction as their planet's rotation and lying close to their planet's equatorial plane.

Clearing the Nebula The vast majority of the hydrogen and helium gas in the solar nebula never became part of any planet. So what happened to it? Apparently, it was cleared away by a combination of radiation from the young Sun and the *solar wind*—a stream of charged particles continually blown outward in all directions from the Sun **[Section 10.1]**. Although the solar wind is fairly weak today, observations show that stars tend to have much stronger winds when they are young. The young Sun therefore should have had a strong solar wind—strong enough to have swept huge quantities of gas out of the solar system.

Remaining gas in the solar nebula was cleared away into space, ending the era of planet formation.

The clearing of the gas sealed the compositional fate of the planets. If the gas had remained longer, it might have continued to cool until hydrogen compounds could have condensed into ices even in the inner solar system. In that case, the terrestrial planets might have accreted abundant ice, and perhaps hydrogen and helium gas as well, changing their basic nature. At the other extreme, if the gas had been blown out much earlier, the raw materials of the planets might have been swept away before the planets could fully form. Although these extreme scenarios did not occur in our solar system, they may sometimes occur around other stars. Planet formation may also sometimes be interrupted when radiation from hot, neighboring stars drives away material in a solar nebula.

• Where did asteroids and comets come from?

The process of planet formation also explains the origin of the many asteroids and comets that populate our solar system (including those large enough to qualify as dwarf planets): They are "leftovers" from the era of planet formation. Asteroids are the rocky leftover planetesimals of the inner solar system, while comets are the icy leftover planetesimals of the outer solar system. We'll see in Chapter 9 why most asteroids ended up grouped in the asteroid belt while most comets ended up split between two regions (the Kuiper belt and the Oort cloud).

Rocky asteroids and icy comets are leftover planetesimals from the era of planet formation.

Evidence that asteroids and comets are leftover planetesimals comes from analysis of meteorites, spacecraft visits to comets and asteroids, and theoretical models of solar system formation. In fact, the nebular theory allowed scientists to make predictions about the locations of comets that weren't verified until decades later, when we discovered large comets orbiting in the vicinity of Neptune and Pluto.

The asteroids and comets that exist today probably represent only a small fraction of the leftover planetesimals that roamed the young solar system. The rest are now gone. Some of these "lost" planetesimals may have been flung into deep space by gravitational encounters, but many others must have collided with the planets. When impacts occur on solid worlds, they leave behind *impact craters* as scars. These impacts have transformed planetary landscapes, and, in the case of Earth, they have altered the course of evolution. For example, an impact is thought to have been responsible for the death of the dinosaurs **[Section 9.4]**.

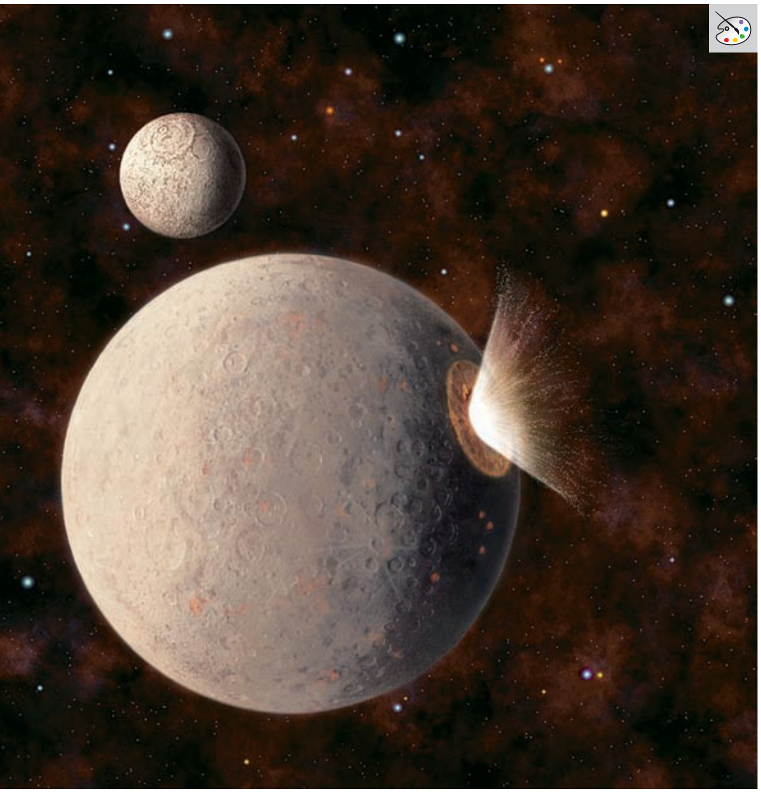


Figure 6.21

Around 4 billion years ago, Earth, its Moon, and the other planets were heavily bombarded by leftover planetesimals. This painting shows the young Earth and Moon, with an impact in progress on Earth.

Although impacts occasionally still occur, the vast majority of these collisions occurred in the first few hundred million years of our solar system's history, during the period we call the **heavy bombardment.** Every world in our solar system must have been pelted by impacts during the heavy bombardment (Figure 6.21), and most of the craters we see on the Moon and other worlds date from this period. These impacts did more than just batter the planets. They also brought materials from other regions of the solar system—a fact that is critical to our existence on Earth today.

Leftover planetesimals battered the planets during the solar system's first few hundred million years.

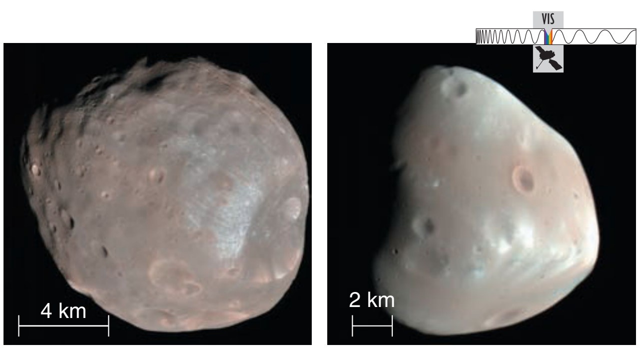
Remember that the terrestrial planets were built from planetesimals made of metal and rock. These planetesimals probably contained no water or other hydrogen compounds at all, because it was too hot for these compounds to condense in our region of the solar nebula. How, then, did Earth come to have the water that makes up our oceans and the gases that first formed our atmosphere? The likely answer is that water, along with other hydrogen compounds, was brought to Earth and other terrestrial planets by the impacts of water-bearing planetesimals that formed farther from the Sun. Remarkably, the water we drink and the air we breathe probably once were part of planetesimals that accreted beyond the orbit of Mars.

• How do we explain the existence of our Moon and other exceptions to the rules?

We have now explained all the major features of our solar system except for the exceptions to the rules, including our surprisingly large Moon. Today, we think that most of these exceptions arose from collisions or close gravitational encounters.

Captured Moons We have explained the orbits of most large jovian planet moons by their formation in a disk that swirled around the forming planet. But how do we explain moons with less orderly orbits, such as those that go in the "wrong" direction (opposite their planet's rotation) or that have large inclinations to their planet's equator? These moons are probably leftover planetesimals that originally orbited the Sun but were then captured into planetary orbit.

It's not easy for a planet to capture a moon. An object cannot switch from an unbound orbit (for example, an asteroid whizzing by Jupiter) to a bound orbit (for example, a moon orbiting Jupiter) unless it somehow loses orbital energy **[Section 4.4]**. For the jovian planets, captures probably occurred when passing planetesimals lost energy to drag in the extended and relatively dense gas that surrounded these planets as they formed. The planetesimals would have been slowed by friction with the gas, just as artificial satellites are slowed by drag in encounters with Earth's atmosphere. If friction reduced a passing planetesimal's orbital energy enough, it could have become an orbiting moon. Because of the random nature of the capture process, captured moons would not necessarily orbit in the same direction as their planet or in its equatorial plane. Most of the small moons of the jovian planets are a few kilometers across, supporting the idea that they were captured in this way. Mars may have similarly captured its two small moons, Phobos and Deimos, at a time when the planet had a much more extended atmosphere than it does today (Figure 6.22).



a Phobos **b** Deimos

Figure 6.22

The two moons of Mars are probably captured asteroids. Phobos is only about 13 kilometers across, and Deimos is only about 8 kilometers across—making each of these two moons small enough to fit within the boundaries of a typical large city. (Images from the *Mars Reconnaissance* orbiter.)

The Giant Impact Formation of Our Moon Capture processes cannot explain our own Moon, because it is much too large to have been captured by a small planet like Earth. We can also rule out the possibility that our Moon formed simultaneously with Earth, because if both had formed together, they would have accreted from planetesimals of the same type and should therefore have approximately the same composition and density. But this is not the case: The Moon's density is considerably lower than Earth's, indicating that it has a very different average composition. So how did we get our Moon? Today, the leading hypothesis suggests that it formed as the result of a **giant impact** between Earth and a huge planetesimal.

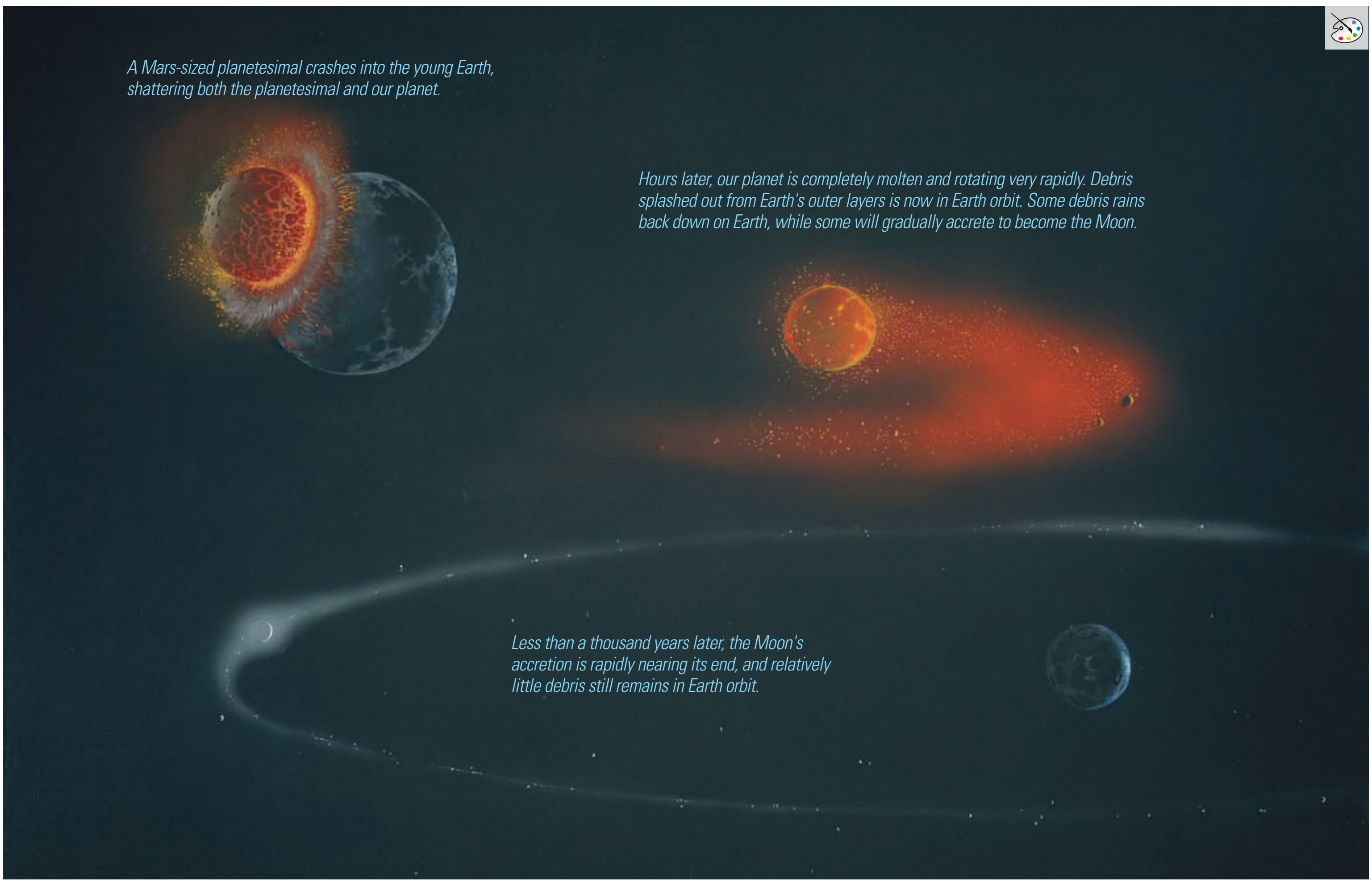
According to models, a few leftover planetesimals may have been as large as Mars. If one of these Mars-size objects struck a young planet, the blow might have tilted the planet's axis, changed the planet's rotation rate, or completely shattered the planet. The giant impact hypothesis holds that a Mars-size object hit Earth at a speed and angle that blasted Earth's outer layers into space. According to computer simulations, this material could have collected into orbit around our planet, and accretion within this ring of debris could have formed the Moon (Figure 6.23).

Our Moon is probably the result of a giant impact that blasted Earth's outer layers into orbit, where the material accreted to form the Moon.

Strong support for the giant impact hypothesis comes from two features of the Moon's composition. First, the Moon's overall

Figure 6.23

Artist's conception of the giant impact hypothesis for the formation of our Moon. The fact that ejected material came mostly from Earth's outer rocky layers explains why the Moon contains very little metal. The impact must have occurred more than 4.4 billion years ago, since that is the age of the oldest Moon rocks. As shown, the Moon formed quite close to a rapidly rotating Earth, but over billions of years, tidal forces have slowed Earth's rotation and moved the Moon's orbit outward **[Section 4.4]**.



composition is quite similar to that of Earth's outer layers—just as we should expect if it were made from material blasted away from those layers. Second, the Moon has a much smaller proportion of easily vaporized ingredients (such as water) than Earth. This fact supports the hypothesis because the heat of the impact would have vaporized these ingredients. As gases, they would not have participated in the process of accretion that formed the Moon.

Other Exceptions Giant impacts may also explain other exceptions to the general trends. For example, Pluto's moon Charon shows signs of having formed in a giant impact similar to the one thought to have formed our Moon, and Mercury's surprisingly high density may be the result of a giant impact that blasted away its outer, lower-density layers. Giant impacts could have also been responsible for tilting the axes of many planets (including Earth) and perhaps for tipping Uranus on its side. Venus's slow and backward rotation could also be the result of a giant impact, though some scientists suspect it is a consequence of processes attributable to Venus's thick atmosphere.

Although we cannot definitively explain these exceptions to the general rules, the overall lesson is clear: The chaotic processes that accompanied planet formation, including the many collisions that surely occurred, are *expected* to have led to at least a few exceptions. We therefore conclude that nebular theory can account for all four of the major features of our solar system. Figure 6.24 summarizes what we have discussed.

• When did the planets form?

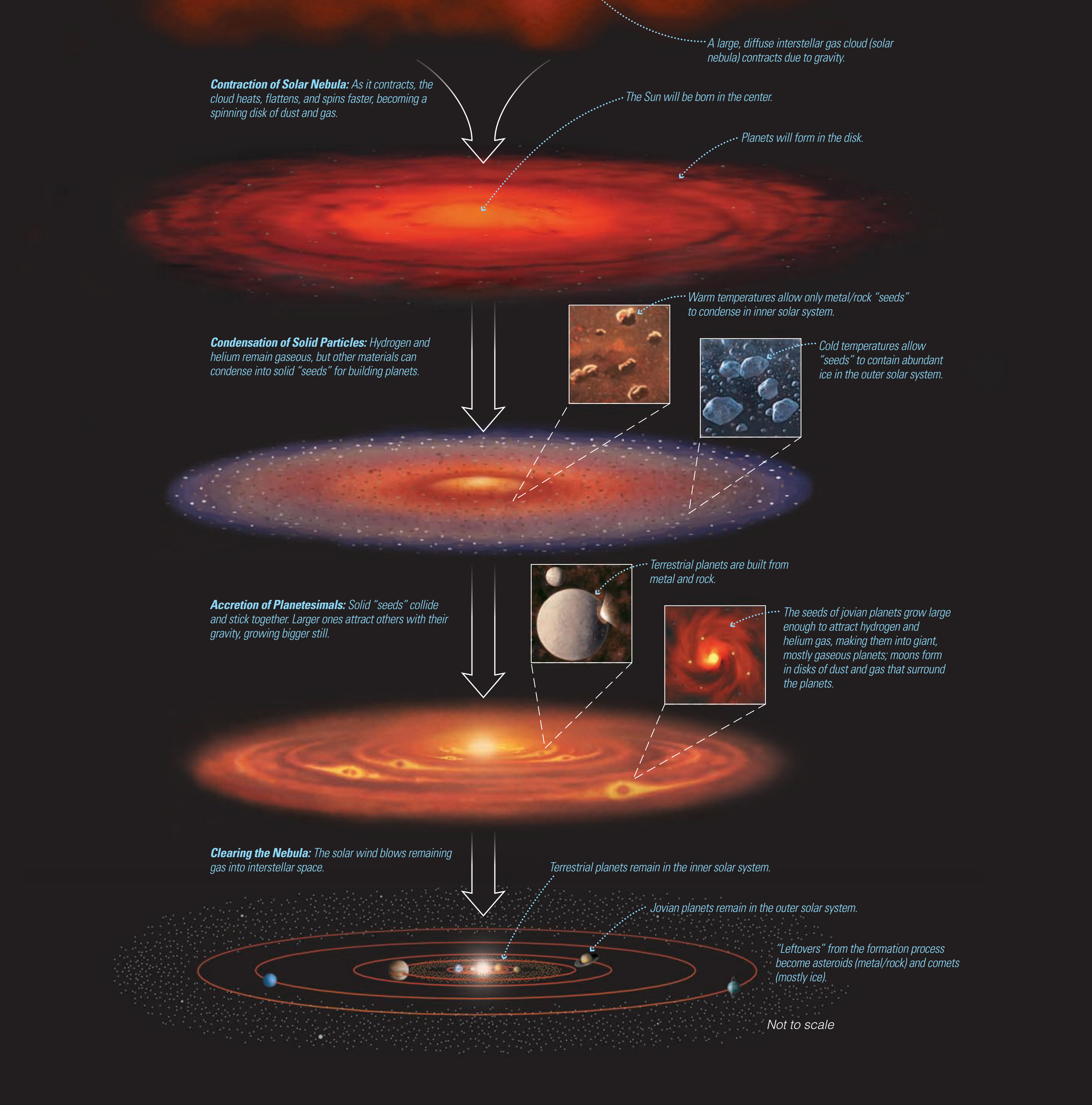
Computer models of planetary formation suggest that the entire process took no more than about 50 million years, and perhaps significantly less. But when did it all occur, and how do we know? The answer is that the planets began to form through accretion just over $4\frac{1}{2}$ billion years ago, a fact we learn by determining the age of the oldest rocks in the solar system.

Dating Rocks The most reliable method for measuring the age of a rock is **radiometric dating**, which relies on careful measurement of the proportions of various atoms and isotopes in the rock. The method works because some atoms undergo changes with time that allow us to determine how long they have been held in place within the rock's solid structure. By analyzing these changes we learn the amount of time that has passed since the atoms became locked together in their present arrangement, which in most cases means the time *since the rock last solidified.*

Remember that each chemical element is uniquely characterized by the number of protons in its nucleus. Different *isotopes* of the same element differ only in their number of neutrons [Section 5.1]. A **radioactive** isotope has a nucleus prone to spontaneous change, or *decay,* such as breaking apart or having one of its protons turn into a neutron. This decay always occurs at the same rate for any particular radioactive isotope, and scientists can measure these rates in the laboratory. We generally characterize decay rates by stating a **half-life**—the length of time it would take for half the nuclei in the collection to decay.

Figure 6.24

A summary of the proccess by which our solar system formed, according to the nebular theory.



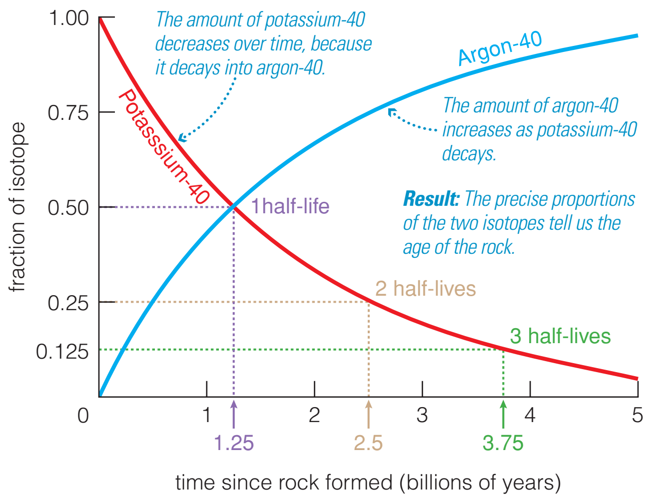


Figure 6.25

Potassium-40 is radioactive, decaying into argon-40 with a half-life of 1.25 billion years. The red curve shows the decreasing amount of potassium-40, and the blue curve shows the increasing amount of argon-40. The remaining amount of potassium-40 drops in half with each successive half-life.

For example, potassium-40 is a radioactive isotope with nuclei that decay when a proton turns into a neutron, changing the potassium-40 into argon-40. The half-life for this decay process is 1.25 billion years. (Potassium-40 also decays by other paths, but we focus only on decay into argon-40 to keep the discussion simple.) Now, consider a small piece of rock that contained 1 microgram of potassium-40 and no argon-40 when it formed (solidified) long ago. The half-life of 1.25 billion years means that half the original potassium-40 had decayed into argon-40 by the time the rock was 1.25 billion years old, so at that time the rock contained $\frac{1}{2}$ microgram of potassium-40 and $\frac{1}{2}$ microgram of argon-40. Half of this remaining potassium-40 had then decayed by the end of the next 1.25 billion years, so after 2.5 billion years the rock contained $\frac{1}{4}$ microgram of potassium-40 and $\frac{3}{4}$ microgram of argon-40. After three half-lives, or 3.75 billion years, only $\frac{1}{8}$ microgram of potassium-40 remained, while $\frac{7}{8}$ microgram had become argon-40. Figure 6.25 summarizes the gradual decrease in the amount of potassium-40 and the corresponding rise in the amount of argon-40.

We can determine the age of a rock through careful analysis of the proportions of various atoms and isotopes within it.

We can now see the essence of radiometric dating. Suppose you find a rock that contains equal numbers of atoms of potassium-40 and argon-40. If you assume that all the argon came from potassium decay (and if the rock shows no evidence of subsequent heating that could have allowed any argon to escape), then it must have taken precisely one half-life for the rock to end up with equal amounts of the two isotopes. You could therefore conclude that the rock is 1.25 billion years old. The only question is whether you are right in assuming that the rock lacked argon-40 when it formed. In this case, knowing a bit of "rock chemistry" helps. Potassium-40 is a natural ingredient of many minerals in rocks, but argon-40 is a gas that does not combine with other elements and did not condense in the solar nebula. If you find argon-40 gas trapped inside minerals, it must have come from radioactive decay of potassium-40.

Radiometric dating is possible with many other radioactive isotopes as well. In many cases, we can date a rock that contains more than one radioactive isotope, so agreement between the ages calculated from the different isotopes gives us confidence that we have dated the rock correctly. We can also check results from radiometric dating against those from other methods of measuring or estimating ages. For example, some fairly recent archaeological artifacts have original dates printed on them, and the dates agree with ages found by radiometric dating. We can validate the $4\frac{1}{2}$-billion-year radiometric age for the solar system as a whole by comparing it to an age based on detailed study of the Sun. Theoretical models of the Sun, along with observations of other stars, show that stars slowly expand and brighten as they age. The model ages are not nearly as precise as radiometric ages, but they confirm that the Sun is between about 4 and 5 billion years old. Overall, the technique of radiometric dating has been checked in so many ways and relies on such basic scientific principles that there is no longer any serious scientific debate about its validity.

Earth Rocks, Moon Rocks, and Meteorites Radiometric dating tells us how long it has been since a rock solidified, which is not the same as the age of a planet as a whole. For example, we find rocks of many different ages on Earth. Some rocks are quite young because they formed recently from molten lava; others are much older. The oldest

Earth rocks are about 4 billion years old, and some small mineral grains are about 4.4 billion years old. Earth itself must be even older.

Moon rocks brought back by the *Apollo* astronauts date as far back as 4.4 billion years ago. Although they are older than Earth rocks, these Moon rocks must still be younger than the Moon itself. The ages of these rocks also tell us that the giant impact thought to have created the Moon must have occurred more than 4.4 billion years ago.

Age dating of meteorites that are unchanged since they condensed and accreted tells us that the solar system is about $4\frac{1}{2}$ billion years old.

To go all the way back to the origin of the solar system, we must find rocks that have not melted or vaporized since they first condensed in the solar nebula. Meteorites that have fallen to Earth are our source of such rocks. Many meteorites appear to have remained unchanged since they condensed and accreted in the early solar system. Careful analysis of radioactive isotopes in these meteorites shows that the oldest ones formed about 4.55 billion years ago, so this time must mark the beginning of accretion in the solar nebula. Because the planets apparently accreted within about 50 million (0.05 billion) years, Earth and the other planets formed about 4.5 billion years ago.

cosmic Calculations 6.1

Radiometric Dating

From the fact that the amount of a radioactive substance decays by half with each half-life, it is possible to derive a simple formula for the age of a rock. If you have measured the current amount of a radioactive substance and determined the original amount (by measuring the abundance of its decay products), and if you know its half-life, t_{half}, then the time t since the rock formed is

$$t = t_{half} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

Even if you are unfamiliar with logarithms, you can work with this formula by using the "log" button on your calculator.

Example: You chemically analyze a small sample of a meteorite. Potassium-40 and argon-40 are present in a ratio of approximately 0.85 unit of potassium-40 atoms to 9.15 units of gaseous argon-40 atoms. (The units are unimportant, because only the relative amounts of the parent and daughter materials matter.) How old is the meteorite?

Solution: Because no argon gas could have been present in the meteorite when it formed, the 9.15 units of argon-40 must originally have been potassium-40 that has decayed with a half-life of 1.25 billion years. The sample must therefore have started with $0.85 + 9.15 = 10$ units of potassium-40 (the original amount), of which 0.85 unit remains (the current amount). The formula now reads

$$t = 1.25 \text{ billion yr} \times \frac{\log_{10}\left(\frac{0.85}{10}\right)}{\log_{10}\left(\frac{1}{2}\right)} = 4.45 \text{ billion yr}$$

This meteorite solidified about 4.45 billion years ago.

MA Detecting Extrasolar Planets Tutorial, Lessons 1–3

6.5 Other Planetary Systems

Just a couple of decades ago, the complete list of known planets in the universe consisted only of those in our own solar system. The nebular theory made it seem likely that planets existed around other stars, but technology was not yet at the point where we could test the idea. As we discussed in Chapter 1, seeing planets around other stars is equivalent to looking for dim ball points or marbles from a distance of thousands of kilometers away—with the star typically a billion times brighter than the planet. Remarkably, we can now detect many of these planets, and this fact has ushered in a new era in astronomy: We can engage in comparative study of planetary *systems,* which allows us to test and refine our ideas about the formation of stars and planets.

• How do we detect planets around other stars?

The first clear-cut discovery of a planet around another Sun-like star—a star called 51 Pegasi—came in 1995. Hundreds of additional extrasolar planets have been discovered since that time, using several planet-finding strategies. If we strip away the details, however, there are really only two basic ways to search for extrasolar planets:

1. Directly: Pictures or spectra of the planets themselves constitute direct evidence of their existence.
2. Indirectly: Precise measurements of a *star's* properties may indirectly reveal the effects of orbiting planets.

Almost all extrasolar planets detected to date have been found indirectly rather than through direct imaging.

Direct detection is preferable because it can tell us far more about the planet's properties, but to date nearly all detections have been indirect.

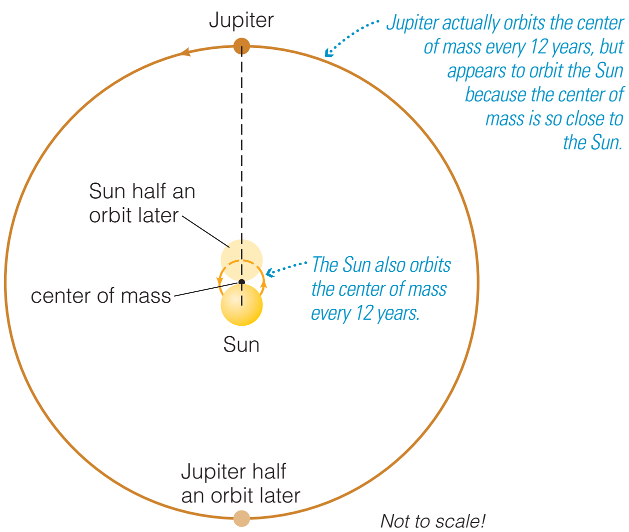


Figure 6.26

This diagram shows how both the Sun and Jupiter actually orbit around their mutual center of mass, which lies very close to the Sun. The diagram is not to scale; the sizes of the Sun and its orbit are exaggerated about 100 times compared to the size shown for Jupiter's orbit, and Jupiter's size is exaggerated even more.

think about it Do a quick Web search on "extrasolar planets" to find the current number of known extrasolar planets. How many have been found in the past year alone?

Gravitational Tugs Two indirect techniques—the *astrometric* and *Doppler* techniques—rely on observing stars in search of motion that we can attribute to gravitational tugs from orbiting planets. Although we usually think of a star as remaining still while planets orbit around it, that is only approximately correct. In reality, all the objects in a star system, including the star itself, orbit the system's *center of mass,* which is in essence the balance point for all the mass of the solar system. Because the Sun is far more massive than all the planets combined, the center of mass of our solar system lies close to the Sun—but not exactly at the Sun's center.

We can see how this fact allows us to discover extrasolar planets by imagining the viewpoint of extraterrestrial astronomers observing our solar system from afar. Let's start by considering only the influence of Jupiter, the most massive planet in our solar system (Figure 6.26). The center of mass between the Sun and Jupiter lies just outside the Sun's visible surface, so what we usually think of as Jupiter's 12-year orbit around the Sun is really a 12-year orbit around this center of mass. Because the Sun and Jupiter are always on opposite sides of the center of mass (otherwise it wouldn't be a "center"), the Sun must orbit this point with the same 12-year period. The Sun's orbit traces out a very small ellipse with each 12-year period, because the Sun's average orbital distance is barely larger than its own radius. Nevertheless, with sufficiently precise measurements, extraterrestrial astronomers could detect this orbital movement of the Sun and thereby deduce the existence of Jupiter—without having ever seen the planet. They could even determine Jupiter's mass from the orbital characteristics of the Sun as it goes around the center of mass. A more massive planet located at the same distance would pull the center of mass farther from the Sun's center, thereby giving the Sun a larger orbit and a faster orbital speed around the center of mass.

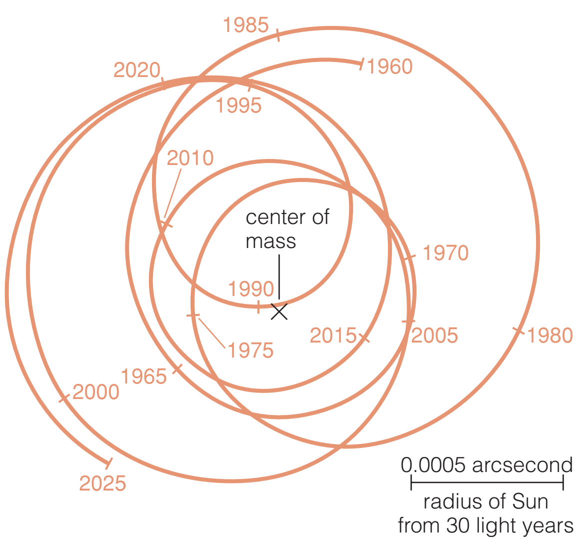


Figure 6.27

This diagram shows the orbital path of the Sun from 1960 to 2025 around the center of mass of our solar system, as it would appear if viewed face-on from a distance of 30 light-years away. The complex motion reveals the gravitational effects of the planets (primarily Jupiter and Saturn). The *astrometric technique* for detecting extrasolar planets works by looking for similar changes in the position of other stars. Notice that the entire range of motion during this period is only about 0.0015 arcsecond, which is almost 100 times smaller than the angular resolution of the Hubble Space Telescope.

see it for yourself To see how a small planet can make a big star wobble, find a pencil and tape a heavier object (such as a set of keys) to one end and a lighter object (perhaps a small stack of coins) to the other end. Tie a string (or piece of floss) at the balance point—the center of mass—so that the pencil is horizontal; then tap the lighter object into "orbit" around the heavier object. What does the heavier object do, and why? How does your model correspond to a planet orbiting a star? You can experiment further with objects of different weights or shorter pencils; explain the differences you see.

The other planets also exert gravitational tugs on the Sun, each adding a small additional effect to the effects of Jupiter. In principle, with sufficiently precise measurements of the Sun's orbital motion made over many decades, an extraterrestrial astronomer could deduce the existence of all the planets of our solar system (Figure 6.27). This is the essence of the **astrometric technique**, in which we make very precise measurements of stellar positions in the sky (*astrometric* means

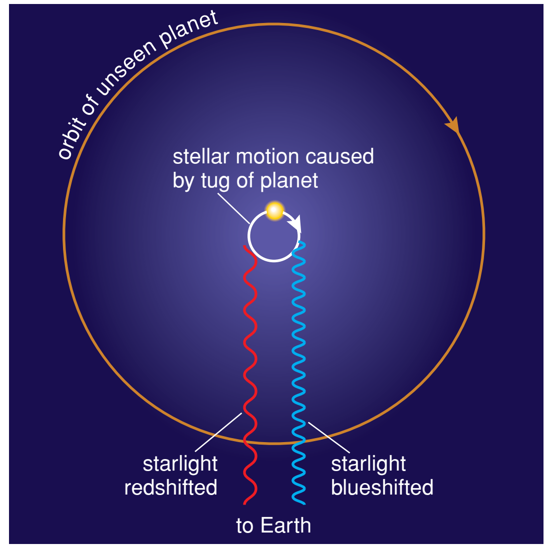
Orbiting planets exert gravitational tugs on their star, so we can detect the planets by observing the star's resulting "wobble" around its average position in the sky.

"measurement of the stars"). If a star "wobbles" gradually around its average position (the center of mass), we must be observing the influence of unseen planets. The primary difficulty with the astrometric technique is that we are looking for changes to position that are very small even for nearby stars, and these changes become smaller for more distant stars. In addition, the stellar motions are largest for massive planets orbiting *far* from their star, but the long orbital periods of such planets mean that it can take decades to notice the motion. As a result, the astrometric technique has been of only limited use to date, but astronomers hope it will prove successful with future space-based telescopes.

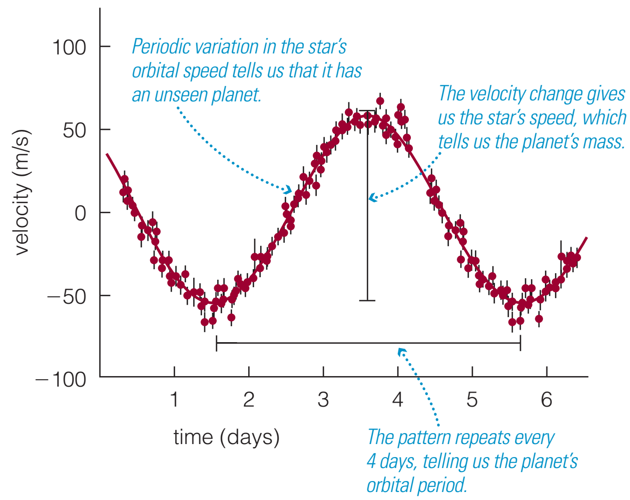
The **Doppler technique** searches for a star's orbital movement around the center of mass by looking for changing Doppler shifts in a star's spectrum **[Section 5.2]**. As long as a planet's orbit is *not* face-on to us, its gravitational influence will cause its star to move alternately with an orbital toward and away from us—motions that cause spectral lines to shift alternately toward the blue and red ends of the spectrum (Figure 6.28a). The 1995 discovery of a planet orbiting 51 Pegasi came when this star was found to have alternating blueshifts and redshifts within a period of four days (Figure 6.28b). The 4-day period of the star's motion must be the orbital period of its planet. We can then use this period with the star's mass and Newton's version of Kepler's third law **[Section 4.4]** to calculate the planet's orbital distance. (In Chapter 11, we'll see how the star's mass and other properties can be known.) The Doppler technique even allows us to estimate the planet's mass from the measured change in the star's velocity.* The data in Figure 6.28b thereby enabled us to learn that the planet orbiting 51 Pegasi is similar to Jupiter in mass but orbits only about 0.05 AU from its star—so close that its surface temperature is probably over 1000 K. It is therefore an example of what we call a **hot Jupiter,** because it has a Jupiter-like mass but a much higher surface temperature.

Alternating Doppler shifts in a star's spectrum, indicating back-and-forth motion, can also reveal the influence of orbiting planets.

The Doppler technique has been used for the vast majority of planet discoveries to date. In some cases, Doppler data are good enough to tell us whether the star has more than one planet. Remember that if two or more planets exert a noticeable gravitational tug on their star, the Doppler data will show the combined effect of these tugs. Dozens of multiple-planet systems have been identified, including one with five planets. Keep in mind, however, that the Doppler technique is best suited to identifying massive planets that orbit relatively close to their star, because the star's orbital speed depends on the strength of the gravitational tug, and gravity is strongest for massive planets with small orbital distances **[Section 4.4]**. This fact probably explains why most of the extrasolar planets discovered to date orbit relatively close to their stars—these planets are easier to find than planets orbiting far from their stars, which would have weaker gravitational effects and such long orbital periods that it might take decades of observations to detect them. It also explains why it is so difficult to detect planets with Earth-like masses: These planets would have such weak gravitational effects on their stars that we could not apply the Doppler technique to find them using current technology.



a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

Figure 6.28 MA **interactive figure**

The Doppler technique for discovering extrasolar planets.

*The Doppler shift tells us the star's full orbital velocity only if we are viewing its planetary system edge-on; in all other cases, it gives us a lower limit on the star's velocity and therefore a lower limit to the planet's mass. However, statistical arguments show that in two out of three cases, the planet's true mass will be no more than double this lower limit.

Transits and Eclipses A third indirect way of detecting distant planets relies on searching for slight changes in a star's brightness that occur when a planet passes in front of or behind it. If we were to examine a large sample of stars with planets, a small number of them (<1%) would by chance be aligned in such a way that one or more of the star's planets pass directly between us and the star during each orbit. The result is a **transit**, in which the planet appears to move across the face of the star, causing a small, temporary dip in the star's brightness. Because a star's brightness can also vary for other reasons, we can assume that a transiting planet is the cause only if the dimming repeats with a regular period.

think about it What kind of planet is most likely to cause a transit across its star that we could observe from Earth: (a) a large planet close to its star? (b) a large planet far from its star? (c) a small planet close to its star? or (d) a small planet far from its star? Explain.

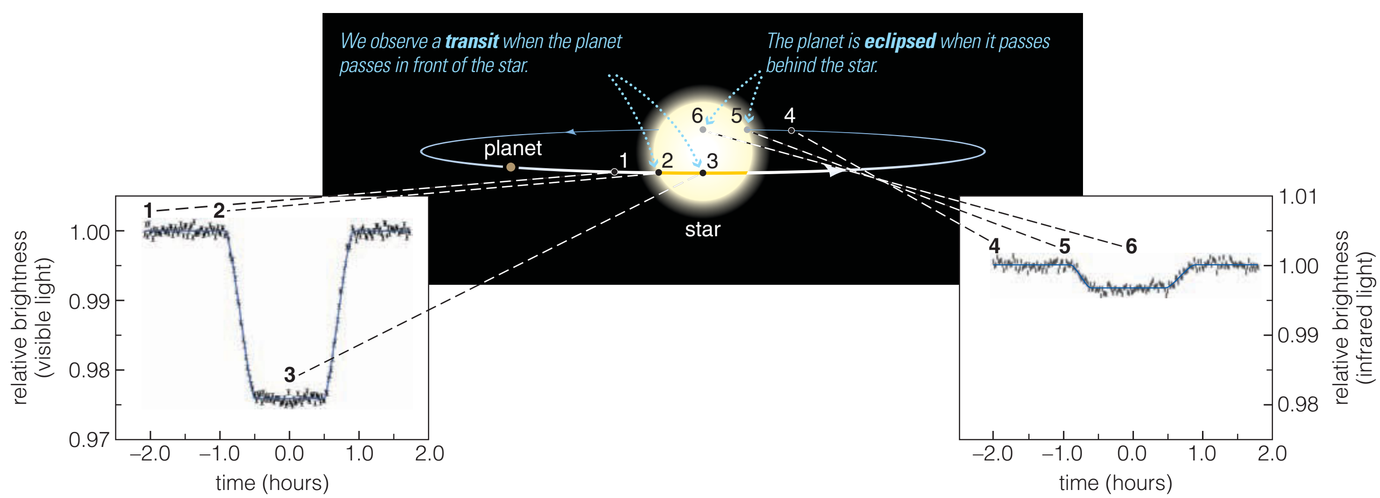
Figure 6.29 shows transit data for a planet orbiting the star HD189733. Transits occur every 2.2 days, telling us the planet's orbital period, and the 2.5% dips in the star's brightness tell us how the planet's radius compares to its star's radius. Half an orbit after a transit, a planet passes behind its star in what we call an **eclipse**. Observing an eclipse is much like observing a transit: In both cases, we actually measure the *combined* light from the star and planet, so in principle there can be a dip in brightness whenever either object blocks light from the other. However, because planets generally emit in the infrared, not in the visible [Section 5.2], the dips that occur during eclipses are usually measurable only at infrared wavelengths. For example, during eclipses in the HD189733 system, the infrared brightness drops by about 0.3%, telling us that the planet emits 0.3% as much infrared radiation as the star (see Figure 6.29). By combining this fact with the planet's radius measured during the transits, astronomers calculate the planet's temperature to be more than 1100 K.

If a planet happens to orbit edge-on as seen from Earth, it will periodically pass in front of its star, causing a dip in the star's brightness.

The primary limitation of the transit and eclipse methods is that they work only for the small fraction of planets whose orbits are nearly edge-on. But the method also has advantages, including the ability to take a spectrum of starlight transmitted through a planet's atmosphere. So far,

Figure 6.29 MA interactive figure

This diagram shows the planet orbiting the star HD189733. The graphs show how the star's brightness changes during transits and eclipses, which each occur once during every 2.2-day orbit. During a transit, the star's brightness drops for about 2 hours by 2.5%, which tells us how the planet's radius compares to the radius of its star. During an eclipse, the infrared signal drops by 0.3%, which tells us about the planet's thermal emission.



astronomers have confirmed the existence of hydrogen, water, methane, and even a hint of sodium in the atmospheres of extrasolar planets. The transit method can also be used to search simultaneously for planets around vast numbers of stars and to detect much smaller planets than is possible with the Doppler technique. NASA's *Kepler* mission, launched in 2009, is monitoring some 100,000 stars for transits. By mid-2010, *Kepler* had already found more than 700 candidates, some not much larger than Earth, but was still awaiting follow-up observations to distinguish planets from eclipsing or variable stars. If Earth-size planets are common, *Kepler* should detect dozens of them. A European Space Agency (ESA) spacecraft called *COROT* has also detected several transiting planets. In addition, small telescopes have been used to discover transiting planets, and it's relatively easy to confirm for yourself some of the transits already detected. What was once considered impossible can now be assigned as homework (see Problem 54 at the end of the chapter).

think about it Find the current status of the *Kepler* and *COROT* missions. What is the smallest planet discovered by either mission so far?

Direct Detection The indirect planet-hunting techniques we have discussed so far have started a revolution in planetary science by demonstrating that our solar system is just one of many planetary systems. However, these indirect techniques tell us relatively little about the planets themselves, aside from their orbital properties and their masses or radii. To learn more about their nature, we need to observe the planets themselves. Even low-resolution images can reveal important surface features, and spectra can tell us about their compositions and properties of their atmospheres.

Direct images and spectra allow us to learn much more about the nature of extrasolar planets.

The great distances and the glare from stars make direct detection extremely difficult. Nevertheless, direct detection capabilities are rapidly improving, and we already have several images and spectra of extrasolar planets. Figure 6.30 shows a remarkable image of a three-planet system whose orbital plane appears nearly face-on. Astronomers are confident that the dots are planets because they observed them more than once and detected their orbital motion around their star. The planets are so young that they are still glowing from the heat of formation. (Figure 6.16 shows another directly detected jovian planet orbiting the star Beta Pictoris.) Figure 6.31 summarizes the major planet detection techniques.

Other Planet-Hunting Strategies The astonishing success of recent efforts to find extrasolar planets has led astronomers to think of many other possible ways of enhancing the search. For example, several planets have been detected using *gravitational lensing*, an effect predicted by Einstein's general theory of relativity that occurs when one object's gravity bends or brightens the light of a more distant object **[Section 16.2]**. While gravitational lensing is a useful technique, the geometry required for its application never repeats, giving no opportunity for follow-up observations. A different strategy looks for the gravitational effects of unseen planets on the disks of dust that surround many stars, while another method searches for the thermal emission from the impacts of accreting planetesimals. As we learn more about extrasolar planets, new search methods are sure to arise.

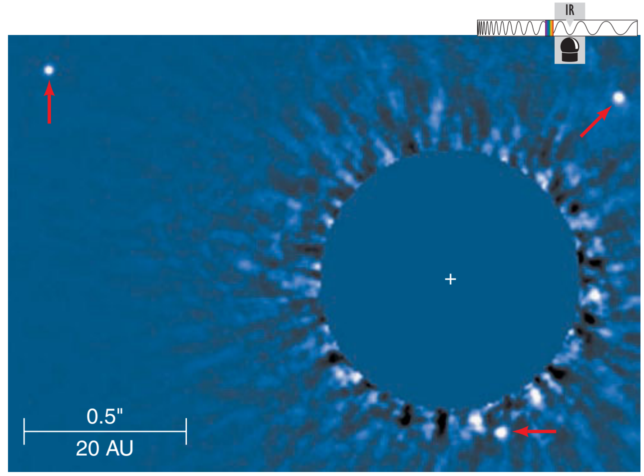


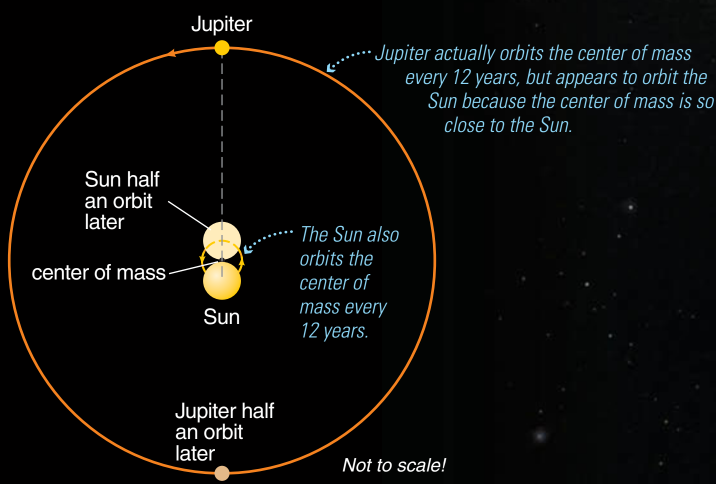
Figure 6.30

This infrared image from the Keck telescope shows three planets (indicated by red arrows) orbiting the star HR 8799. We know they are planets because they have all moved slightly since their discovery. The star itself, located at the + sign, was blocked during the exposure. These planets are much larger and farther from their star than the jovian planets in our solar system.

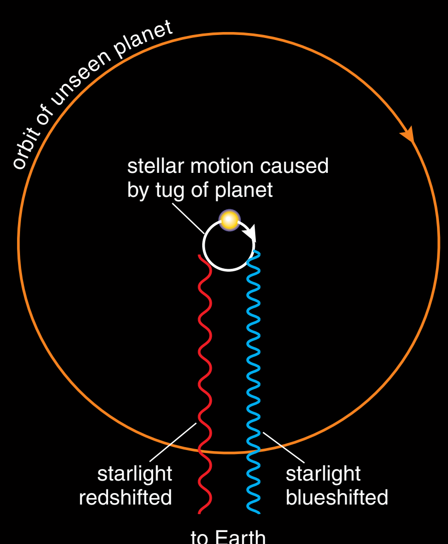
Figure 6.31. Detecting Extrasolar Planets

The search for planets around other stars is one of the fastest growing and most exciting areas of astronomy. This figure summarizes major techniques that astronomers use to search for and study extrasolar planets.

(1) **Gravitational Tugs:** We can detect a planet by observing the small orbital motion of its star as both the star and its planet orbit their mutual center of mass. The star's orbital period is the same as that of its planet, and the star's orbital speed depends on the planet's distance and mass. Any additional planets around the star will produce additional features in the star's orbital motion.

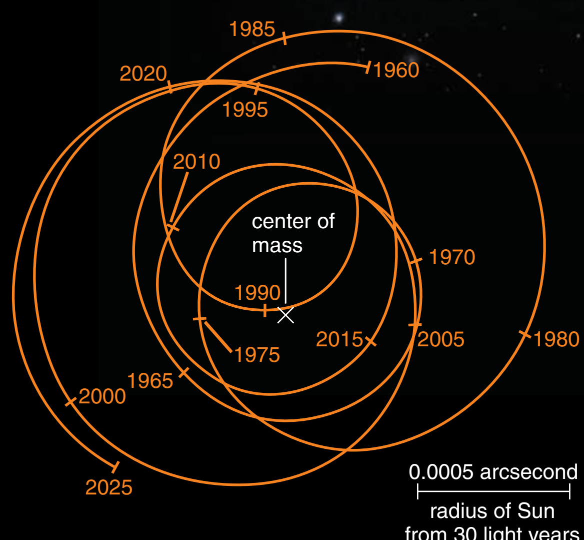


(1a) **The Doppler Technique:** As a star moves alternately toward and away from us around the center of mass, we can detect its motion by observing alternating Doppler shifts in the star's spectrum: a blueshift as the star approaches and a redshift as it recedes. This technique has revealed the vast majority of known extrasolar planets.



Current Doppler-shift measurements can detect an orbital velocity as small as 1 meter per second—walking speed.

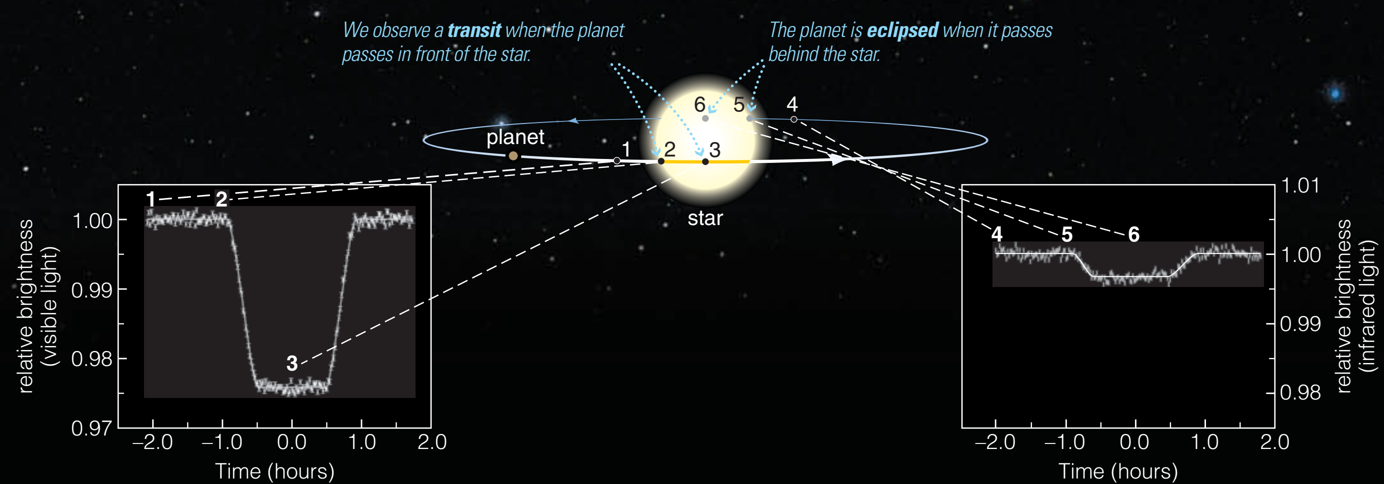
(1b) **The Astrometric Technique:** A star's orbit around the center of mass leads to tiny changes in the star's position in the sky. As we improve our ability to measure these tiny changes, we should discover many more extrasolar planets.



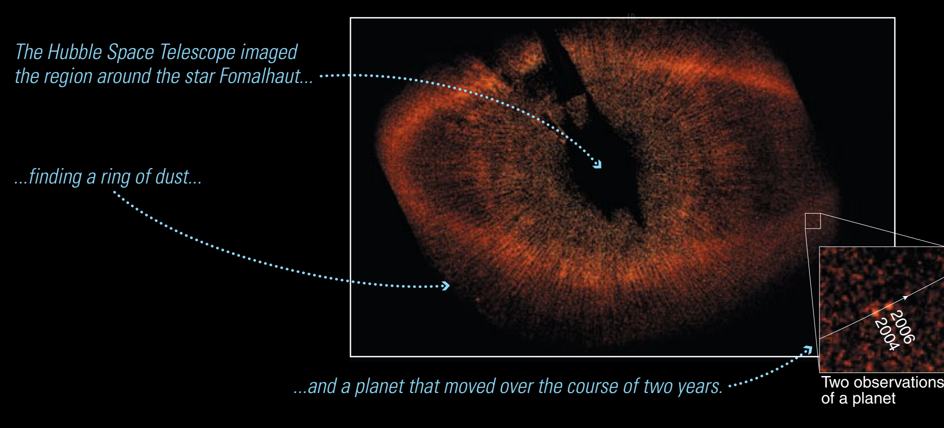
The change in the Sun's apparent position, if seen from a distance of 10 light years, would be similar to the angular width of a human hair at a distance of 5 kilometers.

Artist's conception of another planetary system, viewed near a ringed jovian planet.

2 **Transits and Eclipses:** If a planet's orbital plane happens to lie along our line of sight, the planet will transit in front of its star once each orbit, while being eclipsed behind its star half an orbit later. The amount of starlight blocked by the transiting planet can tell us the planet's size, and changes in the spectrum can tell us about the planet's atmosphere.



3 **Direct Detection:** In principle, the best way to learn about an extrasolar planet is to observe directly either the visible starlight it reflects or the infrared light that it emits. Our technology is only beginning to reach the point where direct detection is possible, but someday we will be able to study both images and spectra of distant planets.



• How do extrasolar planets compare with planets in our solar system?

We have now discovered enough extrasolar planets that we can begin to search for patterns, trends, and groupings that might give us insight into how these planets compare to the planets of our own solar system. The first step in looking for patterns and trends is to organize the existing information. We will therefore begin by summarizing the known properties of extrasolar planets.

Orbits Much as Johannes Kepler first discovered the true layout of our own solar system based on orbital properties **[Section 3.3]**, we are now discovering the layouts of many other solar systems. Figure 6.32 shows the orbital parameters of hundreds of extrasolar planets. At least two important trends should jump out at you. First, notice that only a handful of these planets have orbits beyond about 5 AU, which is Jupiter's distance from our Sun. Most of the planets orbit very close to their host star; many of them orbit closer than Mercury orbits to our Sun. Second, notice that many of the orbits are elliptical instead of nearly circular like the orbits of planets in our own solar system.

Most extrasolar planets discovered to date have different orbital characteristics than planets in our solar system, but this may be a result of the search methods.

These data might seem to suggest that solar systems laid out like our own are quite rare. However, it is also possible that this result is a *selection effect* that occurs because most of these planets have been detected with the Doppler technique. Recall that the Doppler technique is best suited to identifying massive

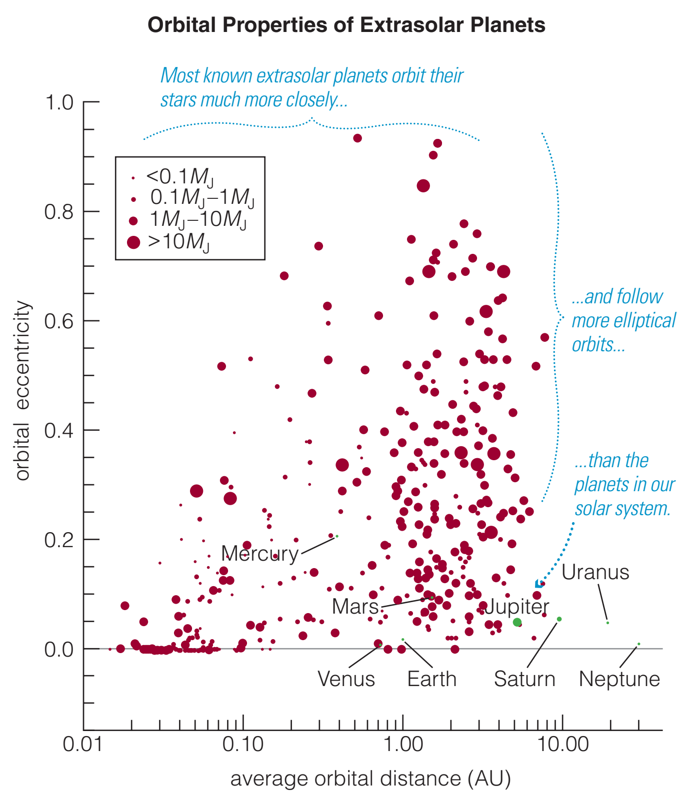


Figure 6.32

These data show orbital characteristics for all extrasolar planets with well-known properties as of 2010. Each dot represents a planet. The farther left a dot is, the closer the planet is to its star; the lower down, the more circular its orbit. Green dots are planets in our solar system.

planets that orbit relatively close to their star. Lower-mass planets are much more difficult to detect with this technique because of their weaker gravitational effects. Massive planets in more distant orbits are also difficult to detect, both because greater orbital distance means a weaker gravitational effect on the star and because long orbital periods can be identified only after many years of observation. We therefore say that the Doppler technique would tend to find, or *select,* massive planets orbiting close to their star, even if such planets are comparatively rare. Until we have more data from other detection techniques, we will not be sure whether orbits like those in our solar system are common or rare.

Another important discovery has come from systems in which we have identified more than one planet. In many of these systems, the planets seem to have orbital resonances with each other **[Section 8.2]**; for example, one planet may have an orbital period that is exactly twice as long as that of another planet. The data suggest that these orbital resonances help shape the overall layout of other planetary systems.

Masses Look again at Figure 6.32. The sizes of the dots indicate the approximate masses of these planets. Masses are even easier to see with a bar chart (Figure 6.33). Notice that most of the known extrasolar planets are more massive than Jupiter, and only a few are less massive than Uranus and Neptune. The smallest detected as of late 2010 is twice as massive as Earth (which has a mass of about 0.003 Jupiter mass). If we go by mass alone, it seems likely that most of the known extrasolar planets are jovian rather than terrestrial in nature. However, this may also be a selection effect that occurs because it is much easier to detect more massive planets.

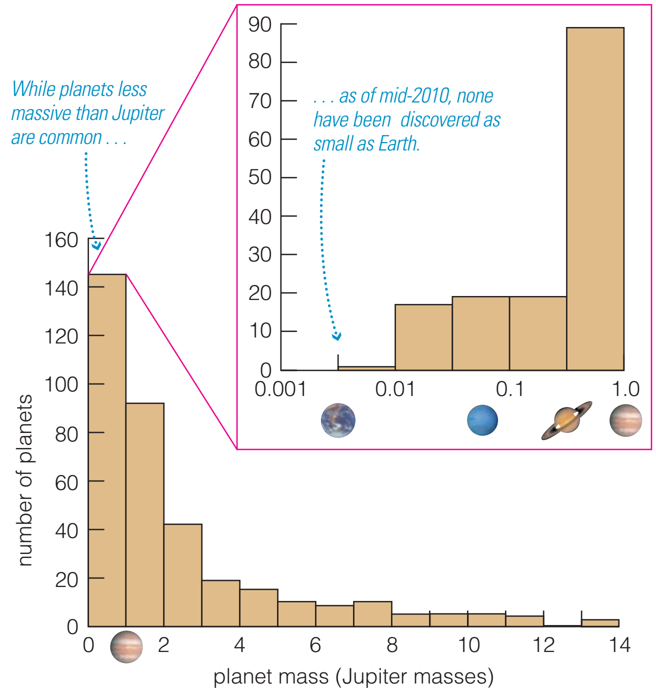


Figure 6.33

This bar chart shows the number of planets in different mass categories for all extrasolar planets with well-known masses as of 2010. Notice that the inset mass axis uses an exponential scale so that the wide range of masses can all fit on the graph.

Compositions We have even less data about the composition of extrasolar planets, because we have been able to obtain crude spectra in only a handful of cases so far. In one case, the spectrum showed evidence of water and methane, consistent with the idea that the planet is a jovian planet.

Sizes and Densities The masses of most known extrasolar planets suggest they are jovian in nature, but mass alone cannot rule out the possibility of "supersize" terrestrial planets—that is, very massive planets made of metal or rock. To distinguish between these possibilities, we also need to know a planet's size, from which we can calculate its density. If the planet is jovian, we expect it to have size and density values consistent with those found for the jovian planets in our solar system.

Unfortunately, we lack size data for the majority of extrasolar planets with measured masses, because they have been detected by the Doppler technique and their orbits are not oriented to produce transits. Nevertheless, we now have dozens of planets for which we know both sizes (from transits) and masses (from the Doppler technique) that can be used to calculate density.

In most of the cases for which we now have density data, planet masses and sizes are generally consistent with what we expect for jovian planets. In some cases, the densities are surprisingly low, but this may be because many of these planets are hot Jupiters. Since they orbit quite close to their stars, their surface temperatures are very

Figure 6.34

A summary of the expected similarities and differences between our solar system's Jupiter and extrasolar hot Jupiters orbiting Sun-like stars.

high, which may puff up their atmospheres and explain their low densities. Models have been used to predict several other interesting features of hot Jupiters, which are contrasted with features of our Jupiter in Figure 6.34.

Most known extrasolar planets are probably jovian, but we've also found "super Earths" likely made of metal and rock.

While most known extrasolar planets appear to be jovian, we have detected at least some "super Earths"—planets with Earth-like densities that are more massive than Earth. The first such discovery came in 2009, when the transiting planet COROT-7b was found to have a density of about 5 g/cm^3, comparable to Earth's. This planet's mass is about 5 Earth masses and its composition must be primarily rock and metal. Because this planet orbits very close to its star, its surface is probably molten. Even more intriguing is the planet GJ 1214b, which is 6.6 times Earth's mass and has a density of less than 2 g/cm^3. Such a low-mass planet cannot be jovian, so its low density must come from a mix of rock and water. It orbits very close to its star, so perhaps this planet is a "steam world," too hot to be habitable.

The Abundance of Planetary Systems Can we yet say anything about how common planetary systems are overall? Among the thousands of Sun-like stars that astronomers have so far examined in search of extrasolar planets, more than 1 in 10 show evidence of planets around them. While this could imply that planetary systems are relatively rare, a more likely hypothesis is that planets are present but more difficult to detect in the other 9 in 10 systems. In essence, we have been hunting for planets with "elephant traps"—and we have been catching elephants. The more common systems with smaller planets may simply be beyond the grasp of our current traps. By some estimates, as many as half of nearby stars possess a Neptune-sized or smaller planet not yet detected. In that case, hot Jupiters might actually be relatively rare, and known in large numbers only because they are easier to detect. Indeed, as technology has improved, we have begun to find systems that more closely resemble our own. The idea that terrestrial planets are common is supported by observations that reveal a correlation between the fraction of elements heavier than helium in a star and the chance that it has planets orbiting it. The more rocks, metals, and hydrogen compounds present in a solar nebula, the more likely the star is to have planets—just as we'd expect from the nebular theory.

see it for yourself It's impossible to see planets orbiting other stars with your naked eye, but you can see some of the stars known to have planets. As of 2010, the brightest star known to have a planet was Pollux, located in the constellation Gemini. Its planet has a mass three times that of Jupiter and orbits Pollux every $1\frac{1}{2}$ years. Use the star charts in Appendix I to find out if, when, and where you can observe Pollux tonight, and look for it if you can. Does knowing that Pollux has its own planetary system alter your perspective when you look at the night sky? Why or why not?

• Do we need to modify our theory of solar system formation?

The discovery of extrasolar planets presents us with an opportunity to test our theory of solar system formation, and it has already presented challenges. For example, the nebular theory clearly predicts that jovian planets should form only in the cold outer regions of star systems and should have nearly circular orbits, so how can our theory account for hot Jupiters or planets with highly elliptical orbits?

One possibility that scientists must always consider is that something is fundamentally wrong with our model of solar system formation, and scientists have considered this possibility. However, more than a decade of re-examination has not turned up any obvious flaws in the basic theory. As a result, scientists now suspect that the hot Jupiters were indeed born with circular orbits far from their stars and that those that now have close-in or highly elliptical orbits underwent some sort of "planetary migration."

Hot Jupiters probably were born in their outer solar systems as the nebular theory predicts, but later migrated inward.

How might planetary migration occur? Our best guess is that it can be caused by waves passing through a gaseous disk (Figure 6.35). A planet's gravity and motion tend to disturb the otherwise evenly distributed disk material, generating waves that travel through the disk. The waves cause material to bunch up as they pass by, and these clumps exert their own gravitational pull on the planet, robbing it of energy and causing it to move inward.

Computer models confirm that waves in the nebula can cause young planets to spiral slowly toward their star. In our own solar system, this migration did not play a major role because the solar wind probably cleared out the gas before it could have much effect. But planets may form earlier in other solar systems, allowing time for jovian planets to migrate substantially inward. In some cases, the planets may form so early that they end up spiraling into their stars.

Another way to account for some of the observed extrasolar planet orbits invokes close encounters between young jovian planets. Such an

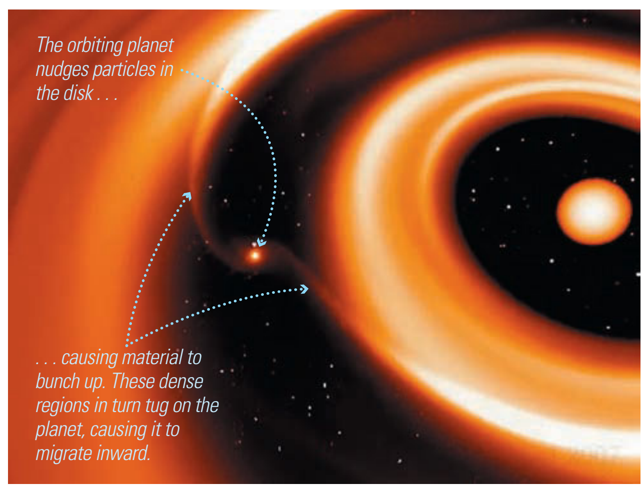


Figure 6.35

This figure shows a simulation of waves created by a planet embedded in a dusty disk of material surrounding its star; these waves may cause the planet to migrate inward.

encounter might send one planet out of the star system entirely while the other is flung inward into a highly elliptical orbit. Alternatively, a jovian planet could migrate inward as a result of multiple close encounters with much smaller planetesimals (as may have happened in our solar system) or jovian planets might periodically line up with one another in a way that would cause their orbits to become more elliptical. Models show that some of these interactions can tilt a planet's orbit sideways or even backwards, and observations have begun to show a few of these unusual planets.

The bottom line is that discoveries of extrasolar planets have shown us that the nebular theory is incomplete. It explains the formation of planets and the simple layout of a solar system such as ours, but it needs new features—such as planetary migration and gravitational encounters—to explain the differing layouts of other solar systems. A much wider range of solar system arrangements now seems possible than we had guessed before the discovery of extrasolar planets.

Planetary scientists are anxious to learn more, and over the past few years NASA and the European Space Agency have developed a series of plans for ambitious missions to try to find many more planets—including Earth-like planets, if they exist—and to study those planets through imaging and spectroscopy. However, budgetary pressures have placed all of those plans on hold for now.

think about it Look back at the discussion of the nature of science in Chapter 3, especially the definition of a scientific theory. Should the nebular theory qualify as a scientific theory even though we know that it needs modification to account for the orbits of planets in other solar systems? Does this mean that the theory was “wrong” as we understood it before? Explain.

the big picture

Putting Chapter 6 into Perspective

In this chapter, we’ve introduced the major features of our solar system and described the current scientific theory of its formation. We’ve seen how this theory explains the major features we observe and how it can be extended to other planetary systems. As you continue your study of the solar system, keep in mind the following “big picture” ideas:

- Our solar system is not a random collection of objects moving in random directions. Rather, it is highly organized, with clear patterns of motion and common traits among families of objects.
- We can explain the major features of our solar system with a theory that holds that the solar system formed from the gravitational collapse of an interstellar gas cloud.
- Most of the general features of the solar system were determined by processes that occurred very early in the solar system’s history, which began some $4\frac{1}{2}$ billion years ago.
- Planet-forming processes are universal. Discoveries of planets around other stars have begun an exciting new era in planetary science.

summary of key concepts

6.1 A Brief Tour of the Solar System

- **What does the solar system look like?**

The planets are tiny compared to the distances between them. Our solar system consists of the Sun, the planets and their moons, and vast numbers of asteroids and comets. Each world has its own unique character, but there are many clear patterns among the worlds.

6.2 Clues to the Formation of Our Solar System

- **What features of our solar system provide clues to how it formed?**

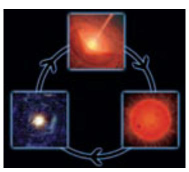
Four major features provide clues: (1) The Sun, planets, and large moons generally rotate and orbit in a very organized way. (2) The planets divide clearly into two groups: **terrestrial** and **jovian**. (3) The solar system contains vast numbers of asteroids and comets, some large enough to qualify as dwarf planets. (4) There are some notable exceptions to these general patterns.

- **What theory best explains the features of our solar system?**

The **nebular theory**, which holds that the solar system formed from the gravitational collapse of a great cloud of gas and dust, successfully explains all the major features of our solar system.

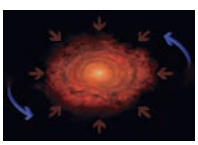
6.3 The Birth of the Solar System

- **Where did the solar system come from?**



The cloud of gas that gave birth to our solar system was the product of recycling of gas through many generations of stars within our galaxy. This gas consisted of 98% hydrogen and helium and 2% all other elements.

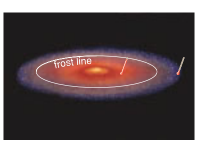
- **What caused the orderly patterns of motion in our solar system?**



A collapsing gas cloud tends to heat up, spin faster, and flatten out as it shrinks in size. Our solar system began as a spinning disk of gas and dust, so the orderly motions we observe today came from the orderly motion of this spinning disk.

6.4 The Formation of Planets

- **Why are there two major types of planets?**

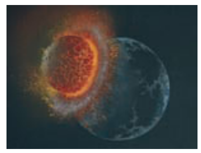


Planets formed around solid "seeds" that condensed from gas and then grew through accretion. In the inner solar system, temperatures were so high that only metal and rock could condense, which explains why terrestrial worlds are made of metal and rock. In the outer solar system, cold temperatures allowed more abundant ices to condense along with metal and rock. Icy planetesimals grew large enough for their gravity to draw in hydrogen and helium gas, forming the massive jovian planets.

- **Where did asteroids and comets come from?**

Asteroids are the rocky leftover planetesimals of the inner solar system, and comets are the icy leftover planetesimals of the outer solar system.

- **How do we explain the existence of our Moon and other exceptions to the rules?**



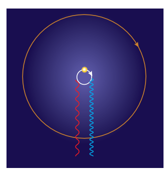
Most of the exceptions probably arose from collisions or close encounters with leftover planetesimals. Our Moon is most likely the result of a **giant impact** between a Mars-size planetesimal and the young Earth.

- **When did the planets form?**

The planets began to accrete in the solar nebula about 4.55 billion years ago, a fact we determine from radiometric dating of the oldest meteorites.

6.5 Other Planetary Systems

- **How do we detect planets around other stars?**



So far, we are best able to detect extrasolar planets indirectly by observing the planet's effects on the star it orbits. Most discoveries to date have been made with the **Doppler technique**, in which Doppler shifts reveal the gravitational tug of a planet (or planets) on a star. We can also search for **transits** and **eclipses** in which a system becomes slightly dimmer as a planet passes in front of or behind its star.

- **How do extrasolar planets compare with planets in our solar system?**

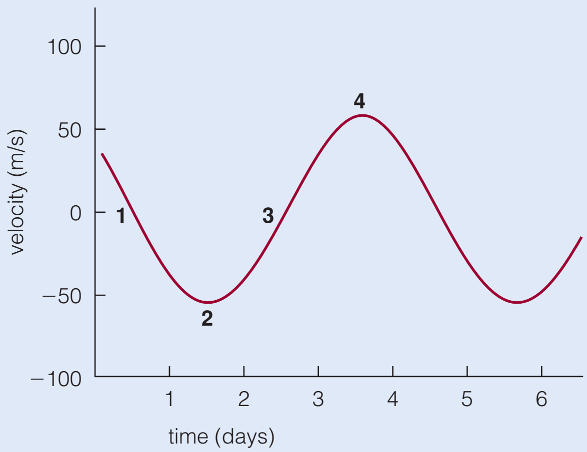
Most known extrasolar planets have masses that suggest they are jovian; limited density and composition data support this idea. Many orbit surprisingly close to their stars, making them **hot Jupiters**, and many have highly elliptical orbits. A few "super Earths"—planets larger than Earth but likely made of metal and rock—have also been discovered.

- **Do we need to modify our theory of solar system formation?**

Our basic theory of solar system formation seems to be sound, but we have had to modify it to allow for planetary migration and gravitational encounters.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 6 Visual Quiz at www.masteringastronomy.com.



This plot, based on Figure 6.28b, shows the periodic variations in the Doppler shift of a star caused by a planet orbiting around it. Positive velocities mean the star is moving away from Earth, and negative velocities mean the star is moving toward Earth. (You can assume that the orbit appears edge-on from Earth.) Answer the following questions based on the information in the graph.

1. How long does it take the star and planet to complete one orbit around their center of mass?
2. What maximum velocity does the star attain?
3. Match the *star's* position at points 1, 2, 3, and 4 in the plot with the descriptions below.
   a. headed straight toward Earth
   b. headed straight away from Earth
   c. closest to Earth
   d. farthest from Earth
4. Match the *planet's* position at points 1, 2, 3, and 4 in the plot with the descriptions in question 3.
5. How would the plot change if the planet were more massive?
   a. It would not change, because it describes the motion of the star, not the planet.
   b. The peaks and valleys would get larger (greater positive and negative velocities) because of larger gravitational tugs.
   c. The peaks and valleys would get closer together (shorter period) because of larger gravitational tugs.

exercises and problems

Mastering ASTRONOMY

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Briefly describe the layout of the solar system as it would appear from beyond the orbit of Neptune.
2. For the Sun and each of the planets in our solar system, describe at least two features that you find interesting.
3. What are the four major features of our solar system that provide clues to how it formed? Describe each one briefly.
4. What are the basic differences between *terrestrial* and *jovian* planets? Which planets in our solar system fall into each group?
5. What is the *nebular theory,* and why is it widely accepted by scientists today?
6. What do we mean by the *solar nebula?* What was it made of, and where did it come from?
7. Describe each of the three key processes that led the solar nebula to take the form of a spinning disk. What observational evidence supports this scenario?
8. List the four categories of materials in the solar nebula by their condensation properties and abundance. Which ingredients are present in terrestrial planets? In jovian planets? Explain why.
9. What was the *frost line* in the solar nebula? Explain how temperature differences led to the formation of two distinct types of planets.
10. Briefly describe the process by which terrestrial planets are thought to have formed. How was the formation of jovian planets similar?

How was it different? Why did the jovian planets end up with so many moons?

11. What are asteroids and comets? How and why are they different?
12. What was the heavy bombardment? When did it occur?
13. How do we think the Moon formed, and what evidence supports this hypothesis?
14. Briefly explain the technique of radiometric dating, and describe how we use it to determine the age of the solar system.
15. Describe three major methods used to detect extrasolar planets indirectly. What does each method tell you about the planet?
16. Why is direct detection of extrasolar planets so difficult? What can we learn from direct detection?
17. Briefly summarize the known characteristics of extrasolar planets.
18. What properties of extrasolar planets and their orbits have forced a re-examination of the nebular theory? How have we modified the theory to explain these properties?

Test Your Understanding

Surprising Discoveries?

Suppose we found a solar system with the property described (these are not real discoveries). Decide whether the discovery should be considered reasonable or surprising. Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

19. A solar system is discovered with four large jovian planets in its inner region and seven small terrestrial planets in its outer reaches.
20. A solar system has ten planets that all orbit the star in approximately the same plane. However, five planets orbit in one direction (e.g., counterclockwise), while the other five orbit in the opposite direction (e.g., clockwise).
21. A solar system has four Earth-size terrestrial planets. Each of the four planets has a single moon that is nearly identical in size to Earth's Moon.
22. A solar system has many rocky asteroids and many icy comets. However, most of the comets orbit in the inner solar system, while the asteroids orbit in far-flung regions much like the Kuiper belt and Oort cloud of our solar system.
23. A solar system has several planets similar in composition to the jovian planets of our solar system but similar in mass to the terrestrial planets of our solar system.
24. Radiometric dating of meteorites from another solar system shows that they are a billion years younger than rocks from the terrestrial planets of the same system.
25. An extrasolar planet is discovered with a year that lasts only 3 days.
26. Within the next few years, astronomers confirm all the planet detections made with the Doppler technique by observing transits of these same planets.
27. It's the year 2025: Astronomers have announced the detection of oxygen in the spectrum of an Earth-size extrasolar planet.
28. It's the year 2040: Scientists announce that our first spacecraft to reach an extrasolar planet is now orbiting a planet around a star near the center of the Milky Way Galaxy.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

29. The largest terrestrial planet and jovian planet are, respectively, (a) Venus and Jupiter. (b) Earth and Jupiter. (c) Earth and Saturn.
30. Which of the following three kinds of objects resides closer to the Sun on average? (a) comets (b) asteroids (c) jovian planets
31. Planetary orbits in our solar system are (a) very eccentric (stretched-out) ellipses and in the same plane. (b) fairly circular and in the same plane. (c) fairly circular but oriented in every direction.
32. The composition of the solar nebula was 98% (a) rock and metal. (b) hydrogen compounds. (c) hydrogen and helium.
33. What's the leading theory for the origin of the Moon? (a) It formed from the solar nebula along with the Earth. (b) It formed from the material ejected in a giant impact. (c) It split out of a rapidly rotating Earth.
34. About how old is the solar system? (a) 4.5 million years (b) 4.5 billion years (c) 4.5 trillion years
35. Most extrasolar planets discovered so far probably resemble (a) terrestrial planets. (b) jovian planets. (c) large icy worlds.
36. What's the best explanation for the location of hot Jupiters? (a) They formed closer to their stars than Jupiter did. (b) They formed farther out like Jupiter but then migrated inward. (c) The strong gravity of their stars pulled them in close.
37. Which technique could detect a planet in an orbit that is face-on to the Earth? (a) Doppler technique (b) transit technique (c) astrometric technique
38. Observations to date suggest that Earth-size planets orbiting Sun-like stars (a) do not exist at all. (b) are extremely rare. (c) may be common, though we cannot yet detect them.

Process of Science

39. *Explaining the Past.* Is it really possible for science to inform us about things that may have happened billions of years ago? To address this question, test the nebular theory against each of the three hallmarks of science discussed in Chapter 3. Be as detailed as possible in explaining whether the theory does or does not satisfy these hallmarks. Use your explanations to decide whether the theory can really tell us about how our solar system formed. Defend your opinion.
40. *Dating the Past.* The method of radiometric dating that tells us the age of our solar system is also used to determine when many other past events occurred. For example, it is used to determine ages of fossils that tell us when humans first evolved and ages of relics that teach us about the rise of civilization. Research one key aspect of human history for which radiometric dating has helped us piece the story together. Write two or three paragraphs explaining how radiometric dating was used in this case (such as what materials were dated and what radioactive elements were used) and what the study or studies concluded. Does your understanding of the method lead you to accept the results? Why or why not?
41. *Confirming Observations.* After the first few discoveries of shifts in stars' spectra using the Doppler technique, some astronomers hypothesized that the stars' companions were brown dwarves in nearly face-on orbits, instead of planets with a random distribution of orbits. How did later observations refute this hypothesis? Discuss both later discoveries with the Doppler technique and observations with other techniques.
42. *Refuting the Theory.* Consider the following three hypothetical observations: (1) the discovery of a lone extrasolar planet that is small and dense like a terrestrial planet but has a Jupiter-like orbit; (2) the discovery of a planetary system in which three terrestrial planets have orbits outside those of two jovian planets;

(3) the discovery that in a majority of planetary systems the jovian planets are nearer to their star than 1 AU and the terrestrial planets are beyond 5 AU. Each of these observations would challenge our current theory of solar system formation, but would any of them shake the very foundations of the theory? Which one(s) would do so, and why? Also explain why the other(s), while posing a challenge, would not necessarily cause major problems.

Group Work Exercise

43. *Refuting the Nebular Theory?* In this exercise, you'll consider the following three hypothetical discoveries concerning systems of planets around other stars:
    a. a system with a lone planet that is small and dense like a terrestrial planet but has a Jupiter-like orbit
    b. a system in which three terrestrial planets orbit their star beyond the orbital distance of two jovian planets
    c. a majority of planetary systems have jovian planets closer than 1 AU to their star and terrestrial planets located beyond 5 AU

    Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Advocate* (argues in favor of the nebular theory), *Skeptic* (points out weaknesses in the nebular theory), and *Moderator* (leads group discussion and makes sure everyone contributes). For each discovery, discuss whether it (1) could be explained with the nebular theory, (2) could be explained with a revision of the nebular theory, or (3) would force us to abandon the nebular theory. After listening to the *Advocate* and *Skeptic* discuss each discovery, the *Scribe* and *Moderator* should choose option (1), (2), or (3) and write down your team's reasoning.

Investigate Further

Short-Answer/Essay Questions

44. *True or False.* Decide whether each statement is true or false, and explain why.
    a. On average, Venus has the hottest surface temperature of any planet in the solar system.
    b. Our Moon is about the same size as moons of the other terrestrial planets.
    c. The weather conditions on Mars today are much different than they were in the distant past.
    d. Moons cannot have atmospheres, active volcanoes, or liquid water.
    e. Saturn is the only planet in the solar system with rings.
    f. Neptune orbits the Sun in the opposite direction of all the other planets.
    g. If Pluto were as large as the planet Mercury, we would classify it as a terrestrial planet.
    h. Asteroids are made of essentially the same materials as the terrestrial planets.
    i. When scientists say that our solar system is about 4 billion years old, they are making a rough estimate based on guesswork about how long it should have taken planets to form.
45. *Planetary Tour.* Based on the brief planetary tour in this chapter, which planet besides Earth do you think is the most interesting, and why? Defend your opinion clearly in two or three paragraphs.
46. *Patterns of Motion.* In one or two paragraphs, summarize the orderly patterns of motion in our solar system and explain why their existence should suggest that the Sun and the planets all formed at one time from one cloud of gas, rather than as individual objects at different times.
47. *Solar System Trends.* Study the planetary data in Table 6.1 to answer each of the following.
    a. Notice the relationship between distance from the Sun and surface temperature. Describe the trend, explain why it exists, and explain any notable exceptions to the trend.
    b. The text says that planets can be classified as either terrestrial or jovian. Describe in general how the columns for density, composition, and distance from the Sun support this classification.
    c. Describe the trend you see in orbital periods and explain the trend in terms of Kepler's third law.
    d. Which column of data would you use to find out which planet has the shortest days? Do you see any notable differences in the length of a day for the different types of planets? Explain.
    e. Which planets would you expect not to have seasons? Why?
48. *Two Kinds of Planets.* The jovian planets differ from the terrestrial planets in a variety of ways. Using phrases or sentences that members of your family would understand, explain why the jovian planets differ from the terrestrial planets in each of the following: composition, size, density, distance from the Sun, and number of satellites.
49. *An Early Solar Wind.* Suppose the solar wind had cleared away the solar nebula before the seeds of the jovian planets could gravitationally draw in hydrogen and helium gas. How would the planets of the outer solar system be different? Would they still have many moons? Explain your answer in a few sentences.
50. *History of the Elements.* Our bodies (and most living things) are made mostly of water (H_2O). Summarize the "history" of a typical hydrogen atom from its creation to Earth's formation. Do the same for a typical oxygen atom. (*Hint:* Which elements were created in the Big Bang, and where were the others created?)
51. *Understanding Radiometric Dating.* Imagine you had the good fortune to find a rocky meteorite in your backyard. Qualitatively, how would you expect its ratio of potassium-40 and argon-40 to be different from other rocks in your yard? Explain why, in a few sentences.
52. *No Hot Jupiters Here.* How do we think hot Jupiters formed? Why didn't one form in our solar system?
53. *Comparing Methods.* What are the advantages and disadvantages of the Doppler and transit techniques? What kinds of planets are easiest to detect with each method? Are there planets that each method cannot detect, even if the planets are very large? Explain. What are the advantages of being able to detect a planet by both methods?
54. *Detect an Extrasolar Planet for Yourself.* Most colleges and many amateur astronomers have the equipment necessary to detect known extrasolar planets using the transit method (Figure 6.29). All that's required is a telescope 10 or more inches in diameter, a CCD camera system, and a computer system for data analysis. The basic method is to take exposures of a few minutes' duration over a period of several hours around the times of predicted transit and to compare the brightness of the star being transited relative to other stars in the same CCD frame. For complete instructions, see www.masteringastronomy.com.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

55. *Dating Lunar Rocks.* You are analyzing Moon rocks that contain small amounts of uranium-238, which decays into lead with a half-life of about 4.5 billion years.
    a. In a rock from the lunar highlands, you determine that 55% of the original uranium-238 remains, while the other 45% has decayed into lead. How old is the rock?
    b. In a rock from the lunar maria, you find that 63% of the original uranium-238 remains, while the other 37% has decayed into lead. Is this rock older or younger than the highlands rock? By how much?
56. *Transit of TrES-1.* The planet orbiting the star TrES-1 has been detected by both the transit and Doppler methods, so we can calculate its density and get an idea of what kind of planet it is.
    a. Using the method described in the text, calculate the radius of the transiting planet. The planetary transits block 2% of the star's light. The star TrES-1 has a radius of about 85% of our Sun's radius.
    b. The mass of the planet is approximately 0.75 times the mass of Jupiter, and Jupiter's mass is about 1.9×10^{27} kilograms. Calculate the average density of the planet. Give your answer in grams per cubic centimeter. Compare this density to the average densities of Saturn (0.7 g/cm^3) and Earth (5.5 g/cm^3). Is the planet terrestrial or jovian in nature? (*Hint:* To find the volume of the planet, use the formula for the volume of a sphere: $V = \left(\frac{4}{3}\right)\pi r^3$. Be careful with unit conversions.)
57. *Planet Around 51 Pegasi.* The star 51 Pegasi has about the same mass as our Sun. A planet discovered orbiting around it has an orbital period of 4.23 days. The mass of the planet is estimated to be 0.6 times the mass of Jupiter. Use Kepler's third law to find the planet's average distance (semimajor axis) from its star. (*Hint:* Because the mass of 51 Pegasi is about the same as the mass of our Sun, you can use Kepler's third law in its original form, $p^2 = a^3$ (Section 3.3). Be sure to convert the period into years before using this equation.)

Discussion Questions

58. *Planetary Priorities.* Suppose you were in charge of developing and prioritizing future planetary missions for NASA. What would you choose as your first priority for a new mission, and why?
59. *Lucky to Be Here?* Considering the overall process of solar system formation, do you think it was likely for a planet like Earth to have formed? Could random events in the early history of the solar system have prevented our being here today? What implications do your answers have for the possibility of Earth-like planets around other stars? Defend your opinions.
60. *So What?* What is the significance of the discovery of extrasolar planets, if any? Justify your answer in the context of this book's discussion of the history of astronomy. Should NASA fund missions to search for more extrasolar planets? Defend your opinion.

Web Projects

61. *Current Planetary Mission.* Find out what missions to the planets of our solar system are currently underway. Visit the Web page for one of these missions. Write a one- to two-page summary of the mission's basic design, goals, and status.
62. *Spitzer Space Telescope.* The Spitzer Space Telescope operates at the infrared wavelengths that are especially useful for studying star and planet formation. Visit the Spitzer Web site to see if recent discoveries are confirming the nebular theory of solar system formation or are requiring us to broaden our understanding of the process. Summarize your findings in a one- to two-page report.
63. *New Planets.* Find the latest information on discoveries of extrasolar planets. Create a personal planet journal, complete with illustrations, with a page for each of at least three recent discoveries of new planets. On each journal page, note the technique that was used to find the planet, give any known information about the nature of the planet, and discuss how the planet does or does not fit in with our current understanding of planetary systems.
64. *The Kepler Mission.* The *Kepler* mission was designed expressly to look for Earth-size planets around other stars. Go to the *Kepler* Web site and learn more about the mission. Write a one- to two-page summary of the mission's goals and its current status.

7

Earth and the Terrestrial Worlds

learning goals

7.1 Earth as a Planet
- Why is Earth geologically active?
- What processes shape Earth's surface?
- How does Earth's atmosphere affect the planet?

7.2 The Moon and Mercury: Geologically Dead
- Was there ever geological activity on the Moon or Mercury?

7.3 Mars: A Victim of Planetary Freeze-Drying
- What geological features tell us that water once flowed on Mars?
- Why did Mars change?

7.4 Venus: A Hothouse World
- Is Venus geologically active?
- Why is Venus so hot?

7.5 Earth as a Living Planet
- What unique features of Earth are important for life?
- How is human activity changing our planet?
- What makes a planet habitable?

It's easy to take for granted the qualities that make Earth so suitable for human life: a temperature neither boiling nor freezing, abundant water, a protective atmosphere, and a relatively stable environment. But we need look only as far as our neighboring terrestrial worlds to see how fortunate we are. The Moon is airless and barren, and Mercury is much the same. Venus is a searing hothouse, while Mars has an atmosphere so thin and cold that liquid water cannot last on its surface today.

How did the terrestrial worlds come to be so different, when all were made from metal and rock that had condensed in the solar nebula? Why did Earth alone develop conditions that permit abundant life? We'll begin to answer these questions by exploring key processes that have shaped Earth and the other terrestrial worlds over time, and then we'll consider the history of each world individually. We will see that the histories of the worlds are not random accidents, but consequences of properties endowed at their births. Once we understand what has happened on other worlds, we'll be ready to return to Earth at the end of the chapter, seeing it in an entirely different way than we could have before the era of planetary exploration.

essential preparation

1. How do light and matter interact? [Section 5.1]
2. What does the solar system look like? [Section 6.1]
3. Why are there two major types of planets? [Section 6.4]
4. Where did asteroids and comets come from? [Section 6.4]

MA Formation of the Solar System Tutorial, Lesson 1

7.1 Earth as a Planet

Earth's surface seems solid and steady, but every so often it offers us a reminder that nothing about it is permanent. If you live in Alaska or California, you've probably felt the ground shift beneath you in an earthquake. In Washington State, you may have witnessed the rumblings of Mount St. Helens. In Hawaii, a visit to the active Kilauea volcano will remind you that you are standing on mountains of volcanic rock protruding from the ocean floor.

Volcanoes and earthquakes are not the only processes acting to reshape Earth's surface. They are not even the most dramatic: Far greater change can occur on the rare occasions when an asteroid or a comet slams into Earth. More gradual processes can also have spectacular effects. The Colorado River causes only small changes in the landscape from year to year, but its unrelenting flow over the past few million years carved the Grand Canyon. The Rocky Mountains were once twice as tall as they are today; they have been cut down in size through tens of millions of years of erosion by wind, rain, and ice. Entire continents move slowly about, completely rearranging the map of Earth every few hundred million years.

Earth is not alone in having undergone tremendous change since its birth. The surfaces of all five terrestrial worlds—Mercury, Venus, Earth, the Moon, and Mars—must have looked quite similar when they were young. All five were made of rocky material that condensed in the solar nebula, and all five were subjected early on to the impacts of the heavy bombardment [Section 6.4]. The great differences in their present-day appearance must therefore be the result of changes that have occurred through time. Ultimately, these changes can be traced to fundamental properties of the planets.

Figure 7.1 shows global views of the terrestrial worlds to scale, along with sample surface views from orbit. Profound differences between these worlds are immediately obvious. Mercury and the Moon show the scars of their battering during the heavy bombardment: They are densely covered by craters except in areas that appear to be volcanic plains. Venus is covered by a thick atmosphere with clouds that hide its surface from view, but radar mapping reveals a surface dotted with volcanoes and other features indicating active geology. Mars, despite its middling size, has the solar system's largest volcanoes and a huge canyon cutting across its surface, along with many features that appear to have been shaped by running water. Earth has surface features similar to all those on the other terrestrial worlds, and more—including a unique layer of living organisms that covers almost the entire surface of the planet.

Our primary goal in this chapter is to gain a deeper understanding of our own planet Earth by investigating how the terrestrial worlds came to be so different. We'll begin by examining the basic nature of our planet.

• Why is Earth geologically active?

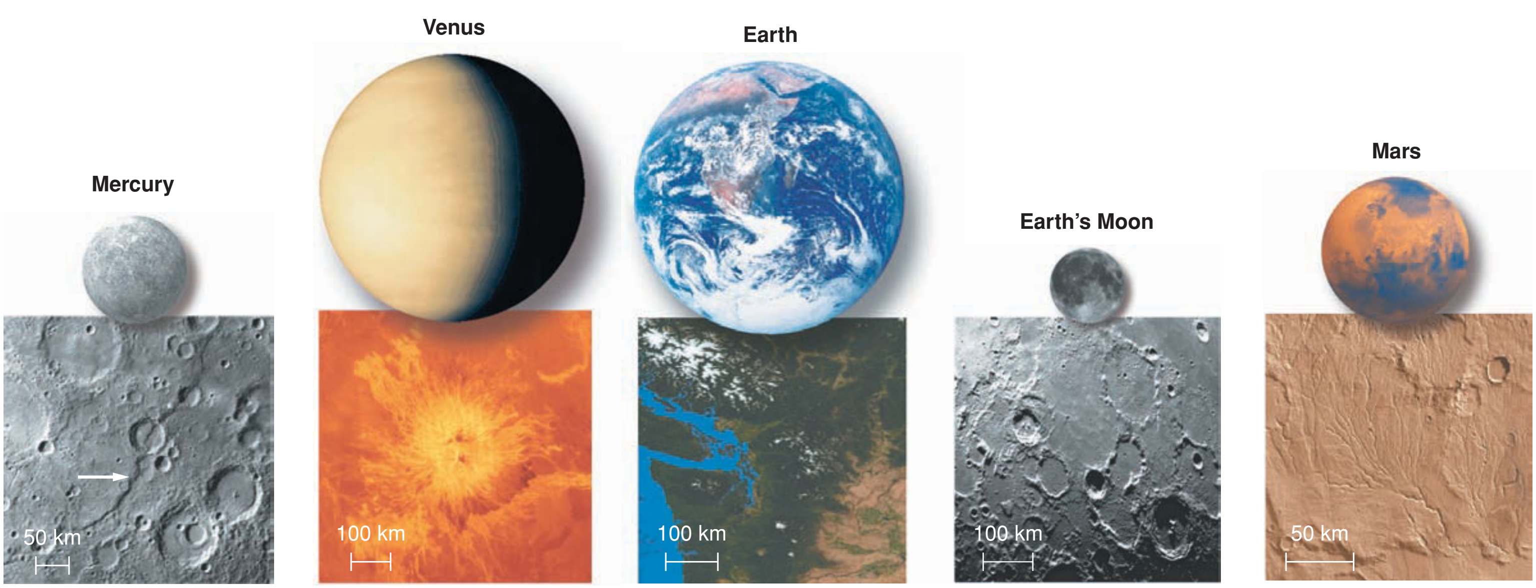
All the terrestrial worlds have changed since their birth, but Earth is unique in the degree to which it continues to change today. We say that Earth is *geologically active,* meaning that its surface is continually being reshaped by volcanic eruptions, earthquakes, erosion, and other geological processes. Most of this geological activity is the result of what goes on deep inside our planet. Consequently, to understand why Earth is so much more geologically active than other worlds, we must examine what the terrestrial worlds are like inside.

Interior Structure Studies of internal structure (see Special Topic, page 195) show that all the terrestrial worlds have layered interiors. We often divide these layers by density into three major categories:

- **Core:** The highest-density material, consisting primarily of metals such as nickel and iron, resides in the central core.

Figure 7.1 VIS

The terrestrial worlds, shown to scale, along with sample surface close-ups from orbiting spacecraft. All the photos were taken with visible light except the Venus close-up.



Heavily cratered Mercury has long steep cliffs (arrow).

Cloud-penetrating radar revealed this twin- peaked volcano on Venus.

A portion of Earth's surface as it appears without clouds.

The Moon's surface is heavily cratered in most places.

Mars has features that look like dry riverbeds; note the impact craters.

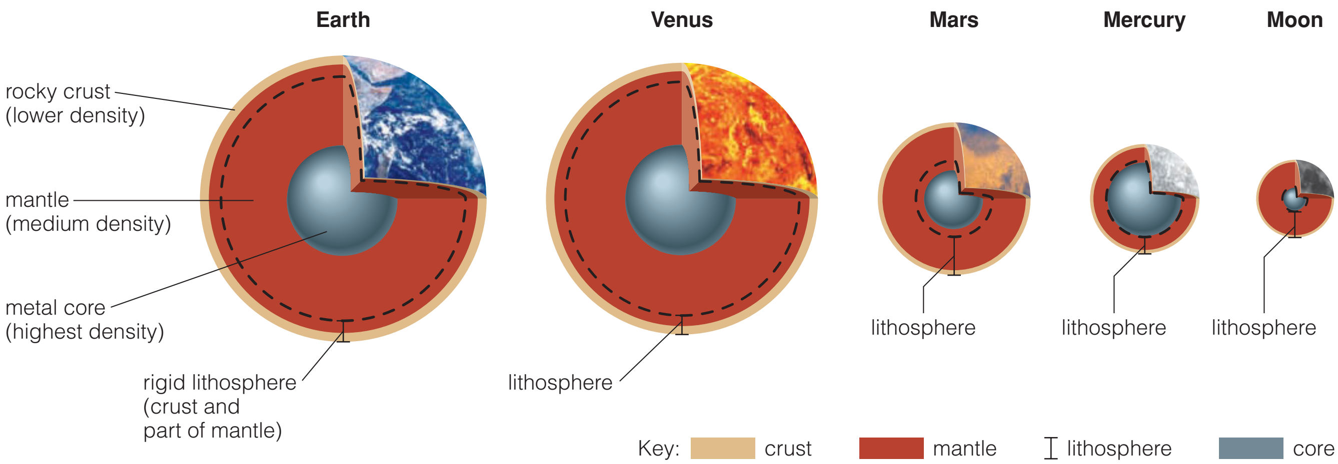


Figure 7.2

Interior structures of the terrestrial worlds, shown to scale and in order of decreasing size. Color coding shows the core-mantle-crust layering by density; a dashed circle represents the inner boundary of the lithosphere, defined by strength of rock rather than by density. The thicknesses of the crust and the lithosphere of Venus and Earth are exaggerated to make them visible in this figure.

- **Mantle:** Rocky material of moderate density—mostly minerals that contain silicon, oxygen, and other elements—forms the thick mantle that surrounds the core.
- **Crust:** The lowest-density rock, such as granite and basalt (a common form of volcanic rock) forms the thin crust, essentially representing the world's outer skin.

Figure 7.2 shows these layers for the five terrestrial worlds. Although not shown in the figure, Earth's metallic core actually consists of two distinct regions: a solid *inner core* and a molten (liquid) *outer core.*

In geology, it's often more useful to categorize interior layers by rock strength instead of density. The idea that rock can vary in strength may seem surprising, but like all matter built of atoms, rock is mostly empty space **[Section 5.1]**. The solidity of rock comes from electrical bonds between its atoms and molecules, and while these bonds are strong, they can still break and re-form when subjected to heat or sustained stress. Over millions and billions of years, even "solid" rock can slowly deform and flow. The long-term behavior of rock is much like that of the popular toy Silly Putty, which breaks like a brittle solid when you pull it sharply but deforms and stretches when you pull it slowly (Figure 7.3). Also like Silly Putty, rock becomes softer and easier to deform when it is warmer.

see it for yourself Roll some room-temperature Silly Putty into a ball and measure its diameter. Put the ball on a table and gently place a heavy book on top. After 5 seconds, measure the height of the squashed ball. Repeat the experiment, but warm the Silly Putty in hot water before you start; repeat again, but cool the Silly Putty in ice water before you start. How does temperature affect the rate of "squashing"? How does the experiment relate to planetary geology?

A planet's *lithosphere* is its outer layer of cool, rigid rock.

In terms of rock strength, Earth's outer layer consists of relatively cool and rigid rock, called the **lithosphere** (*lithos* is Greek for "stone"), that "floats" on warmer, softer rock beneath. The lithosphere encompasses the crust and part of the upper mantle on Earth and extends deeper into the mantle on smaller worlds.

Differentiation and Internal Heat We can understand *why* the interiors are layered by thinking about what happens in a mixture of oil and water: Gravity pulls the denser water to the bottom, driving the less dense oil to the top. This process is called **differentiation**, because it results in

Figure 7.3

Silly Putty stretches when pulled slowly but breaks cleanly when pulled rapidly. Rock behaves just the same, but on a longer time scale.

cosmic Calculations 7.1

The Surface Area–to–Volume Ratio

The total amount of heat contained in a planet depends on its volume, but this heat can escape into space only from its *surface*. As heat escapes, more heat flows upward from the interior to replace it until the interior is no hotter than the surface. The time it takes a planet to lose its internal heat is related to the ratio of the *surface area* through which it loses heat to the *volume* that contains heat:

$$\text{surface area–to–volume ratio} = \frac{\text{surface area}}{\text{volume}}$$

A spherical planet (radius r) has surface area $4\pi r^2$ and volume $\frac{4}{3}\pi r^3$, so the ratio becomes

$$\underset{\text{(for a sphere)}}{\text{surface area–to–volume ratio}} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

Because r appears in the denominator, we conclude that *larger objects have smaller surface area–to–volume ratios.*

Example: Compare the surface area–to–volume ratios of the Moon and Earth. Data:

$$r_{\text{Moon}} = 1738\text{ km};\ r_{\text{Earth}} = 6378\text{ km}.$$

Solution: Dividing the surface area–to–volume ratios for the Moon and Earth, we find

$$\frac{\text{surface area–to–volume ratio (Moon)}}{\text{surface area–to–volume ratio (Earth)}} = \frac{3/r_{\text{Moon}}}{3/r_{\text{Earth}}} = \frac{r_{\text{Earth}}}{r_{\text{Moon}}} = \frac{6378\text{ km}}{1738\text{ km}} = 3.7$$

The Moon's surface area–to–volume ratio is about four times that of Earth, which means the Moon would cool four times as fast if both worlds started with the same temperature and gained no additional heat.

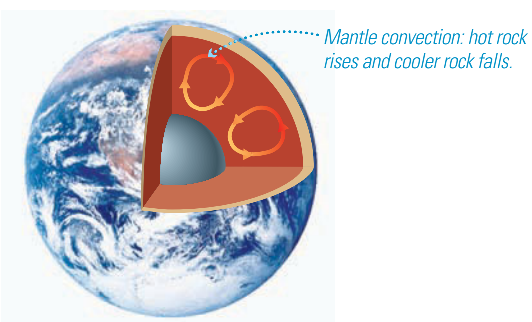


Figure 7.4

Earth's hot interior allows the mantle to undergo convection, in which hot rock gradually rises upward while cool rock gradually falls. Arrows indicate the direction of flow in a portion of the mantle.

layers made of *different* materials. The layered interiors of the terrestrial worlds tell us that they underwent differentiation, which means all these worlds must have been hot enough inside for their interior rock and metal to melt at some time in the past. Dense metals like iron sank toward the center, driving less dense rocky material toward the surface.

Earth and the other terrestrial worlds were once hot enough inside for their interiors to melt, allowing material to settle into layers of differing density.

When they were young, Earth and the other terrestrial worlds were hot inside for two major reasons. First, the planets gained heat from the process of formation itself. During the later stages of accretion, incoming planetesimals collided at high speed with the forming planets, depositing large amounts of energy that turned into heat. The process of differentiation released additional heat as dense materials sank to the core. Second, the metal and rock that make up the terrestrial planets include small but important amounts of radioactive elements. As these radioactive materials decay, they release heat directly into the planetary interiors. Radioactive decay still supplies heat to the terrestrial interiors, though at a lower level than it did when the planets were young (because some of the radioactive material has already decayed).

None of the terrestrial worlds are still hot enough to remain liquid throughout their interiors. However, they differ considerably in the amount of heat they have retained. Size is the most important factor in planetary cooling (Cosmic Calculations 7.1): Just as a hot potato remains hot inside much longer than a hot pea, a large planet stays hot inside much longer than a small one. You can see why size is the critical factor by picturing a large planet as a smaller planet wrapped in extra layers of rock. The extra rock acts as insulation, so it takes much longer for interior heat to reach the surface and escape.

see it for yourself The fact that large objects stay warmer longer than small objects is easy to observe with food and drink. The next time you eat something large and hot, cut off a small piece; notice how much more quickly the small piece cools compared to the rest of it. A similar experiment demonstrates the time it takes a cold object to warm up: Find two ice cubes of the same size; crack one into small pieces with a spoon, and then compare how fast each melts. Explain your observations in terms that your friends would understand.

Internal Heat and Geological Activity Interior heat is the primary driver of geological activity, because this heat supplies the energy needed to move rock and reshape the surface. Inside a planet, temperature increases with depth. If the interior is hot enough, hot rock can gradually rise within the mantle, slowly cooling as it rises. Cooler rock at the top of the mantle gradually falls (Figure 7.4). The process by which hot material expands and rises while cooler material contracts and falls is called **convection**. Keep in mind that mantle convection primarily involves solid rock, not molten rock. Because solid rock flows quite slowly, mantle convection is a very slow process. At the typical rate of mantle convection on Earth—a few centimeters per year—it would take 100 million years for a piece of rock to be carried from the base of the mantle to the top.

Larger planets retain internal heat much longer than smaller ones, and this heat drives geological activity.

Just as planetary size determines how long a planet stays hot, it is also the primary factor in the strength of mantle convection and lithospheric thickness. As a planet's interior cools, the rigid lithosphere grows thicker and convection occurs only deeper inside the planet. A thick lithosphere inhibits volcanic and tectonic activity, because any molten rock is too deeply buried to erupt to the surface and the strong lithosphere resists distortion by tectonic stresses. If the interior cools enough, convection may stop entirely, leaving the planet geologically dead, with no eruptions or crustal movement.

We can now understand the differences in lithospheric thickness shown in Figure 7.2, which go along with differences in geological activity. Earth, the largest of the terrestrial planets, remains quite hot inside and therefore has a thin lithosphere. Venus is probably similar to Earth in its internal heat, though it may have a thicker lithosphere (for reasons we will discuss later). With their small sizes, Mercury and the Moon have very thick lithospheres and no geological activity. Mars, intermediate in size, has cooled significantly but probably retains some internal heat.

common**Misconceptions**

Earth Is Not Full of Molten Lava

Many people guess that Earth is full of molten lava (more technically known as *magma*). This misconception may arise partially because we see molten lava emerging from inside Earth when a volcano erupts. However, Earth's mantle and crust are almost entirely solid. The lava that erupts from volcanoes comes only from a narrow region of partially molten material beneath the lithosphere. The only part of Earth's interior that is fully molten is the outer core, which is so deep within the planet that core material never erupts directly to the surface.

special**Topic** | How Do We Know What's Inside Earth?

Our deepest drills have barely pricked Earth's surface, penetrating less than 1% of the way into the interior. How, then, can we claim to know what our planet is like on the inside?

For Earth, much of our information about the interior comes from *seismic waves*, vibrations created by earthquakes. Seismic waves come in two basic types that are analogous to the two ways that you can generate waves in a Slinky (Figure 1). Pushing and pulling on one end of a Slinky (while someone holds the other end still) generates a wave in which the Slinky is bunched up in some places and stretched out in others. Waves like this in rock are called *P waves*. The P stands for *primary*, because these waves travel fastest and are the first to arrive after an earthquake, but it is easier to think of P for *pressure* or *pushing*. P waves can travel through almost any material—whether solid, liquid, or gas—because molecules can always push on their neighbors no matter how weakly they are bound together. (Sound also travels as a pressure wave quite similar to P waves.)

Shaking a Slinky slightly up and down generates an up-and-down motion all along its length. Such up-and-down (or side-to-side) waves in rock are called *S waves*. The S stands for *secondary* but is easier to remember as meaning *shear* or *side-to-side*. S waves travel only through solids, because the bonds between neighboring molecules in a liquid or gas are too weak to transmit up-and-down or sideways forces.

The speeds and directions of seismic waves traveling through Earth depend on the composition, density, pressure, temperature, and phase (solid or liquid) of the material they pass through. For example, P waves reach the side of the world opposite an earthquake, but S waves do not. This tells us that a liquid layer has stopped the S waves, which is how we know that Earth has a liquid outer core (Figure 2). More careful analysis of seismic waves has allowed geologists to develop a detailed picture of Earth's interior structure.

We have also used seismic waves to study the Moon's interior, thanks to monitoring stations left behind by the *Apollo* astronauts. We use less direct clues to learn about the interiors of other worlds. For example, knowing that the density of surface rock is much less than a planet's overall average density tells us that the planet must contain denser rock or metal inside. We can also learn about a planet's interior from precise measurements of its gravity, which tell us how mass is distributed within the planet; from studies of its magnetic field, which is generated deep inside the planet; and from observations of surface rocks that appear to have emerged from deep within the interior.

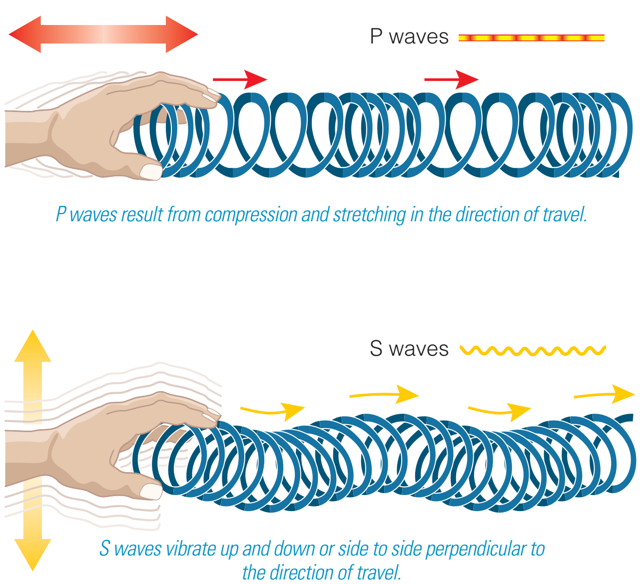


Figure 1

Slinky examples demonstrating P and S waves.

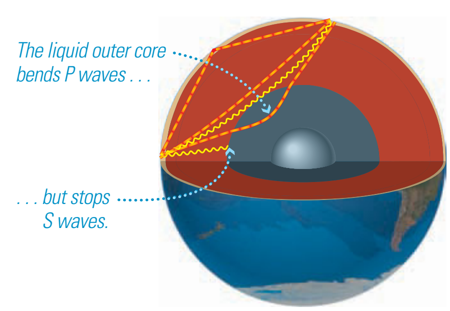
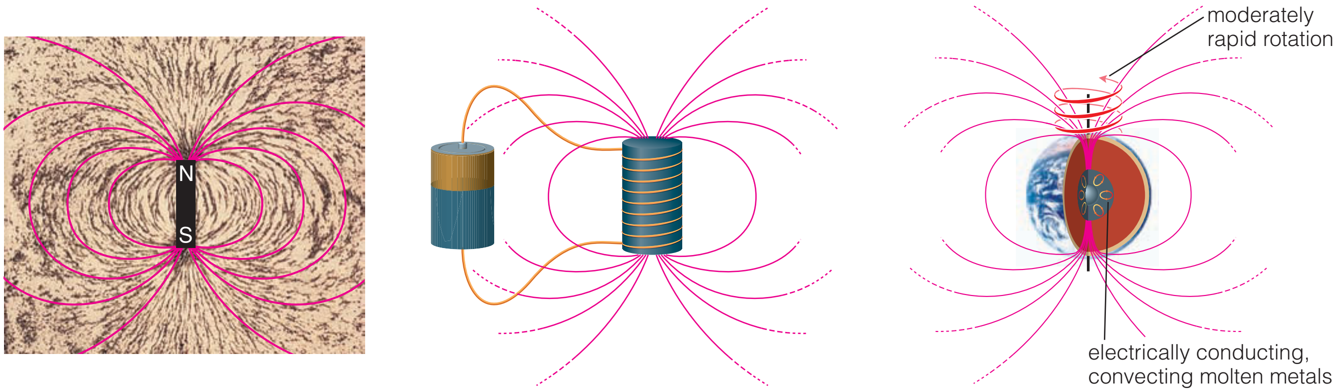


Figure 2

Because S waves do not reach the side of Earth opposite an earthquake, we infer that part of Earth's core is liquid.



a This photo shows how a bar magnet influences iron filings (small black specks) around it. The *magnetic field lines* (red) represent this influence graphically.

b A similar magnetic field is created by an electromagnet, which is essentially a wire wrapped around a metal bar and attached to a battery. The field is created by the battery-forced motion of charged particles (electrons) along the wire.

c Earth's magnetic field also arises from the motion of charged particles. The charged particles move within Earth's liquid outer core, which is made of electrically conducting, convecting molten metals.

Figure 7.5

Sources of magnetic fields.

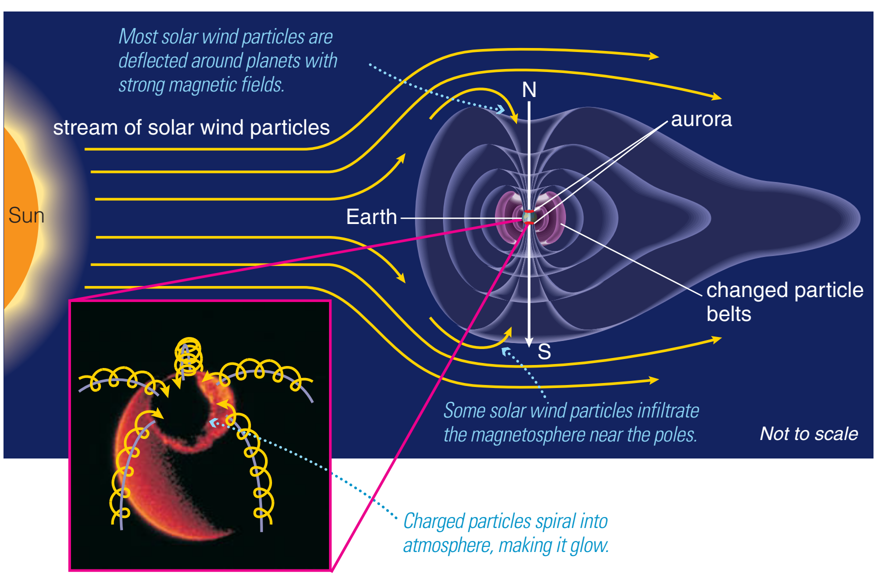
The Magnetic Field Interior heat is also responsible for Earth's global **magnetic field**. You are probably familiar with the general pattern of the magnetic field created by an iron bar (Figure 7.5a). Earth's magnetic field is generated by a process more similar to that of an *electromagnet,* in which the magnetic field arises as a battery forces charged particles to move along a coiled wire (Figure 7.5b).

Earth's magnetic field is generated by the motions of molten metal in its liquid outer core.

Earth does not contain a battery, but charged particles move with the molten metal in its liquid outer core (Figure 7.5c). Internal heat causes the liquid metal to rise and fall (convection), while Earth's rotation twists and distorts the convection pattern. The result is that electrons in the molten metal move within the outer core in much the same way they move in an electromagnet, generating Earth's magnetic field.

Figure 7.6

Earth's magnetosphere acts like a protective bubble, shielding our planet from charged particles coming from the solar wind.



a This diagram shows how Earth's magnetosphere deflects solar wind particles. Some particles accumulate in *charged particle belts* encircling our planet. The inset shows a photo of ring auroras (the crater-like ridge) around the North Pole; the bright and dark regions below the ring are day and night regions of the Earth.

b This photograph shows the aurora near Yellowknife, Northwest Territories, Canada. In a video, you would see these lights dancing about in the sky.

Earth's magnetic field helps protect the surface from energetic particles that continually flow outward from the Sun with the *solar wind* [Section 6.4]. These particles could strip away atmospheric gas and cause genetic damage to living organisms. The magnetic field shields us by creating a **magnetosphere**—a kind of protective bubble that surrounds our planet (Figure 7.6a). The magnetosphere deflects most of the charged particles from the Sun around our planet. The relatively few particles that make it through the magnetosphere tend to be channeled toward the poles, where they collide with atoms and molecules in our atmosphere and produce the beautiful lights of the **aurora** (Figure 7.6b). The aurora is strongest when solar winds buffet the magnetosphere, energizing the charged particles trapped within it.

None of the other terrestrial worlds have magnetic fields as strong as Earth's. As a result, they lack protective magnetospheres—a fact that, as we'll discuss later, has had a profound effect on the planetary histories of Venus and Mars.

MA Shaping Planetary Surfaces Tutorial, Lessons 1–3

• What processes shape Earth's surface?

We are now ready to turn to planetary surfaces. Earth offers a huge variety of geological surface features, and the variety only increases when we survey other worlds. Nevertheless, almost all surface features can be explained by just four major geological processes:

- **Impact cratering:** the excavation of bowl-shaped *impact craters* by asteroids or comets crashing into a planet's surface.
- **Volcanism:** the eruption of molten rock, or *lava,* from a planet's interior onto its surface.
- **Tectonics:** the disruption of a planet's surface by internal stresses.
- **Erosion:** the wearing down or building up of geological features by wind, water, ice, and other phenomena of planetary weather.

Virtually all geological features originate from impact cratering, volcanism, tectonics, and/or erosion.

Before we examine these processes in greater detail, notice that impact cratering is the only one of the four processes with an external cause—impacts of objects from space. The other three processes are attributable to the planet itself and represent what we usually define as *geological activity.*

Impact Cratering An impact crater forms when an asteroid or comet slams into a solid surface (Figure 7.7). Impacting objects typically hit the surface at a speed between about 40,000 and 250,000 kilometers per hour. At such a tremendous speed, the impact releases enough energy to vaporize solid rock and blast out a crater (the Greek word for "cup"). Craters are usually circular because an impact blasts out material in all directions, regardless of the incoming object's direction. Laboratory experiments show that craters are typically about 10 times as wide as the objects that create them and about 10–20% as deep as they are wide. For example, an asteroid 1 kilometer in diameter will blast out a crater about 10 kilometers wide and 1–2 kilometers deep.

We have never witnessed a major impact on Earth (though we have witnessed one, and the aftermath of another, on Jupiter [Section 9.4]), but we have studied the results of past impacts (Figure 7.8). We also see numerous impact craters on other worlds (see Figure 7.1).

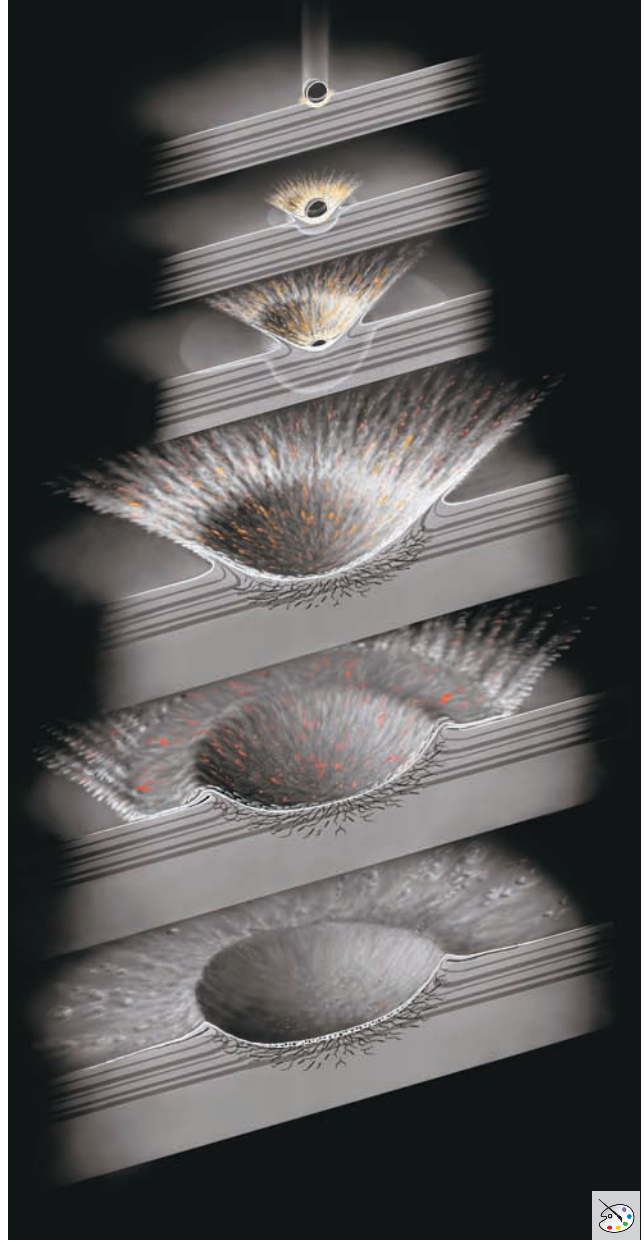


Figure 7.7 MA interactive figure

Artist's conception of the impact process.

Figure 7.8

Meteor Crater in Arizona is more than a kilometer across and nearly 200 meters deep. It was created around 50,000 years ago by the impact of a metallic asteroid about 50 meters across.

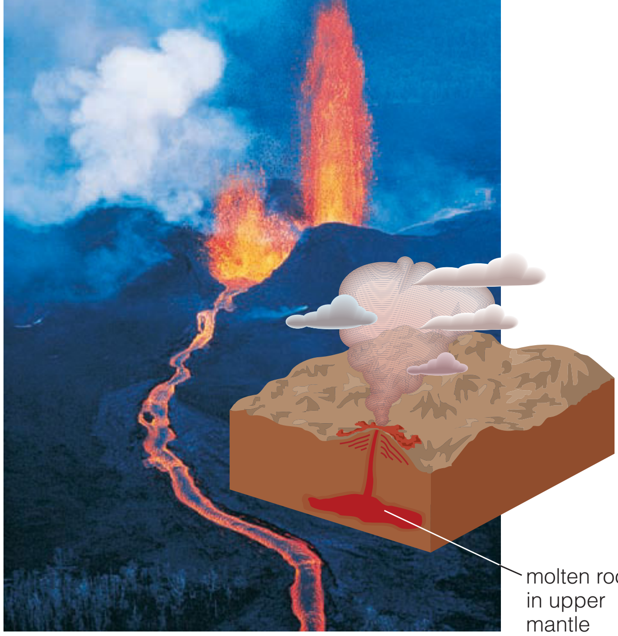


Figure 7.9

Volcanism. The photo shows the eruption of an active volcano on the flanks of Kilauea on the Big Island of Hawaii. The inset shows the underlying process: Molten rock collects in a "magma chamber" and can erupt upward.

Figure 7.10

This photo shows the eruption of Mount St. Helens (Washington State) on May 18, 1980. Note the tremendous outgassing that accompanied the eruption.

Comparing the number of impact craters on the Moon and Earth leads us to an important insight. Throughout its history, Earth must have had at least as many impacts as the Moon, since we occupy the same region of the solar system. Why, then, are there so many more impact craters on the Moon? The answer is that most of Earth's impact craters have been erased with time by geological activity such as volcanic eruptions and erosion.

Like all terrestrial worlds, Earth was bombarded by impacts when it was young, but most ancient craters have been erased by other geological processes.

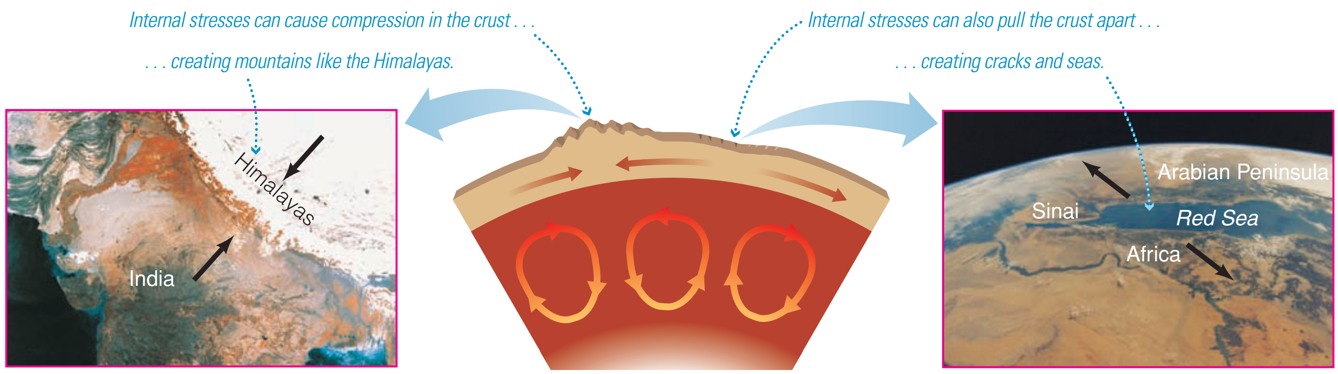
The idea that craters can be erased with time offers us a way to estimate the age of a world's surface—that is, how long it has been since craters were last erased on the surface. Remember that all the planets were battered by impacts during the heavy bombardment that occurred early in our solar system's history **[Section 6.4]**. Most impact craters were made during that time, and relatively few impacts have occurred since. In places where we see numerous craters, such as on much of the Moon's surface, we must be looking at a surface that has stayed virtually unchanged for billions of years. In contrast, when we see very few craters, as we do on Earth, we must be looking at a surface that has undergone recent change. Careful studies of the Moon, where different surface regions have both different numbers of craters and different ages (determined by radiometric dating of Moon rocks), have allowed planetary scientists to determine the rate at which craters were made during much of the solar system's history. Knowing this rate allows scientists to estimate the age of a planetary surface just by photographing it from orbit and counting its craters.

Volcanism Volcanism occurs when underground molten rock finds a path through the lithosphere to the surface (Figure 7.9). Molten rock tends to rise for three main reasons. First, molten rock is generally less dense than solid rock, and lower-density materials tend to rise when surrounded by higher-density materials. Second, because most of Earth's interior is not molten, the solid rock surrounding a chamber of molten rock can squeeze the molten rock, driving it upward under pressure. Third, molten rock often contains trapped gases that expand as it rises, which can make it rise much faster and lead to dramatic eruptions. Erupting lava can make tall, steep volcanoes if the lava is very thick, or vast, flat lava plains if the lava is very runny.

Earth's atmosphere and oceans were made from gases released from the interior by volcanic outgassing.

Volcanic mountains are the most obvious result of volcanism, but volcanism has had a much more profound effect on our planet: It explains the existence of our atmosphere and oceans. Recall that Earth accreted from rocky and metallic planetesimals, while water and other ices were brought in by planetesimals from more distant reaches of the solar system **[Section 6.4]**. Water and gases became trapped beneath the surface in much the same way the gas in a carbonated beverage is trapped in a pressurized bottle. Volcanic eruptions later released some of this gas into the atmosphere in a process known as **outgassing** (Figure 7.10).

Measurements show that the most common gases released by outgassing are water vapor (H_2O), carbon dioxide (CO_2), nitrogen (N_2), and sulfur-bearing gases (H_2S or SO_2). The outgassed water vapor rained down to form our oceans, while the other gases helped make our atmosphere. Much of the nitrogen remains in Earth's atmosphere to this day, where it is now the dominant ingredient (77%). We'll discuss how oxygen came to make up most of the rest of our atmosphere in Section 7.5.



Earth's tallest mountain range, the Himalayas, created as India pushes into the rest of Asia.

The Red Sea, created as the Arabian Peninsula was torn away from Africa.

Figure 7.11 MA interactive figure

Tectonic forces can produce a wide variety of features. Mountains created by tectonic compression and valleys or seas created by tectonic stretching are among the most common. Both images are satellite photos.

Earth's ongoing volcanic activity can be traced to a single property of our planet: its relatively large size, which allows it to retain a lot of internal heat. If Earth had been born much smaller, its interior would have cooled off long ago and it would not have active volcanoes today.

Tectonics The third major geological process, tectonics, refers to any surface reshaping that results from stretching, compression, or other forces acting on the lithosphere. Figure 7.11 shows two examples of tectonic features on Earth, one created by surface compression (the Himalayas) and one created by surface stretching (the Red Sea).

Much of the tectonic activity on any planet is a direct or indirect result of mantle convection. Tectonics is particularly important on Earth, because the underlying mantle convection fractured Earth's lithosphere into more than a dozen pieces, or *plates*. These plates move over, under, and around each other, leading to a special type of tectonics that we call **plate tectonics**. While some type of tectonics has affected every terrestrial world, plate tectonics appears to be unique to Earth. Moreover, as we'll discuss in Section 7.5, plate tectonics may be crucial to explaining life's abundance on Earth.

Tectonics and volcanism generally occur together because both require internal heat and therefore depend on a planet's size.

Tectonic activity usually goes hand in hand with volcanism, because both require internal heat. Like volcanism, Earth's ongoing tectonics is possible only because of our planet's relatively large size, which has allowed it to retain plenty of internal heat.

Erosion The last of our four major geological processes is erosion. *Erosion* is a blanket term for a variety of processes that break down or transport rock through the action of ice, liquid, or gas. The shaping of valleys by glaciers (ice), the carving of canyons by rivers (liquid), and the shifting of sand dunes by wind (gas) are all examples of erosion (Figure 7.12).

Erosion can both break down and build up geological features.

We often associate erosion with the breakdown of existing features, but erosion also builds things. Sand dunes, river deltas, and lake bed deposits are all examples of features built by erosion. Indeed, much of the surface rock on Earth was built by erosion. Over long periods of time, erosion has piled sediments into layers on the floors of oceans and seas, forming what we call **sedimentary rock**.

a The Colorado River has carved the Grand Canyon over the past few million years.

b Glaciers created Yosemite Valley.

c Wind erosion wears away rocks and builds up these desert sand dunes.

d This river delta consists of sediments worn away by wind and rain and then carried downstream.

Figure 7.12

A few examples of erosion on Earth.

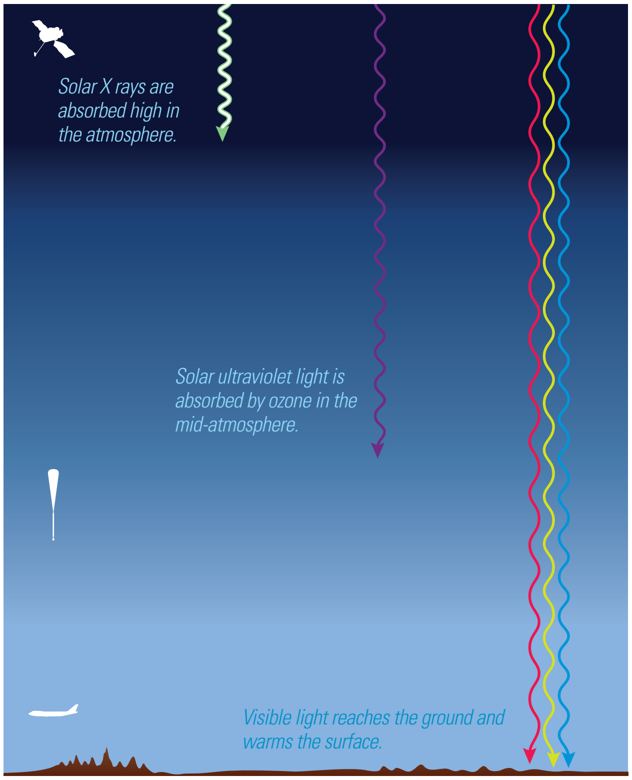


Figure 7.13

This diagram summarizes how different forms of light from the Sun are affected by Earth's atmosphere.

The layered rock of the Grand Canyon is an example of sedimentary rock, built up by erosion long before the canyon formed.

Erosion plays a far more important role on Earth than on any other terrestrial world, primarily because our planet has both strong winds and plenty of water. Strong winds are driven largely by our planet's relatively rapid rotation. Water exists as a result of outgassing by volcanism, and it causes erosion because our planet's temperature is just right to allow water to exist in both liquid and solid form on the surface.

MA Surface Temperatures of Terrestrial Planets Tutorial, Lessons 1–4

• How does Earth's atmosphere affect the planet?

Our atmosphere consists of about 77% nitrogen (N_2), 21% oxygen (O_2), and small amounts of other gases. This atmosphere provides the air we breathe and supplies the pressure that allows liquid water to flow, and as we've seen, it explains the extensive erosion on Earth. But its importance goes far deeper: Without the atmosphere, Earth's surface would be rendered lifeless by dangerous solar radiation and would be so cold that all water would be perpetually frozen.

Remarkably, our atmosphere plays all these roles despite being very thin compared to the planet. About two-thirds of the air in Earth's atmosphere lies within 10 kilometers of the surface. You could represent this air on a standard globe with a layer only as thick as a dollar bill. Let's look more closely at the fundamental roles of our thin atmosphere.

Surface Protection The Sun emits the visible light that allows us to see, but it also emits dangerous ultraviolet and X-ray radiation. In space, astronauts need thick spacesuits to protect them from the hazards of this radiation. On Earth, we are protected by our atmosphere (Figure 7.13).

X-ray photons carry enough energy to knock electrons free from almost any atom or molecule. That is, they *ionize* **[Section 5.2]** the atoms or molecules they strike, which is also why they can damage living tissue. Fortunately, X rays are absorbed so easily by atoms and molecules that all the X rays from the Sun are absorbed high in our atmosphere, leaving none to reach the ground. That is why X-ray telescopes must be placed in space (see Figure 5.21).

Ozone absorbs the Sun's dangerous ultraviolet radiation, while the X rays are absorbed by atoms and molecules higher up in Earth's atmosphere.

Ultraviolet photons from the Sun are not so easily absorbed. Most gases are transparent to ultraviolet light, allowing it to pass through unhindered. We owe our protection from ultraviolet light to a relatively rare gas called **ozone** (O_3). Ozone resides primarily in a middle layer of Earth's atmosphere (the *stratosphere*), where it absorbs most of the dangerous ultraviolet radiation from the Sun. Without ozone, we could not survive.

The Sun emits most of its radiation in the form of visible light. Visible light passes easily through the atmosphere and reaches the surface, allowing us to see and providing energy for photosynthesis. More important, visible light heats the ground when it is absorbed, making it the primary source of heat for Earth's surface.

Although most visible-light photons pass straight through Earth's atmosphere, a few are scattered randomly around the sky. This scattering is the reason our sky is bright rather than dark—which is why we cannot

common Misconceptions

Why Is the Sky Blue?

If you ask around, you'll find a wide variety of misconceptions about why the sky is blue. Some people guess that the sky is blue because of light reflecting from the oceans, but that could not explain blue skies over inland areas. Others claim that "air is blue," a vague statement that is also clearly wrong: If air molecules emitted blue light, then air would glow blue even in the dark; if they were blue because they reflected blue light and absorbed red light, then no red light could reach us at sunset. The real explanation for the blue sky is light scattering which, as shown in Figure 7.14, also explains our red sunsets.

see stars in the daytime. Without scattering, our sky would look like the lunar sky does to an astronaut, with the Sun just a very bright circle set against a black, star-studded background. Scattering also explains why the daytime sky is blue (Figure 7.14). Visible light consists of all the colors of the rainbow, but the colors are not all scattered equally. Gas molecules scatter blue light (higher energy) much more effectively than red light (lower energy). The difference in scattering is so great that, for practical purposes, we can imagine that only the blue light gets scattered. When the Sun is overhead, this scattered blue light reaches our eyes from all directions and the sky appears blue. At sunset or sunrise, the sunlight must pass through a greater amount of atmosphere on its way to us. Most of the blue light is scattered away, leaving only red light to color the sky.

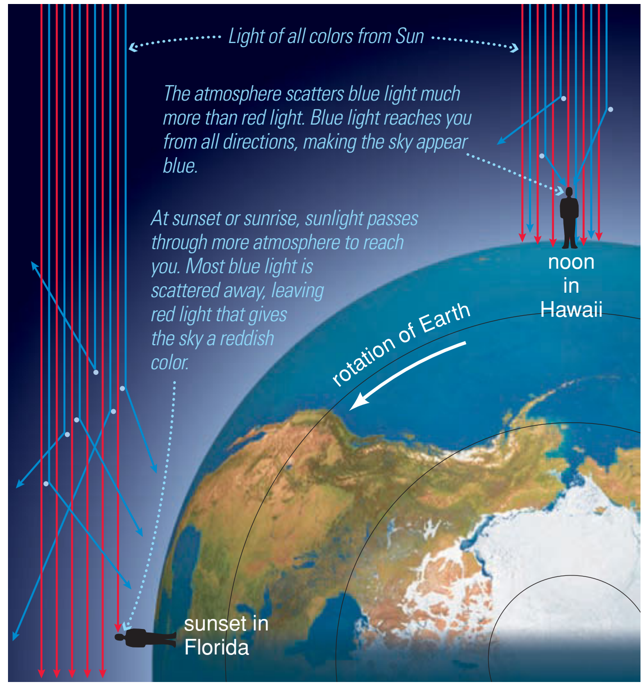


Figure 7.14

This diagram summarizes why the sky is blue and sunsets (and sunrises) are red.

The Greenhouse Effect Visible light warms Earth's surface, but not as much as you might guess. Calculations based on Earth's distance from the Sun (and the percentages of visible light absorbed and reflected by the ground) show that, by itself, visible light would give Earth an average surface temperature of only −16°C (+3°F)—well below the freezing point of water. In fact, Earth's global average temperature is about 15°C (59°F), plenty warm enough for liquid water to flow and life to thrive. Why is Earth so much warmer than it would be from visible-light warming alone? The answer is that our atmosphere traps additional heat through what we call the **greenhouse effect**.

The greenhouse effect keeps Earth's surface much warmer than it would be otherwise, allowing water to stay liquid over most of the surface.

Figure 7.15 shows the basic idea behind the greenhouse effect. Some of the visible light that reaches the ground is reflected and some is absorbed. The absorbed energy must be returned to space—otherwise the ground would rapidly heat up—but planetary surfaces are too cool to emit visible light. (Remember that the type of thermal radiation an object emits depends on its temperature [Section 5.2].) Instead, planetary temperatures are in the range in which they emit energy primarily in the form of infrared rather than visible light. The greenhouse effect occurs when the atmosphere temporarily "traps" some of the infrared light that the ground emits, slowing its return to space.

The greenhouse effect therefore occurs only when the atmosphere contains gases that can absorb infrared light. Gases that are particularly good at absorbing infrared light are called **greenhouse gases**, and they include water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4). These gases absorb infrared light effectively because their molecular structures begin rotating or vibrating when they absorb a photon of infrared light. A molecule then reemits a photon of infrared light in some random direction. This photon can then be absorbed by another gas molecule, which does the same thing. The net result is that greenhouse gases tend to slow the escape of infrared radiation from the lower atmosphere, while their molecular motions heat the surrounding air. In this way, the greenhouse effect makes the surface and the lower atmosphere warmer than they would be from sunlight alone. The more greenhouse gases present, the greater the degree of surface warming.

think about it Molecules that consist of two atoms of the same type—such as the N_2 and O_2 molecules that together make up 98% of Earth's atmosphere—are poor infrared absorbers. But imagine this were not the case. How would Earth be different if nitrogen and oxygen absorbed infrared light effectively?

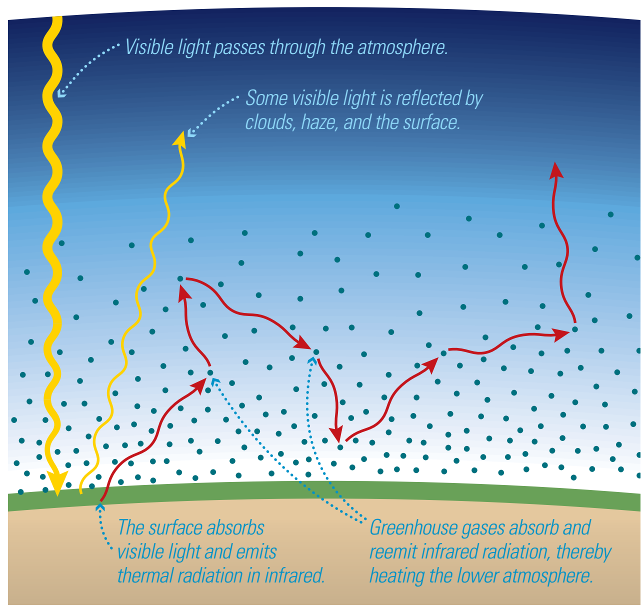


Figure 7.15

The greenhouse effect. The lower atmosphere becomes warmer than it would be if it had no greenhouse gases such as water vapor, carbon dioxide, and methane.

Moon   Mercury

Figure 7.16

Views of the Moon and Mercury, shown to scale. The Mercury photo was obtained during the 2008 *MESSENGER* flyby.

7.2 The Moon and Mercury: Geologically Dead

In the rest of this chapter, we will investigate the histories of the terrestrial worlds, with the ultimate goal of learning how and why Earth became unique. We'll start in this section with the two worlds that have the simplest histories: the Moon and Mercury (Figure 7.16).

The simple histories of the Moon and Mercury are a direct consequence of their small sizes. Both these worlds are considerably smaller than Venus, Earth, or Mars, so they long ago lost most of their internal heat, leaving them without any significant geological activity. Small size also explains their lack of significant atmospheres: Their gravity is too weak to hold gas for long periods of time, and without ongoing volcanism they lack the outgassing needed to replenish gas lost in the past.

• Was there ever geological activity on the Moon or Mercury?

Impact cratering has been by far the most important geological process on both worlds. However, closer examination shows that a few features are volcanic or tectonic in origin and indicate that the Moon and Mercury had geological activity in the past. Long ago, before they had a chance to cool, these worlds were hot enough inside for some volcanism and tectonics to occur.

Geological Features of the Moon The familiar face of the full moon shows that not all regions of the surface look the same (Figure 7.17). Some regions are heavily cratered. Other regions, known as the **lunar maria**, look smoother and darker. Indeed, the maria got their name because they look much like oceans when seen from afar; *maria* (singular, *mare*) is Latin for "seas." The smooth and dark appearance of the lunar maria suggests that they were made by a flood of molten lava, and studies of moon rocks confirm this suggestion.

Figure 7.18 shows how we think the maria formed. During the heavy bombardment, craters covered the Moon's entire surface. The largest impacts violently fractured the Moon's lithosphere beneath the huge craters they created. However, the Moon's interior had already cooled since its formation, and there was no molten rock to flood these craters immediately. Instead, the lava floods came hundreds of millions of years later, thanks to heat released by the decay of radioactive elements in the Moon's interior. This heat gradually built up during the Moon's early history, until mantle material melted about 3 to 4 billion years ago. Molten rock then welled up through the cracks in the lithosphere, flooding the largest impact craters with lava. The maria are generally circular because they are essentially flooded craters (and craters are almost always round). Their dark color comes from the dense, iron-rich rock (basalt) that rose up from the lunar mantle as molten lava.

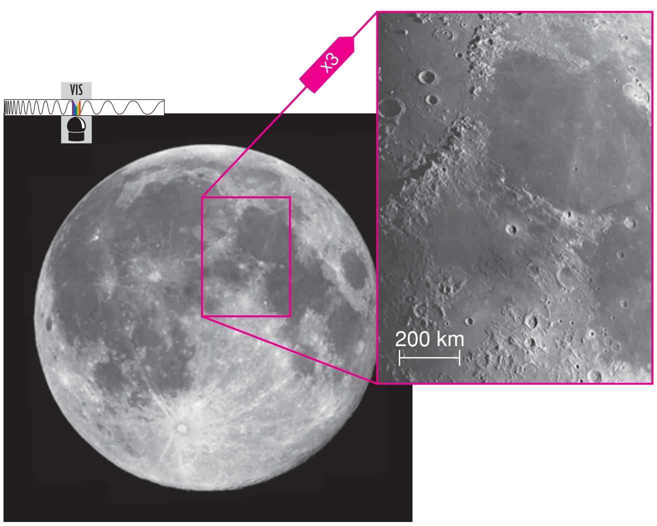
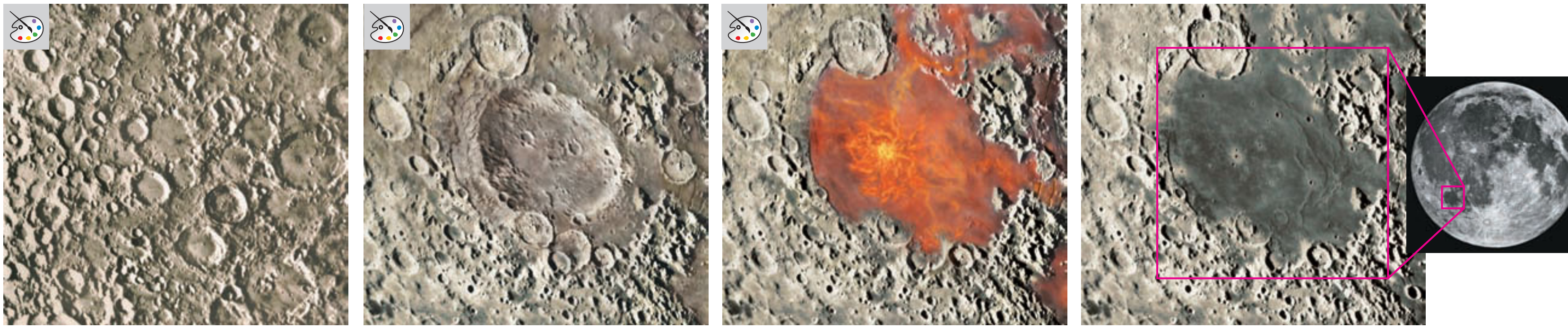


Figure 7.17

The familiar face of the full Moon shows numerous dark, smooth maria.

The Moon's dark, smooth maria were made by floods of molten lava billions of years ago, when the Moon's interior was heated by radioactive decay.

The Moon's interior cooled quickly after that, and there was never again enough radioactive heat to cause further melting. Because the lava floods occurred after the heavy bombardment subsided, the maria have remained much as they were when they first formed. The relatively few craters that we see within them today were made by impacts that occurred after the maria formed.



a This illustration shows the Mare Humorum region as it probably looked about 4 billion years ago, when it would have been completely covered in craters.

b Around that time, a huge impact excavated the crater that would later become Mare Humorum. The impact fractured the Moon's lithosphere and erased the many craters that existed earlier.

c A few hundred million years later, heat from radioactive decay built up enough to melt the Moon's upper mantle. Molten lava welled up through the lithospheric cracks, flooding the impact crater.

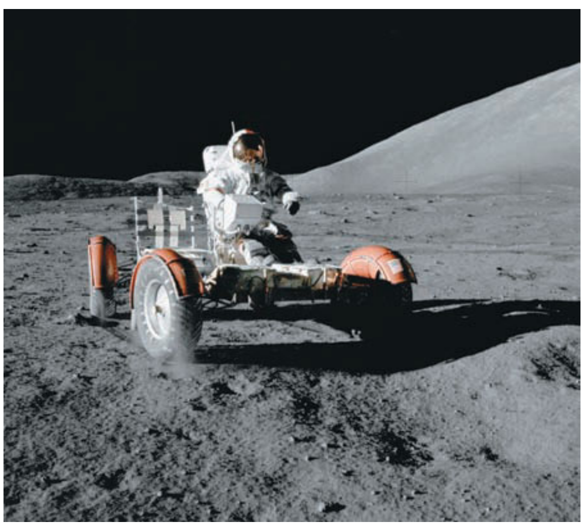
d This photo shows Mare Humorum as it appears today, and the inset shows its location on the Moon.

Figure 7.18

The lunar maria formed between 3 and 4 billion years ago, when molten lava flooded large craters that had formed hundreds of millions of years earlier. This sequence of diagrams represents the formation of Mare Humorum.

The Moon's era of geological activity is long gone. Today, the Moon is a desolate and nearly unchanging place. Rare impacts may occur in the future, but we are unlikely ever to witness a major one. Little happens on the Moon, aside from the occasional visit of robotic spacecraft or astronauts from Earth (Figure 7.19a).

The only ongoing geological change on the Moon is a very slow "sandblasting" of the surface by *micrometeorites,* sand-size particles from space. These tiny particles burn up as meteors in the atmospheres of Earth, Venus, and Mars but rain directly onto the surface of the airless Moon. The micrometeorites gradually pulverize the surface rock, which explains why the lunar surface is covered by a thin layer of powdery "soil." The *Apollo* astronauts left their footprints in this powdery surface (Figure 7.19b). Pulverization by micrometeorites is a very slow process, and the astronauts' footprints will last millions of years before they are finally erased.



a Astronaut Gene Cernan takes the Lunar Roving Vehicle for a spin during the final *Apollo* mission to the Moon (*Apollo 17*, December 1972).

b The *Apollo* astronauts left clear footprints, like this one, in the Moon's powdery "soil." The powder is the result of gradual pulverization of surface rock by micrometeorites. Micrometeorites will eventually erase the astronauts' footprints, but not for millions of years.

Figure 7.19

The Moon today is geologically dead, but it can still tell us a lot about the history of our solar system.

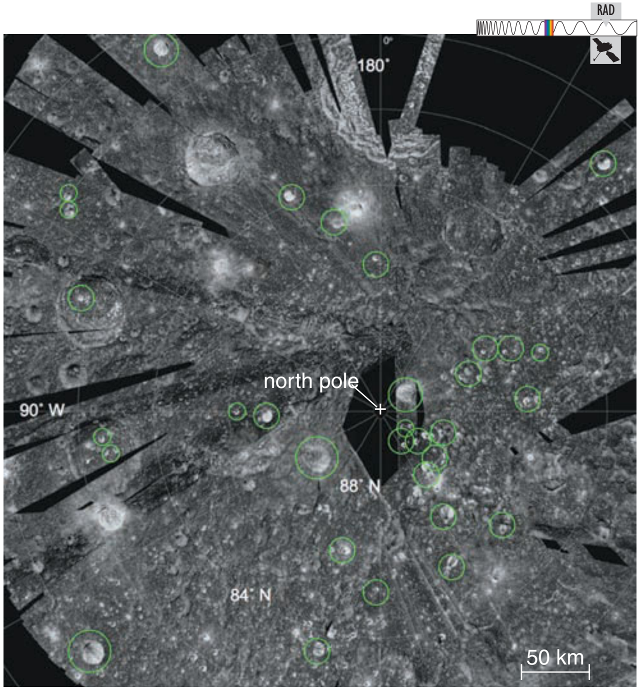


Figure 7.20

This radar map shows a region near the Moon's north pole, imaged by a NASA instrument on India's *Chandrayaan-1* spacecraft. The green circles represent craters in which water ice was detected. The ice lies at the bottoms of craters that are in perpetual shadow. Shadows are not visible since radar was used to take the image.

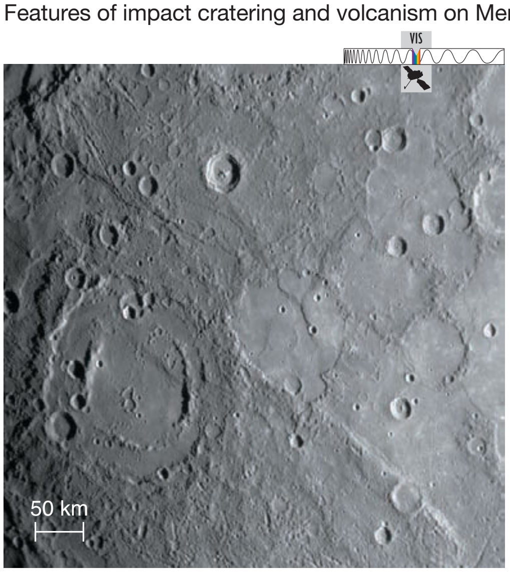
Humans have not returned to the Moon in the decades since *Apollo*, but robotic spacecraft from the United States, China, Japan, and India have taught us more. In particular, scientists had long suspected that water ice might reside in permanently shadowed craters near the lunar poles, deposited by comet impacts over millions of years. This was confirmed in 2009, when scientists sent the rocket from the *LCROSS* spacecraft crashing into a crater near the south pole. The debris that splashed upward revealed the presence of water vaporized from ice in the lunar soil. A radar sensor aboard India's *Chandrayaan-1* spacecraft detected ice deposits in similar craters near the Moon's north pole (Figure 7.20). More surprisingly, other missions detected small amounts of water mixed into the upper layer of lunar soil over much of the lunar surface; the origin of this water is unknown. A supply of water might be useful for future human habitats on the Moon.

Geological Features of Mercury Mercury looks so much like the Moon that it's often difficult to tell which world you are looking at in surface photos. Nevertheless, these two worlds have a few important differences.

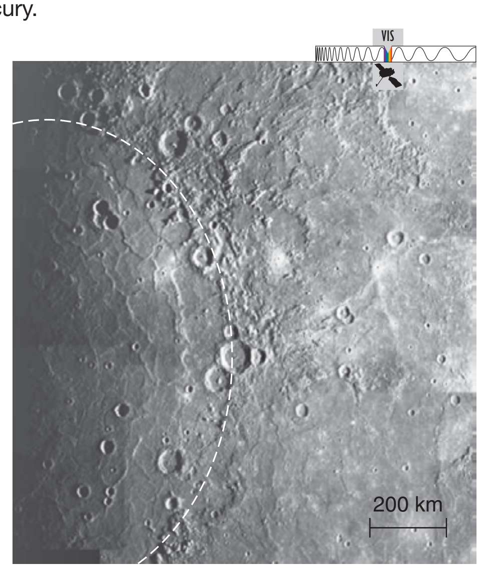
Impact craters are visible almost everywhere on Mercury, indicating an ancient surface. However, Mercury's craters are less crowded together than the craters in the most ancient regions of the Moon, suggesting that molten lava later covered up some of the craters that formed on Mercury during the heavy bombardment (Figure 7.21a). As on the Moon, these lava flows probably occurred when heat from radioactive decay accumulated enough to melt part of the mantle. Although we have not found lava flows as large as those that created the lunar maria, the lesser crater crowding and the many smaller lava plains suggest that Mercury had at least as much volcanism as the Moon, and its volcanoes may have died out a billion years later than the Moon's.

Figure 7.21

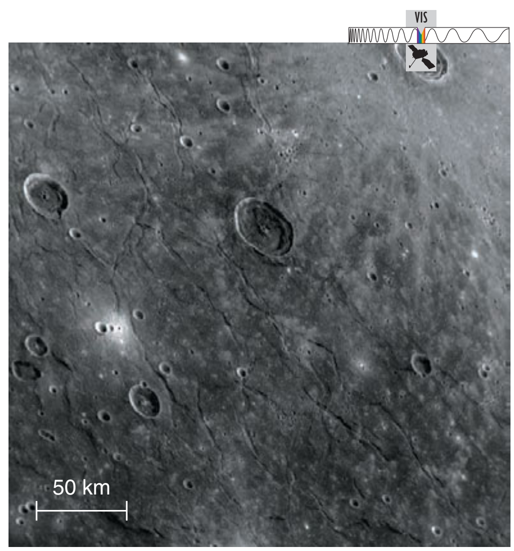
Features of impact cratering and volcanism on Mercury.



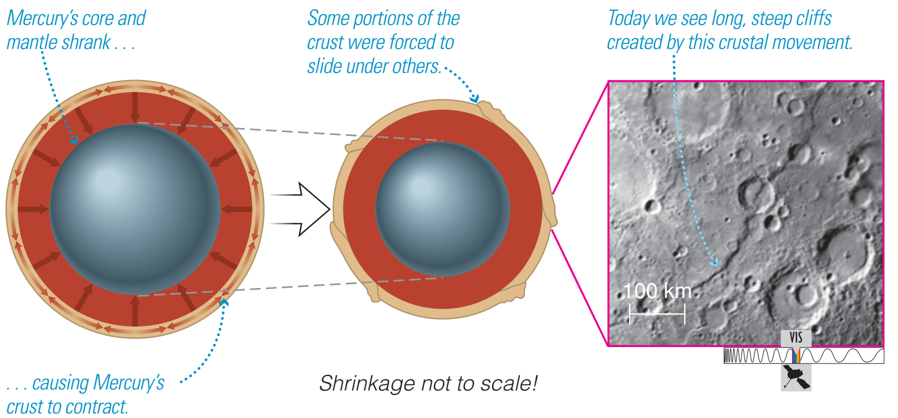
a *MESSENGER* close-up view of Mercury's surface, showing impact craters and smooth regions where lava has covered up craters.



b Part of the Caloris Basin (outlined by the dashed ring), a large impact crater on Mercury (*Mariner 10* image).



c This *MESSENGER* close-up of the floor of the Caloris Basin shows small-scale stretch marks that were probably created as the surface gradually rebounded after the impact.



a Mercury's long cliffs probably formed when its core cooled and contracted, causing the mantle and lithosphere to shrink. This diagram shows how the cliffs probably formed as the surface crumpled.

b This cliff extends more than 100 kilometers in length, and its vertical face is as much as 2 kilometers tall. (Photo from *Mariner 10*.)

Figure 7.22

Long cliffs on Mercury offer evidence that the entire planet shrank early in its history, perhaps by as much as 20 kilometers in radius.

The largest single surface feature on Mercury is a huge impact crater called the *Caloris Basin* (Figure 7.21b and c). The Caloris Basin spans more than half of Mercury's radius, and its multiple rings bear witness to the violent impact that created it. The Caloris Basin has few craters within it, indicating that it must have formed at a time when the heavy bombardment was already subsiding.

The most surprising features of Mercury are its many tremendous cliffs—evidence of a type of past tectonics quite different from anything we have found on any other terrestrial world (Figure 7.22). Mercury's cliffs have vertical faces up to 3 or more kilometers high and typically run for hundreds of kilometers across the surface. They probably formed when tectonic forces compressed the crust, causing the surface to crumple. Because crumpling would have shrunk the portions of the surface it affected, Mercury as a whole could not have stayed the same size unless other parts of the surface expanded. However, we find no evidence of large-scale "stretch marks" on Mercury. Can it be that the whole planet simply shrank?

The planet Mercury appears to have shrunk long ago, leaving behind long, steep cliffs.

Apparently so. Early in its history, Mercury's larger size and greater iron content allowed it to gain more internal heat from accretion and differentiation than did the Moon. This heat caused the large iron core to swell. Later, as the core cooled, it contracted by perhaps as much as 20 kilometers in radius. The mantle and lithosphere must have contracted along with the core, generating the tectonic stresses that created the great cliffs. The contraction probably also closed off any remaining volcanic vents, ending Mercury's period of volcanism. (Scientists have recently discovered similar but smaller cliffs on the Moon, suggesting that it also underwent some shrinking.) Today, Mercury seems just as geologically dead as the Moon. We are rapidly learning more about Mercury's history, thanks to the *MESSENGER* spacecraft, scheduled to be in orbit around Mercury by the time you read this book.

think about it Find the current status of the *MESSENGER* mission. Has it made any new discoveries about Mercury?

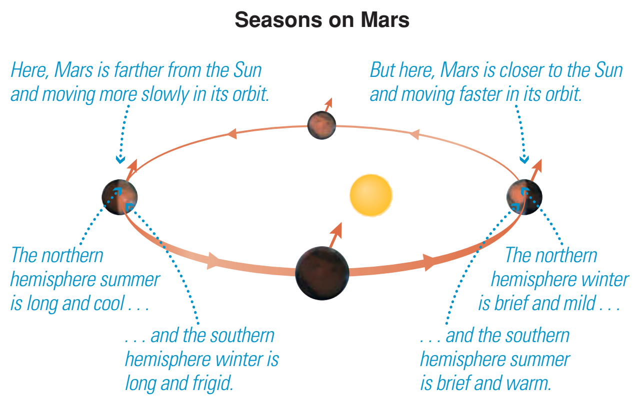


Figure 7.23

The ellipticity of Mars's orbit makes seasons more extreme (warmer summers and colder winters) in the southern hemisphere than in the northern hemisphere.

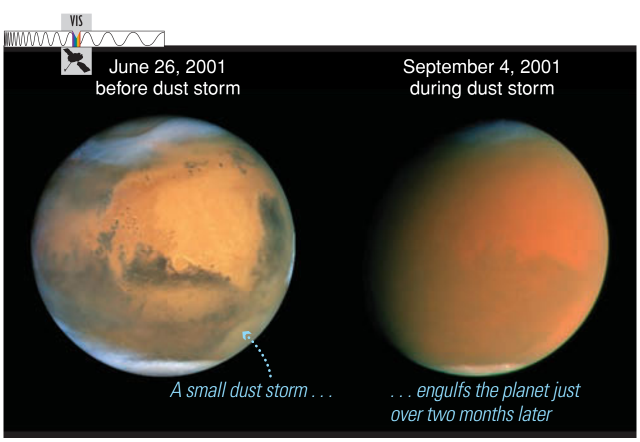


Figure 7.24

These two Hubble Space Telescope photos contrast the appearance of the same face of Mars in the absence (left) and presence (right) of a global dust storm.

7.3 Mars: A Victim of Planetary Freeze-Drying

Based on its relative size (see Figure 7.1), we expect Mars to be more geologically interesting and varied than the Moon or Mercury but geologically less active than Earth or Venus. Observations confirm this basic picture, though Mars's greater distance from the Sun—about 50% farther than Earth is from the Sun—also plays a role in its geology. Mars's size and distance from the Sun have dictated much of its geological history.

The present-day surface of Mars looks much like some deserts or volcanic plains on Earth (see Figure 6.6), and it offers several other similarities to Earth. A Martian day is less than an hour longer than an Earth day, and Mars has polar caps that resemble Earth's, although they contain frozen carbon dioxide in addition to water ice. Mars's rotation axis is tilted about the same amount as Earth's, and as a result it has seasons much like those on Earth. However, unlike Earth's, Mars's seasons are affected by its orbit as well as its tilt (Figure 7.23). Mars's more elliptical orbit puts it significantly closer to the Sun during the southern hemisphere summer and farther from the Sun during the southern hemisphere winter. Mars therefore has more extreme seasons in its southern hemisphere—that is, shorter, warmer summers and longer, colder winters—than in its northern hemisphere.

The superficial similarities between Earth and Mars have made the idea of life on Mars a staple of science fiction. However, Mars in reality is quite different from Earth. The atmosphere is so thin that it creates only a weak greenhouse effect despite being made mostly of the greenhouse gas carbon dioxide. The temperature is usually well below freezing, with a global average of about −50°C (−58°F), and the atmospheric pressure is less than 1% of that on the surface of Earth. The lack of oxygen means that Mars lacks an ozone layer, so much of the Sun's damaging ultraviolet radiation passes unhindered to the surface.

Even Martian winds are very different from those on Earth. Winds on Earth are driven primarily by effects of Earth's rotation and by heat flow from the equator to the poles. In contrast, winds on Mars are strongly affected by its extreme seasonal changes. Temperatures at the winter pole drop so low (to about −130°C) that carbon dioxide condenses into "dry ice" at the polar cap. At the same time, frozen carbon dioxide at the summer pole sublimates into carbon dioxide gas. (*Sublimation* is the process by which an ice turns to a gas without first melting into liquid.) During the peak of summer, nearly all the carbon dioxide may sublime from the summer pole, leaving only a residual polar cap of water ice. The atmospheric pressure therefore increases at the summer pole and decreases at the winter pole. As much as one-third of the total carbon dioxide of the Martian atmosphere moves seasonally between the north and south polar caps. Sometimes these pressure differences initiate huge dust storms, particularly when the more extreme summer approaches in the southern hemisphere (Figure 7.24).

All in all, surface conditions on Mars today make it seem utterly inhospitable to life. However, careful study of Martian geology offers evidence that Mars had a warmer and wetter past. If so, it might have had conditions under which life could have arisen, and it's conceivable that such life could still survive under the surface. The search for past or present life is a major reason why we are sending more spacecraft to Mars than to any other planet.

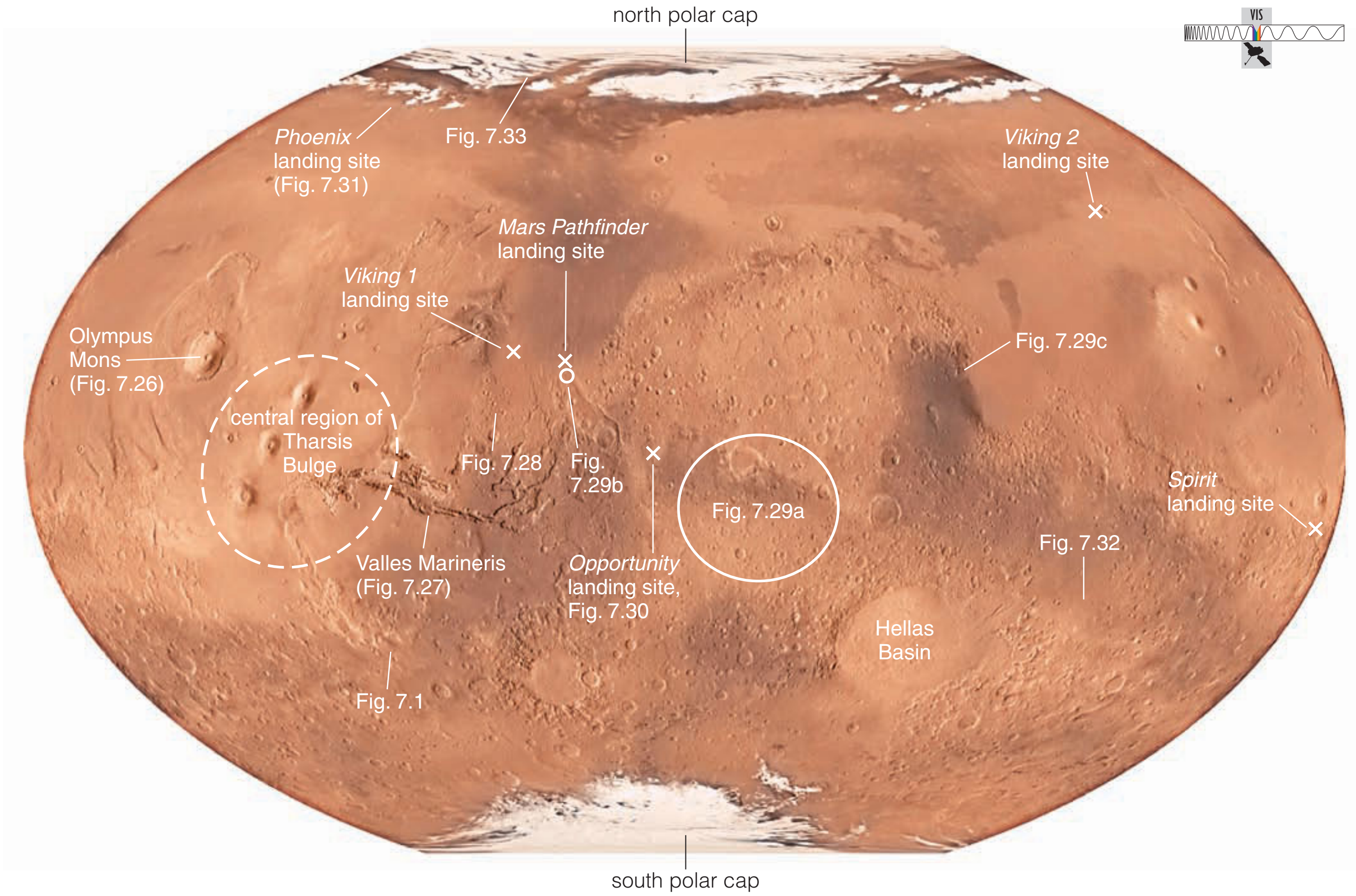


Figure 7.25 MA **interactive figure**

This image showing the full surface of Mars is a composite made by combining more than 1000 images with more than 200 million altitude measurements from the *Mars Global Surveyor* mission. Several key geological features are labeled, and the locations of features shown in close-up photos elsewhere in this book are marked.

• What geological features tell us that water once flowed on Mars?

No liquid water exists on the surface of Mars today. We know this not only because we've studied most of the surface in reasonable detail but also because the surface conditions do not allow it. In most places and at most times, Mars is so cold that any liquid water would immediately freeze into ice. Even when the temperature rises above freezing, as it often does at midday near the equator, the air pressure is so low that liquid water would quickly evaporate. If you donned a spacesuit and took a cup of water outside your pressurized spaceship, the water would rapidly freeze or boil away (or do a combination of both).

Nevertheless, Mars offers ample evidence of past water flows. Because water could not have flowed for long unless the Martian atmosphere were thicker and warmer, it appears that Mars must have had at least some warm and wet periods in the distant past. Let's investigate the geological evidence for this past, more hospitable world.

The Geology of Mars To recognize features we can attribute to past water flows, we first need a global picture of Martian geology. Figure 7.25 shows the full surface of Mars. Aside from the polar caps, the most striking feature is the dramatic difference in terrain around different parts of the planet. Much of the southern hemisphere has relatively high elevation and is scarred by numerous large impact craters, including the large crater known as the Hellas Basin. In contrast, the northern plains show few impact craters and tend to be below the average Martian surface level. The differences in crater crowding tell us that the southern highlands are

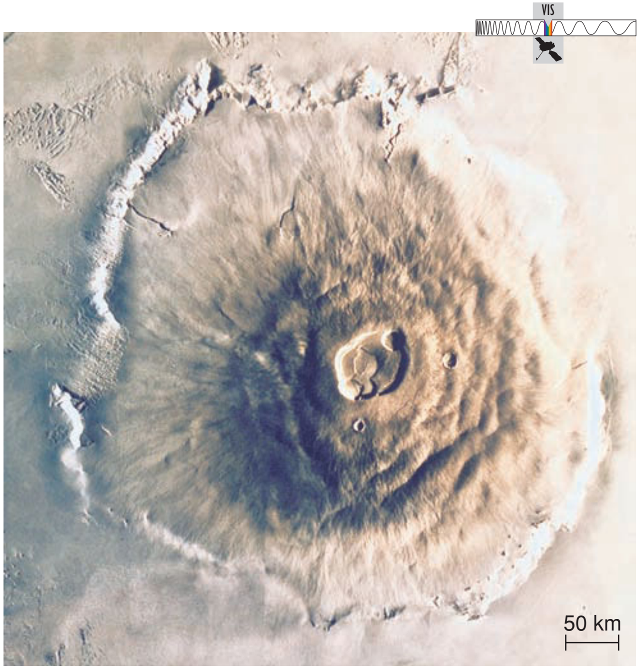


Figure 7.26

Olympus Mons, the largest volcano in the solar system, covers an area the size of Arizona and rises higher than Mount Everest on Earth. Note the tall cliff around its rim and the central volcanic crater from which lava erupted.

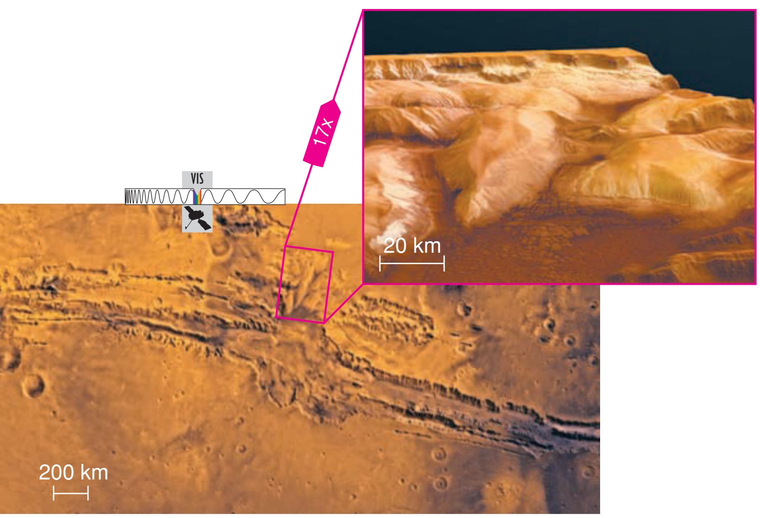


Figure 7.27

Valles Marineris is a huge valley on Mars created in part by tectonic stresses. It extends nearly a fifth of the way around the planet (see Figure 7.25), and in some places is 10 kilometers deep. The inset shows a perspective view looking north across the center of the canyon, obtained by *Mars Express*.

a much older surface than the northern plains, which must have had their early craters erased by other geological processes. Further study suggests that volcanism was the most important of these processes.

More dramatic evidence of volcanism on Mars comes from several towering volcanoes. One of these, Olympus Mons, is the tallest known volcano in the solar system (Figure 7.26). Its base is some 600 kilometers across, large enough to cover an area the size of Arizona. Its peak stands about 26 kilometers above the average Martian surface level, about three times as high as Mount Everest stands above sea level on Earth. Much of Olympus Mons is rimmed by a cliff that in places is 6 kilometers high.

Mars has had extremely active volcanism in the past, and its surface is dotted with numerous large volcanoes.

Olympus Mons and several other large volcanoes are concentrated on or near the continent-size *Tharsis Bulge*. Tharsis is some 4000 kilometers across, and most of it rises several kilometers above the average Martian surface level. It was probably created by a long-lived plume of rising mantle material that bulged the surface upward and provided the molten rock for the eruptions that built the giant volcanoes.

Mars also has tectonic features, though none on a global scale like the plate tectonics of Earth. The most prominent tectonic feature is the long, deep system of valleys called *Valles Marineris* (Figure 7.27). Valles Marineris extends almost a fifth of the way along the planet's equator. It is as long as the United States is wide and almost four times as deep as Earth's Grand Canyon. No one knows exactly how Valles Marineris formed, but its location suggests a link to the Tharsis Bulge. Perhaps it formed through tectonic stresses accompanying the uplift of material that created Tharsis, cracking the surface and leaving the tall cliff walls of the valleys.

Is there any ongoing volcanic or tectonic activity on Mars? Until recently, we didn't think so. We expect Mars to be much less geologically active than Earth, because its smaller size has allowed its interior to cool faster. However, radiometric dating of meteorites that appear to have come from Mars (so-called *Martian meteorites* **[Section 9.1]**) shows some of them to be made of volcanic rock that solidified from molten lava as little as 180 million years ago—quite recent in the $4\frac{1}{2}$-billion-year history of the solar system. In that case, it is likely that Martian volcanoes will erupt again someday. Nevertheless, the Martian interior is presumably cooling and its lithosphere thickening. Within a few billion years, Mars will become as geologically dead as the Moon and Mercury.

Ancient Water Flows Impacts, volcanism, and tectonics explain most of the major geological features of Mars, but close examination also shows features of water erosion. For example, Figure 7.28 looks much like a dry riverbed on Earth seen from above. These channels appear to have been carved by running water, though no one knows whether the water came from runoff after rainfall, from erosion by water-rich debris flows, or from an underground source. Regardless of the specific mechanism, water was almost certainly responsible, because it is the only substance that could have been liquid under past Martian conditions and that is sufficiently abundant to have created such extensive erosion features. But the water apparently stopped flowing long ago. Notice that a few impact craters lie on top of the channels. From counts of the craters in and near them, it appears that these channels are at least 2–3 billion years old, meaning that water has not flowed through them since that time.

Other orbital evidence also argues that Mars had rain and surface water in the distant past. Figure 7.29a shows a broad region of the ancient, heavily cratered southern highlands. Notice the indistinct rims of many large

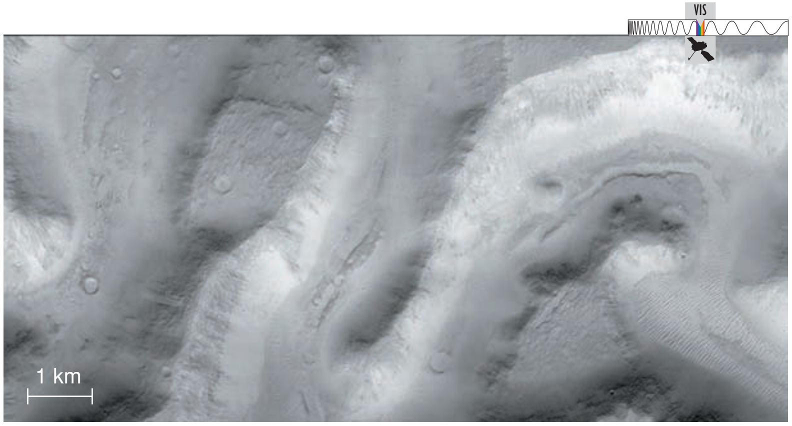


Figure 7.28

This photo, taken by the *Mars Reconnaissance Orbiter*, shows what appears to be a dried-up meandering riverbed, now filled with dunes of windblown dust. Notice the numerous small craters, indicating that the riverbed dried out billions of years ago.

craters and the relative lack of small craters. Both facts argue for ancient rainfall, which would have eroded crater rims and erased small craters altogether. Figure 7.29b shows a three-dimensional perspective of the surface that suggests water once flowed between two ancient crater lakes. Figure 7.29c shows what looks like a river delta where water flowed into an ancient crater. Further evidence that the crater was once a lake comes from images and spectra indicating the presence of clay minerals on the crater floor, presumably deposited by sediments flowing down the river.

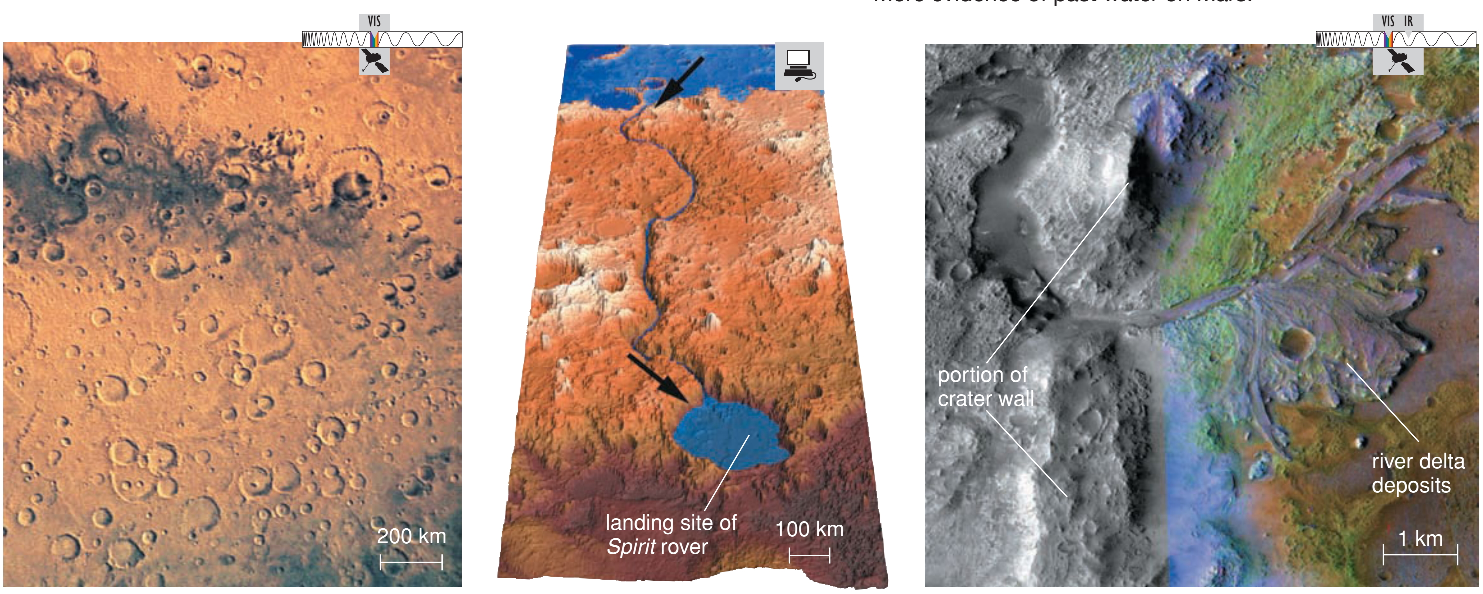
Dried up riverbeds and other signs of erosion show that water flowed on Mars in the distant past.

Surface studies provide additional evidence for past water. In 2004, the robotic rovers *Spirit* and *Opportunity* landed on nearly opposite sides of Mars. The twin rovers carried cameras, instruments to identify rock composition, and a grinder to expose fresh rock for analysis. The rovers, designed for just 3 months of operation, were still collecting data as this book was being written, more than 6 years after their arrival.

Both rovers found compelling evidence that liquid water was once plentiful on Mars. Rocks at the *Opportunity* landing site contain tiny spheres—nicknamed "blueberries," although they're neither blue nor as

Figure 7.29

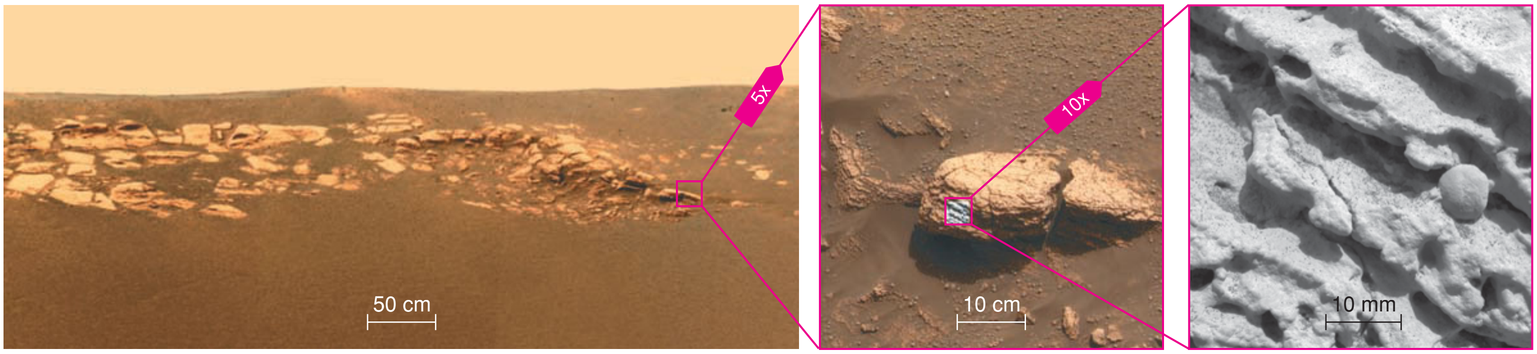
More evidence of past water on Mars.



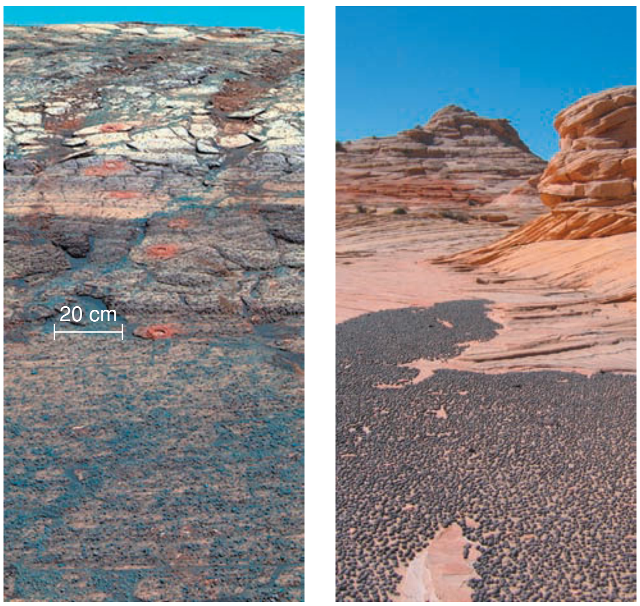
a This photo shows a broad region of the southern highlands on Mars. The eroded rims of large craters and the lack of many small craters suggest erosion by rainfall.

b This computer-generated perspective view shows how a Martian valley forms a natural passage between two possible ancient lakes (shaded blue). Vertical relief is exaggerated 14 times to reveal the topography.

c Combined visible/infrared image of an ancient river delta that formed where water flowing down a valley emptied into a lake filling a crater. Clay minerals are identified in green.



a This sequence zooms in on a knee-high rock outcropping near the rover's landing site. The close-up shows a piece of the rock about 3 centimeters across. The layered structure, odd indentations, and small sphere all support the idea that the rock formed from sediments in standing water.



b "Blueberries" on two planets. In both cases, the foreground shows hematite "blueberries," which formed within sedimentary rock layers like those in the background, then eroded out and rolled downhill; the varying tilts of the rock layers hint at changing winds or waves during formation. The background rocks are about twice as far away from the camera in the Earth photo as in the Mars photo (taken by the *Opportunity* rover).

Figure 7.30 VIS

Surface studies by the *Mars Exploration* rovers have provided evidence of a warmer, wetter Mars long ago.

large as berries—and odd indentations suggesting that they formed in standing water, or possibly by groundwater percolating through rocks (Figure 7.30). Compositional analysis shows that the "blueberries" contain the iron-rich mineral hematite, and other rocks contain the sulfur-rich mineral jarosite. Both minerals form in water, and chemical analysis supports the case for formation in a salty environment such as a pond or a lake, apparently made acidic by dissolving in some atmospheric SO_2. Other minerals may have been formed in environments like those of hot springs on Earth. Taken together, the orbital and surface studies provide convincing evidence for abundant water in Mars's past.

Martian Water Today If water once flowed over the surface of Mars, where did it all go? As we'll discuss shortly, much of the water was probably lost to space forever. However, significant amounts of water still remain, frozen at the polar caps and in the top meter or so of the surface soil around much of the rest of the planet. Recent research has shown that the polar caps are made mostly of water ice, overlaid with a thin layer (at most a few meters thick) of CO_2 ice. More water ice is found in vast layers of dusty ice surrounding the poles. The extent of this water ice is only beginning to become clear; scientists were surprised to find surface ice sitting right under the *Phoenix* lander when it arrived in 2008 (Figure 7.31). Orbital studies of Mars have revealed the presence of even more water ice mixed into the upper layers of soil. If all the ice now known on Mars melted, it could make an ocean 11 meters deep over the whole planet.

Additional water ice probably lies deeper underground. It is even possible that some liquid water exists underground near sources of volcanic heat, providing a potential home to microscopic life. Moreover, if there is enough volcanic heat, ice might occasionally melt and flow along the surface for the short time until it freezes or evaporates. Although we have found no geological evidence to suggest that any large-scale water flows have occurred on Mars in the past billion years, orbital photographs offer evidence of smaller-scale water flows in much more recent times.

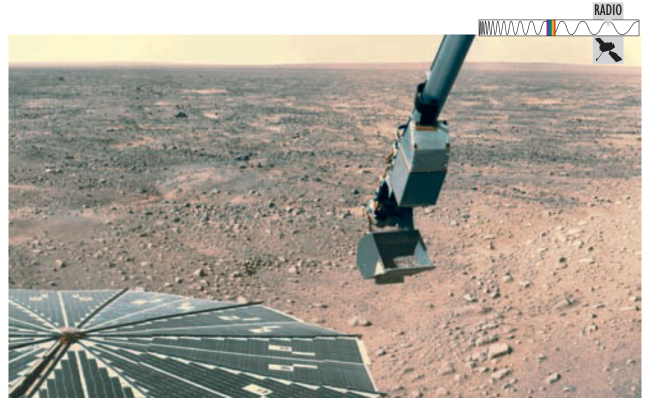
Gullies on crater walls suggest that water might still occasionally flow on Mars today.

The strongest evidence comes from photos of gullies on crater and channel walls (Figure 7.32). These gullies look strikingly similar to the gullies we see on eroded slopes on Earth. One hypothesis suggests that the gullies form when snow accumulates on the crater walls in winter and melts away from the base of the snowpack in spring. If this hypothesis is correct, the water at the base could melt (rather than sublimating directly to water vapor as ice normally does on Mars) because of the angle of sunlight and the pressure of the overlying snow; such melting may have occurred during a period within the past million years or so when Mars's axis tilt was slightly different than it is today. Alternatively, the gullies may be formed by landslides, which have been seen to occur elsewhere on Mars with the change of seasons (Figure 7.33).

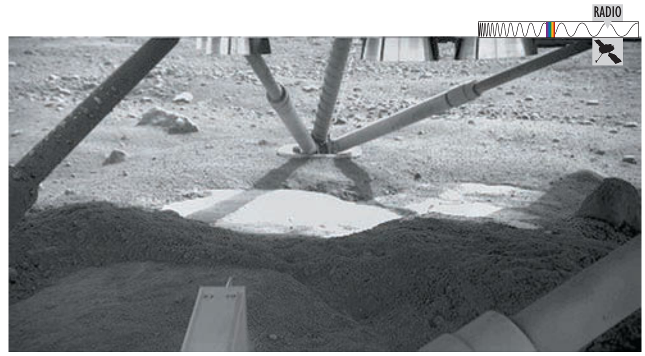
• Why did Mars change?

There seems little doubt that Mars had wetter and possibly warmer periods, probably with rainfall, before about 3 billion years ago. The full extent of these periods is a topic of considerable scientific debate. Some scientists suspect that Mars was continuously warm and wet for much of its first billion years of existence, and some findings suggest an ocean may have covered much of the northern hemisphere. Others think that Mars had only intermittent periods of rainfall, perhaps triggered by the heat of large impacts, and that ancient lakes, ponds, or oceans may have been completely ice-covered. Either way, Mars apparently underwent major and permanent climate change, turning a world that could sustain liquid water into a frozen wasteland.

The idea that Mars once had a thicker atmosphere makes sense, because we would expect that its many volcanoes outgassed plenty of atmospheric gas. Much of this gas should have been water vapor and carbon dioxide, and these greenhouse gases would have warmed the planet. Ancient sulfur dioxide levels (inferred from study of sulfurous minerals on the surface) should have also contributed to a stronger greenhouse effect. If Martian volcanoes outgassed greenhouse gases in the same proportions as do volcanoes on Earth, Mars would have had enough water to fill oceans tens or even hundreds of meters deep. The heat of impacts may also have released water vapor into the atmosphere, enhancing the greenhouse effect until the water rained out.



a The *Phoenix* lander used a robotic arm to scoop up Martian soil for analysis by on-board instruments. Results will help scientists determine whether and when Mars's polar regions may have been habitable.



b The robotic arm camera of the *Phoenix* lander found a bright patch of water ice underneath it. The spacecraft's landing rockets (visible at top) blasted away an overlying layer of dust.

Figure 7.31

The *Phoenix* lander touched down near the north polar ice cap in 2008.

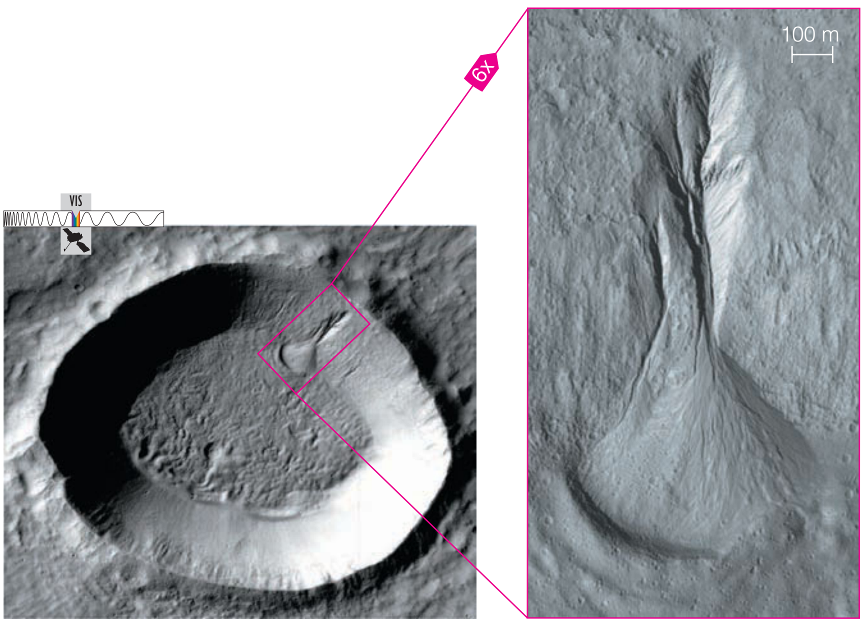


Figure 7.32

These *Mars Reconnaissance* orbiter images support the hypothesis that running water has etched gullies into crater walls. The main image shows a crater, and the close-up shows a gully network that has carried sediments downward. The lack of small impact craters on the sediment deposits indicates that the gullies formed within the last million years or so.

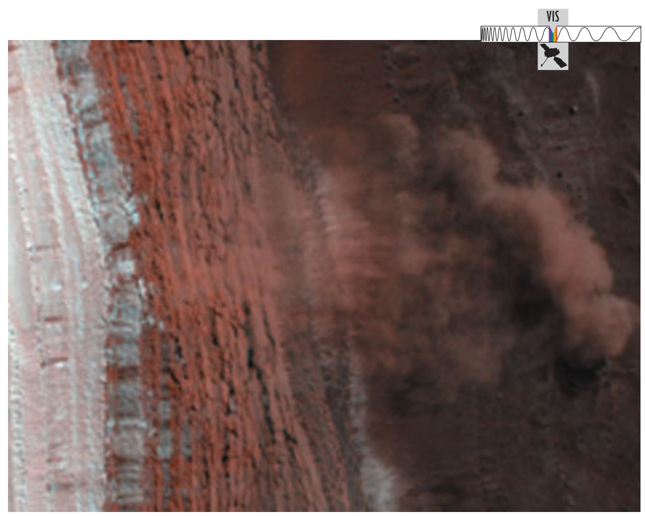


Figure 7.33

The *Mars Reconnaissance* orbiter captured this landslide in Mars's north polar regions. In a cliff over 700 meters high, layers of ice mixed with dust thawed during the northern spring, causing the landslide.

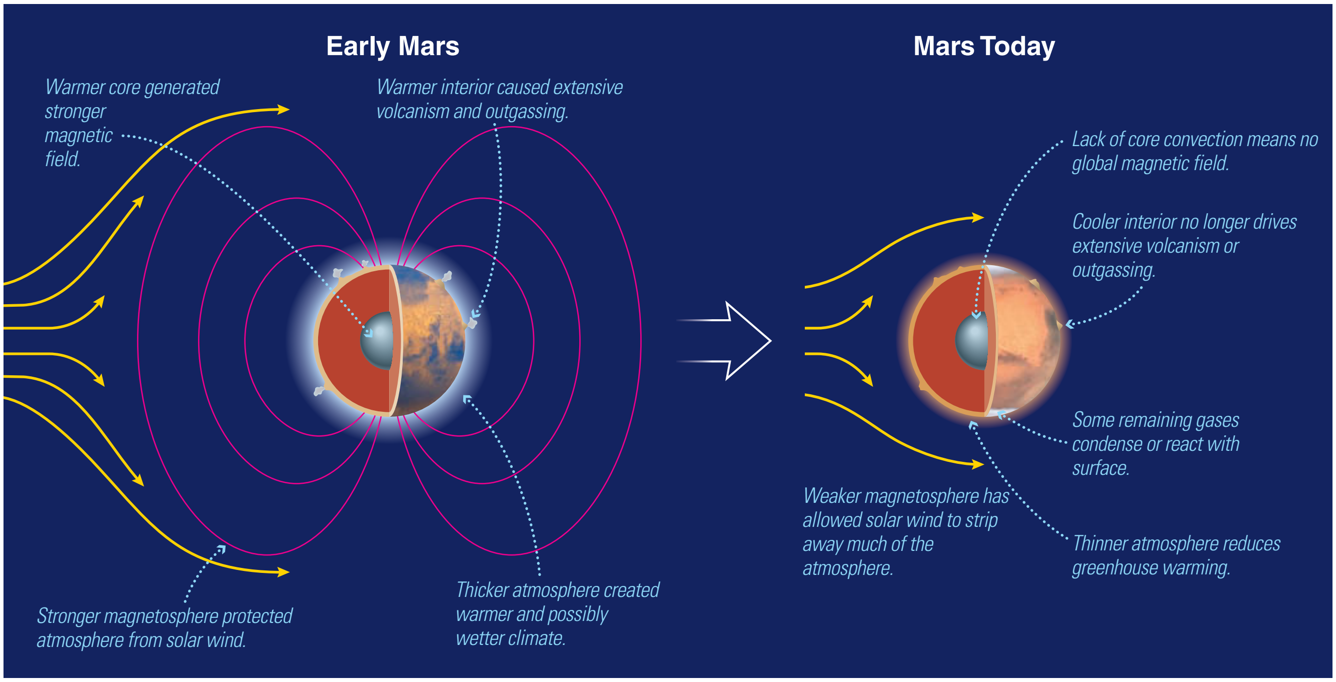


Figure 7.34

Some 3 billion years ago, Mars underwent dramatic climate change, ensuring that rain could never fall again.

The bigger question is not whether Mars once had a denser atmosphere, but where all the atmospheric gas went. Mars must have somehow lost most of its carbon dioxide gas. This loss would have weakened the greenhouse effect until the planet essentially froze over. Some of the carbon dioxide condensed and became part of the polar caps, and some may be chemically bound to surface rock. However, the bulk of the gas was probably lost to space.

Early in its history, Mars probably had a dense atmosphere from volcanic outgassing, with a stronger greenhouse effect than it has today.

The precise way in which Mars lost its carbon dioxide gas is not clear, but recent data suggest a close link to a change in Mars's magnetic field (Figure 7.34). Early in its history, Mars probably had molten convecting metals in its core, much like Earth today. The combination of this core convection and the planet's rotation should have produced a magnetic field and a protective magnetosphere around Mars. The magnetic field would have weakened as Mars cooled and the core ceased to convect, leaving the atmosphere vulnerable to solar wind particles. These solar wind particles could have stripped gases out of the Martian atmosphere and into space.

Mars underwent permanent climate change about 3 billion years ago, when it lost much of its atmospheric carbon dioxide and water to space.

Much of the water once present on Mars is also probably gone for good. Like the carbon dioxide, some water vapor may have been stripped away by the solar wind. However, Mars also lost water in another way. Because the Martian atmosphere lacks ultraviolet-absorbing gases, atmospheric water molecules would have been easily broken apart by ultraviolet photons. The hydrogen atoms that broke away from the water molecules would have been lost rapidly to space. With these hydrogen atoms gone, the water molecules could not be made whole again. Initially, oxygen from the water molecules would have remained in the atmosphere, but over time this oxygen was lost too. Some was probably stripped away by the solar wind, and the rest was drawn out of the atmosphere through chemical reactions with surface rock. This process literally rusted the Martian rocks, giving the "red planet" its distinctive tint.

We should learn much more about Mars with upcoming missions. The *Mars Science Laboratory*, scheduled for launch in 2011 and landing on Mars in 2012, is a nuclear-powered lab on wheels, designed to determine whether Mars has ever been suitable for life. The orbiting *MAVEN* mission, scheduled for launch in 2013, will measure the escape of gases from Mars's atmosphere today, and should help us learn whether the hypothesis summarized in Figure 7.34 stands up under close scrutiny.

Still, we already know enough to draw a general conclusion: Mars's fate was shaped primarily by its relatively small size. It was big enough for volcanism and outgassing to release water and atmospheric gas early in its history, but too small to maintain the internal heat needed to keep this water and gas. As its interior cooled, its volcanoes quieted and it lost its magnetic field, allowing gas to be stripped away to space. If Mars had been as large as Earth, so that it could still have outgassing and a global magnetic field, it might still have a moderate climate today.

think about it Could Mars still have flowing water today if it had formed closer to the Sun? Use your answer to explain how Mars's fate has been shaped not just by its size, but also by its distance from the Sun.

7.4 Venus: A Hothouse World

We have seen that planetary size is a major factor in explaining why the histories of the Moon, Mercury, and Mars have been so different from that of Earth. On the basis of size alone, we would expect Venus and Earth to be quite similar: Venus is only about 5% smaller than Earth in radius (see Figure 7.1), and its overall composition is about the same as that of Earth. However, as we saw in our planetary tour in Section 6.1, the surface of Venus is a searing hothouse, quite unlike the surface of Earth. In this section, we'll investigate how a planet so similar in size and composition to Earth ended up so different in almost every other respect.

• Is Venus geologically active?

As we did for Mars, let's begin our study of Venus by looking at what its surface geology tells us about its history. Venus's thick cloud cover prevents us from seeing through to its surface, but we can study its geological features with radar (because radio waves can pass through clouds). *Radar mapping* bounces radio waves off the surface and uses the reflections to create three-dimensional images of the surface. For four years, the *Magellan* spacecraft used radar to map the surface of Venus, discerning features as small as 100 meters across. Careful study suggests that Venus is indeed geologically active, just as we would expect for a planet almost as large as Earth.

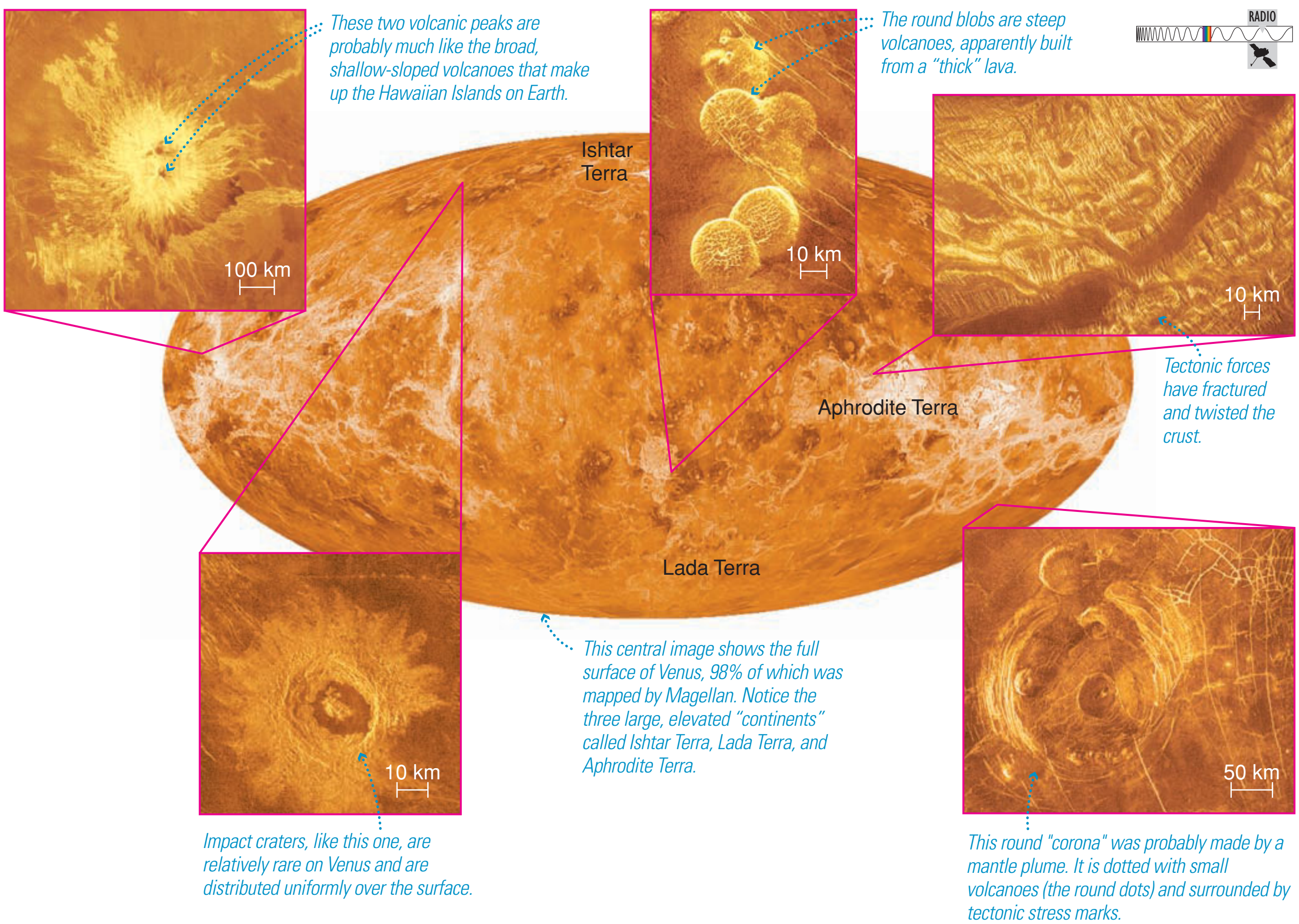


Figure 7.35

These images show the surface of Venus as revealed by radar observations from the *Magellan* spacecraft. Bright regions represent rough areas or higher altitudes.

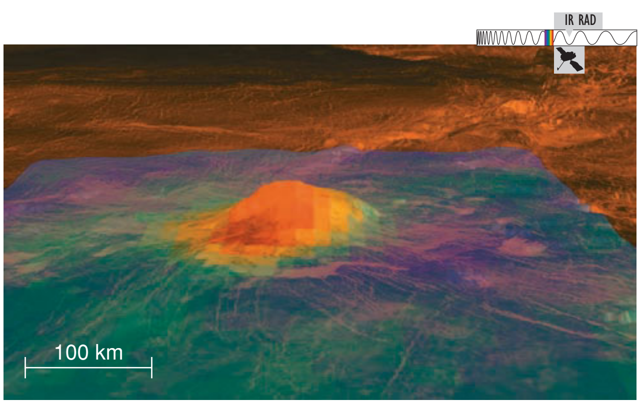


Figure 7.36

This composite image shows a volcano called Idunn Mons on Venus. Surface topography details are from NASA's *Magellan* radar mapper (enlarged about 30 times to make the volcano easier to see), and colors represent infrared data from the *Venus Express* spacecraft. Red colors indicate relatively new rock that has not been chemically altered by Venus's harsh atmosphere, suggesting that lava flows occurred within the past 250,000 years.

Geological Features of Venus Figure 7.35 shows a global map and selected close-ups of Venus based on the *Magellan* radar observations. We see many geological features similar to Earth's, including occasional impact craters, volcanoes, and a lithosphere that has been contorted by tectonic forces. Venus also has some unique features, such as the large, circular *coronae* (Latin for "crowns") that were probably made by hot, rising plumes of mantle rock. These plumes probably also forced lava to the surface, explaining the volcanoes found near coronae.

Venus shows features of volcanism and tectonics, just as we expect for a planet of similar size to Earth.

Venus almost certainly remains geologically active today, since it should still retain nearly as much internal heat as Earth. Its relatively few impact craters confirm that its surface is geologically young. In addition, the composition of Venus's clouds suggests that volcanoes must still be active on geological time scales (erupting within the past 100 million years). The clouds contain sulfuric acid, which is made from sulfur dioxide (SO_2) and water. Sulfur dioxide enters the atmosphere through volcanic outgassing, but once in the atmosphere it is gradually removed by chemical reactions with surface rocks. The fact that sulfuric acid clouds still exist means that outgassing must continue to supply sulfur dioxide to the atmosphere. The European Space Agency's *Venus Express* spacecraft, orbiting Venus since 2006, detected an infrared spectral feature on three volcanoes that suggests their rocks are "fresh," erupted perhaps as recently as 250,000 years ago (Figure 7.36). Scientists hope to learn more about Venus's atmosphere from Japan's *Akatsuki* mission, launched in 2010.

The biggest difference between the geology of Venus and that of Earth is the lack of erosion on Venus. We might naively expect Venus's thick atmosphere to produce strong erosion, but the view both from orbit and on the surface suggests that erosion is only a minor process. The former Soviet Union sent several landers to Venus in the 1970s and early 1980s. Before the intense surface heat destroyed them, the probes returned images of a bleak, volcanic landscape with little evidence of erosion (Figure 7.37). We can trace the lack of erosion on Venus to two facts. First, Venus is far too hot for any type of rain or snow on its surface. Second, Venus has virtually no wind or weather because of its slow rotation. Venus rotates so slowly—once every 243 days—that its atmosphere barely stirs the surface. Without any glaciers, rivers, rain, or strong winds, there is very little erosion on Venus.

Figure 7.37

This photo from one of the former Soviet Union's *Venera* landers shows Venus's surface; part of the lander is in the foreground. Many volcanic rocks are visible, hardly affected by erosion despite their presumed age of about 750 million years (the age of most of the surface).

The Absence of Plate Tectonics We can easily explain the lack of erosion on Venus, but another "missing feature" of its geology is more surprising: Venus shows no evidence of Earth-like plate tectonics. Plate tectonics shapes nearly all of Earth's major geological features, including mid-ocean ridges, deep ocean trenches, and long mountain ranges like the Rockies and Himalayas.

Venus lacks any similar features. Instead, Venus shows evidence of a very different type of global geological change. On Earth, plate tectonics resculpts the surface gradually, so that different regions have different ages. On Venus, the relatively few impact craters are distributed fairly uniformly over the entire planet, suggesting that the surface is about the same age everywhere. Crater counts suggest that the surface is about 750 million years old. Apparently, the entire surface of Venus was somehow "repaved" at that time.

We do not know how much of the repaving was due to tectonic processes and how much was due to volcanism, but both probably were important. It is even possible that plate tectonics played a role before and during the repaving, only to stop after the repaving episode was over. Either way, the absence of present-day plate tectonics on Venus poses a major mystery.

Earth's lithosphere was broken into plates by forces due to the underlying mantle convection. The lack of plate tectonics on Venus therefore suggests either that it has weaker mantle convection or that its lithosphere somehow resists fracturing. The first possibility seems unlikely: Venus's similar size to Earth means it should have a similar level of mantle convection. Most scientists therefore suspect that Venus's lithosphere resists fracturing into plates because it is thicker and stronger than Earth's lithosphere, though we have no direct evidence to support this hypothesis.

Venus's lack of Earth-like plate tectonics poses a scientific mystery, but may arise because Venus has a thicker and stronger lithosphere than Earth.

Even if a thicker and stronger lithosphere explains the lack of plate tectonics on Venus, we are still left with the question of why the lithospheres of Venus and Earth should differ. One possible answer invokes Venus's high surface temperature. Venus is so hot that any water in its crust and mantle has probably been baked out over time. Water tends to soften and lubricate rock, so its loss would have thickened and strengthened Venus's lithosphere. If this idea is correct, then Venus might have had plate tectonics if it had not become so hot in the first place.

• Why is Venus so hot?

It's tempting to attribute Venus's high surface temperature solely to the fact that it is closer than Earth to the Sun, but Venus would actually be quite cold without its strong greenhouse effect. Venus absorbs less sunlight than Earth, despite being closer to the Sun, because its clouds reflect so much sunlight back to space. Calculations show that Venus's average surface temperature would be a frigid −40°C (−40°F) without the greenhouse effect, rather than its actual temperature of about 470°C (880°F). The real question, then, is why Venus has such a strong greenhouse effect.

Venus's thick carbon dioxide atmosphere creates the extremely strong greenhouse effect that makes Venus so hot.

On a simple level, the answer is the huge amount of carbon dioxide in Venus's atmosphere. Venus has a far thicker atmosphere than Earth—its surface pressure is about 90 times that on Earth—and this atmosphere is about 96% carbon dioxide. The total amount of carbon dioxide in Venus's atmosphere is nearly 200,000 times that in Earth's atmosphere, and it creates an extremely strong greenhouse effect.

However, a deeper question still remains. Given their similar sizes and compositions, we expect Venus and Earth to have had similar levels of volcanic outgassing—and the released gas ought to have had about the same composition on both worlds. Why, then, is Venus's atmosphere so different from Earth's?

Atmospheric Composition We expect that huge amounts of water and carbon dioxide should have been outgassed into the atmospheres of both Venus and Earth. Venus's atmosphere does indeed have huge amounts of carbon dioxide, but it has virtually no water. Earth's atmosphere has very little of either gas. We conclude that Venus must have somehow lost its outgassed water, while Earth has lost both water vapor and carbon dioxide. But how were these gases lost?

Earth has as much carbon dioxide as Venus, but it is mostly locked away in rocks rather than in our atmosphere.

We can easily account for both missing gases on Earth. The huge amounts of water vapor released into our atmosphere condensed into rain, forming our oceans. In other words, the water is still here, but mostly in liquid rather than gaseous form. The huge amount of carbon dioxide released into our atmosphere is also still here, but in solid form: Carbon dioxide dissolves in water, where it can undergo chemical reactions to make **carbonate rocks** (rocks rich in carbon and oxygen) such as limestone. Earth has about 170,000 times as much carbon dioxide locked up in rocks as in its atmosphere—which means that Earth does indeed have about as much total carbon dioxide as Venus. Of course, the fact that Earth's carbon dioxide is mostly in rocks rather than in the atmosphere makes all the difference in the world: If this carbon dioxide were in our atmosphere, our planet would be nearly as hot as Venus and certainly uninhabitable.

We are left with the question of what happened to Venus's water. Venus has no oceans and little atmospheric water, and as noted earlier, any water in its crust and mantle was probably baked out long ago. This absence of water explains why Venus retains so much carbon dioxide in its atmosphere: Without oceans, carbon dioxide cannot dissolve or become locked away in carbonate rocks. If it is true that a huge amount of water was outgassed on Venus, it has somehow disappeared.

The leading hypothesis for the disappearance of Venus's water invokes one of the same processes thought to have removed water from Mars. Ultraviolet light from the Sun breaks apart water molecules in

Venus's atmosphere. The hydrogen atoms then escape to space, ensuring that the water molecules can never re-form. The oxygen from the water molecules is lost to a combination of chemical reactions with surface rocks and stripping by the solar wind; Venus's lack of magnetic field leaves its atmosphere vulnerable to the solar wind.

Venus retains carbon dioxide in its atmosphere because it lacks oceans to dissolve the carbon dioxide and lock it away in rock.

Acting over billions of years, the breakdown of water molecules and the escape of hydrogen can easily explain the loss of an ocean's worth of water from Venus—as long as the water was in the atmosphere rather than in liquid oceans. Our quest to understand Venus's high temperature thereby leads to one more question: Why didn't Venus get oceans like Earth, which would have prevented its water from being lost to space?

The Runaway Greenhouse Effect

To understand why Venus does not have oceans, let's consider what would happen if we could magically move Earth to the orbit of Venus (Figure 7.38).

The greater intensity of sunlight would almost immediately raise Earth's global average temperature by about 30°C, from its current 15°C to about 45°C (113°F). Although this is still well below the boiling point of water, the higher temperature would lead to increased evaporation of water from the oceans. The higher temperature would also allow the atmosphere to hold more water vapor before the vapor condensed to make rain. The combination of more evaporation and greater atmospheric capacity for water vapor would substantially increase the total amount of water vapor in Earth's atmosphere. Now, remember that water vapor, like carbon dioxide, is a greenhouse gas. The added water vapor would therefore strengthen the greenhouse effect, driving temperatures a little higher. The higher temperatures, in turn, would lead to even more ocean evaporation and more water vapor in the atmosphere—strengthening the greenhouse effect even further. In other words, we'd have a positive feedback loop in which each little bit of additional water vapor in the atmosphere would mean higher temperature and even more water vapor. The process would careen rapidly out of control as a **runaway greenhouse effect.**

The runaway process would cause Earth to heat up until the oceans were completely evaporated and the carbonate rocks had released all their carbon dioxide back into the atmosphere. By the time the process was complete, temperatures on our "moved Earth" would be even higher than they are on Venus today, thanks to the combined greenhouse effects of carbon dioxide and water vapor in the atmosphere. The water vapor would then gradually disappear, as ultraviolet light broke water molecules apart and the hydrogen escaped to space. In short, moving Earth to Venus's orbit would essentially turn our planet into another Venus.

Venus is too close to the Sun to have liquid water oceans. Without water to dissolve carbon dioxide gas, Venus was doomed to its runaway greenhouse effect.

We have arrived at a simple explanation of why Venus is so much hotter than Earth. Even though Venus is only about 30% closer to the Sun than Earth, this difference was enough to be critical. On Earth, it was cool enough for water to rain down to make oceans. The oceans then dissolved carbon dioxide and chemical reactions locked it away in carbonate rocks, leaving our atmosphere with only enough greenhouse gases to make our planet pleasantly warm. On Venus, the greater intensity of sunlight made it just enough warmer that oceans either never formed or soon evaporated, leaving Venus with a thick atmosphere full of greenhouse gases.

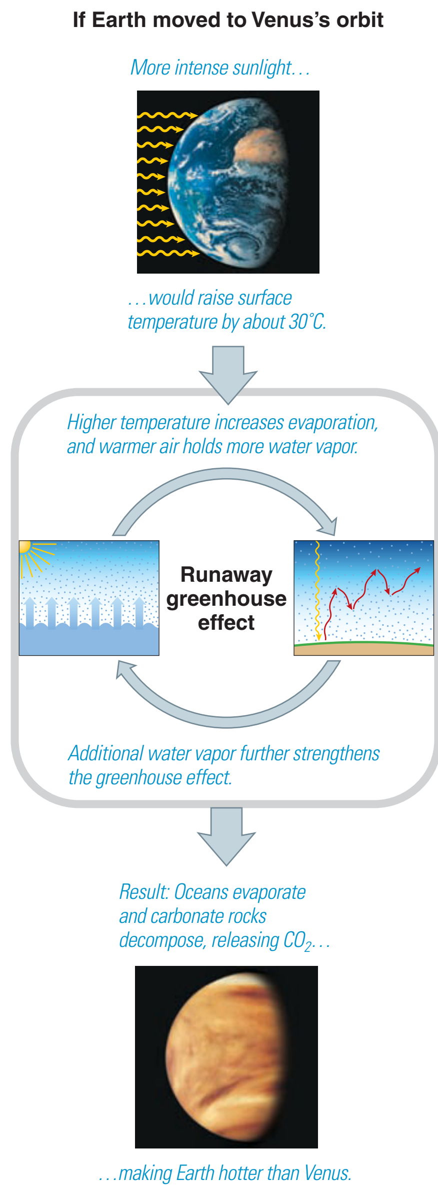


Figure 7.38

This diagram shows how, if Earth were placed at Venus's distance from the Sun, the runaway greenhouse effect would cause the oceans to evaporate completely.

The next time you see Venus shining brightly as the morning or evening "star," consider the radically different path it has taken from that taken by Earth—and thank your lucky star. If Earth had formed a bit closer to the Sun or if the Sun had been slightly hotter, our planet might have suffered the same greenhouse-baked fate.

think about it We've seen that moving Earth to Venus's orbit would cause our planet to become Venus-like. If we could somehow move Venus to Earth's orbit, would it become Earth-like? Why or why not?

7.5 Earth as a Living Planet

We began this chapter by discussing Earth as a planet, looking at features and processes that it shares in common with some of our planetary neighbors. We then explored the histories of the other terrestrial worlds, finding that we could understand them by thinking about fundamental planetary properties (such as size and distance from the Sun) and processes familiar to us from Earth. However, we have not yet discussed the feature that makes Earth truly unique: its abundance of life, including human life. It is time for us to turn our attention back to Earth, to see how and why our planet is such a pleasant place for us to live.

• What unique features of Earth are important for life?

If you think about what we've learned about the terrestrial worlds, you can probably identify a number of features that are unique to Earth. Four unique features turn out to be particularly important to life on Earth:

- **Surface liquid water:** Earth is the only planet on which temperature and pressure conditions allow surface water to be stable as a liquid.
- **Atmospheric oxygen:** Earth is the only planet with significant oxygen in its atmosphere and an ozone layer.
- **Plate tectonics:** Earth is the only planet with a surface shaped largely by this distinctive type of tectonics.
- **Climate stability:** Earth differs from the other terrestrial worlds with significant atmospheres (Venus and Mars) in having a climate that has remained relatively stable throughout its history.

Our Unique Oceans and Atmosphere The first and second items in our list—abundant liquid water and atmospheric oxygen—are clearly important to our existence. Life as we know it requires water **[Section 18.1]**, and animal life requires oxygen. We have already explained the origin of Earth's water: Water vapor outgassed from volcanoes rained down on the surface to make the oceans and neither froze nor evaporated thanks to our moderate greenhouse effect and distance from the Sun. But where did the oxygen in our atmosphere come from?

Oxygen (O_2) is not a product of volcanic outgassing. In fact, no geological process can explain how oxygen came to make up such a large fraction (21%) of Earth's atmosphere. Moreover, oxygen is a highly reactive gas that would disappear from the atmosphere in just a few million years if it were not continuously resupplied. Fire, rust, and the discoloration of freshly cut fruits and vegetables are everyday examples of chemical reactions that remove oxygen from the atmosphere. Similar

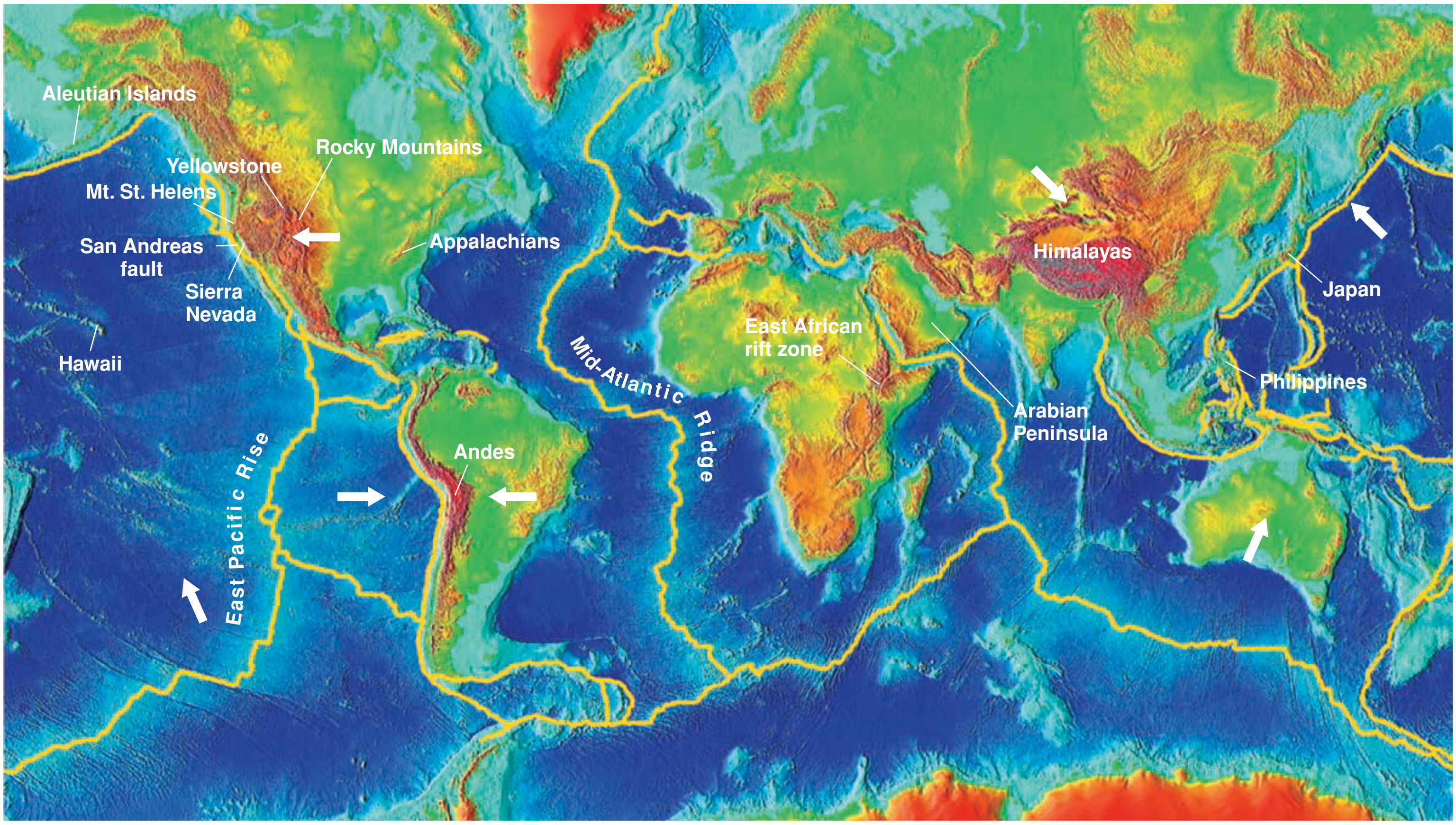


Figure 7.39

This relief map shows plate boundaries (solid yellow lines), with arrows to represent directions of plate motion. Color represents elevation, progressing from blue (lowest) to red (highest).

reactions between oxygen and surface materials give rise to the reddish appearance of much of Earth's rock and clay, including the beautiful reds of Arizona's Grand Canyon. So we must explain not only how oxygen got into Earth's atmosphere in the first place, but also how the amount of oxygen remains relatively steady even though chemical reactions remove it rapidly from the atmosphere.

Without life, there would be no oxygen in Earth's atmosphere.

The answer to the oxygen mystery is life itself. Plants and many microorganisms release oxygen through photosynthesis. Photosynthesis takes in CO_2 and releases O_2. The carbon becomes incorporated into living tissues. Virtually all Earth's oxygen was originally released into the atmosphere by photosynthetic life. Today, photosynthetic organisms return oxygen to the atmosphere in approximate balance with the rate at which animals and chemical reactions consume it, which is why the oxygen concentration remains relatively steady. This oxygen is also what makes possible Earth's protective ozone layer, since ozone (O_3) is produced from ordinary oxygen (O_2).

think about it Suppose that, somehow, all photosynthetic life (such as plants) died out. What would happen to the oxygen in our atmosphere? Could animals, including us, still survive?

Plate Tectonics The third and fourth items on our list—plate tectonics and climate stability—turn out to be closely linked. Recall that Earth's lithosphere is broken into more than a dozen plates that slowly move about through the action we call *plate tectonics* (Figure 7.39). The plate motions are barely noticeable on human time scales. On average, plates move at speeds of only a few centimeters per year—about the same

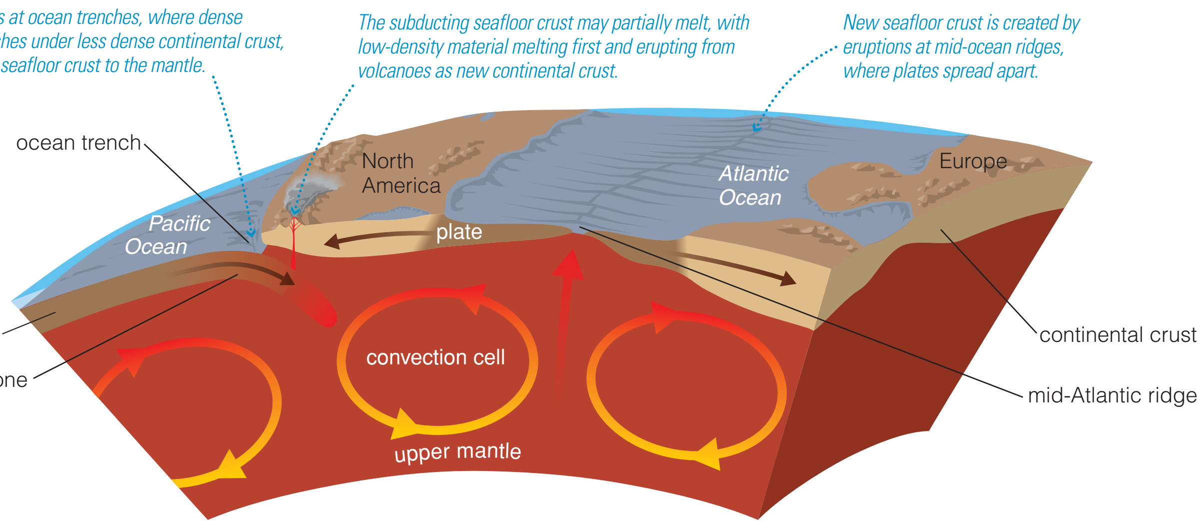


Figure 7.40

Plate tectonics acts like a giant conveyor belt for Earth's lithosphere.

speed at which your fingernails grow. Nevertheless, over millions of years, these motions rearrange the locations of continents, open ocean basins between continents, build mountain ranges, and much more.

The movements of plate tectonics act like a giant conveyor belt for Earth's lithosphere, creating new crust and recycling old crust back into the mantle (Figure 7.40). Mantle material rises upward and erupts to the surface along mid-ocean ridges, becoming new crust for the seafloor, or **seafloor crust** for short. This newly emerging material causes the seafloor to spread away from the ridge, which is why the ridges are found in the middle of the ocean. Over tens of millions of years, any piece of seafloor crust gradually makes its way across the ocean bottom, then finally gets recycled into the mantle in the process we call **subduction**.

Plate tectonics acts like a giant conveyor belt for Earth's lithosphere, continually recycling seafloor crust and building up the continents.

Subduction occurs where seafloor plates run into continental plates. As seafloor crust descends into the mantle, it is heated and may partially melt. This molten rock then erupts from volcanoes over the subduction zones, which is why so many active volcanoes tend to be found along the edges of continents. Moreover, the lowest-density material tends to melt first, so the **continental crust** emerging from these landlocked volcanoes is much lower in density than seafloor crust. This lower density explains why continents rise above the seafloor. Radiometric dating confirms this picture of plate tectonics. Seafloor crust is never more than a couple of hundred million years old (because it is recycled at the subduction zones) and is younger near the mid-ocean ridges (where it first emerges and solidifies).

In fact, almost all Earth's active geology is tied to plate tectonics. For example, compression of the crust and mountain building occurs where continental plates are pushed together, and valleys or seas can form where continental plates are pulling apart (see Figure 7.11). Earthquakes tend to occur when two plates get "stuck" against one another and then lurch violently when the pressure builds to the breaking point. Even the present arrangement of the continents is due to plate tectonics, since the continents are slowly pushed around as seafloors spread and subduct (Figure 7.41).

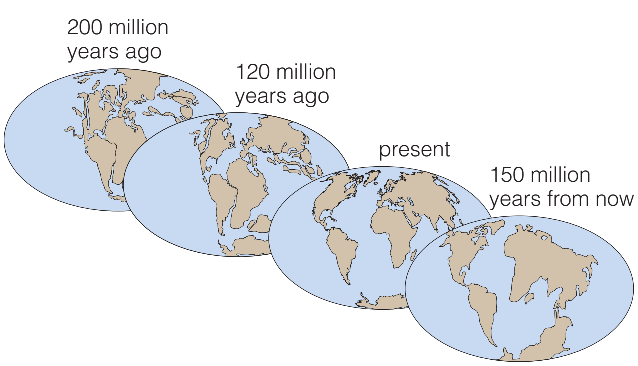


Figure 7.41

Past, present, and future arrangements of Earth's continents. Notice how the present shapes of South America and Africa reflect the way they fit together in the past. The continents are always in motion, so the arrangement looked different at earlier times and will look different in the future.

think about it By studying the plate boundaries in Figure 7.39, explain why the west coast states of California, Oregon, and Washington are prone to more earthquakes and volcanoes than other parts of the United States. Find the locations of recent earthquakes and volcanic eruptions worldwide. Do the locations fit the pattern you expect?

Climate Stability Earth's long-term climate stability has clearly been important to the ongoing evolution of life—and hence to our own relatively recent arrival as a species (see Figure 1.10). Had our planet undergone a runaway greenhouse effect like Venus, life would certainly have been extinguished. If Earth had suffered loss of atmosphere and a global freezing like Mars, any surviving life would have been driven to hide in underground pockets of liquid water.

Earth's climate is not perfectly stable—our planet has endured numerous ice ages and warm periods in the past. Nevertheless, even in the deepest ice ages and warmest warm periods, Earth's temperature has remained in a range in which some liquid water could still exist and harbor life. This long-term climate stability is even more remarkable, because models suggest that the Sun has brightened substantially (about 30%) over the past 4 billion years, yet Earth's temperature has managed to stay in the same range throughout this time. The key to this climate stability must lie with the greenhouse effect: The strength of the greenhouse effect somehow self-adjusts to keep the climate stable.

The mechanism by which Earth self-regulates its temperature is called the **carbon dioxide cycle**, or the **CO_2 cycle** for short. Let's follow the cycle as illustrated in Figure 7.42, starting at the top center:

- Atmospheric carbon dioxide dissolves in rainwater, creating a mild acid.
- The mildly acidic rainfall erodes rocks on Earth's continents, and rivers carry the broken-down minerals to the oceans.
- In the oceans, the eroded minerals combine with dissolved carbon dioxide and fall to the ocean floor, making carbonate rocks such as limestone.
- Over millions of years, the conveyor belt of plate tectonics carries the carbonate rocks to subduction zones, where they are carried downward.
- As they are pushed deeper into the mantle, some of the subducted carbonate rock melts and releases its carbon dioxide, which then outgasses back into the atmosphere through volcanoes.

The CO_2 cycle acts as a long-term thermostat for Earth, because the overall rate at which carbon dioxide is pulled from the atmosphere is very sensitive to temperature: the higher the temperature, the higher the rate at which carbon dioxide is removed. As a result, a small change in Earth's temperature will be offset by a change in the CO_2 cycle.

Earth has remained habitable for billions of years because its climate is kept stable by the natural action of the carbon dioxide cycle.

Consider first what happens if Earth warms up a bit. The warmer temperature means more evaporation and rainfall, pulling more CO_2 out of the atmosphere. The reduced atmospheric CO_2 concentration leads to a weakened greenhouse effect that counteracts the initial warming and cools the planet back down. Similarly, if Earth cools a bit, precipitation decreases and less CO_2 is dissolved in rainwater, allowing the CO_2 released by volcanism to build back up in the atmosphere. The increased CO_2 concentration strengthens the greenhouse effect and warms the planet back up. Overall, the natural thermostat of the carbon dioxide cycle has allowed the greenhouse effect to strengthen or weaken just enough to keep Earth's climate fairly stable, regardless of what other changes have occurred on our planet. Note, however, that this cycle operates on a time scale of a few hundred thousand years, which means it has no effect on short-term changes, such as those we will discuss next.

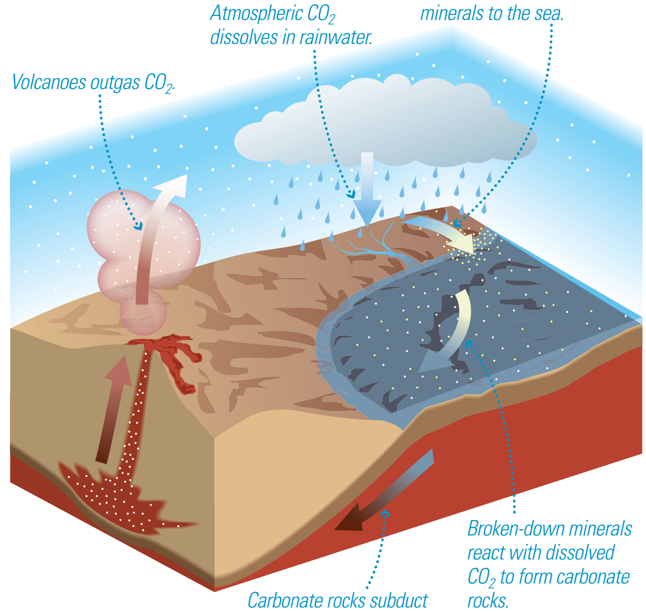


Figure 7.42

This diagram shows how the CO_2 cycle continually moves carbon dioxide from the atmosphere to the ocean to rock and back to the atmosphere. Notice that plate tectonics (subduction in particular) plays a crucial role in the cycle.

common Misconceptions

The Greenhouse Effect Is Bad

The greenhouse effect is often in the news, usually in discussions about environmental problems, but in itself the greenhouse effect is not a bad thing. In fact, we could not exist without it, since it is responsible for keeping our planet warm enough for liquid water to flow in the oceans and on the surface. The "no greenhouse" temperature of Earth is well below freezing. Why, then, is the greenhouse effect discussed as an environmental problem? The reason is that human activity is adding more greenhouse gases to the atmosphere—and scientists agree that the additional gases are changing Earth's climate. While the greenhouse effect makes Earth livable, it is also responsible for the searing 470°C temperature of Venus—proving that it's possible to have too much of a good thing.

We can now see why plate tectonics is so intimately connected to our existence. Plate tectonics is a crucial part of the CO_2 cycle; without plate tectonics, CO_2 would remain locked up in seafloor rocks rather than being recycled through outgassing. Earth's climate might then have undergone changes as dramatic as those that occurred on Venus and Mars.

• How is human activity changing our planet?

We humans are well adapted to the unique, present-day conditions on our planet. The amount of oxygen in our atmosphere, the average temperature of our planet, and the ultraviolet-absorbing ozone layer are just what we need to survive. We have seen that these "ideal" conditions are no accident—they are consequences of our planet's unique geology and biology.

Nevertheless, the stories of the dramatic and permanent climate changes that occurred on Venus and Mars should teach us to take nothing for granted. Our planet may regulate its own climate quite effectively over long time scales, but fossil and geological evidence tells us that substantial and rapid swings in global climate can occur on shorter ones. For example, Earth cycles in and out of ice ages on geologically short time scales of tens of thousands of years, and in some cases the climate seems to have warmed several degrees Celsius in just decades. Evidence also shows that these past climate changes have had dramatic effects on local climates by raising or lowering sea level, altering ocean currents that keep coastlines warm, and transforming rainforests into deserts.

These past climate changes have been due to "natural" causes. For example, cycles of ice ages have been linked to small, cyclical changes in Earth's axis tilt and other characteristics of Earth's rotation and orbit (called *Milankovitch cycles*). More rapid changes may be linked to major volcanic eruptions, sudden releases of trapped carbon dioxide from the oceans, or a variety of other geological processes. Today, however, Earth is undergoing climate change for a new reason: Human activity is rapidly increasing the atmospheric concentration of carbon dioxide and other greenhouse gases (such as methane). Effects of this increase in greenhouse gas concentration are apparent already: Global average temperatures have risen by about 0.8°C (1.4°F) in the past century (Figure 7.43). This **global warming** is one of the most important issues of our time.

Global Warming Global warming has been a hot political issue, both because some people debate its cause and because efforts to slow or stop the warming would require finding new energy sources and making

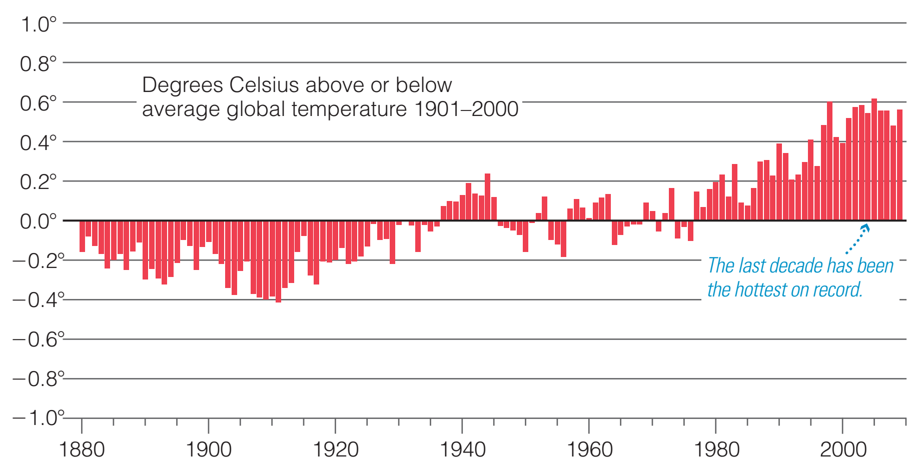


Figure 7.43

Average global temperatures from 1880 through 2009. Notice the clear global warming trend of the past few decades. (Data from the National Climate Data Center.)

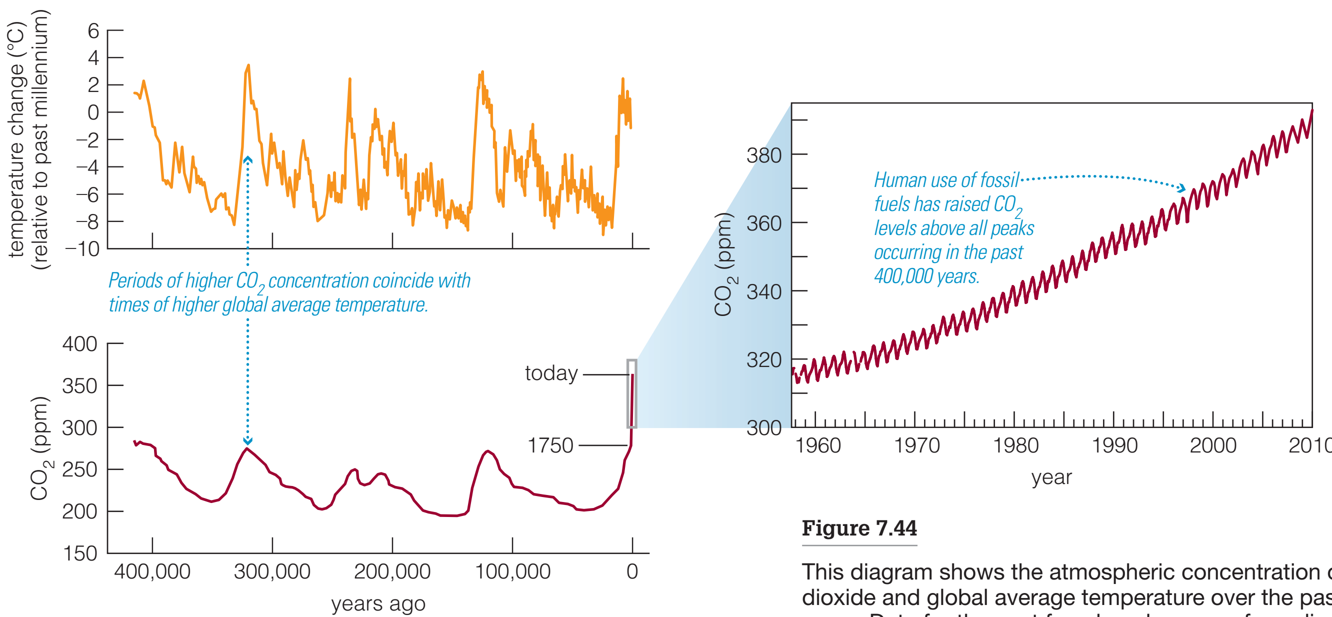


Figure 7.44

This diagram shows the atmospheric concentration of carbon dioxide and global average temperature over the past 400,000 years. Data for the past few decades come from direct measurements; most of the earlier data come from studies of air bubbles trapped in Antarctic ice (ice core samples). The recent CO_2 increase is due to fossil fuels, because carbon from these fuels has a different isotopic makeup than that from other sources. The CO_2 concentration is measured in parts per million (ppm), which is the number of CO_2 molecules among every 1 million air molecules.

other changes that would dramatically affect the world's economy. However, a major research effort has gradually added to our understanding of the potential threat, particularly in the past decade. The case linking global warming with human activity rests on three basic facts:

1. The greenhouse effect is a simple and well-understood scientific model. We can be confident in our understanding of it because it so successfully explains the observed surface temperatures of other planets. Given this basic model, there is no doubt that a rising concentration of greenhouse gases would make our planet warm up more than it would otherwise; the only debate is about how soon and how much.
2. The burning of fossil fuels and other human activity are clearly increasing the amounts of greenhouse gases in the atmosphere. Observations show that the current atmospheric concentration of carbon dioxide is significantly higher (about 30%) than it has been at any time during the past million years, and it is rising rapidly (Figure 7.44).
3. Climate models that ignore human activity fail to match the observed rise in global temperatures. In contrast, climate models that include the enhanced greenhouse effect from human production of greenhouse gases match the observed temperature trend quite well (Figure 7.45). Comparisons between observations and models therefore provide evidence that global warming results from human activity.

These facts, summarized in Figure 7.46, offer convincing evidence that we humans are now tinkering with the climate in a way that may cause major changes not just in the distant future, but in our own lifetimes. The same models that convince scientists of the reality of human-induced global warming tell us that if current trends in greenhouse gas concentrations continue—that is, if we do nothing to slow our emissions of carbon dioxide and other greenhouse gases—the warming trend will continue to accelerate. By the end of this century, the global average temperature will be 3°–5°C (6°–10°F) higher than it is now, giving our children and

Human activity is rapidly increasing the atmospheric concentrations of greenhouse gases, causing the global average temperature to rise.

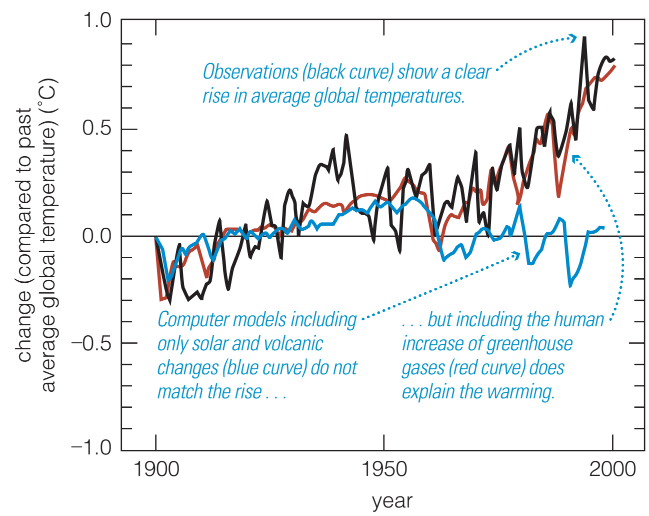


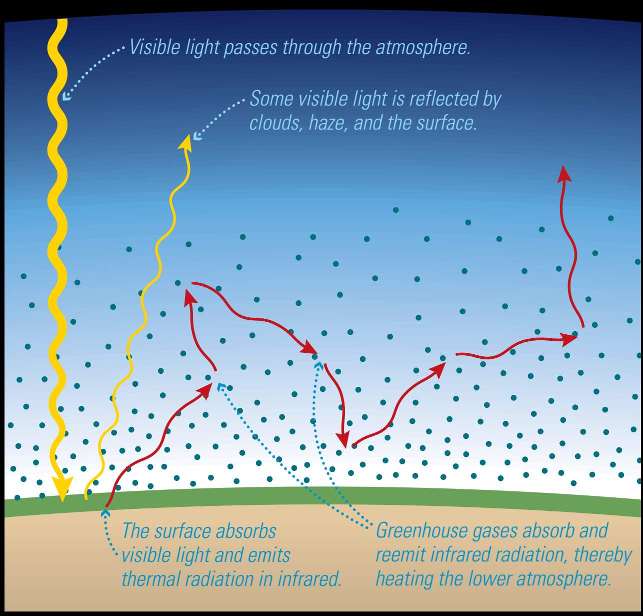
Figure 7.45

This graph compares observed temperature changes (black curve) with the predictions of climate models. The blue curve represents model predictions that include only natural factors, such as changes in the brightness of the Sun and effects of volcanoes. The red curve represents model predictions that include the human contribution due to increasing greenhouse gas concentrations along with the natural factors. Notice that only the red curve matches the observations well, especially for recent decades, providing very strong evidence that global warming is a result of human activity. (The red and blue model curves are each averages of many scientists' independent models of global warming, which generally agree with each other within 0.1–0.2°C.)

Figure 7.46. Global Warming

Scientific studies of global warming apply the same basic approach used in all areas of science: We create models of nature, compare the predictions of those models with observations, and use our comparisons to improve the models. We have found that climate models agree more closely with observations if they include human production of greenhouse gases like carbon dioxide, making scientists confident that human activity is indeed causing global warming.

1. The greenhouse effect makes a planetary surface warmer than it would be otherwise because greenhouse gases such as carbon dioxide, methane, and water vapor slow the escape of infrared light radiated by the planet. Scientists have great confidence in models of the greenhouse effect because they successfully predict the surface temperatures of Venus, Earth, and Mars.

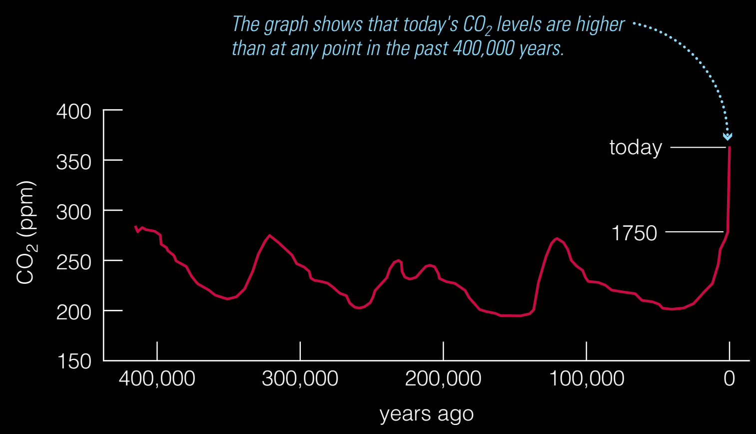


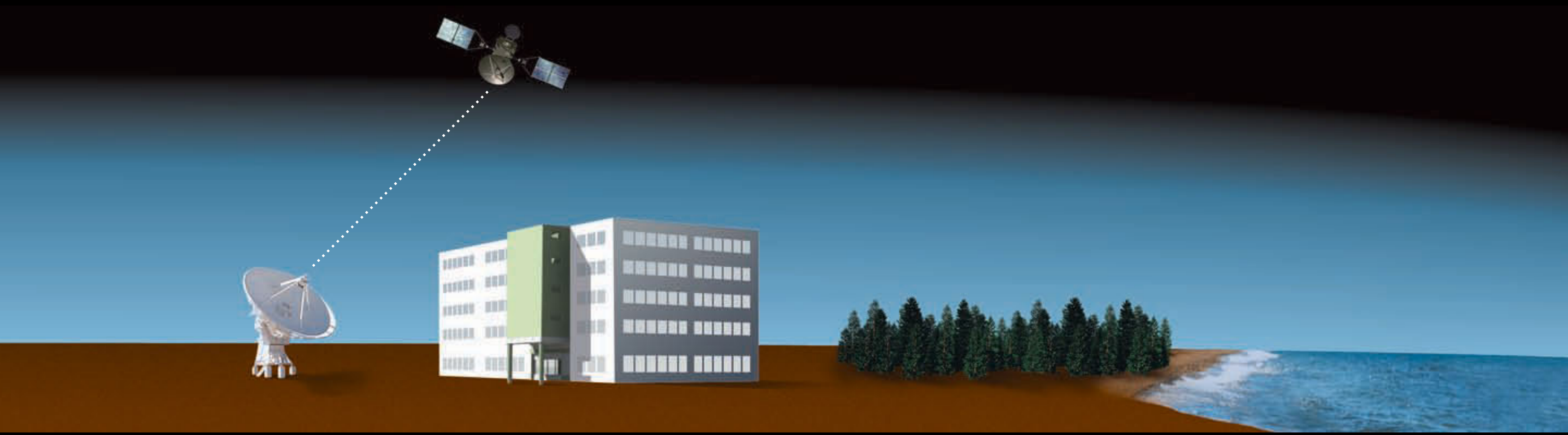
Global Average Surface Temperature

Planet	Temperature Without Greenhouse Effect	Temperature With Greenhouse Effect
Venus	–40°C	470°C
Earth	–16°C	15°C
Mars	–56°C	–50°C

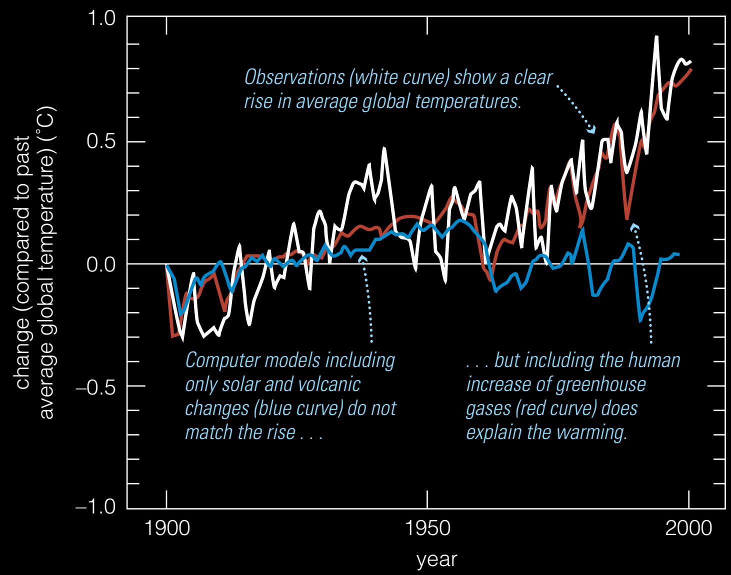
This table shows planetary temperatures as they would be without the greenhouse effect and as they actually are with it. The greenhouse effect makes Earth warm enough for liquid water and Venus hotter than a pizza oven.

2. Human activity is adding carbon dioxide and other greenhouse gases to the atmosphere. While the carbon dioxide concentration also varies naturally, it is now much higher than it has been at any time in the previous million years, and it is continuing to rise rapidly.





3 Observations show that Earth's average surface temperature has risen during the last several decades. Computer models of Earth's climate show that an increased greenhouse effect triggered by CO_2 from human activities can explain the observed temperature increase.



HALLMARK OF SCIENCE **Science progresses through creation and testing of models of nature that explain the observations as simply as possible.** Observations showing a rise in Earth's temperature demand a scientific explanation. Models that include an increased greenhouse effect due to human activity explain those observations better than models without human activity.

4 Models can also be used to predict the consequences of a continued rise in greenhouse gas concentrations. These models show that, without significant reductions in greenhouse gas emissions, we should expect further increases in global average temperature, rising sea levels, and more intense and destructive weather patterns.

This diagram shows the change in Florida's coastline that would occur if sea levels rose by 1 meter. Some models predict that this rise could occur within a century. The light blue regions show portions of the existing coastline that would be flooded.

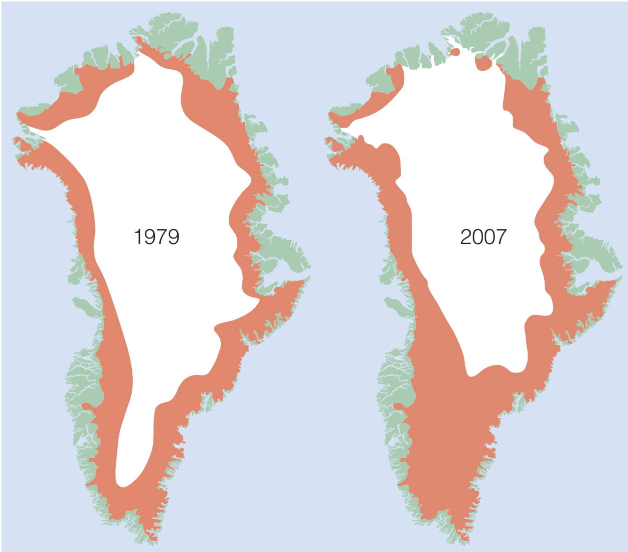


Figure 7.47

These maps contrast the extent of the year-round Greenland ice sheet, shown in white, in 1979 and 2007. The orange area indicates the region where melting occurs during the warm season. Notice that the melt region has expanded significantly, extending both further inland (to higher elevations) and further north.

grandchildren the warmest climate that any generation of *Homo sapiens* has ever experienced.

Consequences of Global Warming An increase in temperature of a few degrees might not sound so bad, but small changes in *average* temperature can lead to much more dramatic changes in climate patterns. These changes will cause some regions to warm much more than the average, while other regions may actually cool. Some regions might experience more rainfall or might become deserts.

Polar regions will warm the most, causing polar ice to melt. This is clearly threatening to the species of these regions (polar bears, which depend on an abundance of ice floes, are already under pressure), but it also warms the oceans everywhere and changes their salt content as melting ice pours more fresh water into the sea. The fact that the waters of the Gulf of Mexico are at their warmest level in at least a century may be contributing to the greater strength of hurricanes that have recently blown out of the Caribbean, though it is difficult to cite causes for specific storms. More generally, the greater overall warmth of the atmosphere will increase evaporation from the oceans, leading to more numerous and more intense storms; ironically, this fact means that global warming could mean more severe winter blizzards. Some researchers also worry that the influx of large quantities of fresh water into the oceans may alter major ocean currents, such as the Gulf Stream—a "river" within the ocean that regulates the climate of western Europe and parts of the United States.

Melting polar ice may significantly increase sea level in the future, but global warming has already caused a rise in sea level for a different reason. Water expands very slightly as it warms—so slightly that we don't notice the change in a glass of water, but enough that sea level has risen some 20 centimeters in the past hundred years. This effect alone could cause sea level to rise as much as another meter during this century, with potentially devastating effect to coastal communities and low-lying countries such as Bangladesh. The added effect of melting ice could increase sea level much more. While the melting of ice in the Arctic Ocean does not affect sea level—it is already floating—melting of landlocked ice does. Such melting appears to be occurring already. For example, the famous "snows" (glaciers) of Mount Kilimanjaro are rapidly retreating and may be gone within the next decade or so. More ominously, recent data suggest that the Greenland ice sheet is melting much more rapidly than models have predicted (Figure 7.47). If this trend continues, sea level could rise as much as several *meters*—enough to flood much of Florida by the end of this century (see Step 4 in Figure 7.46). Looking further ahead, complete melting of the polar ice caps would increase sea level by some 70 meters (more than 200 feet). Although such melting would probably take centuries or millennia, it suggests the disconcerting possibility that future generations will have to send deep-sea divers to explore the underwater ruins of many of our major cities.

Fortunately, most scientists believe that we still have time to avert the most serious consequences of global warming, provided we dramatically and rapidly curtail our greenhouse gas emissions. The most obvious way to cut back on these emissions is to improve energy efficiency. Doubling the average gas mileage of cars—which we could do easily with current technology—would immediately cut automobile-related carbon dioxide emissions in half. Other tactics include replacing fossil fuels with alternative energy sources such as solar, wind, nuclear, and biofuels, and perhaps even finding ways to bury the carbon dioxide by-products of the fossil fuels that we still use. The key idea to keep in mind is that global warming is a global problem, and it will therefore require significant international cooperation if we hope to solve it. But there is precedent for success: In the 1980s and 1990s, as we learned that human-produced chemicals (known as CFCs) were causing great damage to the ozone layer, the nations of the world agreed on a series of treaties that ultimately phased those chemicals out of production. As a result, the ozone layer is beginning to recover from its earlier damage, and we learned that people can indeed be moved to act in the face of a threat to the environment on which we depend for survival.

think about it If you were a political leader, how would you deal with the threat of global warming?

• What makes a planet habitable?

We have discussed the features of our planet that have made our world habitable for a great variety of life, including us. But why is Earth the only terrestrial world that has these features?

Our comparative study of the terrestrial worlds tells us there are two primary answers, both summarized in Figure 7.48. First, Earth is habitable because it is large enough to have remained geologically active

Figure 7.48

This illustration shows how a terrestrial world's size and distance from the Sun help determine its geological history and whether it has conditions suitable for life. Earth is habitable because it is large enough and at a suitably moderate distance from the Sun.

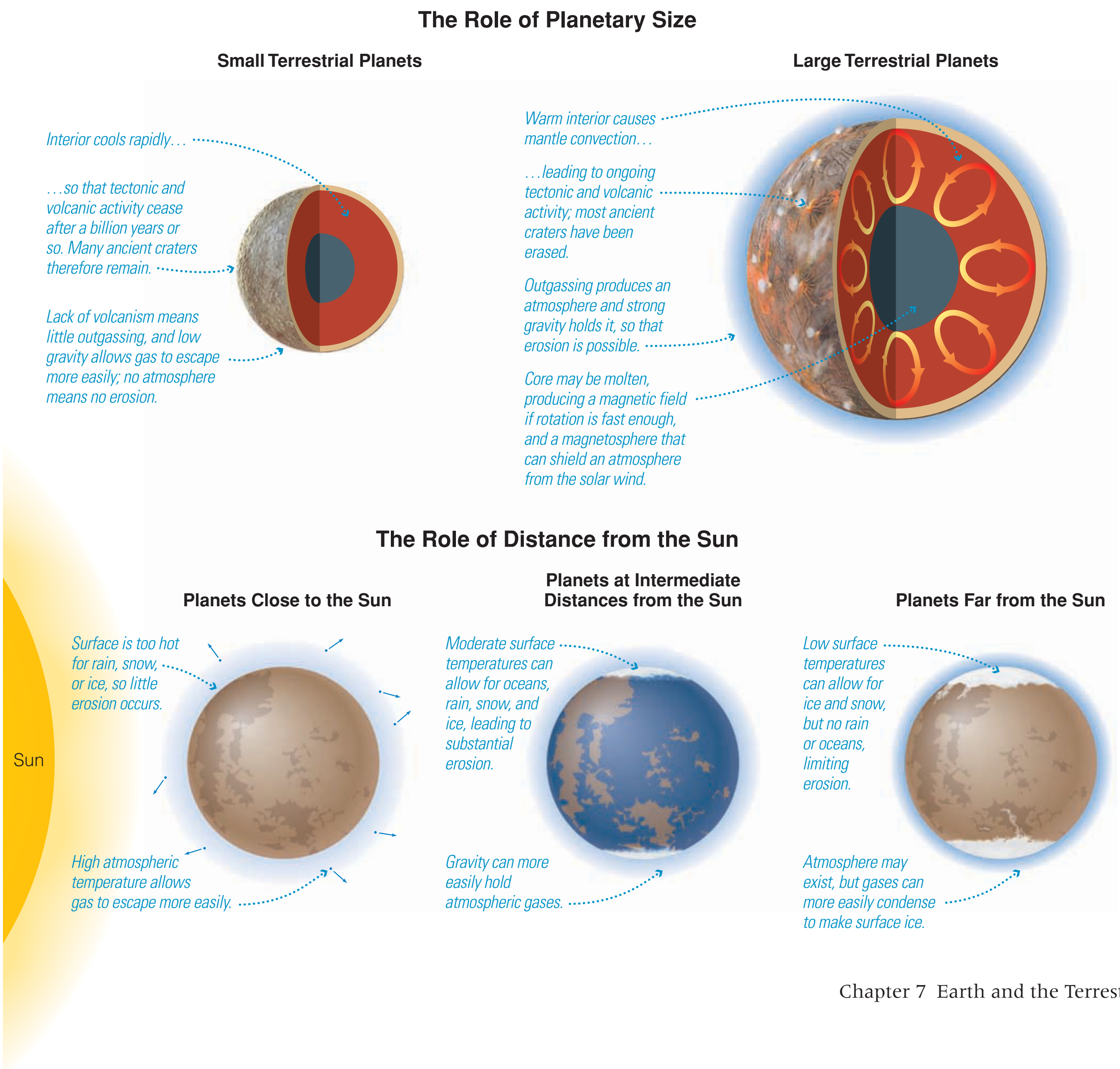
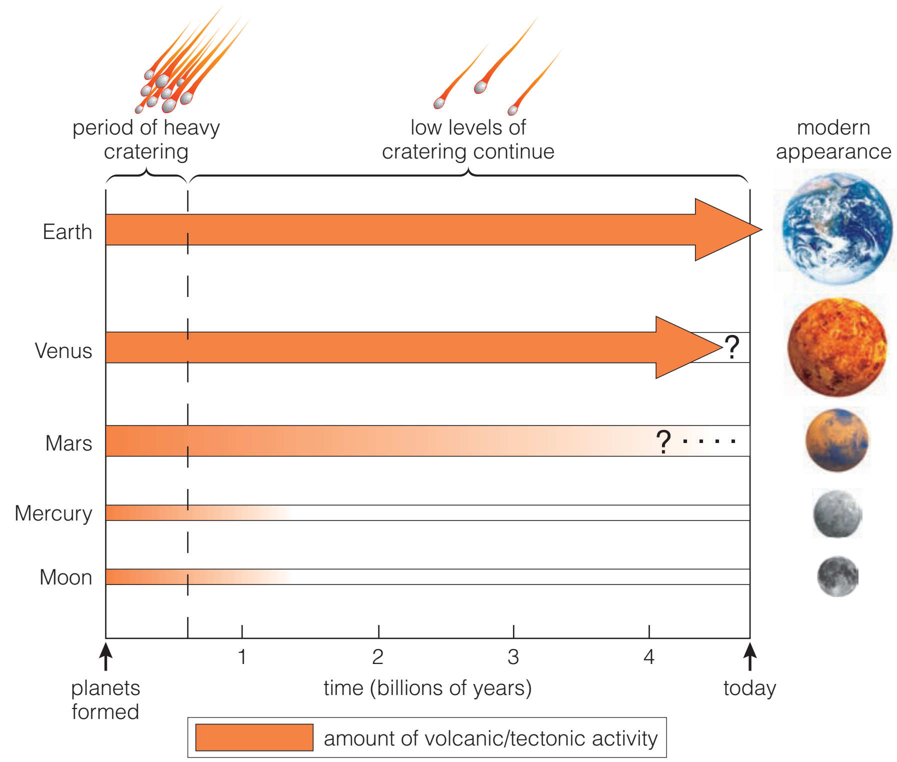


Figure 7.49

This diagram summarizes the geological histories of the terrestrial worlds. The brackets along the top indicate that impact cratering has affected all worlds similarly. The arrows represent volcanic and tectonic activity. A thicker and darker arrow means more volcanic/tectonic activity, and the arrow length tells us how long this activity persisted. Notice that the trend follows the order of planetary size: Earth remains active to this day. Venus has also been quite active, though we are uncertain whether it remains so. Mars has had an intermediate level of activity and might still have low-level volcanism. Mercury and the Moon have had very little volcanic/tectonic activity. Erosion is not shown, because it has played a significant role only on Earth (ongoing) and on Mars (where it was quite significant in the past and continues at low levels today).



since its birth, so that outgassing could release the water and gases that formed our atmosphere and oceans. In addition, the core has remained hot enough that Earth has retained a global magnetic field, which generates a magnetosphere that protects our atmosphere from the solar wind. Second, we are located at a distance from the Sun where outgassed water vapor was able to condense and rain down to form oceans, making possible the carbon dioxide cycle that regulates our climate.

Earth is habitable because it is large enough to remain geologically active and located at a distance from the Sun where oceans were able to form.

Figure 7.49 shows the trends we've seen for the terrestrial planets in our solar system, which should make sense as you examine the role of planetary size. In principle, these lessons mean we can now predict the geological and atmospheric properties of terrestrial worlds that we may someday find around other stars. Only a suitably large terrestrial planet located at an intermediate distance from its star is likely to have conditions under which life could thrive. Of course, we do not yet know whether simply having conditions suitable for life means that life will actually arise. We will consider current understanding of this fascinating question in Chapter 18, when we consider the prospects of finding life beyond Earth.

the big picture — Putting Chapter 7 into Perspective

In this chapter, we have explored the histories of the terrestrial worlds. As you think about the details you have learned, keep the following "big picture" ideas in mind:

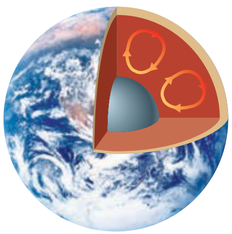
- The terrestrial worlds all looked much the same when they were born, so their present-day differences are a result of geological processes that occurred in the ensuing $4\frac{1}{2}$ billion years.

- The primary factor in determining a terrestrial world's geological history is its size, because only a relatively large world can retain internal heat long enough for ongoing geological activity. However, the differences between Venus and Earth show that distance from the Sun also plays an important role.
- A planet's distance from the Sun is important to its surface temperature, but the cases of Venus and Earth show that the strength of the greenhouse effect can play an even bigger role. Humans are currently altering the balance of greenhouse gases in Earth's atmosphere, with potentially dire consequences.
- The histories of Venus and Mars show that a stable climate like Earth's is more the exception than the rule. The stable climate that makes our existence possible is a direct consequence of our planet's unique geology, including its plate tectonics and carbon dioxide cycle.

summary of key concepts

7.1 Earth as a Planet

- **Why is Earth geologically active?**

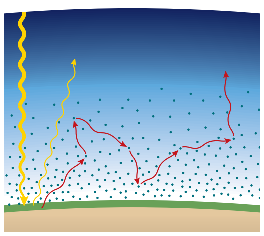


Internal heat drives geological activity, and Earth retains internal heat because of its relatively large size for a terrestrial world. This heat causes mantle **convection** and keeps Earth's lithosphere thin, ensuring active surface geology. It also keeps part of Earth's core melted, and circulation of this molten metal creates Earth's magnetic field.

- **What processes shape Earth's surface?**

The four major geological processes are **impact cratering**, **volcanism**, **tectonics**, and **erosion**. Earth has experienced many impacts, but most craters have been erased by other processes. We owe the existence of our atmosphere and oceans to volcanic **outgassing**. A special type of tectonics—**plate tectonics**—shapes much of Earth's surface. Ice, water, and wind drive rampant erosion on our planet.

- **How does Earth's atmosphere affect the planet?**



Two crucial effects are (1) protecting the surface from dangerous solar radiation—ultraviolet is absorbed by ozone and X rays are absorbed high in the atmosphere—and (2) the **greenhouse effect**, without which the surface temperature would be below freezing.

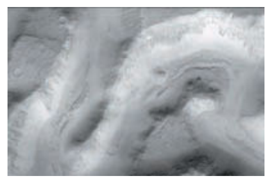
7.2 The Moon and Mercury: Geologically Dead

- **Was there ever geological activity on the Moon or Mercury?**

Both the Moon and Mercury had some volcanism and tectonics when they were young. However, because of their small sizes, their interiors long ago cooled too much for ongoing geological activity.

7.3 Mars: A Victim of Planetary Freeze-Drying

- **What geological features tell us that water once flowed on Mars?**



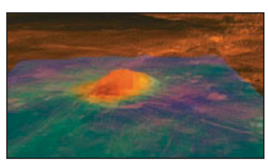
Dry riverbeds, eroded craters, and chemical analysis of Martian rocks all show that water once flowed on Mars, though any periods of rainfall seem to have ended at least 3 billion years ago. Mars today still has water ice underground and in its polar caps and could possibly have pockets of underground liquid water.

- **Why did Mars change?**

Mars's atmosphere must once have been thicker with a stronger greenhouse effect, so change must have occurred due to loss of atmospheric gas. Much of the lost gas probably was stripped away by the solar wind, after Mars lost its magnetic field and protective magnetosphere. Mars also lost water, because solar ultraviolet light split water molecules apart and the hydrogen escaped to space.

7.4 Venus: A Hothouse World

- **Is Venus geologically active?**



Venus almost certainly remains geologically active today. Its surface shows evidence of major volcanic or tectonic activity in the past billion years, and it should retain nearly as much internal heat as Earth. However, geological activity on Venus differs from that on Earth in at least two key ways: lack of erosion and lack of plate tectonics.

- **Why is Venus so hot?**

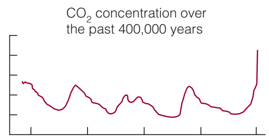
Venus's extreme surface heat is a result of its thick, carbon dioxide atmosphere, which creates a very strong greenhouse effect. The reason Venus has such a thick atmosphere is its distance from the Sun: It was too close to develop liquid oceans like those on Earth, where most of the outgassed carbon dioxide dissolved in water and became locked away in **carbonate rock**. Carbon dioxide remained in Venus's atmosphere, creating a **runaway greenhouse effect**.

7.5 Earth as a Living Planet

- **What unique features of Earth are important for life?**

Unique features of Earth on which we depend for survival are (1) surface liquid water, made possible by Earth's moderate temperature; (2) atmospheric oxygen, a product of photosynthetic life; (3) plate tectonics, driven by internal heat; and (4) climate stability, a result of the **carbon dioxide cycle**, which in turn requires plate tectonics.

- **How is human activity changing our planet?**



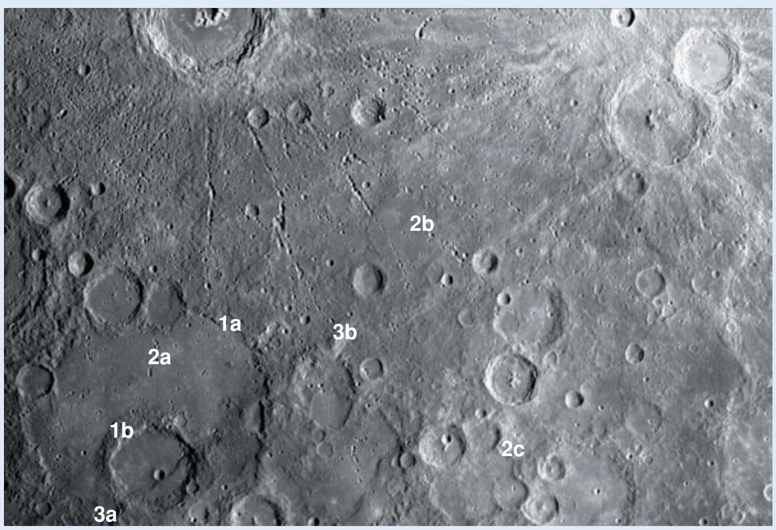
The global average temperature has risen about 0.8°C over the past hundred years, accompanied by an even larger rise in the atmospheric CO_2 concentration—a result of fossil fuel burning and other human activity. The current CO_2 concentration is higher than at any time in the past million years, and climate models indicate that this higher concentration is indeed the cause of **global warming**.

- **What makes a planet habitable?**

We can trace Earth's habitability to its relatively large size and its distance from the Sun. Its size keeps the internal heat that allowed volcanic outgassing to lead to our oceans and atmosphere, and also drives the plate tectonics that helps regulate our climate through the carbon dioxide cycle. Its distance from the Sun is neither too close nor too far, thereby allowing liquid water to exist on Earth's surface.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 7 Visual Quiz at www.masteringastronomy.com.



This image from the *MESSENGER* flyby shows evidence of impact cratering, volcanism, and tectonic activity on Mercury. Answer the following questions based on the image. Remember that craters are bowl-shaped and rough-floored when they form, and wipe out any pre-existing features in the area. Lava on Mercury appears to be fairly runny and makes flat, smooth plains as it spreads out.

1. Label 1a lies on the rim of a large crater, and 1b lies on the rim of a smaller one. Which crater must have formed first?
   a. crater 1a
   b. crater 1b
   c. cannot be determined
2. The region around 2b has far fewer craters than the region around 2c. The crater floor at 2a is also flat and smooth, without many smaller craters on it. Why are regions 2a and 2b so smooth?
   a. Few small craters ever formed in these regions.
   b. Erosion erased craters that once existed in these regions.
   c. Lava flows covered craters that once existed in these regions.

3. A tectonic ridge appears to connect points 3a and 3b, crossing several craters. From its appearance, we can conclude that it must have formed
   a. before the area was cratered.
   b. after the area was cratered.
   c. at the same time the area was cratered.

4. Using your answers from questions 1–3, list the following features in order from oldest to youngest:
   a. the tectonic ridge from 3a to 3b
   b. crater 1a
   c. the smooth floor of crater 1b

exercises and problems

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Review Questions

1. What are Earth's basic layers by composition? What do we mean by the *lithosphere,* and why isn't it listed as one of the three layers by composition?
2. What is *differentiation,* and how did it affect the internal structures of the terrestrial worlds?
3. Why do large planets retain internal heat longer than smaller planets? Briefly explain how internal heat is related to mantle convection and lithospheric thickness.
4. Why does Earth have a global *magnetic field?* What is the *magnetosphere?*
5. Define each of the four major geological processes, and give examples of features on Earth shaped by each process.
6. What is *outgassing,* and how did it lead to the existence of Earth's atmosphere and oceans?
7. Describe how Earth's atmosphere protects the surface from harmful radiation. What is the role of *ozone?*
8. What does the *greenhouse effect* do to a planet? Explain the role of greenhouse gases and describe the basic mechanism of the greenhouse effect.
9. How do crater counts tell us the age of a planetary surface? Briefly explain why the Moon is so much more heavily cratered than Earth.
10. Briefly summarize the geological history of the Moon. How did the lunar maria form?
11. Briefly summarize the geological history of Mercury. How are Mercury's great cliffs thought to have formed?
12. Describe at least three similarities and three differences between Earth and Mars.
13. Choose five features on the global map of Mars (Figure 7.25), and explain the nature and likely origin of each.
14. Explain why liquid water is not stable on Mars today, but why we nonetheless think it flowed in the distant past on Mars. Could there still be liquid water anywhere on Mars today? Explain.
15. Briefly summarize how and why Mars lost much of its atmosphere some 3 billion years ago.
16. Describe at least three major geological features of Venus. Why is it surprising that Venus lacks plate tectonics? What might explain this lack?
17. What do we mean by a *runaway greenhouse effect?* Explain why this process occurred on Venus but not on Earth.
18. List four unique features of Earth in comparison to other terrestrial worlds, and briefly explain what we mean by each one.
19. What is *plate tectonics?* How does it change the arrangement of the continents with time?
20. What is the *carbon dioxide cycle,* and why is it so crucial to life on Earth?
21. Briefly summarize the problem of global warming and its potential consequences if we do not act to stop it.
22. Based on Figure 7.48, write a paragraph each on the role of planetary size and the role of distance from the Sun in explaining the current nature of the terrestrial worlds.

Test Your Understanding

Surprising Discoveries?

Suppose we were to make the following discoveries. (These are not real discoveries.) In light of your understanding of planetary geology, decide whether the discovery should be considered reasonable or surprising. Explain your reasoning clearly, if possible tracing your logic back to basic planetary properties of size or distance from the Sun; because not all of these have definitive answers, your explanation is more important than your chosen answer.

23. The *MESSENGER* mission to Mercury photographs part of the surface never seen before and detects vast fields of sand dunes.
24. New observations show that several of the volcanoes on Venus have erupted within the past few million years.
25. A Venus radar mapper discovers extensive regions of layered sedimentary rocks, similar to those found on Earth.
26. Radiometric dating of rocks brought back from one lunar crater shows that the crater was formed only a few tens of millions of years ago.
27. New, high-resolution orbital photographs of Mars show many crater bottoms filled with pools of liquid.
28. Clear-cutting in the Amazon rain forest on Earth exposes vast regions of ancient terrain that is as heavily cratered as the lunar highlands.
29. Drilling into the Martian surface, a robotic spacecraft discovers liquid water a few meters beneath the slopes of a Martian volcano.
30. We find a planet in another solar system that has an Earth-like atmosphere with plentiful oxygen but no life of any kind.
31. We find a planet in another solar system that has Earth-like plate tectonics; the planet is the size of the Moon and orbits 1 AU from its star.
32. We find evidence that the early Earth had more carbon dioxide in its atmosphere than Earth does today.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

33. Which heat source continues to contribute to Earth's *internal* heat? (a) accretion (b) radioactive decay (c) sunlight
34. In general, what kind of terrestrial planet would you expect to have the thickest lithosphere? (a) a large planet (b) a small planet (c) a planet located far from the Sun
35. Which of a planet's fundamental properties has the greatest effect on its level of volcanic and tectonic activity? (a) size (b) distance from the Sun (c) rotation rate
36. Which describes our understanding of flowing water on Mars? (a) It was never important. (b) It was important once, but no longer. (c) It is a major process on the Martian surface today.
37. What do we conclude if a planet has few impact craters of any size? (a) The planet was never bombarded by asteroids or comets. (b) Its atmosphere stopped impactors of all sizes. (c) Other geological processes have erased craters.
38. How many of the five terrestrial worlds are considered "geologically dead"? (a) none (b) two (c) four (Be sure to explain *why* these worlds became geologically dead.)
39. Which terrestrial world has the most atmospheric gas? (a) Venus (b) Earth (c) Mars
40. Which of the following is a strong greenhouse gas? (a) nitrogen (b) water vapor (c) oxygen
41. The oxygen in Earth's atmosphere was released by (a) volcanic outgassing. (b) the CO_2 cycle. (c) life.
42. Where is most of the CO_2 that has outgassed from Earth's volcanoes? (a) in the atmosphere (b) escaped to space (c) locked up in rocks

Process of Science

43. *What Is Predictable?* We've found that much of a planet's geological history is destined from its birth. Briefly explain why, and discuss the level of detail that is predictable. For example, was Mars's general level of volcanism predictable? Could we have predicted a mountain as tall as Olympus Mons or a canyon as long as Valles Marineris? Explain.
44. *Science with Consequences.* Some people are still skeptical of global warming. Research the opinions of such skeptics in newspapers, in magazines, and on the Internet. Do they disagree with the data, saying that Earth is not getting warmer? Do they disagree with the conclusion that humans are the primary cause? Do they disagree with the idea that action must be taken? Defend or refute their findings based on your own studies and your understanding of the hallmarks of science discussed in Chapter 3.
45. *Unanswered Questions.* As discussed in this chapter, our exploration of Mars suggests that it may have been habitable in the past. Choose one important but unanswered question about Mars's past, and write two or three paragraphs discussing how we might answer this question in the future. Be as specific as possible, focusing on the type of evidence necessary to answer the question and the method(s) that should be used to gather the evidence. What would be the benefits of finding answers to this question?

Group Work Exercise

46. *Are We Causing Global Warming?* One of the most important public discussions today is about the role of humans in altering Earth's climate. This exercise is intended to help you understand the scientific evidence behind this discussion. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Advocate* (argues in favor of the claim that human activity is causing global warming), *Skeptic* (points out weaknesses in the arguments made by the *Advocate*), and *Moderator* (leads group discussion and makes sure everyone contributes).
    a. Work together to make a list of scientific observations that have been proposed as evidence that humans are causing global warming. Your list should include, but is not limited to, the evidence in Figures 7.43–7.45.
    b. *Advocate* presents the case that humans are causing global warming, drawing on the evidence from part (a).
    c. *Skeptic* attempts to refute the *Advocate's* case using scientific arguments.
    d. After hearing these arguments, the *Moderator* and *Scribe* decide whose arguments were more persuasive and explain their reasoning.
    e. Each person in the group writes up a summary of the discussion.

Investigate Further

Short-Answer/Essay Questions

47. *Miniature Mars.* Suppose Mars had turned out to be significantly smaller than its current size—say, the size of our Moon. How would this have affected the number of geological features due to each of the four major geological processes? Do you think Mars would still be a good candidate for harboring extraterrestrial life? Summarize your answers in two or three paragraphs.
48. *Two Paths Diverged.* By looking back to fundamental properties such as size and distance from the Sun, explain why Earth has oceans and very little atmospheric carbon dioxide, while similar-size Venus has a thick, carbon dioxide atmosphere.
49. *Change in Formation Properties.* Consider Earth's size and distance from the Sun. Choose one property and suppose that it had been different (for example, smaller size or greater distance). Describe how this change might have affected Earth's subsequent history and the possibility of life on Earth.
50. *Experiment: Planetary Cooling in a Freezer.* Fill two small plastic containers of similar shape but different size with cold water and put both into the freezer at the same time. Every hour or so, record the time and your estimate of the thickness of the "lithosphere" (the frozen layer) in each container. How long does it take the water in each container to freeze completely? Describe in a few sentences the relevance of your experiment to planetary geology. Extra credit: Plot your results on a graph with time on the x-axis and lithospheric thickness on the y-axis. What is the ratio of the two freezing times?
51. *Amateur Astronomy: Observing the Moon.* Any amateur telescope has a resolution adequate to identify geological features on the Moon. The light highlands and dark maria should be evident, and shadowing is visible near the line between night and day. Try to observe the Moon near the first- or third-quarter phase. Sketch

or photograph the Moon at low magnification, and then zoom in on a region of interest. Again sketch or photograph your field of view, label its features, and identify the geological process that created them. Look for craters, volcanic plains, and tectonic features. Estimate the size of each feature by comparing it to the size of the whole Moon (radius = 1738 kilometers).

52. *Global Warming.* What, if anything, should we be doing to alleviate the threat of global warming that we are not doing already? Write a one-page editorial summarizing and defending your opinion.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

53. *Moon and Mars.* Compare the surface area–to–volume ratios of the Moon and Mars. Based on your answer, what should you expect about the cooling time of Mars compared to that of the Moon?
54. *Earth and Venus.* Compare the surface area–to–volume ratios of Venus and Earth. Based on your answer, how should you expect the cooling time to compare for these two worlds?
55. *Doubling Your Size.* Just as the surface area–to–volume ratio depends on size, so can other properties. To see how, suppose that your size suddenly doubled; that is, your height, width, and depth all doubled. (For example, if you were 5 feet tall before, you now are 10 feet tall.)
    a. By what factor has your waist size increased?
    b. How much more material will be required for your clothes? (*Hint:* Clothes cover the *surface area* of your body.)
    c. By what factor has your weight increased? (*Hint:* Weight depends on the *volume* of your body.)
    d. The pressure on your weight-bearing joints depends on how much *weight* is supported by the *surface area* of each joint. How has the pressure on your weight-bearing joints changed?
56. *Impact Energies.* An asteroid 1 kilometer in diameter will make a crater of about 10 kilometers in diameter. How much kinetic energy does the asteroid have if it strikes the surface at 20 kilometers per second? Assume the asteroid density is 3 g/cm^3. (The amount of kinetic energy is given by the formula $\frac{1}{2}mv^2$.) Convert your answer to megatons of TNT: 1 megaton is about 4×10^{15} joules. Compare the impactor to the largest nuclear weapons, currently less than 100 megatons of energy.
57. *Internal vs. External Heating.* In daylight, the Earth's surface absorbs about 400 watts per square meter. Earth's internal radioactivity produces a total of 30 trillion watts that leak out through our planet's entire surface. Calculate the amount of heat from radioactive decay that flows outward through each square meter of Earth's surface (your answer should have units of watts per square meter). Compare this quantitatively to solar heating, and comment on why internal heating drives geological activity.
58. *Plate Tectonics.* Typical motions of one plate relative to another are 1 centimeter per year. At this rate, how long would it take for two continents 3000 kilometers apart to collide? What are the global consequences of motions like this?
59. *Planet Berth.* Imagine a planet, which we'll call *Berth*, orbiting a star identical to the Sun at a distance of 1 AU. Assume that Berth has eight times as much mass as Earth and is twice as large as Earth in diameter.
    a. How does Berth's density compare to Earth's?
    b. How does Berth's surface area compare to Earth's?
    c. Based on your answers to (a) and (b), discuss how Berth's geological history is likely to have differed from Earth's.

Discussion Questions

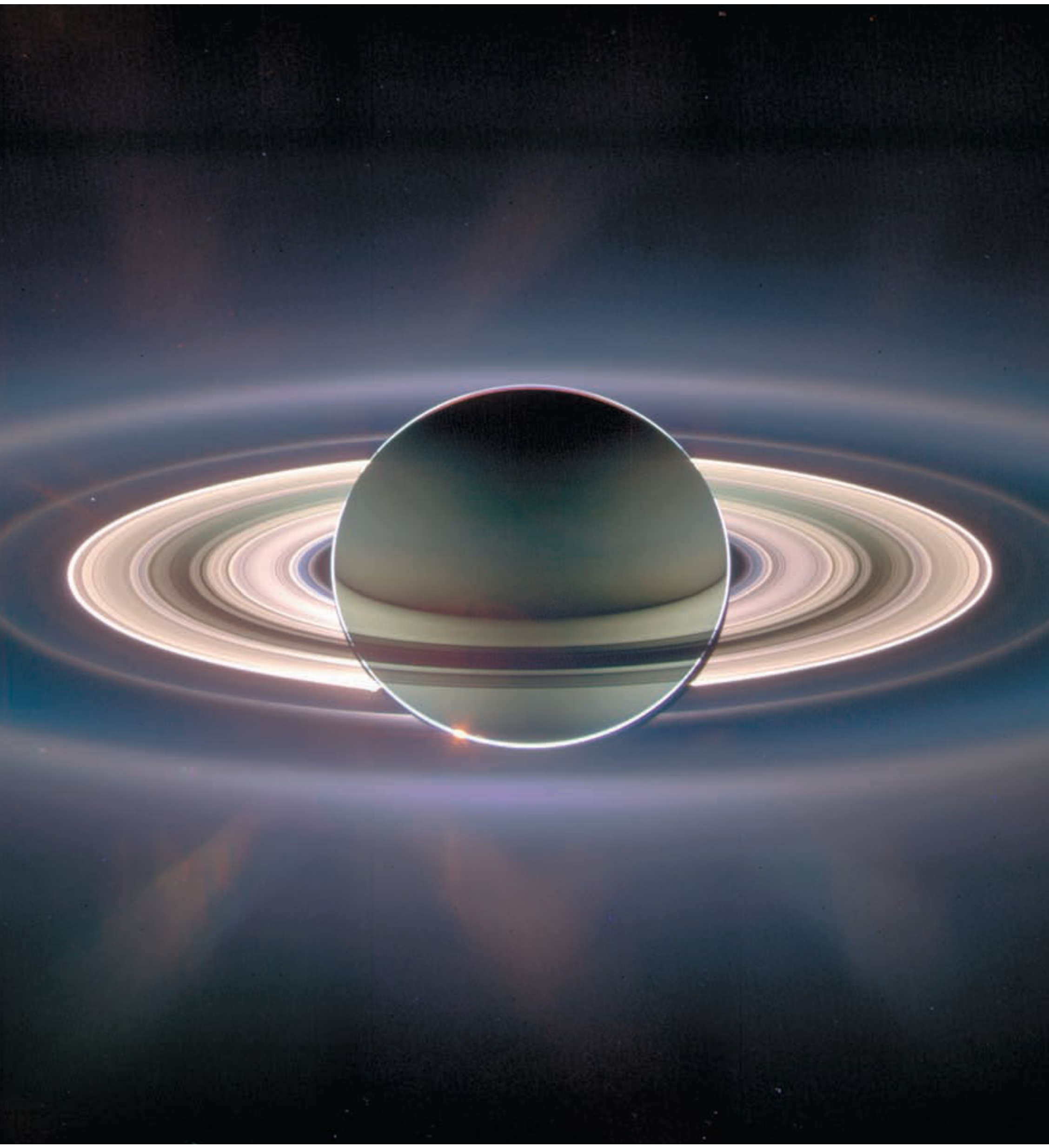
60. *Worth the Effort?* Politicians often argue over whether planetary missions are worth the expense involved. Based on what we have learned by comparing the geologies of the terrestrial worlds, do you think the missions that have given us this knowledge have been worth their expense? Defend your opinion.
61. *Lucky Earth.* The climate histories of Venus and Mars make it clear that it's not "easy" to get a pleasant climate like that of Earth. How does this affect your opinion about whether Earth-like planets might exist around other stars? Explain.
62. *Terraforming Mars.* Some people have suggested that we might be able to carry out planetwide engineering of Mars that would cause its climate to warm and its atmosphere to thicken. This type of planet engineering is called *terraforming,* because its objective is to make a planet more Earth-like and therefore easier for humans to live on. Discuss possible ways to terraform Mars, at least in principle. Do any of these ideas seem practical? Does it seem like a good idea? Defend your opinions.

Web Projects

63. *"Coolest" Surface Photo.* Visit the Astronomy Picture of the Day Web site, and search for past images of the terrestrial worlds. After looking at many of the images, choose the one you think is the "coolest." Make a printout, write a short description of what it shows, and explain what you like about it.
64. *Water on Mars.* Go to the Web site for NASA's Mars Exploration Program, and look for the latest evidence concerning recent water flows on Mars. Write a few paragraphs describing the new evidence and what it tells us.
65. *Mars Colonization.* Visit the Web site of a group that advocates human colonization of Mars, such as the Mars Society. Learn about the challenges of human survival on Mars and about prospects for terraforming Mars. Do you think colonization of Mars is a good idea? Write a short essay describing what you've learned and defend your opinions.
66. *Human Threats to Earth.* Write a three- to five-page research report about current understanding of and controversy over one of the following issues: global warming, ozone depletion, or the loss of species on Earth due to human activity. Be sure to address both the latest knowledge about the issue and proposals for alleviating any dangers associated with it. End your report by making your own recommendations about what, if anything, needs to be done to prevent further damage.

8

Jovian Planet Systems



Saturn, photographed by the *Cassini* spacecraft while it was in Saturn's shadow. The small blue dot of light just inside Saturn's rings at the left (about the 10:00 position) is Earth, far in the distance.

learning goals

8.1 A Different Kind of Planet
- What are jovian planets made of?
- What are jovian planets like on the inside?
- What is the weather like on jovian planets?

8.2 A Wealth of Worlds: Satellites of Ice and Rock
- What kinds of moons orbit the jovian planets?
- Why are Jupiter's Galilean moons geologically active?
- What geological activity do we see on Titan and other moons?
- Why are jovian moons more geologically active than small rocky planets?

8.3 Jovian Planet Rings
- What are Saturn's rings like?
- Why do the jovian planets have rings?

In Roman mythology, the namesakes of the jovian planets are rulers among gods: Jupiter is the king of the gods, Saturn is Jupiter's father, Uranus is the lord of the sky, and Neptune rules the sea. However, our ancestors could not have foreseen the true majesty of the four jovian planets. The smallest, Neptune, is large enough to contain the volume of more than 50 Earths. The largest, Jupiter, has a volume some 1400 times that of Earth. These worlds are totally unlike the terrestrial planets. They are essentially giant balls of gas, with no solid surface.

Why should we care about a set of worlds so different from our own? Apart from satisfying natural curiosity, studies of the jovian planets and their moons help us understand the birth and evolution of our solar system—which in turn helps us understand our own planet Earth. In addition, the jovian planets provide stepping stones to understanding the hundreds of planets so far discovered around other stars, because most of these planets are probably jovian in nature. In this chapter, we'll explore the jovian planet systems, first focusing on the planets themselves, then on their many moons, and finally on their beautifully complex rings.

MA Formation of the Solar System Tutorial, Lesson 1

essential preparation

1. How does gravity cause tides? **[Section 4.4]**
2. What does the solar system look like? **[Section 6.1]**
3. Why are there two major types of planets? **[Section 6.4]**
4. Why is Earth geologically active? **[Section 7.1]**

8.1 A Different Kind of Planet

The jovian planets are radically different from the terrestrial planets. They are far larger in size and very different in composition. They are orbited by rings and numerous moons. They even rotate much faster than the terrestrial planets.

We toured the jovian planets briefly in Section 6.1. Now we are ready to explore these planets in a little more depth. As you'll see from both the discussion and the selection of photos in this chapter, much of our present knowledge has come from spacecraft visits, especially from the *Voyager 1* and *2* missions that flew past these planets in the late 1970s and 1980s and the *Galileo* spacecraft that orbited Jupiter from 1995 until 2003. Currently, scientists are learning much more from the *Cassini* spacecraft now orbiting Saturn.

• What are jovian planets made of?

The jovian planets are often called "gas giants," making it sound as if they are entirely gaseous like air on Earth. While this idea is not entirely wrong, the reality is somewhat more complex.

Figure 8.1 shows a montage of the jovian planets compiled by the *Voyager* spacecraft, along with basic data and Earth included for scale. The immense sizes of the jovian worlds are apparent. But while all four are enormous, there are important differences between them. In particular, they differ substantially in mass, density, and overall composition.

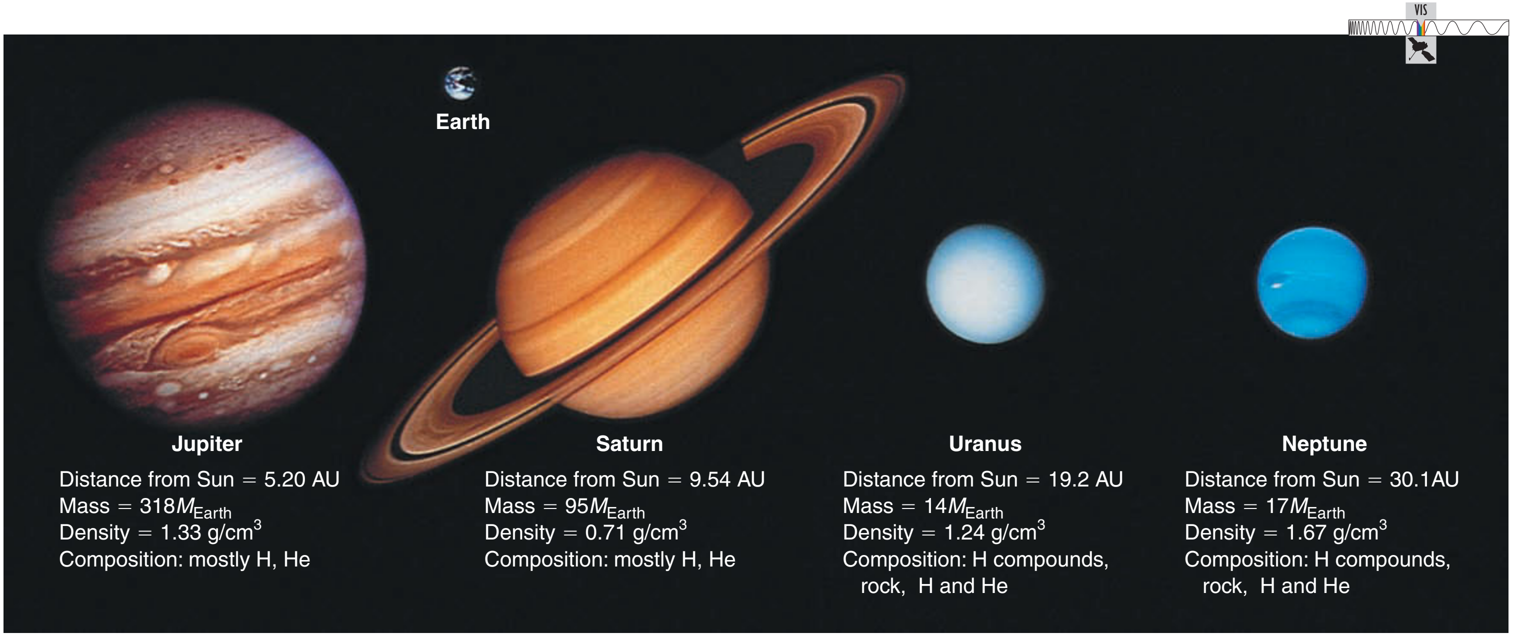


Figure 8.1

Jupiter, Saturn, Uranus, and Neptune, shown to scale with Earth for comparison.

General Composition of Jovian Planets Jupiter and Saturn are made almost entirely of hydrogen and helium, with just a few percent of their masses coming from hydrogen compounds and even smaller amounts of rock and metal. In fact, their overall compositions are much more similar to the composition of the Sun than to the compositions of the terrestrial planets. Some people even call Jupiter a "failed star" because it has a starlike composition but lacks the nuclear fusion needed to make it shine. This is a consequence of its size: Although Jupiter is large for a planet, it is much less massive than any star. As a result, its gravity is too weak to compress its interior to the extreme temperatures and densities needed for nuclear fusion. (Jupiter would have needed to grow to about 80 times its current mass to have become a star.) Of course, where some people see a failed star, others see an extremely successful planet.

The jovian planets are made mostly of hydrogen, helium, and hydrogen compounds, making them very different in composition from terrestrial worlds.

Uranus and Neptune are much smaller than Jupiter and Saturn overall, and also contain proportionally much smaller amounts of hydrogen and helium. In fact, Uranus and Neptune are made primarily of hydrogen compounds such as water (H_2O), methane (CH_4), and ammonia (NH_3), along with smaller amounts of metal and rock in their cores and an outer layer of hydrogen and helium gas. We can understand the differences in composition and size among the jovian planets by looking at the way in which we think they formed.

Gas Capture in the Solar Nebula Recall that the jovian planets formed in a very different way from the terrestrial planets [Section 6.4]. The terrestrial planets accreted from planetesimals containing only rock and metal. Because rock and metal were rare in the solar nebula, the terrestrial planets never grew massive enough for their gravity to hold any of the abundant hydrogen and helium gas that made up most of the nebula.

The jovian planets formed in the outer solar system (beyond the frost line), where it was cold enough for hydrogen compounds to condense into ices (see Figure 6.17). Because hydrogen compounds were so much more abundant than metal and rock, some of the ice-rich planetesimals of the outer solar system grew to great size. Once these planetesimals became sufficiently massive, their gravity allowed them to draw in the hydrogen and helium gas that surrounded them. All four jovian planets are thought to have grown from ice-rich planetesimals of about the same mass—roughly 10 times the mass of Earth. The differences in their composition stem from the amounts of hydrogen and helium gas that they captured.

Jupiter and Saturn captured so much hydrogen and helium gas that these gases now make up the vast majority of their masses. The ice-rich planetesimals from which they grew now represent only a small fraction of their overall masses—about 3% in Jupiter's case and about 10% in Saturn's case.

Uranus and Neptune pulled in much less hydrogen and helium gas. Uranus has about 14 times the mass of Earth. Assuming that it began as an ice-rich planetesimal with about 10 times Earth's mass, Uranus obtained only about a third of its total mass from drawn-in hydrogen and helium gas. The bulk of its mass consists of material from the original ice-rich planetesimal: hydrogen compounds mixed with smaller amounts of rock and metal. The same is true for Neptune, though its higher density suggests that it may have formed around a slightly more massive ice-rich planetesimal.

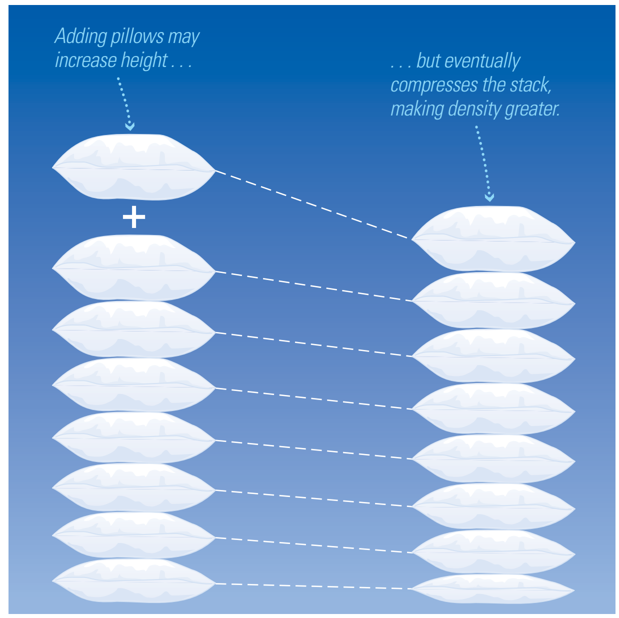
The jovian planets nearer to the Sun captured more hydrogen and helium gas, making them larger and leaving them with smaller proportions of hydrogen compounds, rock, and metal.

We can trace these differences in the amounts of captured gas to differences in distance from the Sun. As the solar system formed, the solid particles that condensed far from the Sun must have been much more widely spread out than particles that condensed nearer to the Sun. At greater distances from the Sun, it took longer for small particles to accrete into large, icy planetesimals with gravity strong enough to pull in gas from the surrounding nebula. Jupiter would have been the first jovian planet whose icy planetesimal grew large enough to start drawing in gas, followed by Saturn, Uranus, and Neptune. Because all the planets stopped accreting gas at the same time—when the solar wind blew the remaining gas into interstellar space—the more distant planets had less time to capture gas and ended up smaller in size.

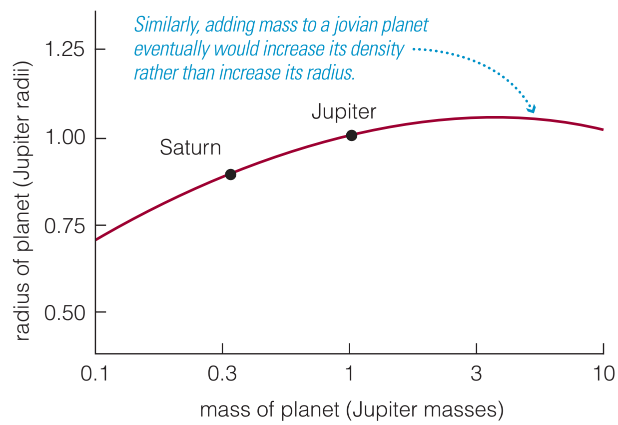
Density Differences Figure 8.1 shows that Saturn is considerably less dense than Uranus or Neptune. This should make sense when you compare compositions, because the hydrogen compounds, rock, and metal that make up Uranus and Neptune are normally much more dense than hydrogen or helium gas. By the same logic, we'd expect Jupiter to be even less dense than Saturn—but it's not. To understand Jupiter's surprisingly high density, we need to think about how massive planets are affected by their own gravity.

Building a planet of hydrogen and helium is a bit like making one out of fluffy pillows. Imagine assembling a planet pillow by pillow. As each new pillow is added, those on the bottom are compressed more by those above. As the lower pillows are forced closer together, their mutual gravitational attraction increases, compressing them even further. At first the stack grows substantially with each pillow, but eventually the growth slows until adding pillows barely increases the height of the stack (Figure 8.2a).

see it for yourself Measure the thickness of your pillow; then put it at the bottom of a stack of other pillows, folded blankets, or clothing. How much has the pillow been compressed by the stack above it? Insert your hand between the different layers to feel the pressure differences—and imagine the kind of pressures and compression you'd find in a stack tens of thousands of kilometers tall!



a Adding pillows to a stack may increase its height at first but eventually compresses the stack, making its density greater.



b This graph shows how radius depends on mass for a hydrogen/helium planet. Notice that Jupiter is only slightly larger in radius than Saturn, despite being three times as massive. Gravitational compression of a planet much more massive than Jupiter would actually make its radius smaller.

Figure 8.2

The relationship between mass and radius for a planet made of hydrogen and helium.

This analogy explains why Jupiter is only slightly larger than Saturn in radius even though it is more than three times as massive. The extra mass of Jupiter compresses its interior to a much higher density. More precise calculations show that Jupiter's radius is almost the maximum possible radius for a jovian planet. If much more gas were added to Jupiter, its weight would actually compress the interior enough to make the planet *smaller* rather than larger (Figure 8.2b). Indeed, some extrasolar planets that are larger in mass than Jupiter are probably smaller in size.

think about it Saturn's average density of 0.71 g/cm^3 is less than that of water. As a result, it is sometimes said that Saturn could float on a giant ocean. Suppose there really were a gigantic planet with a gigantic ocean and we put Saturn on the ocean's surface. Would it float? If not, what would happen?

• What are jovian planets like on the inside?

Jupiter and Saturn might at first seem to deserve the name "gas giants," since they are made primarily of hydrogen and helium—substances that are gaseous on Earth and were gaseous in the solar nebula. The name may seem less fitting for Uranus and Neptune, since they are made mostly of materials other than pure hydrogen and helium. However, closer inspection shows that the name is a little misleading even for Jupiter and Saturn, because their strong gravity compresses most of the "gas" into forms of matter quite unlike anything we are familiar with in everyday life on Earth. Let's begin by considering what Jupiter is like on the inside, then extend these ideas to the other jovian planets.

Inside Jupiter Jupiter's lack of a solid surface makes it tempting to think of the planet as "all atmosphere," but you could not fly through Jupiter's interior in the way airplanes fly through air. A spacecraft plunging into Jupiter would find increasingly higher temperatures and pressures as it descended. The *Galileo* spacecraft dropped a scientific probe into Jupiter in 1995 that collected measurements for about an hour before the ever-increasing pressures and temperatures destroyed it. The probe provided valuable data about Jupiter's atmosphere but didn't last long enough to sample the interior: It survived to a depth of only about 200 kilometers, or about 0.3% of Jupiter's radius.

If you plunged below Jupiter's clouds, you'd never encounter a solid surface—just ever-denser and hotter hydrogen/helium compressed into bizarre liquid and metallic phases.

While Jupiter has no solid surface, computer models tell us that it still has fairly distinct interior layers. The layers do not differ much in composition—all except the core are mostly hydrogen and helium. Instead, they differ in the phase of their hydrogen. From the tops of its clouds to its core, Jupiter's interior layers are (Figure 8.3):

- Gaseous hydrogen: In the outer layer, conditions are moderate enough for hydrogen to remain in its familiar, gaseous form. This layer extends about 10% of the way from the cloudtops toward the center. In the outer portions of this layer, the gas would seem much like air on Earth (but with a different composition), so we usually think of this region as Jupiter's atmosphere.

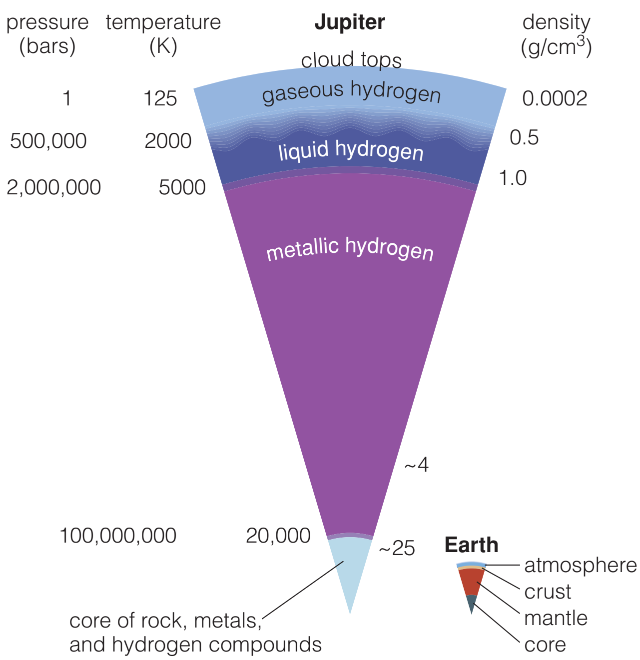


Figure 8.3

Jupiter's interior structure, labeled with the pressure, temperature, and density at various depths. Earth's interior structure is shown to scale for comparison. (Notes on units: 1 bar is approximately the atmospheric pressure at sea level on Earth; the density of liquid water is 1 g/cm^3.)

- Liquid hydrogen: This layer occupies about the next 10% of Jupiter's interior. The temperature exceeds 2000 K and the pressure exceeds 500,000 times the pressure on Earth's surface. Laboratory experiments show that hydrogen acts more like a liquid than a gas under these conditions. Notice that the density in this layer (ranging from 0.5 to almost 1.0 g/cm^3) is only slightly less than the density of water.
- Metallic hydrogen: In most of the rest of Jupiter, the temperatures and pressures are so extreme that hydrogen is forced into a compact, metallic form (which still flows like a liquid). Just as is the case with everyday metals, electrons are free to move around in metallic hydrogen, so it conducts electricity quite effectively. As we'll see shortly, Jupiter's magnetic field is generated in this layer of metallic hydrogen.
- Core: The core is a mix of hydrogen compounds, rock, and metal. However, the high temperature and extreme pressure ensure that this mix bears little resemblance to familiar solids or liquids. The core contains about 10 times as much mass as the entire Earth, but it is only about the same size as Earth because it is compressed to such high density.

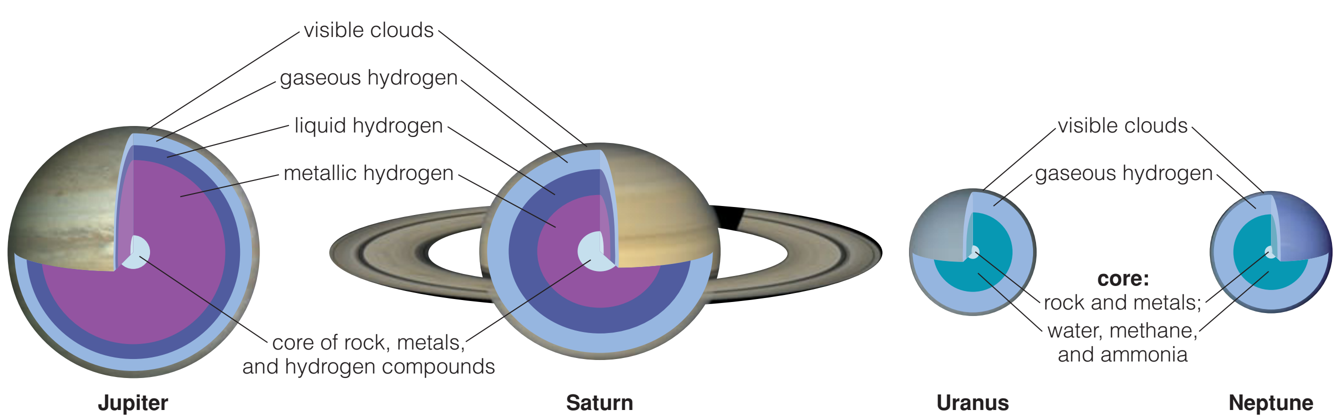
Comparing Jovian Interiors Because all four jovian planets have cores of about the same mass, their interiors differ mainly in the hydrogen/helium layers that surround their cores. Figure 8.4 contrasts the four jovian interiors. Remember that while the outer layers are named for the phase of their hydrogen, they also contain helium and hydrogen compounds.

Saturn is the most similar to Jupiter, just as we should expect given its similar size and composition. Its four interior layers differ from those of Jupiter only because of its lower mass and weaker gravity. The lower mass makes the weight of the overlying layers less on Saturn than on Jupiter, so you must travel deeper into Saturn to find the layer where pressure changes hydrogen from one phase to another. That is why Saturn has a thicker layer of gaseous hydrogen and a thinner and more deeply buried layer of metallic hydrogen.

Pressures within Uranus and Neptune are not high enough to form liquid or metallic hydrogen at all. Each of these two planets has only a thick layer of gaseous hydrogen surrounding its core of hydrogen compounds, rock, and metal. This core material may be liquid, making for very odd "oceans" buried deep inside Uranus and Neptune. The less extreme interior conditions make Uranus's and Neptune's cores less compressed, and allow them to differentiate so that hydrogen compounds reside in a layer above a central layer of rock and metal.

Figure 8.4

These diagrams compare the interior structures of the jovian planets, shown approximately to scale. All four planets have cores of rock, metal, and hydrogen compounds, with masses about 10 times the mass of Earth's core. They differ primarily in the depth of the hydrogen/helium layers that surround their cores. The cores of Uranus and Neptune are differentiated into separate layers of rock/metal and hydrogen compounds.



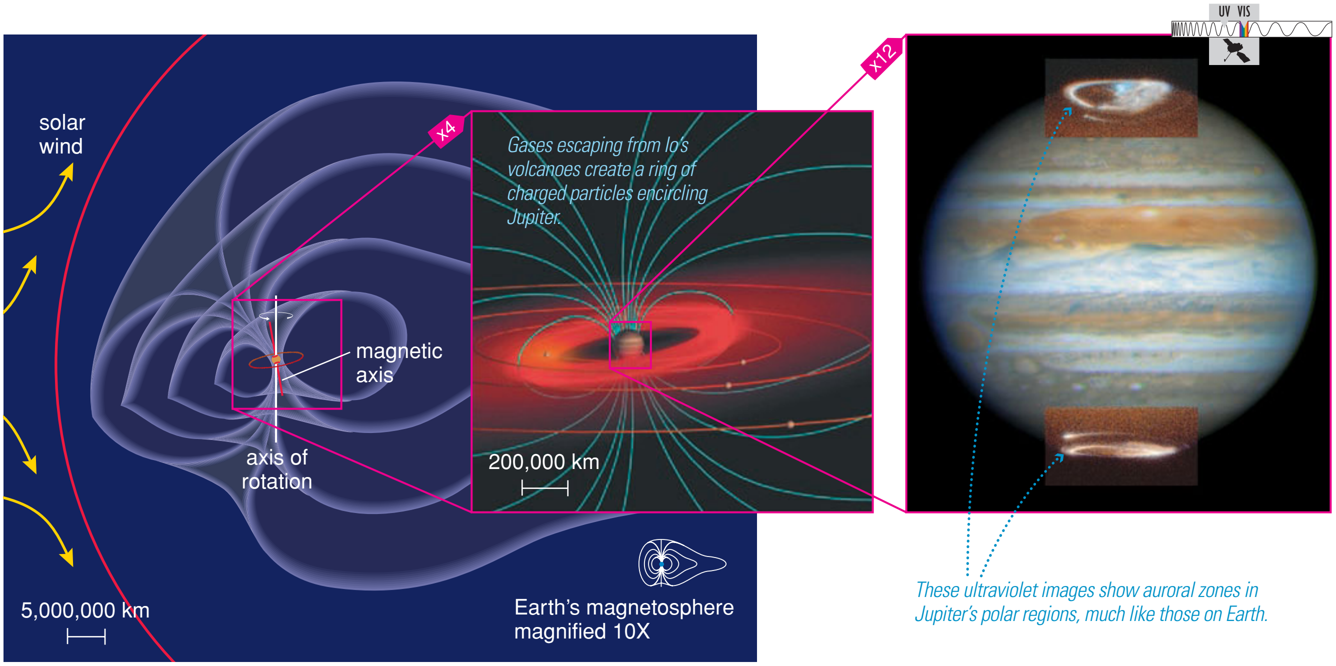


Figure 8.5

Jupiter's strong magnetic field gives it an enormous magnetosphere. Gases escaping from Io feed the donut-shaped Io torus, and particles entering Jupiter's atmosphere near its magnetic poles contribute to auroras on Jupiter. The image at the right is a composite of ultraviolet images of the polar regions overlaid on a visible image of the whole planet, all taken by the Hubble Space Telescope.

Magnetic Fields Recall that Earth has a global magnetic field generated by the movements of charged particles in our planet's outer core of molten metal (see Figure 7.5). The jovian planets also have global magnetic fields generated by motions of charged particles deep in their interiors.

Jupiter's magnetic field is by far the strongest—some 20,000 times as strong as Earth's. This strong field is generated in Jupiter's thick layer of metallic hydrogen. Just as on Earth, Jupiter's magnetic field creates a *magnetosphere* that surrounds the planet and shields it from the solar wind. But like almost everything else about Jupiter, its magnetosphere is enormous. It begins to deflect the solar wind some 3 million kilometers (about 40 Jupiter radii) before the solar wind even reaches the planet (Figure 8.5). If our eyes could see this part of Jupiter's magnetosphere, it would be larger than the full moon in our sky.

Jupiter's magnetosphere traps far more charged particles than Earth's. These particles contribute to auroras on Jupiter. They also create belts of very intense radiation around Jupiter, which can cause damage to orbiting spacecraft. The main source of the many charged particles is Jupiter's volcanically active moon Io. Gases escaping from Io's volcanoes become ionized and feed a donut-shaped charged particle belt (called the *Io torus*) that approximately traces Io's orbit.

The other jovian planets also have magnetic fields and magnetospheres, but theirs are much weaker than Jupiter's (although still much stronger than Earth's). Saturn's magnetic field is weaker than Jupiter's because it has a thinner layer of electrically conducting metallic hydrogen. Uranus and Neptune, smaller still, have no metallic hydrogen at all. Their relatively weak magnetic fields must be generated in their core "oceans" of hydrogen compounds, rock, and metal.

• What is the weather like on jovian planets?

Jovian atmospheres have dynamic winds and weather, with colorful clouds and enormous storms readily visible to telescopes and spacecraft. Weather on these planets is driven not only by energy from the Sun (as on the terrestrial planets), but also by heat generated within the planets themselves. All but Uranus generate a great deal of internal heat. No one knows the precise source of the internal heat on jovian planets, but it probably comes from the conversion of gravitational potential energy to thermal energy inside them. The best guesses are that this conversion comes from a slow but imperceptible contraction in overall size, or from ongoing differentiation as heavier materials continue to sink toward the core.

As we did for the jovian planetary interiors, let's examine different aspects of their atmospheres by starting with Jupiter as the prototype for each feature. We'll then use the general differences between the jovian planets to understand differences in their weather.

Clouds and Colors The spectacular colors of the jovian planets are probably the first thing that jumps out at you when you look at the photos in Figure 8.1. Many mysteries remain about precisely why the jovian planets are so colorful, but at least some major color features are caused by clouds. Earth's clouds look white from space because they are made of water that reflects the white light of the Sun. The jovian planets have clouds of several different types, and some of these reflect light of other colors.

Clouds form when a gas condenses to make tiny liquid droplets or solid flakes. Water vapor is the only gas that can condense in Earth's atmosphere, which is why clouds on Earth are made of water droplets or flakes that can produce rain or snow. In contrast, Jupiter's atmosphere has several gases that can condense to form clouds. Each of these gases condenses at a different temperature, leading to distinctive cloud layers at different altitudes.

Jupiter has three primary cloud layers, which we can understand by considering temperatures at different altitudes (Figure 8.6). Just as the temperature tends to fall as you climb up a mountain on Earth, Jupiter's atmosphere is colder at higher altitudes. About 100 kilometers below the highest cloudtops, the temperatures are nearly Earth-like and water can condense to form clouds. Higher up, at about 50 kilometers above the water clouds, it is cold enough for a gas called ammonium hydrosulfide (NH_4SH) to condense into clouds. These ammonium hydrosulfide clouds reflect brown and red light (though no one knows why), producing many of the dark colors of Jupiter. Higher still, the temperature is so cold that ammonia (NH_3) condenses to make an upper layer of white clouds.

Saturn has the same set of three cloud layers as Jupiter, but these layers occur deeper in Saturn's atmosphere. The reason is that Saturn's outer atmosphere is colder than Jupiter's, both because Saturn is farther from the Sun and because it has weaker gravity. For example, to find the relatively warm temperatures at which water vapor can condense to form water clouds, we must look about 200 kilometers deeper into Saturn than into Jupiter. The fact that Saturn's clouds lie deeper in its atmosphere than Jupiter's probably explains Saturn's more subdued colors: Less light penetrates to the depths at which Saturn's clouds are found, and the light they reflect is more obscured by the atmosphere above them.

All the jovian planets have cloudy skies, but clouds of different kinds form at different altitudes in each planet's atmosphere.

Uranus and Neptune are so cold that any cloud layers similar to those of Jupiter or Saturn would be buried too deep in their atmospheres for us to see. Instead, the colors of Uranus and Neptune come mainly from methane gas and clouds (Figure 8.7). These two planets have much more methane gas than Jupiter or Saturn, and the cold temperatures allow some of this methane to condense into clouds. Methane gas absorbs red light, allowing only blue light to penetrate to the level at which the methane clouds form. The methane clouds reflect this blue light upward, giving the planets their blue colors.

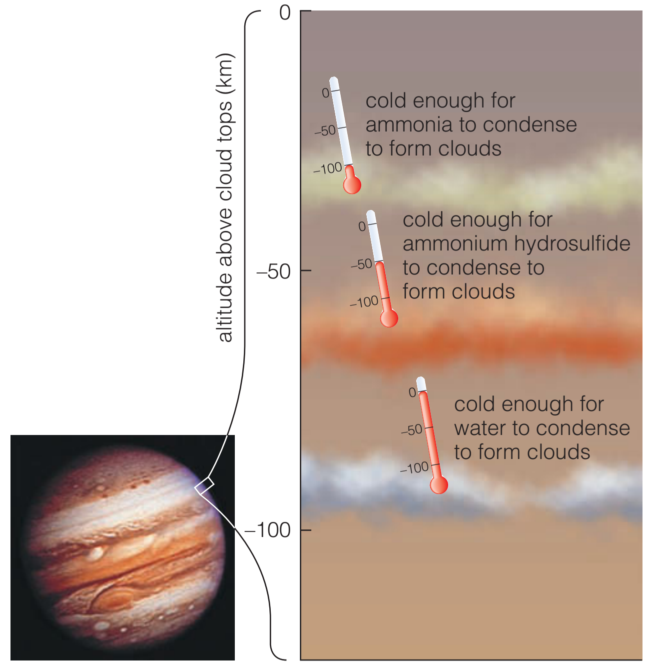


Figure 8.6

This diagram shows the temperature structure of Jupiter's atmosphere. Jupiter has at least three distinct cloud layers because different atmospheric gases condense at different temperatures and hence at different altitudes. The tops of the ammonia clouds are usually considered the zero altitude for Jupiter, which is why lower altitudes are negative.

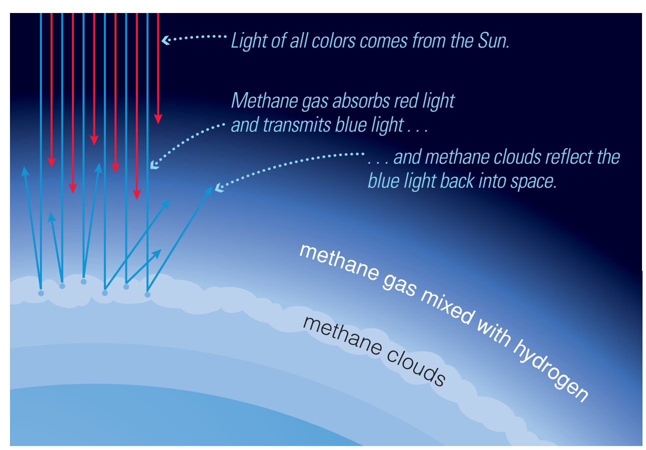
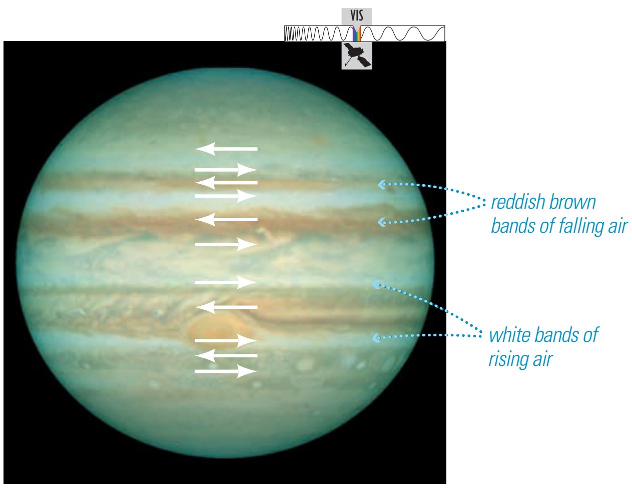


Figure 8.7

Neptune and Uranus look blue because methane gas absorbs red light but transmits blue light. Clouds of methane snowflakes reflect the transmitted blue light back to space.

a This photograph shows how storms circulate around low pressure regions (L) on Earth. Earth's rotation causes this circulation, which is in opposite directions in the two hemispheres.



b Jupiter's faster rotation and larger size essentially stretch out the circulation patterns that occur on Earth into planet-wide bands of fast moving air.

Figure 8.8 MA interactive figure

Wind patterns on both Earth and Jupiter arise from the way planetary rotation affects rising and falling air.

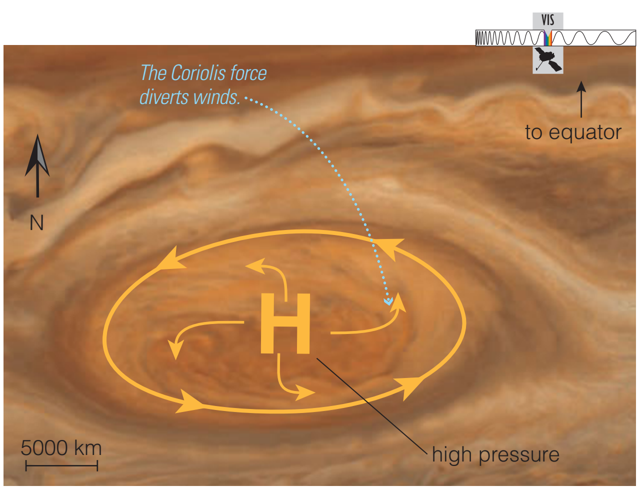


Figure 8.9 MA interactive figure

This photograph shows Jupiter's Great Red Spot, a huge, high-pressure storm that is large enough to swallow two or three Earths. The overlaid diagram shows a weather map of the region.

Global Winds and Storms In photographs, Jupiter shows alternating east-west stripes of white and reddish-brown clouds. The stripes represent alternating bands of rising and falling air, and they stretch around the planet because of Jupiter's rapid rotation.

You are probably familiar with circulation of storms on Earth (Figure 8.8a). Storms around low-pressure regions tend to circulate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Earth's rotation causes these circulation patterns by diverting north- or south-flowing air. (More technically, Earth's rotation produces something called the *Coriolis effect,* which diverts the paths of missiles or rockets as well as winds.) The same effect occurs on Jupiter, but Jupiter's faster rotation and larger size make the effect much stronger. In essence, the circular patterns we see in Earth's atmosphere become stretched out to the east and west on Jupiter, to such an extent that they end up going all the way around the planet (Figure 8.8b). This leads to very high east-west wind speeds—sometimes more than 400 kilometers per hour (250 miles per hour).

The colors of the stripes come from the cloud layers. The entire planet is blanketed with the reddish-brown clouds that make up the middle layer of ammonium hydrosulfide clouds (see Figure 8.6). However, we see these clouds only in places where none of the white ammonia clouds lie above them. The white clouds form in bands of rising air, because this air rises to the high, cold altitudes at which white ammonia snowflakes can condense. Ammonia "snow" falls from these clouds, depleting the rising air of ammonia. When the rising air reaches its highest point, it spills north or south and descends in the bands of falling air. Because this air now lacks ammonia, no ammonia clouds can form and we can see down to the reddish-brown ammonium hydrosulfide clouds that lie deeper in the atmosphere. That is why the bands of falling air have their dark color.

The rapid rotation of the jovian planets helps drive strong winds, creating their banded appearances and sometimes giving rise to huge storms.

Just as unusually large hurricanes occasionally arise on Earth, Jupiter also has its share of powerful storms. Of course, because it is Jupiter, its storms dwarf those on Earth. White and brown ovals that frequently appear in Jupiter's atmosphere are low-pressure storms, but many are as large as the entire Earth. Jupiter's most famous feature—its **Great Red Spot**—is also a gigantic storm.

The Great Red Spot is more than twice as wide as Earth. It is somewhat like a hurricane on Earth, except that its winds circulate around a high-pressure region rather than a low-pressure region (Figure 8.9). It is also extremely long-lived compared to storms on Earth: Astronomers have seen it throughout the three centuries during which telescopes have been powerful enough to detect it. No one knows why the Great Red Spot has lasted so long. However, storms on Earth tend to lose their strength when they pass over land. Perhaps Jupiter's biggest storms last for centuries simply because there's no solid surface effect to sap their energy. Two long-lived storms have recently been observed to undergo a mysterious change, turning red. The more recent one was torn apart by the Great Red Spot as it passed nearby (Figure 8.10a). Scientists hope to learn more about Jupiter's weather by studying storms like these.

The other jovian planets also have dramatic weather patterns (Figure 8.10b–d). As on Jupiter, Saturn's rapid rotation creates alternating bands of rising and falling air, along with rapid east-west winds. In fact, Saturn's winds are even faster than Jupiter's—a surprise that scientists have yet to explain. Neptune's atmosphere is also banded, and we

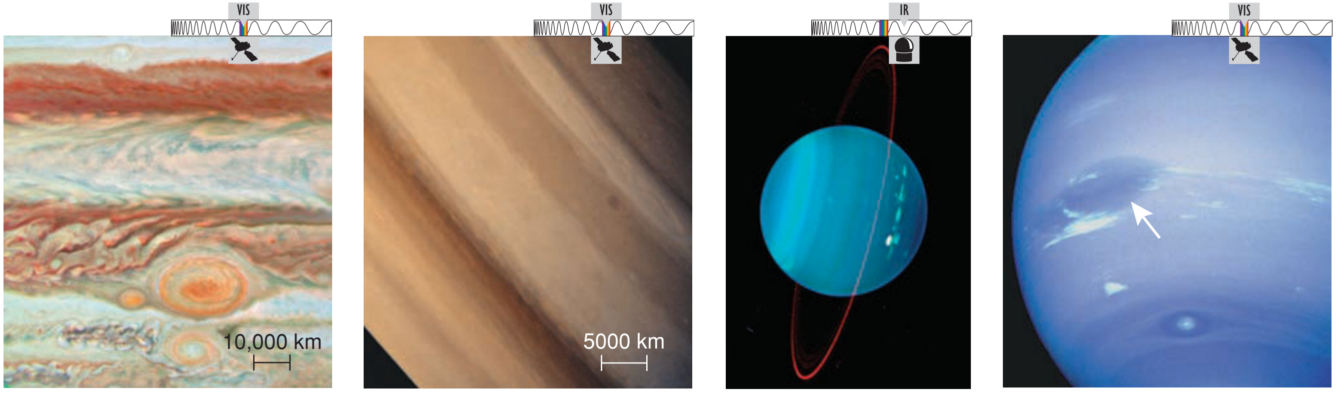


Figure 8.10

Selected views of weather patterns on the four jovian planets.

a This Hubble Space Telescope image shows Jupiter's southern hemisphere with the Great Red Spot, "Baby Red" (to its left), and "Red Jr." (below). Baby Red was torn apart by the Great Red Spot a few days later.

b Saturn's atmosphere, photographed by *Voyager 1*. Its banded appearance is very similar to that of Jupiter, but it has even faster winds.

c This infrared photograph from the Keck telescope shows several storms (the bright blotches) brewing on Uranus. Uranus's rings show up in red.

d Neptune's atmosphere, viewed from *Voyager 2*, shows bands and occasional strong storms. The large storm (white arrow) was called the Great Dark Spot.

have seen a high-pressure storm, called the Great Dark Spot, similar to Jupiter's Great Red Spot. However, the Great Dark Spot did not last as long; it disappeared from view just 6 years after its discovery.

The greatest surprise in jovian weather comes from Uranus. When *Voyager 2* flew past Uranus in 1986, photographs revealed virtually no clouds and no banded structure like those found on the other jovian planets. Scientists attributed the lack of weather to the lower internal heat of Uranus. However, subsequent observations from the Hubble Space Telescope and ground-based adaptive optics telescopes showed storms raging in Uranus's atmosphere. The storms were brewing because of the changing seasons: Thanks to Uranus's extreme axis tilt and 84-year orbit of the Sun, its northern hemisphere was seeing sunlight for the first time in decades.

8.2 A Wealth of Worlds: Satellites of Ice and Rock

The jovian planets are majestic and fascinating, but they are only the beginning of our exploration of jovian planet *systems*. Each of the four jovian systems includes numerous moons and a set of rings. The total mass of all the moons and rings put together is minuscule compared to any one of the jovian planets, but the remarkable diversity of these satellites makes up for their lack of size. In this section, we'll explore a few of the most interesting aspects of the jovian moons.

• What kinds of moons orbit the jovian planets?

We now know of more than 160 moons orbiting the jovian planets. Jupiter has the most, with more than 60 moons known to date. It's helpful to organize these moons into three groups by size: small moons less than about 300 kilometers in diameter, medium-size moons ranging from about 300 to 1500 kilometers in diameter, and large moons more than 1500 kilometers in diameter. These categories are useful because size relates to geological activity. In general, larger moons are more likely to show evidence of past or present geological activity.

Figure 8.11 shows a montage of all the medium-size and large moons. These moons resemble the terrestrial planets in many ways.

Figure 8.11

The medium-size and large moons of the jovian planets, with sizes (but not distances) shown to scale. Mercury, the Moon, and Pluto are included for comparison.

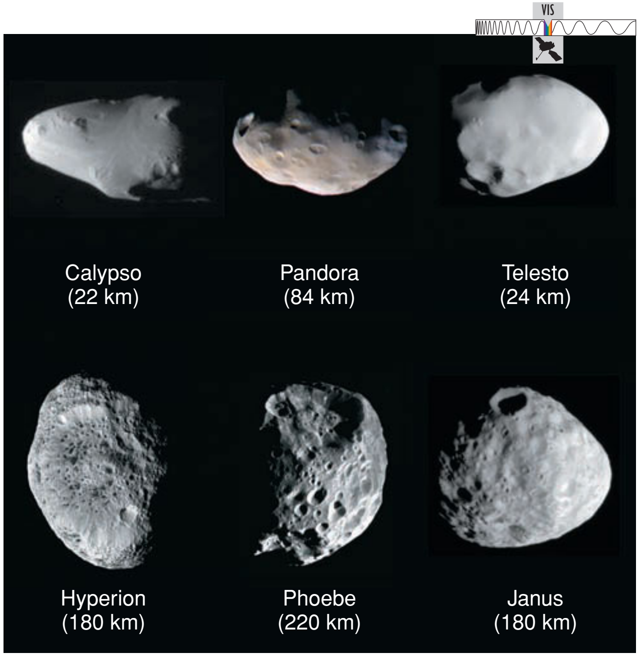


Figure 8.12

These photos from the *Cassini* spacecraft show six of Saturn's smaller moons. All are much smaller than the smallest moons shown in Figure 8.11. Their irregular shapes are due to their small size, which makes their gravities too weak to force them into spheres. The sizes in parentheses represent approximate lengths along their longest axes.

Each is spherical with a solid surface and its own unique geology. Some possess atmospheres, hot interiors, and even magnetic fields. The two largest—Jupiter's moon Ganymede and Saturn's moon Titan—are larger than the planet Mercury, while four others (Jupiter's moons Io, Europa, and Callisto and Neptune's moon Triton) are larger than the largest known dwarf planets, Pluto and Eris. However, they differ from terrestrial worlds in their compositions: Because they formed in the cold outer solar system, most of these moons contain substantial amounts of ice in addition to metal and rock.

Most of the medium-size and large moons probably formed by accretion within the disks of gas surrounding individual jovian planets **[Section 6.4]**. That explains why their orbits are almost circular and lie close to the equatorial plane of their parent planet, and also why these moons orbit in the same direction in which their planet rotates. In contrast, many of the numerous small moons are probably captured asteroids or comets, and thus do not follow any particular orbital patterns. Dozens of the smallest moons have been discovered only within the past few years (see Appendix E.3 for a current list), and many more may yet be discovered.

A few jovian moons rival the smallest planets in size and geological interest, while vast numbers of smaller moons are captured asteroids and comets.

The small moons' shapes generally resemble potatoes (Figure 8.12), because their gravities are too weak to force their rigid material into spheres. We have not studied these moons in depth, but we expect their small sizes to allow for little if any geological activity. For the most part, the small moons are just chunks of ice and rock held captive by the gravity of their parent planet.

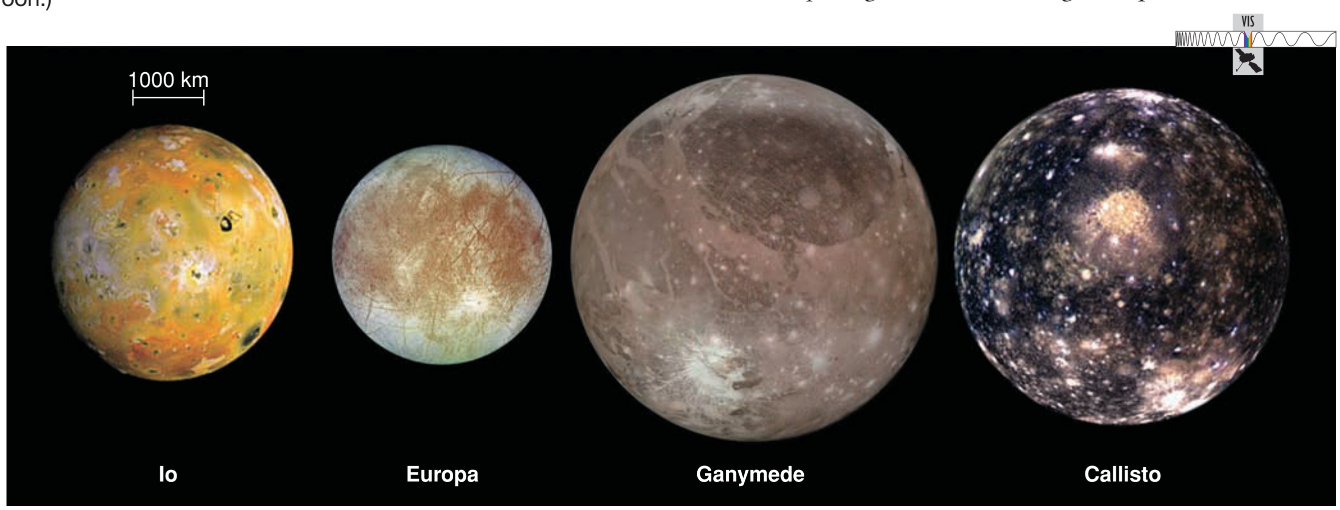
• Why are Jupiter's Galilean moons geologically active?

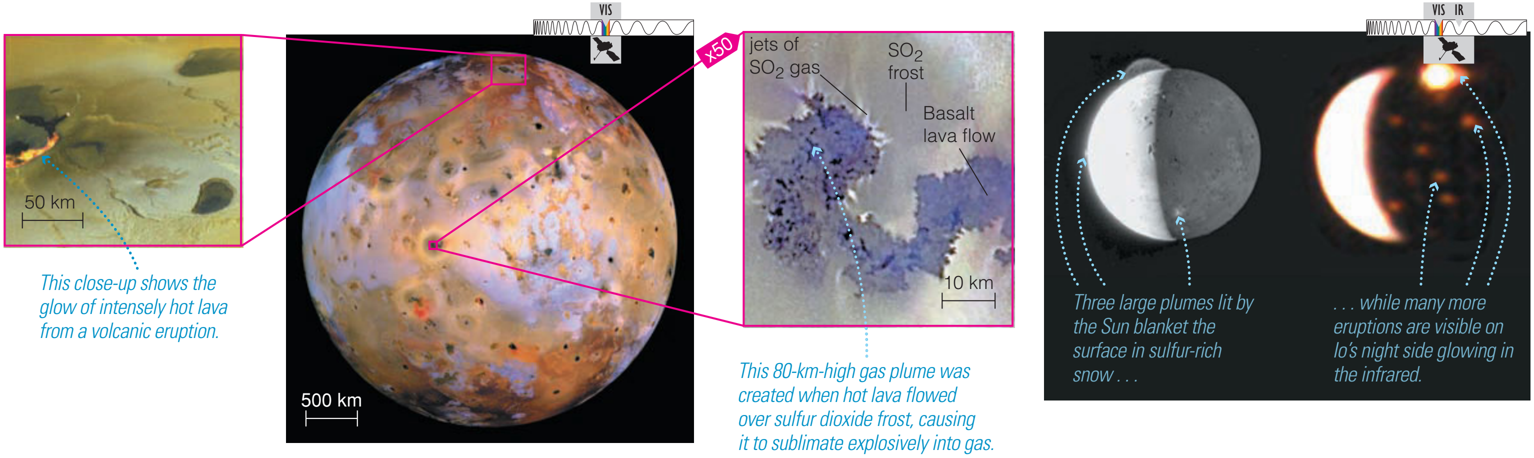
We are now ready to embark on a brief tour of the most interesting moons of the jovian planets. Our first stop is Jupiter. Jupiter's four largest moons, known as the *Galilean moons* because Galileo discovered them **[Section 3.3]**, are all large enough that they would count as planets or dwarf planets if they orbited the Sun (Figure 8.13).

Io: The Most Volcanically Active World in the Solar System For anyone who thinks of moons as barren, geologically dead places like our own Moon, Io shatters the stereotype. When the *Voyager* spacecraft first photographed Io up close about three decades ago, we discovered a world with a surface so young that not a single impact crater has survived.

Figure 8.13

This set of photos, taken by the *Galileo* spacecraft, shows global views of the four Galilean moons as we know them today. Sizes are shown to scale. (Io is about the size of Earth's Moon.)





a Most of the black, brown, and red spots on Io's surface are recently active volcanic features. White and yellow areas are sulfur dioxide (SO_2) and sulfur deposits, respectively, from volcanic gases. (Photographs from the *Galileo* spacecraft; some colors slightly enhanced or altered.)

b Two views of Io's volcanoes taken by *New Horizons* on its way to Pluto.

Figure 8.14 MA **interactive figure**

Io is the most volcanically active body in the solar system.

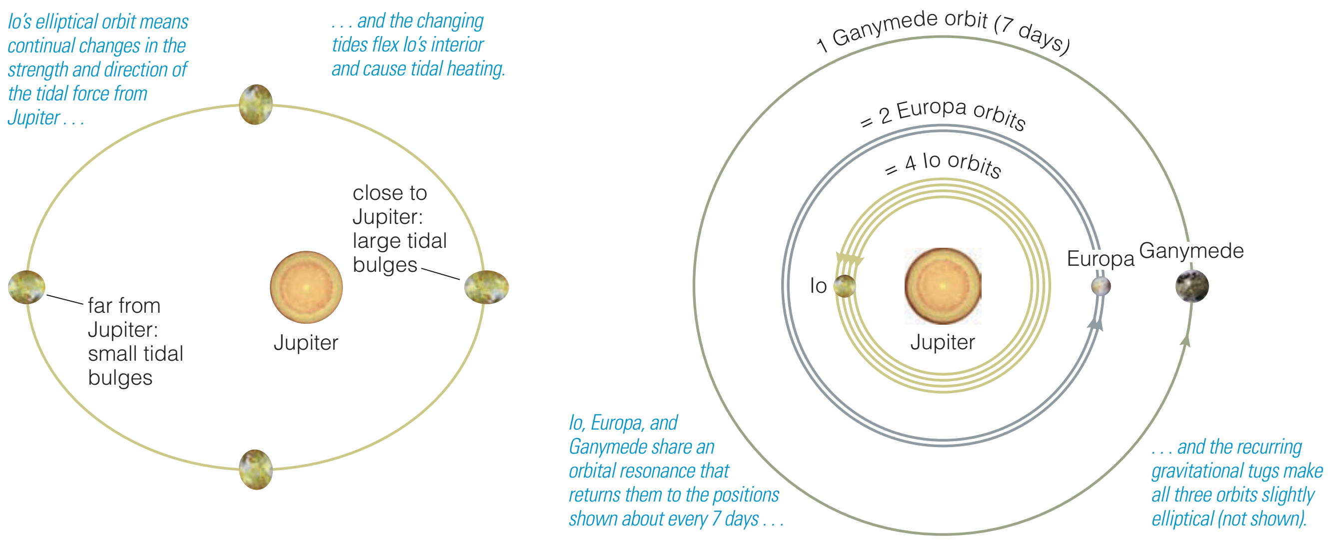
Moreover, *Voyager* cameras recorded volcanic eruptions in progress as the spacecraft passed by. We now know that Io is by far the most volcanically active world in our solar system. Large volcanoes pockmark its entire surface (Figure 8.14), and eruptions are so frequent that they have buried virtually every impact crater. Io probably also has tectonic activity, because tectonics and volcanism generally go hand in hand. However, debris from volcanic eruptions has probably buried most tectonic features.

Io's active volcanoes tell us that it must be quite hot inside. However, Io is only about the size of our geologically dead Moon, so it should have long ago lost any heat from its birth and is too small for radioactivity to provide much ongoing heat. How, then, can Io be so hot inside? The only possible answer is that some other ongoing process must be heating Io's interior. Scientists have identified this process and call it **tidal heating**, because it arises from effects of tidal forces exerted by Jupiter.

Just as Earth exerts a tidal force that causes the Moon to keep the same face toward us at all times **[Section 4.4]**, a tidal force from Jupiter makes Io keep the same face toward Jupiter as it orbits. But Jupiter's mass makes this tidal force far larger than the tidal force that Earth exerts on the Moon. Moreover, Io's orbit is slightly elliptical, so its orbital speed and distance from Jupiter vary. This variation means that the strength and direction of the tidal force change slightly as Io moves through each orbit, which in turn changes the size and orientation of Io's tidal bulges (Figure 8.15a). The result is that Io is continuously being flexed in different directions, which generates friction inside it. The flexing heats the interior in the same way that flexing warms Silly Putty. Tidal heating generates tremendous heat on Io—precise calculations show that it can indeed explain Io's incredible volcanic activity.

see it for yourself Pry apart the overlapping ends of a paper clip, and hold one end in each hand. Flex the ends apart and together until the paper clip breaks. Lightly touch the broken end to your finger or lips—can you feel the the warmth produced by flexing? How is this heating similar to the tidal heating of Io?

But we are still left with a deeper question: Why is Io's orbit slightly elliptical, when almost all other large satellites' orbits are virtually circular? The answer lies in an interesting dance executed by Io and its neighboring moons (Figure 8.15b). During the time Ganymede takes to complete one orbit of Jupiter, Europa completes exactly two orbits and Io completes exactly four orbits. The three moons therefore line up periodically, and



a Tidal heating arises because Io's elliptical orbit (exaggerated in this diagram) causes varying tides.

b Io's orbit is elliptical because of the orbital resonance it shares with Europa and Ganymede.

Figure 8.15 MA interactive figure

These diagrams explain the cause of tidal heating on Io. Tidal heating has a weaker effect on Europa and Ganymede, because they are farther from Jupiter and tidal forces weaken with distance.

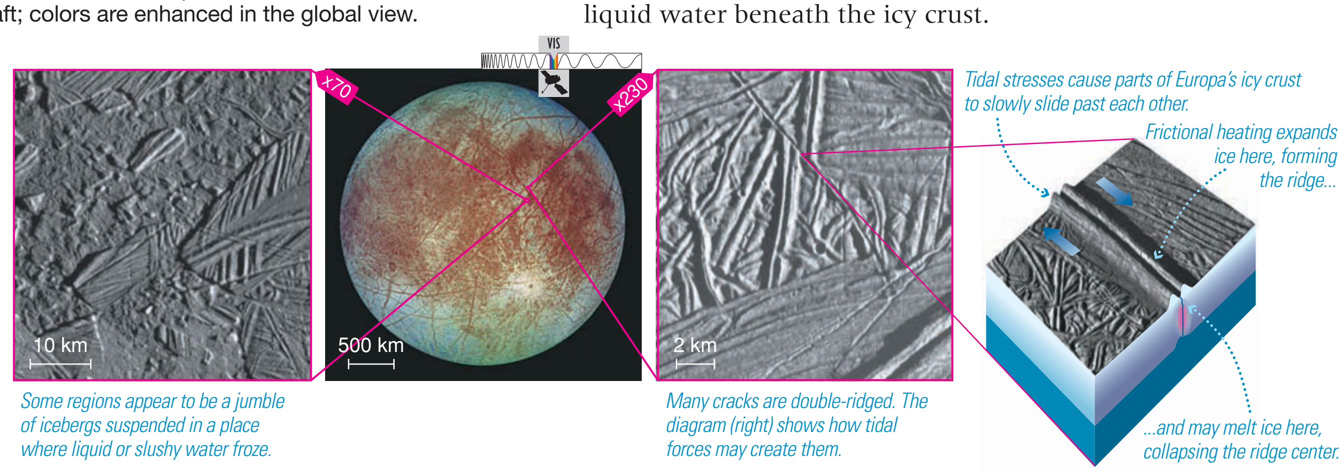
the gravitational tugs they exert on one another add up over time. Because the tugs are always in the same direction with each alignment, they tend to stretch out the orbits, making them slightly elliptical. The effect is much like that of pushing a child on a swing. If timed properly, a series of small pushes can add up to a *resonance* that causes the child to swing quite high. For the three moons, the **orbital resonance** that makes their orbits elliptical comes from the small gravitational tugs that repeat at each alignment.

Orbital resonances among the Galilean moons make Io's orbit slightly elliptical, leading to the tidal heating that makes Io the most volcanically active place in the solar system.

Europa: The Water World? Europa offers a stark contrast to Io. Instead of active volcanoes dotting its surface, Europa is covered by water ice (Figure 8.16). Nevertheless, its fractured, frozen surface must hide an interior made hot by the same type of tidal heating that powers Io's volcanoes—but tidal heating is weaker on Europa because it lies farther from Jupiter. Europa has only a handful of impact craters, which means that ongoing geological activity must have erased the evidence of nearly all past impacts. Scientists suspect that this geological activity is driven either by ice that is soft enough to undergo convection or by liquid water beneath the icy crust.

Figure 8.16

Europa's icy crust may hide a deep, liquid water ocean beneath its surface. These photos are from the *Galileo* spacecraft; colors are enhanced in the global view.



In fact, we have good reason to suspect that a deep water ocean lies beneath Europa's icy skin. Data collected by the *Galileo* spacecraft suggest that Europa has a metallic core and rocky mantle surrounded by a thick layer of water (H_2O). While the top of this layer is frozen as brittle ice, calculations suggest that tidal heating could supply enough heat to make most of this layer into an ocean of liquid water (Figure 8.17). Several pieces of observational evidence support the existence of a liquid water ocean, including close-up photos of the surface and careful studies of Europa's magnetic field.

Tidal heating may create a deep ocean of liquid water beneath Europa's icy crust.

If it really exists, Europa's liquid ocean may be more than 100 kilometers deep. If so, it contains more than twice as much liquid water as all of Earth's oceans combined. Perhaps as on Earth's seafloor, lava erupts from vents on Europa's seafloor, sometimes violently enough to jumble the icy crust above. And, knowing that primitive life thrives near seafloor vents on Earth, we can wonder whether Europa might also be a home to life—a possibility we will explore further in Chapter 18.

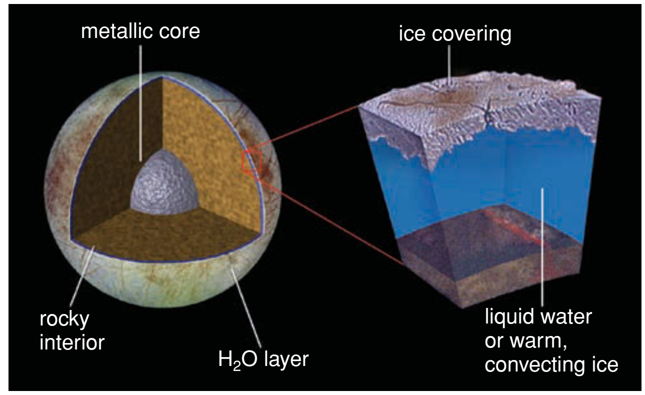


Figure 8.17

This diagram shows one model of Europa's interior structure. There is little doubt that the H_2O layer is real, but questions remain about whether the material beneath the icy crust is liquid water, relatively warm, convecting ice, or some of each.

Ganymede and Callisto Jupiter's two other large moons, Ganymede and Callisto, also show intriguing geology. Like Europa, both have surfaces of water ice.

The surface of Ganymede, the largest moon in the solar system, appears to have a dual personality (Figure 8.18). Some regions are dark and densely cratered, suggesting that they look much the same today as they did billions of years ago. Other regions are light-colored with very few craters, suggesting that liquid water has recently erupted and refrozen. Moreover, magnetic field data indicate that Ganymede, like Europa, could have a subsurface ocean of liquid water. If so, we'd need to explain the source of the heat that melts Ganymede's subsurface ice. Ganymede has some tidal heating, but calculations suggest that it is not strong enough to account for an ocean. Perhaps ongoing radioactive decay supplies enough additional heat to make an ocean. Or perhaps not—no one yet knows what secrets Ganymede hides.

Tidal heating is weak on Ganymede and absent on Callisto, yet both moons show some evidence of subsurface oceans.

The outermost Galilean moon, Callisto, looks most like what scientists originally expected for an outer solar system satellite: a heavily cratered iceball (Figure 8.19). The bright patches on its surface are impact craters. However, the surface still holds some surprises. Close-up images show a dark, powdery substance concentrated in low-lying areas, leaving ridges and crests bright white. The nature of this material and how it got there are unknown. Even more surprising, magnetic field data suggest that Callisto, too, could hide a subsurface ocean. No one knows what might heat the interior of Callisto, since it does not participate in the orbital resonances of the other Galilean moons and therefore has no tidal heating at all. Nevertheless, the potential for an ocean raises the intriguing possibility that there could be three "water worlds" orbiting Jupiter—with far more total ocean than we find here on Earth.

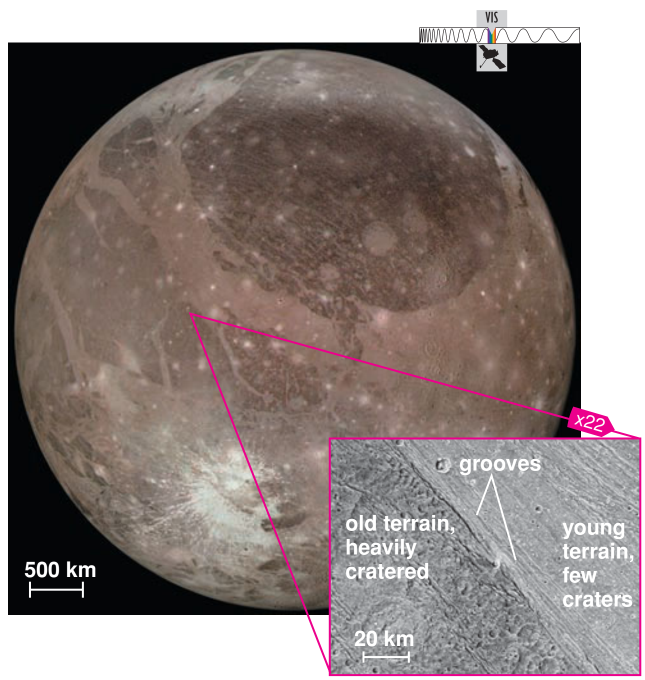
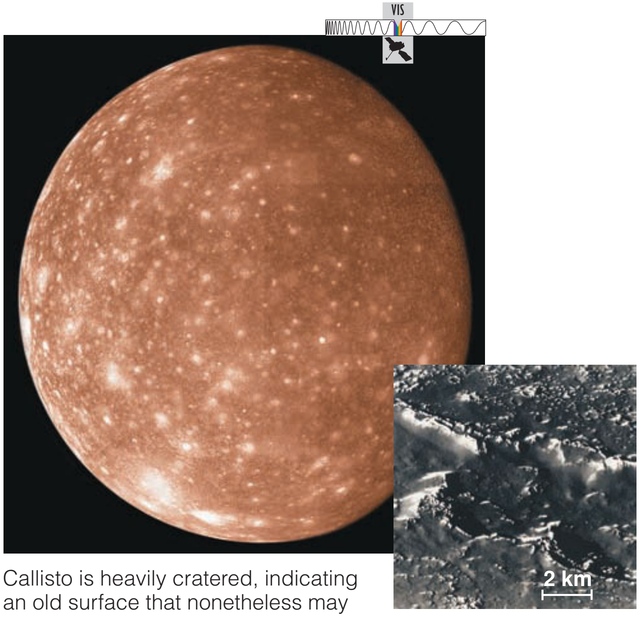


Figure 8.18

Ganymede, the largest moon in the solar system, has both old and young regions on its surface of water ice. The dark regions are heavily cratered and must be billions of years old, while the light regions are younger landscapes where eruptions of water have presumably erased ancient craters; the long grooves in the light regions were probably formed by water erupting along surface cracks. Notice that the boundary between the two types of terrain can be quite sharp.

• What geological activity do we see on Titan and other moons?

Aside from the four Galilean moons, the rest of Jupiter's moons fall in the small category, for which we expect no geological activity. However, if you look back at Figure 8.11, you'll see that the remaining jovian planets have



Callisto is heavily cratered, indicating an old surface that nonetheless may hide a deeply buried ocean.

Close-up photo shows a dark powder overlaying the low areas of the surface.

Figure 8.19

Callisto, the outermost of the four Galilean moons, has a heavily cratered icy surface.

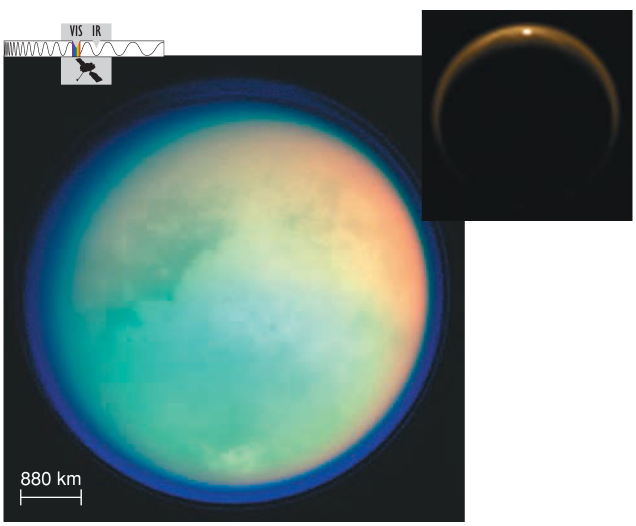


Figure 8.20

Saturn's moon Titan, as photographed by the *Cassini* spacecraft, is enshrouded by a thick atmosphere of nitrogen and hydrogen compounds extending hundreds of kilometers above the surface. *Cassini* was outfitted with filters designed to look at the specific near-infrared wavelengths of light that are least affected by the atmosphere. The inset shows sunlight reflecting off Kraken Mare, Titan's largest lake.

14 more medium- or large-size moons among them: seven for Saturn, five for Uranus, and two for Neptune. Thanks especially to the *Cassini* spacecraft, orbiting Saturn since 2004, we are learning that even some of the smaller of these moons can have surprisingly active geology.

Titan Saturn's moon Titan is the second-largest moon in the solar system (after Ganymede). It is also unique among the moons of our solar system in having a thick atmosphere—so thick that it hides the surface from view, except at a few specific wavelengths of light (Figure 8.20). Titan's reddish color comes from chemicals in its atmosphere much like those that make smog over cities on Earth. The atmosphere is more than 95% nitrogen, not that different from the 77% nitrogen content of Earth's atmosphere. However, the rest of Earth's atmosphere is mostly oxygen, while the rest of Titan's consists of argon, methane (CH_4), ethane (C_2H_6), and many other hydrogen compounds.

Titan has a thick atmosphere, leading to methane rain and surprising erosional geology.

Where did Titan's unique atmosphere come from? Titan's icy composition has supplied methane and ammonia gas through evaporation, sublimation, and possibly volcanic eruptions. Solar ultraviolet light breaks down some of those molecules, releasing hydrogen atoms and leaving highly reactive compounds containing carbon and nitrogen. The light hydrogen atoms can completely escape from Titan, while the remaining molecular fragments react to make the other ingredients of Titan's atmosphere. For example, the abundant molecular nitrogen is made after ultraviolet light breaks down ammonia (NH_3) molecules, and ethane is made from methane.

The methane and ethane in Titan's atmosphere are both greenhouse gases, and therefore give Titan an appreciable greenhouse effect **[Section 7.1]** that makes it warmer than it would be otherwise. Still, because of its great distance from the Sun, its surface temperature is a frigid 93 K (−180°C). The surface pressure on Titan is about 1.5 times the sea level pressure on Earth, which would be fairly comfortable if not for the lack of oxygen and the cold temperatures.

A moon with a thick atmosphere is intriguing enough, but we have at least two other reasons for our special interest in Titan. First, its complex atmospheric chemistry produces numerous organic chemicals—the chemicals that are the basis of life. Most scientists suspect Titan is too cold to support life, but many hope that further study of Titan will teach us about the chemistry that may have occurred on Earth before life actually arose. Second, although it is far too cold for liquid water to exist on Titan, conditions are right for methane or ethane rain, which creates rivers feeding into lakes or oceans.

NASA and the European Space Agency (ESA) combined forces to explore Titan, with NASA's *Cassini* "mother ship" releasing the ESA-built probe called *Huygens* (pronounced "Hoy-guns") to parachute to the surface in 2005 (Figure 8.21). During its descent, the probe photographed river valleys merging together, flowing down to what looks like a shoreline. On landing, instruments on the probe discovered that the surface has a hard crust but is a bit squishy below, perhaps like sand with liquid mixed in, and has "ice boulders" rounded by erosion. All these results support the idea of a wet climate—but wet with liquid methane rather than liquid water.

Cassini observations have also taught us a great deal about Titan's surface. The brighter regions in the photographs in Figure 8.21 are icy hills that may have been made by ice volcanoes. The dark valleys were probably created when methane rain carried down "smog particles" that concentrate on river bottoms. The vast plains into which the valleys

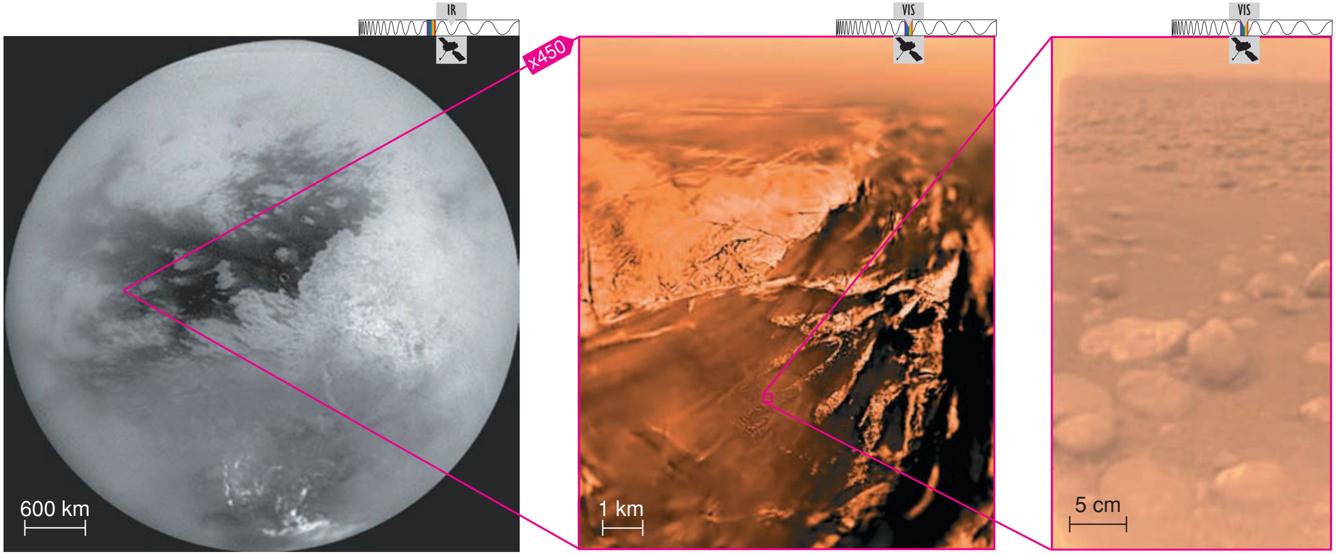


Figure 8.21 MA interactive figure

This sequence zooms in on the *Huygens* landing site on Titan. Left: a global view taken by the orbiting *Cassini* spacecraft. Center: an aerial view from the descending probe. Right: a surface view taken by the probe after landing; the "rocks," which are 10–20 centimeters across, are presumably made of ice.

appear to empty are low-lying regions, but they do not appear to be liquid. Instead, they are probably covered by smog particles carried down by the rivers and then sculpted into vast dune fields by Titan's global winds. All in all, conditions in Titan's equatorial regions appear to be analogous to the desert southwest of the United States, where infrequent rainfall carves valleys and creates vast dry lakes called "playas" where the water evaporates or soaks into the ground.

The polar regions of Titan, revealed by *Cassini* radar, contain numerous lakes of liquid methane or ethane (Figure 8.22). Images also reveal polar storm clouds (see Figure 8.21) and rivers flowing into the lakes, suggesting that Titan has a methane/ethane cycle resembling the water cycle on Earth. Almost all the lakes lie at high northern latitudes, where it was winter when they were discovered. Cooler winter temperatures may favor condensation, and lakes may form in the south as the seasons change. Alternatively, northern winters may always cause greater precipitation due to the combined effects of the tilt of the Saturn system and Saturn's slightly elliptical orbit.

One of the most astonishing results from the *Huygens* mission is how familiar the landscape looks in this alien environment with unfamiliar materials. Instead of liquid water, Titan has liquid methane and ethane. Instead of rock, Titan has ice. Instead of molten lava, Titan has a slush of water ice mixed with ammonia. Instead of surface dirt, Titan's surface has smog-like particles that rain out of the sky and accumulate on the ground. The similarities between the physical processes that occur on Titan and Earth appear to be far more important in shaping the landscapes than the fact that the two worlds have very different compositions and temperatures.

The *Cassini* mission has been extended to 2017, and scientists hope that additional radar mapping through the changing seasons will teach us more about this remarkable world.

think about it What other geological features might you expect on Titan, given its similarities to Earth? How might those features be different, given its differences?

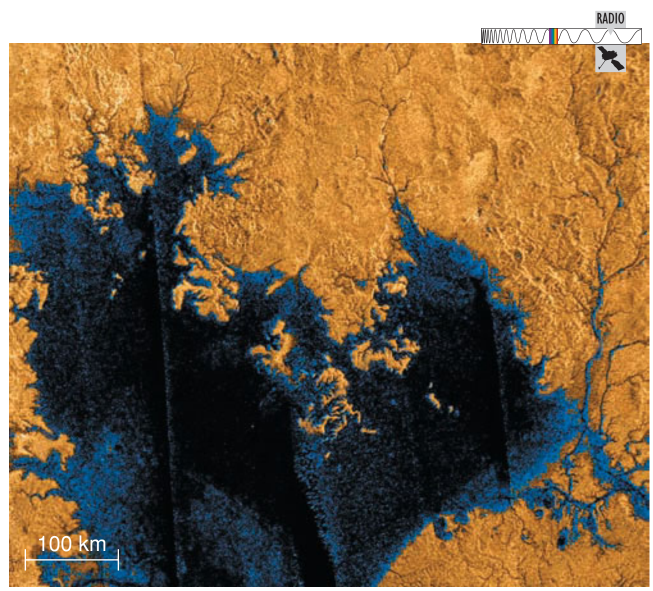


Figure 8.22

Radar image of Ligeia Mare near Titan's north pole showing lakes of liquid methane and ethane at a temperature of −180°C. Most solid surfaces reflect radar well, and these regions are artificially shaded tan to suggest land. The liquid surfaces reflect radar poorly, and these regions are shaded blue and black to suggest lakes.

Saturn's Medium-Size Moons The *Cassini* mission is also teaching us more about Saturn's other moons, especially its six medium-size moons (Figure 8.23). The photographs suggest that these moons have had a complex history.

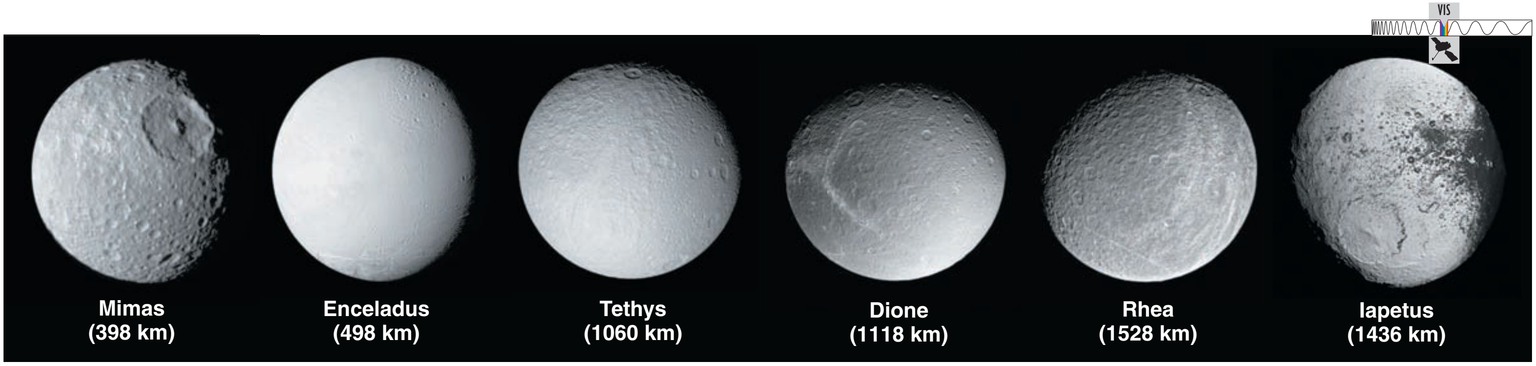


Figure 8.23

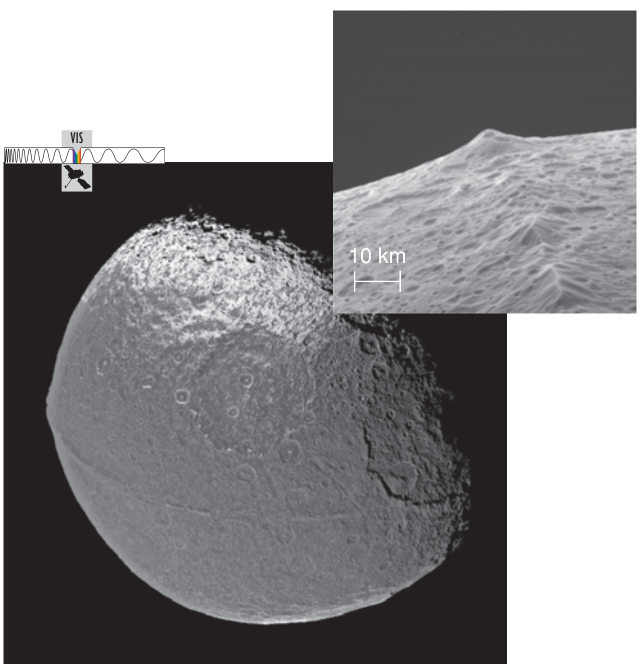
Portraits taken by the *Cassini* spacecraft of Saturn's medium-size moons (not to scale). All but Mimas show evidence of past volcanism and/or tectonics.

Only Mimas, the smallest of these six moons, shows little evidence of past volcanism or tectonics. It is essentially a heavily cratered iceball, with one huge crater nicknamed "Darth Crater" because of Mimas's resemblance to the Death Star in the *Star Wars* movies. Most of Saturn's other medium-size moons also have heavily cratered surfaces, confirming that they lack global geological activity today. However, we find abundant evidence of volcanism and/or tectonics that must have occurred more recently. Smooth regions appear to be places where icy lava once flowed, and close-up views of the bright streaks (such as the long streaks visible on Dione) show them to be vast sets of tectonic cliffs running parallel to one another.

Iapetus is particularly bizarre (Figure 8.24). It has an astonishing ridge more than 10 km high that spans nearly half its circumference, curiously aligned along the equator. No one knows its origin, but it is likely the result of tectonic activity. Moreover, much of Iapetus appears coated in very dark dust. Scientists have recently confirmed that the dust comes from Saturn's distant moon Phoebe (see Figure 8.12). The dust forms a ring as it spirals inward toward Iapetus.

Figure 8.24

Saturn's moon Iapetus has a 10-kilometer-tall equatorial ridge that spans nearly half its circumference. The inset shows a portion of the ridge in perspective.



Enceladus is the smallest moon in the solar system known to be geologically active today.

Enceladus provided an even bigger surprise: This moon is barely 500 kilometers across—small enough to fit inside the borders of Colorado—and yet it shows clear evidence of *ongoing* geological activity (Figure 8.25). Scientists knew that Enceladus undergoes some tidal heating through resonances, but were surprised to learn that the heating is enough to make this moon active today. Its surface has very few impact craters—and some regions have none at all—telling us that recent geological activity has erased older craters. Moreover, the strange grooves near its south pole are measurably warmer than the surrounding terrain, and photographs show this region venting huge clouds of water vapor and ice crystals, some containing salt. These fountains must have some subsurface source, which could potentially mean the existence of an ocean beneath the icy crust. In that case, there would be at least a slim possibility that Enceladus could harbor life **[Section 18.2]**.

Moons of Uranus and Neptune We know far less about the moons of Uranus and Neptune, because they have been photographed close-up only once each, during the *Voyager 2* flybys of the 1980s. Nevertheless, we again see evidence of surprising geological activity.

Uranus has five medium-size moons (and no large moons), and at least three of them show evidence of past volcanism or tectonics. Miranda, the smallest of the five, is the most surprising (Figure 8.26). Despite its small size, it shows tremendous tectonic features and relatively few craters. Apparently, it underwent geological activity well after the heavy bombardment ended **[Section 6.4]**, erasing its early craters.

The surprises continue with Neptune's moon Triton (Figure 8.27). Triton is a strange moon to begin with: It is a large moon, but it does not follow the orbital patterns of all other large moons in the outer solar system. Instead, it orbits Neptune "backward" (opposite to Neptune's rotation) and at a high inclination to Neptune's equator. These are telltale signs of a moon that was captured rather than having formed in the disk of gas around its planet. No one knows how a moon as large as Triton could have been captured, but models suggest one possible mechanism: Triton could have been part of a binary Kuiper belt object that passed so close to Neptune that Triton lost energy and was captured while its companion gained energy and was flung away at high speed.

Triton orbits Neptune "backward" and shows evidence of relatively recent geological activity.

Triton's geology is just as surprising as its origin. It is smaller than our own Moon, yet its surface shows evidence of relatively recent geological activity. Some regions show signs of past volcanism, while others show wrinkly ridges (nicknamed "cantaloupe terrain") that appear tectonic in nature. Triton even has a very thin atmosphere that has left some wind streaks on its surface. It's likely that Triton was originally captured into an elliptical orbit, which may have led to enough tidal heating to explain its geological activity.

Figure 8.25

Cassini photo of Saturn's moon Enceladus. The blue "tiger stripes" near the bottom of the main photo are regions of fresh ice that must have recently emerged from below. The colors are exaggerated; the image is a composite made at near-ultraviolet, visible, and near-infrared wavelengths. The inset shows Enceladus backlit by the Sun, with fountains of ice particles (and water vapor) clearly visible as they spray out of the south polar region.

• Why are jovian moons more geologically active than small rocky planets?

Based on what we learned when studying the geology of the terrestrial worlds, the active geology of the jovian moons seems out of character with their sizes. Numerous jovian moons remained geologically active far longer than Mercury or our Moon, yet they are no bigger and in many cases much smaller in size. However, there are two crucial differences between the jovian moons and the terrestrial worlds: composition and tidal heating.

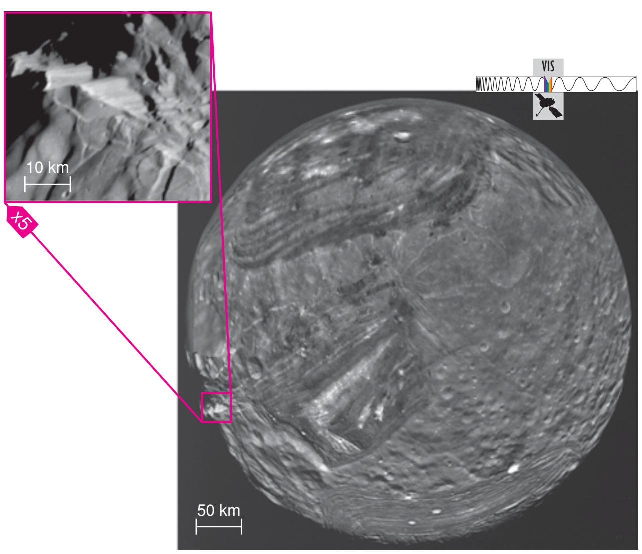
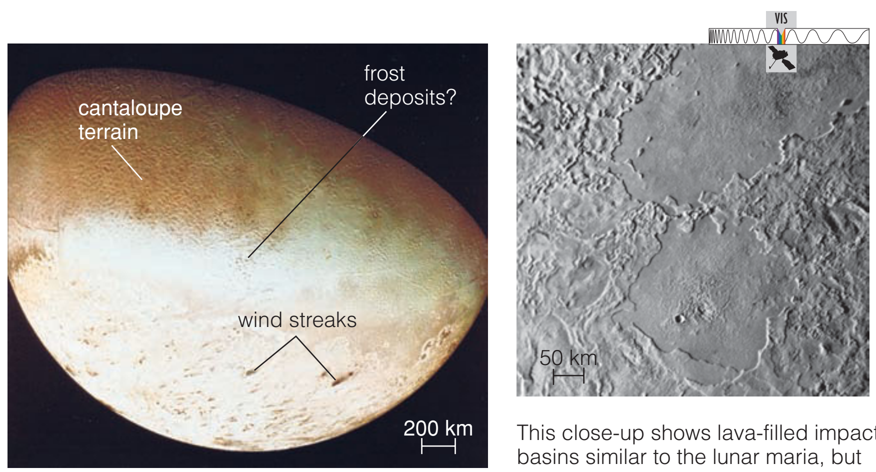


Figure 8.26

The surface of Uranus's moon Miranda shows astonishing tectonic activity despite its small size. The cliff walls seen in the inset are higher than those of the Grand Canyon on Earth.

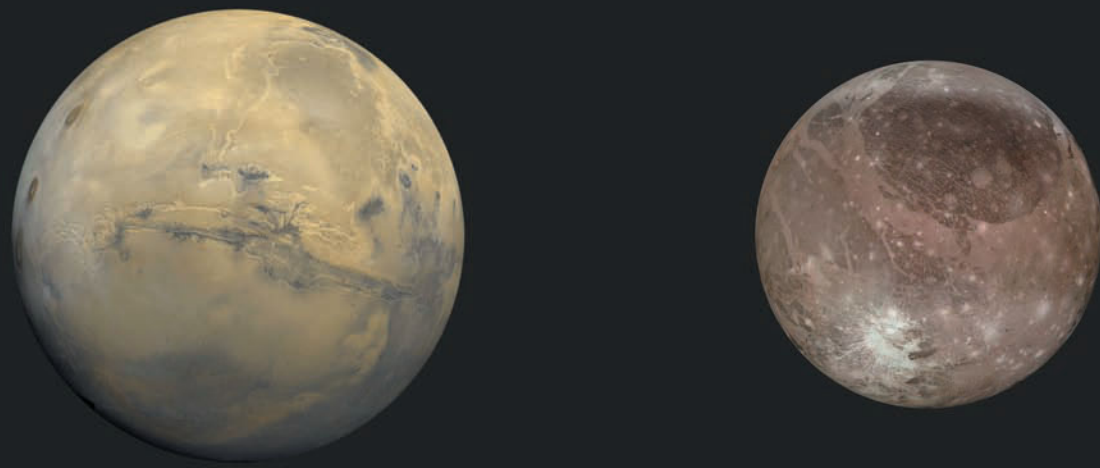


Triton's southern hemisphere as seen by *Voyager 2*.

This close-up shows lava-filled impact basins similar to the lunar maria, but the lava was water or slush rather than molten rock.

Figure 8.27

Neptune's moon Triton shows evidence of a surprising level of past geological activity.



Terrestrial Planet Geology

- Internal heat, primarily from radioactive decay, can cause volcanic and tectonic activity.
- Only large planets retain enough internal heat to stay geologically active today.
- Example: Mars (photo above) probably retains some internal heat. If it had been smaller, like Mercury, it would be geologically "dead" today. If it had been larger, like Earth, it would probably have much more active and ongoing tectonics and volcanism.

Jovian Moon Geology

- Tidal heating can cause tremendous geological activity on moons with elliptical orbits around massive planets.
- Even without tidal heating, icy materials can melt and deform at lower temperatures than rock, increasing the likelihood of geological activity.
- Together, these effects explain why icy moons are much more likely to have ongoing geological activity than rocky terrestrial worlds of the same size.
- Example: Ganymede (photo above) shows evidence of recent geological activity, even though it is similar in size to the geologically dead terrestrial planet Mercury.

Figure 8.28

Jovian moons can be much more geologically active than terrestrial worlds of similar size due to their icy compositions and tidal heating, which is not an important factor on the terrestrial worlds.

Most of the jovian moons contain ices that can melt or deform at far lower temperatures than rock. As a result, they can experience geological activity even when their interiors have cooled to temperatures far below what they were at their births. Indeed, except on Io, most of the volcanism that has occurred in the outer solar system probably did not produce any hot lava at all. Instead, it produced icy lava that was essentially liquid water, perhaps mixed with methane and ammonia.

Tidal heating plus the easy melting and deformation of ices mean that even small icy moons can sustain geological activity.

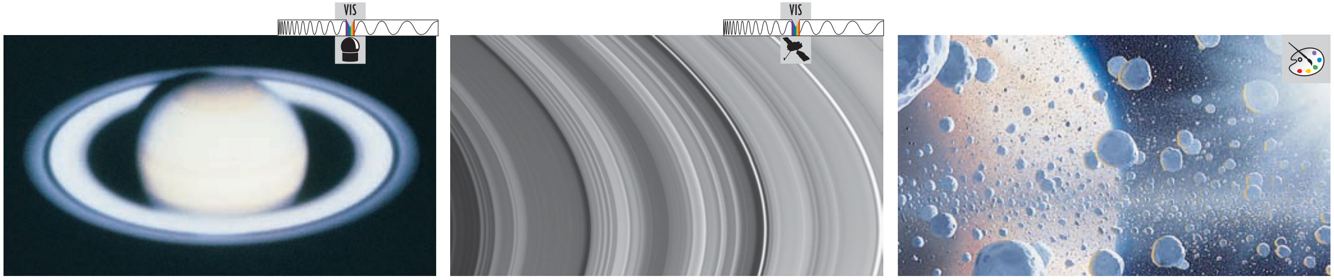
The major lesson, then, is that "ice geology" is possible at far lower temperatures than "rock geology." This fact, combined in many cases with tidal heating, explains how the jovian moons have had such interesting geological histories despite their small sizes. Figure 8.28 summarizes the differences between the geology of jovian moons and that of the terrestrial worlds.

8.3 Jovian Planet Rings

The jovian planet systems have three major components: the planets themselves, the moons, and the rings that encircle the planets. We have already studied the planets and their moons, so we now turn our attention to their amazing rings. We'll begin by exploring the rings of Saturn, since they are by far the most spectacular.

• What are Saturn's rings like?

You can see Saturn's rings through a backyard telescope, but learning their true nature requires higher resolution (Figure 8.29). From Earth, the rings appear to be continuous, concentric sheets of material separated



a This Earth-based telescopic view of Saturn makes the rings look like large, concentric sheets. The dark gap within the rings is called the Cassini division.

b This image of Saturn's rings from the *Cassini* spacecraft reveals many individual rings separated by narrow gaps.

c Artist's conception of particles in a ring system. All the particles are moving slowly relative to one another and occasionally collide.

Figure 8.29 MA interactive figure

Zooming in on Saturn's rings.

by a large gap (called the *Cassini division*). Spacecraft images reveal these "sheets" to be made of many individual rings, each separated from the next by a narrow gap. But even these appearances are somewhat deceiving. If we could wander into Saturn's rings, we'd find that they are made of countless icy particles ranging in size from dust grains to large boulders. All are far too small to be photographed even from spacecraft passing nearby.

Ring Particle Characteristics Spectroscopy reveals that Saturn's ring particles are made of relatively reflective water ice. The rings look bright where they contain enough particles to intercept sunlight and scatter it back toward us. We see gaps in places where there are few particles to reflect sunlight.

Saturn's rings are made of vast numbers of icy particles ranging in size from dust grains to boulders, each circling Saturn according to Kepler's laws.

Each individual ring particle orbits Saturn independently in accord with Kepler's laws, so the rings are much like myriad tiny moons. The individual ring particles are so close together that they collide frequently. In the densest parts of the rings, each particle collides with another every few hours. However, the collisions are fairly gentle: Despite the high orbital speeds of the ring particles, nearby ring particles are moving at nearly the same speed and touch only gently when they collide.

think about it Which ring particles travel faster: those closer to Saturn or those farther away? Explain why. (*Hint:* Review Kepler's third law.)

The frequent collisions explain why Saturn's rings are one of the thinnest known astronomical structures. They span more than 270,000 kilometers in diameter but are only a few tens of *meters* thick. To understand how collisions keep the rings thin, imagine what would happen to a ring particle on an orbit slightly inclined to the central ring plane. The particle would collide with other particles every time its orbit intersected the ring plane, and its orbital tilt would be reduced with every collision. Before long, these collisions would force the particle to conform to the orbital pattern of the other particles, and any particle that moved away from the narrow ring plane would soon be brought back within it.

Rings and Gaps Close-up photographs show an astonishing number of rings, gaps, ripples, and other features—as many as 100,000 altogether (Figure 8.30). Scientists are still struggling to explain all the features, but some general ideas are now clear.

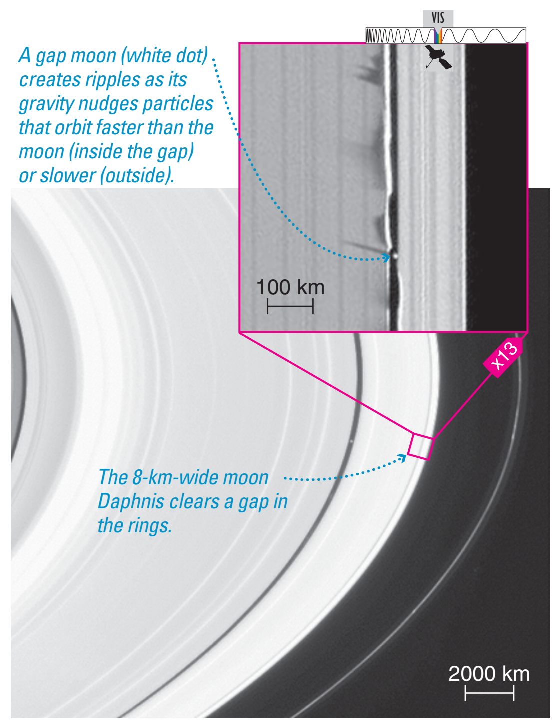


Figure 8.30

Small moons within the rings have important effects on ring structure (*Cassini* photos). The inset image was taken near Saturn's equinox, so the moon and ripples cast long shadows to the left.

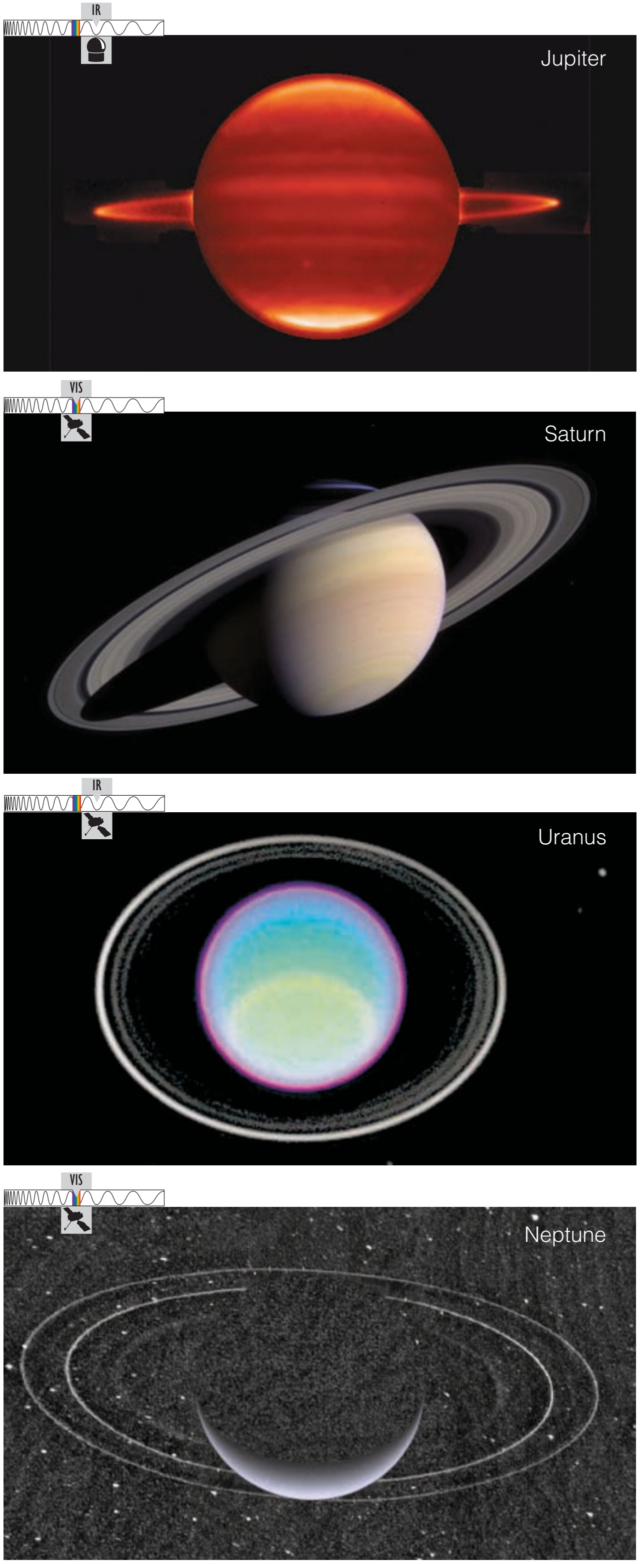


Figure 8.31

Four ring systems (not to scale). The rings differ in appearance and in the composition and sizes of the ring particles. (Jupiter: Keck telescope, infrared; Saturn: *Cassini*, visible; Uranus: Hubble Space Telescope, infrared; Neptune: *Voyager 2*, visible.)

Rings and gaps are caused by particles bunching up at some orbital distances and being forced out at others. This bunching happens when gravity nudges the orbits of ring particles in some particular way. One source of nudging comes from small moons located within the gaps in the rings themselves, sometimes called *gap moons*. The gravity of a gap moon can effectively keep the gap clear of smaller ring particles. In some cases, two nearby gap moons can force particles between them into a very narrow ring. (The gap moons are often called *shepherd moons* in those cases, because they shepherd particles into line.)

Ring particles also may be nudged by the gravity from larger, more distant moons. For example, a ring particle orbiting about 120,000 kilometers from Saturn's center will circle the planet in exactly half the time it takes the moon Mimas to orbit. Every time Mimas returns to a certain location, the ring particle will also be at its original location and therefore will experience the same gravitational nudge from Mimas. The periodic nudges reinforce one another and clear a gap in the rings—in this case, the Cassini division. This type of reinforcement due to repeated gravitational tugs is another example of an *orbital resonance,* much like the orbital resonance that makes Io's orbit elliptical (see Figure 8.15b). Other orbital resonances, caused by moons both within the rings and farther out from Saturn, probably explain most of the intricate structures we see.

• Why do the jovian planets have rings?

Saturn's rings were once thought to be unique in the solar system, leading scientists to assume they were formed by some kind of rare event, such as a moon wandering too close to Saturn and being torn apart by tidal forces. However, we now know that all four jovian planets have rings (Figure 8.31). Although Saturn's rings have more numerous and more reflective particles than the other ring systems, we can no longer think that rings are rare. We therefore need an explanation for rings that doesn't require rare events to have happened for all four planets.

Some scientists once guessed that the ring particles might be leftover chunks of rock and ice that condensed in the disks of gas that orbited each jovian planet when it was young. This would explain why all four jovian planets have rings, because tidal forces near each planet would have prevented these chunks from accreting into a full-fledged moon. However, we now know that the ring particles cannot be leftovers from the birth of the planets, because they could not have survived for billions of years. Ring particles are continually being ground down in size, primarily by the impacts of the countless sand-size particles that orbit the Sun—the same types of particles that become meteors in Earth's atmosphere and cause micrometeorite impacts on the Moon **[Section 7.2]**. Millions of years of such tiny impacts would have ground the existing ring particles to dust long ago.

We are left with only one reasonable possibility: New particles must be continually supplied to the rings to replace those that are destroyed. These new particles must come from a source that lies in each planet's equatorial plane. The most likely source is numerous small "moonlets"—moons the size of gap moons (see Figure 8.30)—that formed in the disks of material orbiting the young jovian planets. Like the ring particles themselves, tiny impacts are gradually grinding away these small moons, but they are large enough to still exist despite $4\frac{1}{2}$ billion years of such sandblasting.

Ring particles cannot last for billions of years, so the rings we see today must be made of particles created recently.

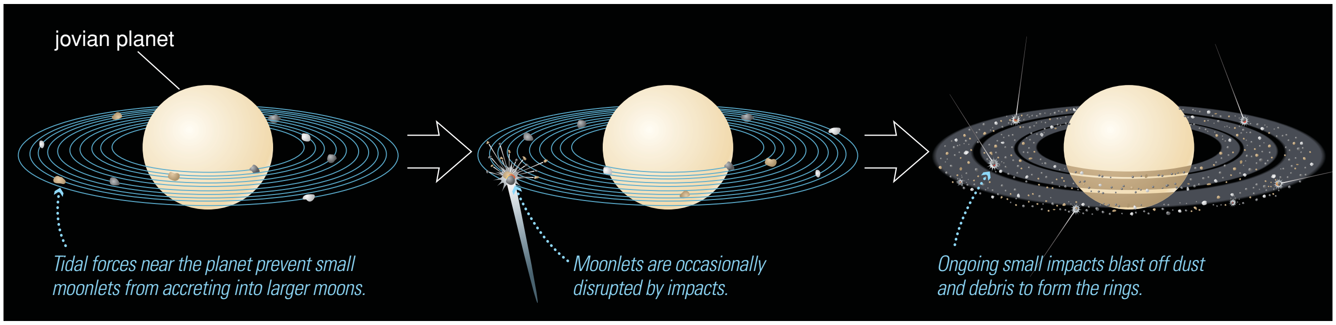


Figure 8.32

This illustration summarizes the origin of rings around the jovian planets.

The small moons contribute ring particles in two ways. First, each tiny impact releases particles from a small moon's surface, and these released particles become new, dust-size ring particles. Ongoing impacts ensure that some ring particles are present at all times. Second, occasional larger impacts can shatter a small moon completely, creating a supply of boulder-size ring particles. The frequent tiny impacts then slowly grind these boulders into smaller ring particles. Some of these particles are "recycled" by forming into small clumps, only to come apart again later on; others are ground down to dust and slowly spiral onto their planet. In summary, all ring particles ultimately come from the gradual dismantling of small moons that formed during the birth of the solar system (Figure 8.32).

New ring particles are released by impacts on small moons within the rings.

the big picture — Putting Chapter 8 into Perspective

In this chapter, we saw that the jovian planets really are a different kind of planet and, indeed, a different kind of planetary system. The jovian planets dwarf the terrestrial planets. Even some of their moons are as large as terrestrial worlds. As you continue your study of the solar system, keep in mind the following "big picture" ideas:

- The jovian planets may lack solid surfaces on which geology can occur, but they are interesting and dynamic worlds with rapid winds, huge storms, strong magnetic fields, and interiors in which common materials behave in unfamiliar ways.
- Despite their relatively small sizes and frigid temperatures, many jovian moons are geologically active by virtue of their icy compositions—a result of their formation in the outer regions of the solar nebula—and tidal heating.
- Ring systems probably owe their existence to small moons formed in the disks of gas that produced the jovian planets billions of years ago. The rings we see today are composed of particles liberated from those moons quite recently.
- Understanding jovian planet systems forced us to modify many of our earlier ideas about the solar system by adding the concepts of ice geology, tidal heating, and orbital resonance. Each new set of circumstances we discover offers new opportunities to learn how our universe works.

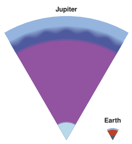
summary of key concepts

8.1 A Different Kind of Planet

- **What are jovian planets made of?**

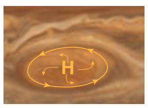
Jupiter and Saturn are made almost entirely of hydrogen and helium, while Uranus and Neptune are made mostly of hydrogen compounds mixed with metal and rock. These differences arose because all four planets started from ice-rich planetesimals of about the same size but captured different amounts of hydrogen and helium gas from the solar nebula.

- **What are jovian planets like on the inside?**



The jovian planets have layered interiors with very high internal temperatures and pressures. All have a core about 10 times as massive as Earth, consisting of hydrogen compounds, metals, and rock. They differ mainly in their surrounding layers of hydrogen and helium, which can take on unusual forms under the extreme internal conditions of the planets.

- **What is the weather like on jovian planets?**



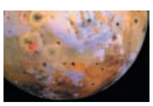
The jovian planets all have multiple cloud layers that give them distinctive colors, fast winds, and large storms. Some storms, such as the Great Red Spot, can apparently rage for centuries or longer.

8.2 A Wealth of Worlds: Satellites of Ice and Rock

- **What kinds of moons orbit the jovian planets?**

We can categorize the sizes of the many known moons as small, medium, or large. Most of the medium and large moons probably formed with their planet in the disks of gas that surrounded the jovian planets when they were young. Smaller moons are often captured asteroids or comets.

- **Why are Jupiter's Galilean moons geologically active?**



Io is the most volcanically active object in the solar system, thanks to an interior kept hot by **tidal heating**—which occurs because Io's close orbit is made elliptical by **orbital resonance** with other moons. Europa (and possibly Ganymede) may have a deep, liquid water ocean under its icy crust, also due to tidal heating. Callisto is the least geologically active, since it has no orbital resonance or tidal heating.

- **What geological activity do we see on Titan and other moons?**

Titan, the only moon in our solar system with a thick atmosphere, shows evidence of active surface geology, including erosion caused by methane rain. Other medium-size moons of Saturn and Uranus show evidence of past geology. Saturn's moon Enceladus is geologically active today, as evidenced by fountains of ice and water vapor that shoot out from its surface. Neptune's large moon Triton is almost certainly a captured object and also shows evidence of recent geological activity.

- **Why are jovian moons more geologically active than small rocky planets?**

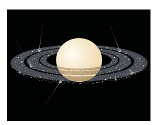
Ices deform and melt at much lower temperatures than rock, allowing icy volcanism and tectonics at surprisingly low temperatures. In addition, some jovian moons have a heat source—tidal heating—that is not important for the terrestrial worlds.

8.3 Jovian Planet Rings

- **What are Saturn's rings like?**

Saturn's rings are made up of countless individual particles, each orbiting Saturn independently like a tiny moon. The rings lie in Saturn's equatorial plane, and they are extremely thin.

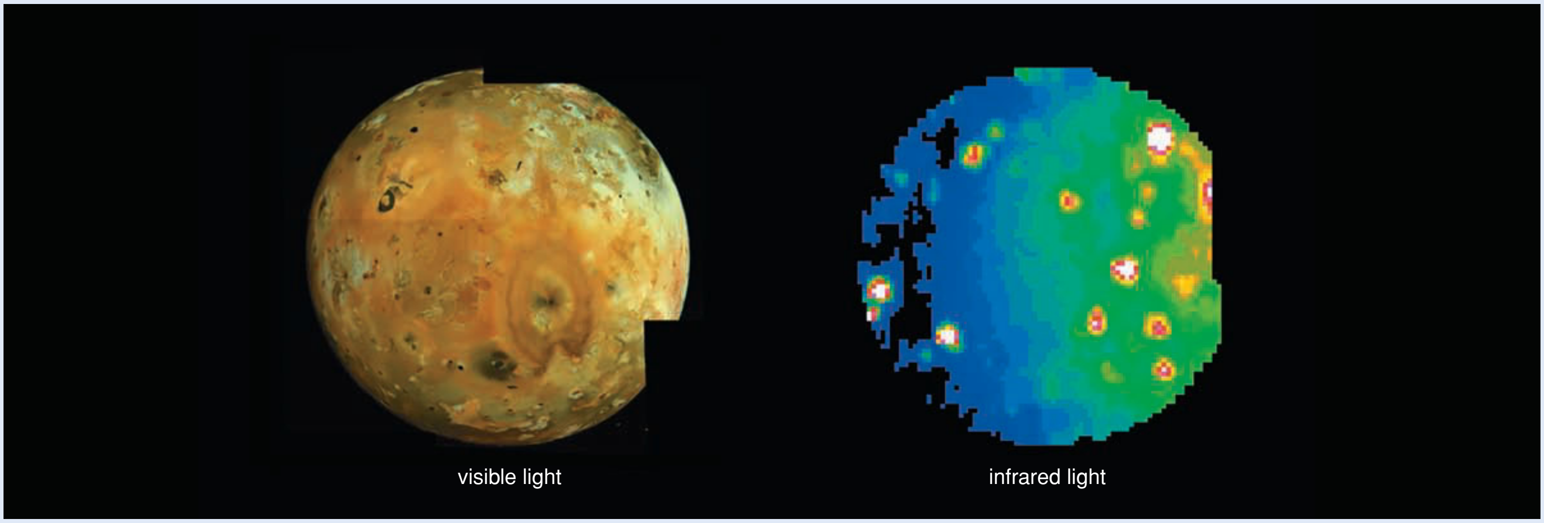
- **Why do the jovian planets have rings?**



Ring particles probably come from the dismantling of small moons formed in the disks of gas that surrounded the jovian planets billions of years ago. Small ring particles come from countless tiny impacts on the surfaces of these moons, while larger ones come from impacts that shatter the moons.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 8 Visual Quiz at www.masteringastronomy.com.



The left image shows the approximate colors of Io in visible light; the black spots are volcanoes that are still active or have recently gone inactive. The right image shows infrared thermal emission from Io; the bright spots are active volcanoes. (Both images are composed from *Galileo* photos, but taken at different times.) Answer the following questions by comparing the two images.

1. What do the colors represent in the right image?
   a. the actual colors of Io's surface
   b. the colors we would see if we had infrared eyes
   c. the intensity of the infrared light
   d. regions of different chemical composition on the surface
2. Which color in the right image represents regions with the highest temperature?
   a. blue b. green c. orange
   d. red e. white
3. The image on the right was obtained when only part of Io was in sunlight. Based on the colors shown over Io's surface as a whole, which part of the image was in sunlight?
   a. the left side
   b. the right side
   c. only the peaks of the volcanoes
4. The bright spots in the infrared image are active volcanoes, and the black spots in the visible image are volcanoes that may or may not be active now. By comparing the two images, what can you conclude about Io's volcanoes?
   a. Every black spot in the visible image has a bright spot in the infrared image, so all of Io's volcanoes were active when the photos were taken.
   b. There are more black spots in the visible image than bright spots in the infrared image, so many of Io's volcanoes were inactive when the photos were taken.
   c. There are more bright spots in the infrared image than black spots in the visible image, so new eruptions must have started after the visible photo was taken.

exercises and problems

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Briefly describe how differences in composition among the jovian planets can be traced to their formation.
2. Why is Jupiter so much more dense than Saturn? Could a planet be smaller in size than Jupiter but greater in mass? Explain.
3. Briefly describe the interior structure of Jupiter and why it is layered in this way. How do the interiors of the other jovian planets compare to that of Jupiter?
4. Why does Jupiter have such a strong magnetic field? Describe a few features of Jupiter's magnetosphere.
5. Briefly describe Jupiter's cloud layers. How do the cloud layers help explain Jupiter's colors? Why are Saturn's colors more subdued? Why are Uranus and Neptune blue?
6. Briefly describe Jupiter's weather patterns and contrast them with those on the other jovian planets. What is the *Great Red Spot?*

7. Briefly describe how we categorize jovian moons by size. What is the origin of most of the medium and large moons? What is the origin of many of the small moons?
8. What are the key features of Jupiter's four Galilean moons? Explain the role of tidal heating and orbital resonance in explaining these features.
9. Describe the atmosphere of Titan. What did the *Cassini/Huygens* mission learn about Titan's surface?
10. Why do we think Triton is a captured Moon?
11. How do we know that Enceladus has active geology? Briefly explain why active geology is seen on icy moons that are much smaller than rocky worlds with no active geology.
12. What are planetary rings made of, and how do they differ among the four jovian planets? Briefly describe the effects of gap moons and orbital resonance on ring systems.
13. Explain why we think that ring particles must be replenished over time. Will the jovian planet rings always look the same?

Test Your Understanding

Surprising Discoveries?

Suppose someone claimed to make the discoveries described below. (These are not real discoveries.) Decide whether each discovery should be considered reasonable or surprising. Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

14. Saturn's core is pockmarked with impact craters and dotted with volcanoes erupting basaltic lava.
15. Neptune's deep blue color is not due to methane, as previously thought, but instead is due to its surface being covered with an ocean of liquid water.
16. A jovian planet in another star system has a moon as big as Mars.
17. An extrasolar planet is discovered that is made primarily of hydrogen and helium. It has approximately the same mass as Jupiter but is the same size as Neptune.
18. A new small moon orbits Jupiter outside the orbits of other known moons. It is smaller than Jupiter's other moons but has several large, active volcanoes.
19. A new moon orbits Neptune in the planet's equatorial plane and in the same direction that Neptune rotates, but it is made almost entirely of metals such as iron and nickel.
20. An icy, medium-size moon orbits a jovian planet in a star system that is only a few hundred million years old. The moon shows evidence of active tectonics.
21. A jovian planet is discovered in a star system that is much older than our solar system. The planet has no moons at all, but it has a system of rings as spectacular as the rings of Saturn.
22. Radar measurements of Titan indicate that most of the moon is heavily cratered.
23. During a future mission to Uranus, scientists discover it is orbited by another 20 previously unknown moons.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

24. Which lists the jovian planets in order of increasing distance from the Sun? (a) Jupiter, Saturn, Uranus, Pluto (b) Saturn, Jupiter, Uranus, Neptune (c) Jupiter, Saturn, Uranus, Neptune
25. Why does Neptune appear blue and Jupiter red? (a) Neptune is hotter, which gives bluer thermal emission. (b) Methane in Neptune's atmosphere absorbs red light. (c) Neptune's air molecules scatter blue light, much as Earth's atmosphere does.
26. Why is Jupiter denser than Saturn? (a) It has a larger proportion of rock and metal. (b) It has a larger proportion of hydrogen. (c) Its higher mass and gravity compress its interior.
27. Some jovian planets give off more energy than they receive because of (a) fusion in their cores. (b) tidal heating. (c) ongoing contraction or differentiation.
28. The main ingredients of most moons of the jovian planets are (a) rock and metal. (b) hydrogen compound ices. (c) hydrogen and helium.
29. Why is Io more volcanically active than our moon? (a) Io is much larger. (b) Io has a higher concentration of radioactive elements. (c) Io has a different internal heat source.
30. What is unusual about Triton? (a) It orbits its planet backward. (b) It does not keep the same face toward its planet. (c) It is the only moon with its own rings.
31. Which moon shows evidence of rainfall and erosion by some liquid substance? (a) Europa (b) Titan (c) Ganymede
32. Saturn's many moons affect its rings through (a) tidal forces. (b) orbital resonances. (c) magnetic field interactions.
33. Saturn's rings (a) have looked basically the same since they formed along with Saturn. (b) were created long ago when tidal forces tore apart a large moon. (c) are continually supplied with new particles by impacts with small moons.

Process of Science

34. *Europan Ocean.* Scientists strongly suspect that Europa has a subsurface ocean, even though we cannot see through the surface ice. Briefly explain why scientists think this ocean exists. Is the "belief" in a Europan ocean scientific? Explain.
35. *Breaking the Rules.* As discussed in Chapter 7, the geological "rules" for the terrestrial worlds tell us that a world as small as Io should not have any geological activity. However, the *Voyager* images of Io's volcanoes proved that the old "rules" had been wrong. Based on your understanding of the nature of science **[Section 3.4]**, should this be seen as a failure in the process of the science? Defend your opinion.
36. *Unanswered Question.* Choose one unanswered question about a jovian planet or moon. Write a few paragraphs discussing the question and the specific types of evidence needed to answer it.

Group Work Exercise

37. *Comparing Jovian Moons.* Comparing the masses, radii, and densities of jovian moons reveals clues about their composition and their history. In this exercise, your team will draw on the data in Appendix E to develop a hypothesis about the moons of Jupiter. Before you begin, assign the following roles to the people in your group: *Scribe* (collects data and takes notes on the group's activities), *Proposer* (proposes hypotheses and explanations of the data), *Skeptic* (points out weaknesses in the hypotheses and explanations), *Moderator* (leads group discussion and makes sure everyone contributes). Each person should write down the answers for each part of the exercise.
    a. *Scribe* collects data on Jupiter's four largest moons from Table E.2 in Appendix E and determines which of Jupiter's moons has the greatest density.
    b. *Moderator* uses Table E.2 to determine what other solar system moon most resembles the moon from part (a) in mass, radius, and density.

c. *Proposer* proposes a hypothesis about the composition of the moon from part (a), based on its resemblance to the moon from part (b).
d. *Skeptic* questions the hypothesis from part (c), stating concerns about its viability.
e. *Scribe* and *Moderator* use Table E.2 to determine whether there is a trend in density with orbital distance among the major moons of Jupiter and briefly describe any trends they discover.
f. *Proposer* offers a hypothesis that accounts for any trend found in part (e).
g. *Skeptic* raises questions about the revised hypothesis, stating any reasons to doubt it.
h. Together, the team develops and describes an experiment that could test the hypotheses in parts (c) and (f).

Investigate Further

Short-Answer/Essay Questions

38. *The Importance of Rotation.* Suppose the material that formed Jupiter came together without any rotation so that no "jovian nebula" formed and the planet today wasn't spinning. How else would the jovian system be different? Think of as many effects as you can, and explain each in a sentence.
39. *Comparing Jovian Planets.* You can do comparative planetology armed only with telescopes and an understanding of gravity.
    a. The small moon Amalthea orbits Jupiter at about the same distance in kilometers at which Mimas orbits Saturn, yet Mimas takes almost twice as long to orbit. From this observation, what can you conclude about how Jupiter and Saturn differ? Explain.
    b. Jupiter and Saturn are not very different in radius. When you combine this information with your answer to part (a), what can you conclude? Explain.
40. *Minor Ingredients Matter.* Suppose the jovian planets' atmospheres were composed only of hydrogen and helium, with no hydrogen compounds at all. How would the atmospheres be different in terms of clouds, color, and weather? Explain.
41. *Hot Jupiters.* Many of the planets orbiting other stars are more massive than Jupiter but orbit much closer to their stars. Assuming that they would be Jupiter-like if they orbited at a greater distance from their stars, how would you expect these new planets to differ from the jovian planets of our solar system? How would you expect their moons to differ?
42. *The New View of Titan.* What planet or moon in the solar system does Titan most resemble, in your opinion? Summarize the similarities and differences in a few sentences.
43. *Observing Project: Jupiter's Moons.* Using binoculars or a small telescope, view the moons of Jupiter. Make a sketch of what you see, or take a photograph. Repeat your observations several times (nightly, if possible) over a period of a couple of weeks. Can you determine which moon is which? Can you measure the moons' orbital periods? Can you determine their approximate distances from Jupiter? Explain.
44. *Observing Project: Saturn's Rings.* Using binoculars or a small telescope, view the rings of Saturn. Make a sketch of what you see, or take a photograph. What season is it in Saturn's northern hemisphere? How far do the rings extend above Saturn's atmosphere? Can you identify any gaps in the rings? Describe any other features you notice.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

45. *Disappearing Moon.* Io loses about a ton (1000 kilograms) of sulfur dioxide per second to Jupiter's magnetosphere.
    a. At this rate, what fraction of its mass would Io lose in $4\frac{1}{2}$ billion years?
    b. Suppose sulfur dioxide currently makes up 1% of Io's mass. When will Io run out of this gas at the current loss rate?
46. *Ring Particle Collisions.* Each ring particle in the densest part of Saturn's rings collides with another about every 5 hours. If a ring particle survived for the age of the solar system, how many collisions would it undergo?
47. *Prometheus and Pandora.* These two moons orbit Saturn at 139,350 and 141,700 kilometers, respectively.
    a. Using Newton's version of Kepler's third law, find their two orbital periods. Find the percent difference in their distances and in their orbital periods.
    b. Consider the two in a race around Saturn: In one Prometheus orbit, how far behind is Pandora (in units of time)? In how many Prometheus orbits will Pandora have fallen behind by one of its own orbital periods? Convert this number of periods back into units of time. This is how often the satellites pass by each other.
48. *Orbital Resonances.* Using the data in Appendix E, identify the orbital resonance relationship between Titan and Hyperion. (*Hint:* If the orbital period of one were 1.5 times that of the other, we would say that they are in a 3:2 resonance.) Which medium-size moon is in a 2:1 resonance with Enceladus?
49. *Titanic Titan.* What is the ratio of Titan's mass to all the other satellites of Saturn whose mass is listed in Appendix E? Calculate the strength of gravity on Titan compared to that on Mimas. Comment on how this affects the possibility of atmospheres on each.
50. *Saturn's Thin Rings.* Saturn's ring system is over 270,000 kilometers wide and approximately 50 meters thick. Assuming the rings could be shrunk down so that their diameter was the width of a dollar bill (6.6 centimeters), how thick would the rings be? Compare your answer to the actual thickness of a dollar bill (0.01 centimeter).

Discussion Questions

51. *Jovian Planet Mission.* We can study terrestrial planets up close by landing on them, but jovian planets have no surfaces to land on. Suppose that you are in charge of planning a long-term mission to "float" in the atmosphere of a jovian planet. Describe the technology you would use and how you would ensure survival for any people assigned to this mission.
52. *Pick a Moon.* Suppose you could choose any one moon to visit in the solar system. Which one would you pick, and why? What dangers would you face in your visit to this moon? What kinds of scientific instruments would you want to bring along for studies?

Web Projects

53. *News from Cassini.* Find the latest news about the *Cassini* mission to Saturn. What is the current mission status? Write a short report about the mission's status and results too recent to be in the textbooks.
54. *Oceans of Europa.* The possibility of a subsurface ocean on Europa holds great scientific interest. Investigate plans for future study of Europa, either from Earth or with spacecraft. Write a short summary of the plans and how they might help us learn whether Europa really has an ocean and, if so, what it might contain.

9

Asteroids, Comets, and Dwarf Planets

Their Nature, Orbits, and Impacts


Comet McNaught and the Milky Way Galaxy over Patagonia, Argentina (2007). The fuzzy patch above the comet's tail is the Small Magellanic Cloud, a satellite galaxy of the Milky Way.

learning goals

9.1 Asteroids and Meteorites
- Why is there an asteroid belt?
- How are meteorites related to asteroids?

9.2 Comets
- How do comets get their tails?
- Where do comets come from?

9.3 Pluto: Lone Dog No More
- How big can a comet be?
- What are Pluto and other large objects of the Kuiper belt like?

9.4 Cosmic Collisions: Small Bodies versus the Planets
- Have we ever witnessed a major impact?
- Did an impact kill the dinosaurs?
- Is the impact threat a real danger or just media hype?
- How do other planets affect impact rates and life on Earth?

Asteroids and comets might at first seem insignificant compared to the planets and moons we've discussed so far, but there is strength in numbers. The trillions of smaller bodies orbiting our Sun are far more important than their sizes might suggest.

The appearance of comets has more than once altered the course of human history when our ancestors acted on superstitions related to comet sightings. More profoundly, asteroids or comets falling to Earth have scarred our planet with impact craters and have altered the course of biological evolution. Asteroids and comets are also important scientifically: As remnants from the birth of our solar system, they teach us about how the solar system formed.

In this chapter, we will explore asteroids, comets, and the rocks that fall to Earth as meteorites. Along the way, we'll see that Pluto, until recently considered the ninth planet, is actually just one of many similar objects orbiting the Sun beyond Neptune—and not even the largest of these objects. Finally, we will explore the dramatic effects of the occasional collisions between small bodies and the planets, including collisions that have altered the course of Earth's history.

essential preparation

1. What does the solar system look like? **[Section 6.1]**
2. Where did asteroids and comets come from? **[Section 6.4]**
3. What processes shape Earth's surface? **[Section 7.1]**

9.1 Asteroids and Meteorites

We begin our study of small bodies by focusing on asteroids and meteorites. Recall that asteroids are rocky leftover planetesimals—chunks of rock that still orbit the Sun because they never managed to become part of a planet **[Section 6.4]**. Meteorites are pieces of rock that have fallen to the ground from space. Asteroids and meteorites are therefore closely related: Most meteorites are pieces of asteroids that orbited the Sun for billions of years before colliding with Earth.

Asteroids are virtually undetectable to the naked eye and remained unknown for almost two centuries after the invention of the telescope. The first asteroids were discovered only about 200 years ago, and it took 50 years to discover the first 10 asteroids. Today, advanced telescopes can discover far more than that in a single night, and more than 400,000 asteroids have been catalogued. Asteroids can be recognized in telescopic images because they move relative to the stars (Figure 9.1).

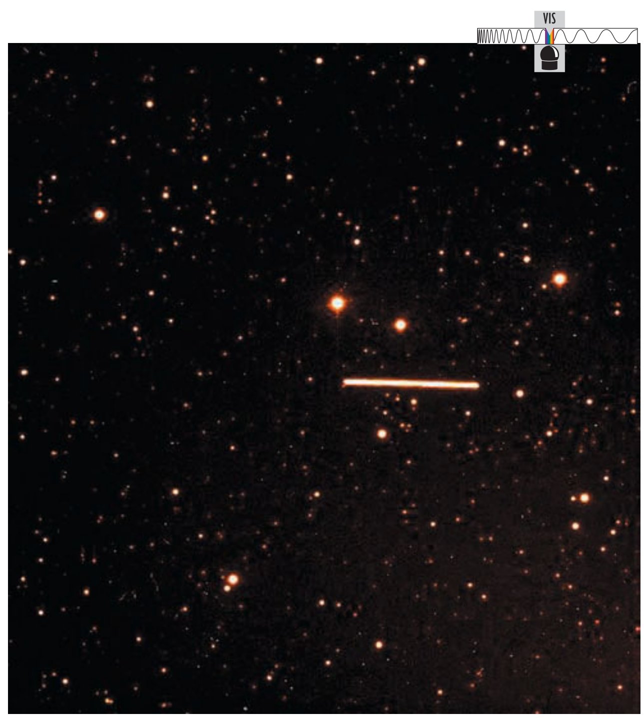
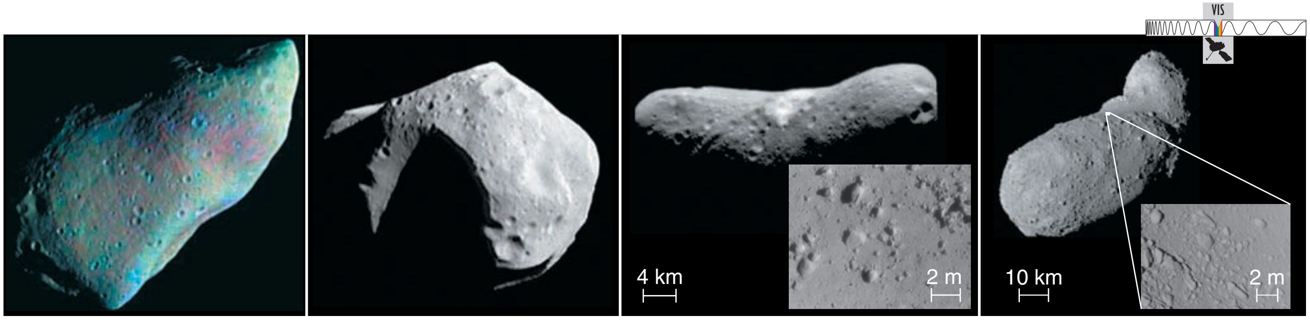


Figure 9.1 MA **interactive photo**

Because asteroids orbit the Sun, they move through our sky relative to the stars. In this long-exposure image, stars show up as distinct dots, while the motion of an asteroid relative to the stars makes it show up as a short streak.

Asteroids come in a wide range of sizes. The largest, Ceres, is just under 1000 kilometers in diameter, or a little less than a third the diameter of our Moon. At this size, it is large enough for its own gravity to have made it round, so Ceres qualifies as a *dwarf planet*. About a dozen other asteroids are large enough that we would call them medium-size moons if they orbited a planet, and a few of these may yet prove to be round enough to qualify as dwarf planets. Scientists hope to learn more about large asteroids with the *Dawn* mission, which launched in 2007 on a trajectory designed to reach Vesta (the third largest asteroid) in 2011 and Ceres in 2015.

Smaller asteroids are far more numerous. There are probably more than a million asteroids with diameters greater than 1 kilometer and many more even smaller in size. Several small asteroids have been



a Gaspra, photographed by the *Galileo* spacecraft. Colors are exaggerated to show detail.

b Mathilde, photographed by the *Near-Earth Asteroid Rendezvous* (*NEAR*) spacecraft on its way to Eros.

c Eros, photographed by the *NEAR* spacecraft, which orbited Eros for a year before ending its mission with a soft landing on the asteroid's surface.

d Itokawa, photographed by the Japanese *Hayabusa* mission, which landed on the surface and attempted to capture a sample for return to Earth.

Figure 9.2

Close-up views of asteroids studied by spacecraft.

photographed by spacecraft (Figure 9.2). They are not spherical, because they are too small for their gravity to have reshaped their rocky material. The images also reveal numerous impact craters, telling us that asteroids, like planets and moons, have been battered by impacts. Indeed, many asteroids have odd shapes because they are fragments of larger asteroids that were shattered in collisions.

Despite their large numbers, asteroids don't add up to much in total mass. If we could put all the asteroids together (including Ceres and the other large asteroids) and allow gravity to compress them into a sphere, they'd make an object less than 2000 kilometers in diameter, just over half the diameter of our Moon.

• Why is there an asteroid belt?

The asteroid belt between Mars and Jupiter gets its name because it is where we find the majority of asteroids (Figure 9.3). But why are asteroids located mainly in this region, rather than being spread throughout the inner solar system?

The answer is that the asteroid belt was the only place where rocky planetesimals could survive for billions of years. During the birth of the solar system, planetesimals formed throughout the inner solar system. However, most of those within Mars's orbit ultimately accreted into one of the four inner planets. The relatively few asteroids that orbit in the inner solar system today are almost certainly "impacts waiting to happen." Some of these asteroids pass near Earth's orbit and may pose a potential threat to our planet—a threat we will discuss in Section 9.4.

Rocky planetesimals survived in the asteroid belt between Mars and Jupiter because they did not accrete into a planet.

In contrast, the asteroids in the asteroid belt stay clear of any planet and can therefore survive in their current orbits for billions of years. But this leaves us with a deeper question: Why didn't a fifth terrestrial planet form in this region beyond the orbit of Mars, sweeping up asteroids as it grew in size?

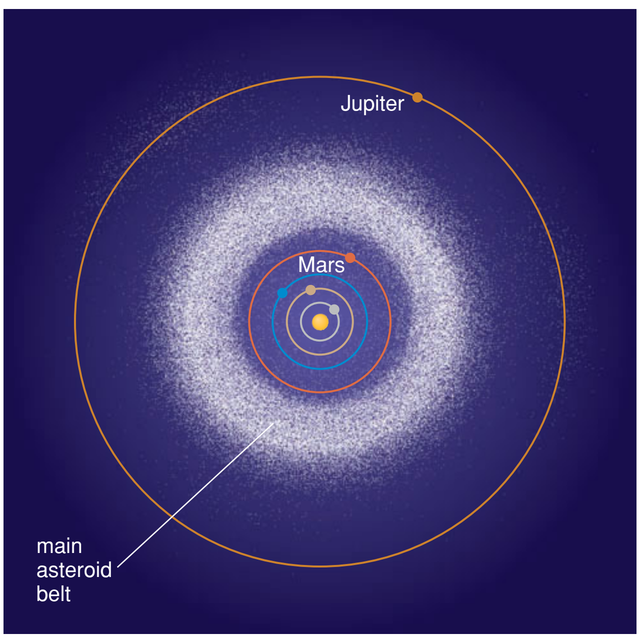


Figure 9.3

Calculated positions of 152,942 asteroids for midnight, January 1, 2004. The asteroids that share Jupiter's orbit, found 60° ahead of and behind Jupiter, are called *Trojan asteroids*. To scale, the asteroids themselves would be much smaller than the dots shown.

think about it Recall that the frost line in the solar nebula lay between the present-day orbits of Mars and Jupiter (see Figure 6.17), just outside the region where we find the asteroid belt today. Use this fact to explain why we generally do not find asteroids in the outer solar system.

Resonances with Jupiter A key to understanding the asteroid belt comes from examining asteroid orbits more closely. Figure 9.4 shows the number of asteroids with various orbital periods (listed along the lower axis) that correspond to particular average orbital distances (listed along the top of the graph). Notice that most asteroids tend to share a few particular orbital periods and distances, leaving gaps between them in which there are very few asteroids. (The gaps are often called *Kirkwood gaps,* after their discoverer.)

The gaps in the asteroid belt are not random. They occur at orbital periods that bear special and simple relationships to Jupiter's nearly 12-year orbital period. For example, the arrow labeled $\frac{1}{4}$ in Figure 9.4 points to a gap at an orbital period that is exactly one-quarter the length of Jupiter's orbital period. Similarly, the arrow labeled $\frac{1}{2}$ points to a gap at an orbital period that is exactly half as long as Jupiter's.

The gaps occur at these special places because of *orbital resonances* with Jupiter. We've encountered orbital resonances twice before: first, in explaining the elliptical orbits of Jupiter's moons Io, Europa, and Ganymede **[Section 8.2]**; second, in explaining the gaps in Saturn's rings **[Section 8.3]**. Recall that resonances arise whenever objects periodically line up with each other so that gravity affects them over and over again in the same direction. Asteroids with orbital periods that are simple fractions of Jupiter's orbital period are repeatedly nudged by Jupiter's gravity. For example, any asteroid in an orbit that takes 6 years to circle the Sun—half of Jupiter's 12-year orbital period—would receive the same gravitational nudge from Jupiter every 12 years. These repeated nudges would soon push the asteroid out of this 6-year orbit, which is why we do not find any asteroids with orbital periods exactly half that of Jupiter. Other resonances explain the other gaps identified in Figure 9.4.

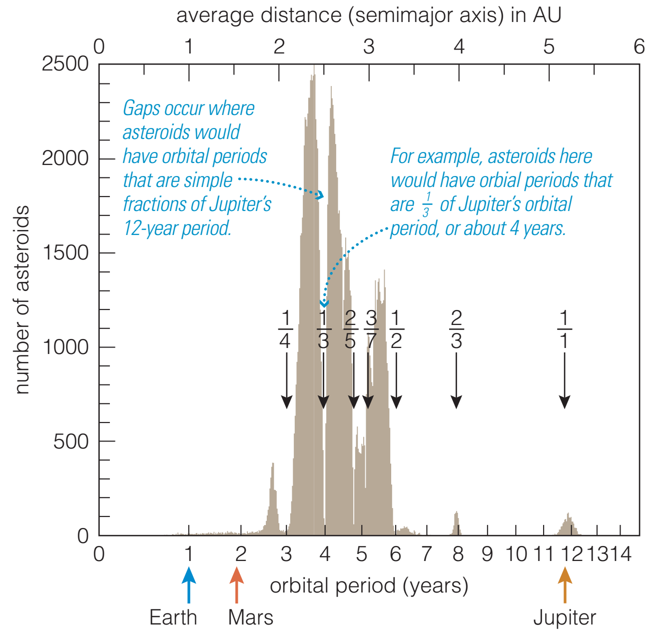


Figure 9.4

This graph shows the number of asteroids with various orbital periods, which correspond to different average distances from the Sun (labeled along the top). Notice the gaps created by orbital resonances with Jupiter. (Some orbital resonances, such as $\frac{1}{1}$ [meaning asteroids with the same orbital period as Jupiter] are stable and therefore have many asteroids rather than few.)

Jupiter's Role in the Asteroid Belt Jupiter's gravity does much more than just explain the locations of the gaps. It also explains why no planet ever formed in the asteroid belt.

Jupiter's gravity, through the influence of orbital resonances, stirred up asteroid orbits and thereby prevented their accretion into a planet.

When the solar system was forming, the region now occupied by the asteroid belt probably contained enough rocky material to form another planet as large as Earth or Mars. However, resonances with the young planet Jupiter disrupted the orbits of this region's planetesimals, preventing them from accreting into a full-fledged terrestrial planet. Over the next $4\frac{1}{2}$ billion years, ongoing orbital disruptions gradually kicked pieces of this "unformed planet" out of the asteroid belt altogether. Once booted from the asteroid belt, these objects either crashed into a planet or moon or were flung out of the solar system. The asteroid belt thereby lost most of its original mass, which explains why the total mass of all its asteroids is now less than that of any terrestrial planet.

The asteroid belt is still undergoing slow change. Jupiter's gravity continues to nudge asteroid orbits, sending asteroids on collision courses with each other and occasionally the planets. A major collision occurs somewhere in the asteroid belt every 100,000 years or so. Over long periods of time, larger asteroids continue to be broken into smaller ones, with each collision also creating numerous dust-size particles. The asteroid belt has been grinding itself down for more than 4 billion years and will continue to do so for as long as the solar system exists.

common Misconceptions

Dodge Those Asteroids!

Science fiction movies often show brave spacecraft pilots navigating through crowded fields of asteroids, dodging this way and that as they heroically pass through with only a few bumps and bruises. It's great drama, but not very realistic. The asteroid belt looks crowded when we draw it on paper as in Figure 9.3, but in reality it is an enormous region of space. Despite their large numbers, asteroids are thousands to millions of kilometers apart on average—so far apart that it would take incredibly bad luck to crash into one by accident. Indeed, spacecraft must be carefully guided to fly close enough to an asteroid to take a decent photograph. Future space travelers will have plenty of dangers to worry about, but dodging asteroids is not likely to be one of them.

Figure 9.5

This large meteorite, called the Ahnighito Meteorite, is located at the American Museum of Natural History in New York. Its dark, pitted surface comes from its fiery passage through Earth's atmosphere. Meteorites enter the atmosphere at speeds of up to 250,000 kilometers per hour (150,000 miles per hour).

• How are meteorites related to asteroids?

Because asteroids are leftovers from the birth of our solar system, studying samples of them should teach us a lot about how Earth and the other planets formed. You might think it would be difficult to obtain such samples, but in fact, we already have tens of thousands of them—the rocks called *meteorites* that fall from the sky.

The Difference Between Meteors and Meteorites Before we discuss what we can learn from meteorites, let's be clear about what they are. In everyday language, people often use the terms *meteors* and *meteorites* interchangeably. Technically, however, a **meteor** is only a flash of light caused by a particle entering our atmosphere at high speed, not the particle itself. The vast majority of the particles that make meteors are no larger than peas and burn up completely before ever reaching the ground.

Only in rare cases are meteors caused by something large enough to survive the plunge through our atmosphere and leave a **meteorite** on the ground. Those cases make unusually bright meteors, called *fireballs*. Observers find a few meteorites each year by following the trajectories of fireballs.

Unless you actually see a meteorite fall, it can be difficult to distinguish meteorites from terrestrial rocks. Fortunately, a few clues can help. Meteorites are usually covered with a dark, pitted crust resulting from their fiery passage through the atmosphere (Figure 9.5). Some have an unusually high metal content, enough to attract a magnet hanging on a string. The ultimate judge of extraterrestrial origin is laboratory analysis. Meteorites often contain elements such as iridium that are rare in Earth rocks, and even common elements in meteorites tend to have different ratios among their isotopes **[Section 5.1]** than rocks from Earth. Many museums will analyze a small chip of a suspected meteorite free of charge.

Types of Meteorites The origin of meteorites was long a mystery, but in recent decades we've been able to determine where in our solar system they come from. The most direct evidence comes from the relatively few meteorites whose trajectories have been observed or filmed as they fell to the ground. In every case so far, these meteorites clearly originated in the asteroid belt. Detailed analysis of thousands of meteorites shows that they come in two basic types:

- **Primitive meteorites** (Figure 9.6a) are simple mixtures of rock and metal, sometimes also containing carbon compounds and small amounts of water. Radiometric dating **[Section 6.4]** shows them to be nearly 4.6 billion years old, making them remnants from the birth of our solar system, essentially unchanged since they first accreted in the solar nebula.
- **Processed meteorites** (Figure 9.6b) appear to be pieces of large asteroids that, like the terrestrial worlds, underwent differentiation into a core-mantle-crust structure **[Section 7.1]**. Some are made mostly of iron, suggesting that they came from the core of a shattered asteroid. Others are rocky and either came from the mantle or crust of a shattered asteroid or were blasted off the surface of a large asteroid by an impact. Radiometric dating shows that processed meteorites are typically a few hundred million years younger than primitive meteorites.

Both types of meteorite teach us important lessons about our solar system. Primitive meteorites represent samples of some of the first material to condense and accrete in the solar nebula. They therefore provide information about the composition of the solidified material from which the planets originally formed. In addition, their ages tell us when the process of accretion first began, which is why we use them to determine the age of the solar system **[Section 6.4]**. Differences in composition among primitive meteorites reflect where they condensed: Those made only of metal and rock must have condensed in the inner regions of the asteroid belt, while those with carbon compounds must have condensed farther out, where it was cool enough for such compounds and even some water to condense. Indeed, asteroids in the outer regions of the asteroid belt are much darker in color, as expected for their carbon-rich composition.

Most meteorites are pieces of asteroids, and they teach us much about the early history of our solar system.

Processed meteorites represent direct samples of shattered worlds. Those that come from the surfaces of asteroids are often so close in composition to volcanic rocks on Earth that we conclude that some asteroids had active volcanoes when they were young. Processed meteorites that come from the cores or mantles of shattered asteroids tell us what those asteroids were like on the inside. They also represent direct evidence of the fact that large enough worlds really did undergo differentiation (confirming what we infer from seismic studies of Earth **[Section 7.1]**). Indeed, processed meteorites show that some large asteroids must be geologically quite similar to small terrestrial worlds, one reason why some are now considered to be dwarf planets.

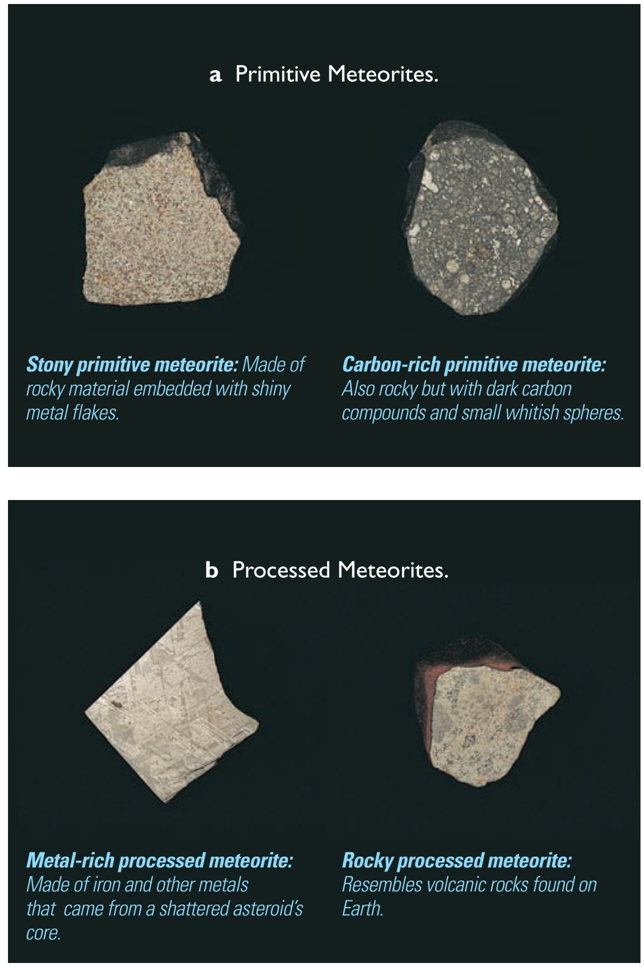


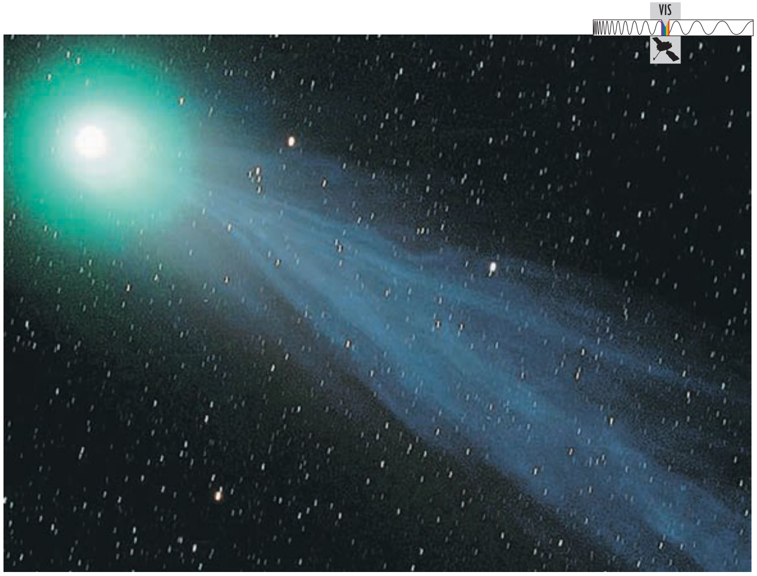
Figure 9.6

There are two basic types of meteorites: (a) primitive and (b) processed. Each also has two subtypes. They are shown slightly smaller than actual size. (The meteorites have flat faces because they have been sliced with rock saws.)

Meteorites from the Moon and Mars In a few cases, the compositions of processed meteorites do not appear to match any known asteroids. Analysis suggests that some of these meteorites have come from the Moon and others from Mars. Moderately large impacts can blast surface material from terrestrial worlds into interplanetary space. Once they are blasted into space, the rocks orbit the Sun until they come crashing down on another world. Calculations show that it is not surprising that we should have found a few meteorites chipped off the Moon and Mars in this way. Study of these *lunar meteorites* and *Martian meteorites* is providing new insights into conditions on the Moon and Mars. One Martian meteorite may even offer clues about whether life ever existed on Mars **[Section 18.2]**.

9.2 Comets

Asteroids are one of the two major categories of small bodies in the solar system. The other is comets, to which we now turn our attention. Asteroids and comets have much in common. Both are leftover planetesimals from the birth of our solar system. Both come in a wide range of sizes. The primary difference between them is in composition, which reflects where they formed. Asteroids are rocky because they formed in the inner solar system where metal and rock condensed. Comets are ice-rich because they formed beyond the frost line, where abundant hydrogen compounds condensed into ice **[Section 6.4]**. Note that we refer to any icy, leftover planetesimal orbiting the Sun as a comet, regardless of its size, whether it has a tail, or where it resides or comes from.



a Comet Hyakutake.

b Comet Hale–Bopp, photographed at Mono Lake, CA.

Figure 9.7 MA **interactive photo**

Brilliant comets can appear at almost any time, as demonstrated by the back-to-back appearances of Comet Hyakutake in 1996 and Comet Hale–Bopp in 1997.

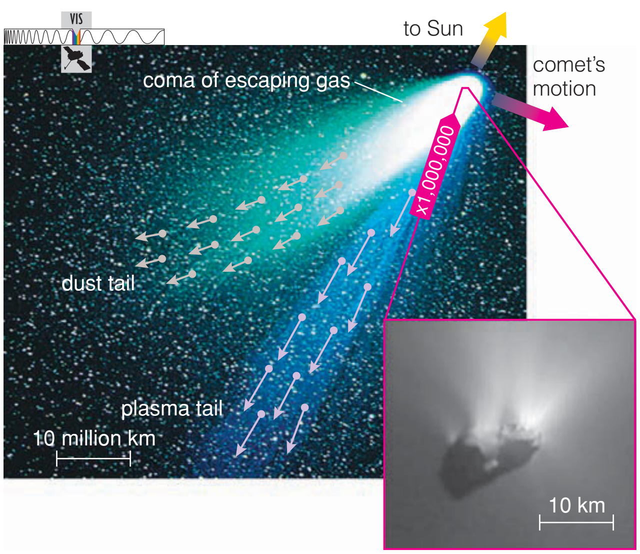


Figure 9.8

Anatomy of a comet. The inset photo is the nucleus of Halley's Comet, photographed by the *Giotto* spacecraft; the coma and tails shown are those of Comet Hale–Bopp in a ground-based photo. A comet grows a coma and tail around its nucleus only if it happens to come close to the Sun. Most comets never do this, instead remaining perpetually frozen in the far outer solar system.

• How do comets get their tails?

For most of human history, comets were familiar only from their occasional presence in the night sky. Every few years, a comet becomes visible to the naked eye, appearing as a fuzzy ball with a long tail (Figure 9.7; see also the photo on page 260). In photographs, the tails make it look as if comets are racing across the sky, but they are not. If you watch a comet for minutes or hours, you'll see it staying nearly stationary relative to the stars around it in the sky. Over many days it will rise and set just like the stars, while gradually moving relative to the constellations. You'll be able to see it night after night for several weeks or more, until it finally fades from view.

Today, we know that the vast majority of comets do not have tails and are never visible in our skies. Most comets never venture anywhere close to Earth, instead remaining in the outer reaches of our solar system. There, they slowly orbit the Sun forever unless their orbits are changed by the gravitational influence of a planet, another comet, or stars passing by in the distance.

Most comets remain perpetually frozen in the outer solar system. Only a few enter the inner solar system, where they can grow tails.

The comets that appear with long tails in the night sky are the rare ones that have had their orbits changed, causing them to venture into the inner solar system. Most of these comets will not return to the inner solar system for thousands of years, if ever. A few happen to pass near enough to a planet to have their orbits changed further, and some end up on elliptical orbits that periodically bring them close to the Sun. The most famous example is Halley's Comet, which orbits the Sun every 76 years. It last passed through the inner solar system in 1986, and it will return in 2061.

see it for yourself As you can see from the chapter-opener photo and Figure 9.7, bright comets can be quite photogenic. Go to the Astronomy Picture of the Day Web site, search for comet photos taken from Earth, and examine a few. Which is your favorite? Which has the best combination of beauty and scientifically interesting detail?

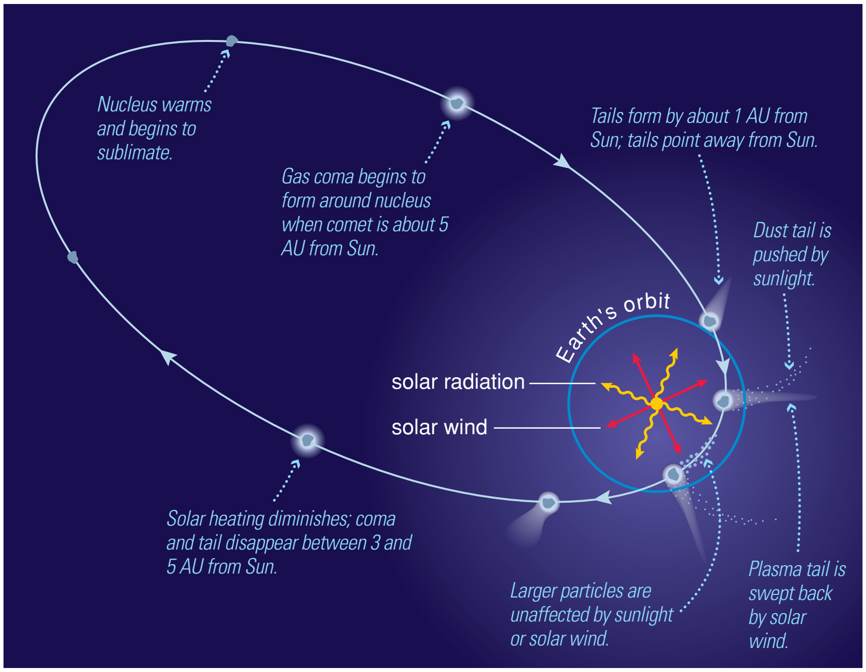


Figure 9.9

This diagram shows the changes that occur when a comet's orbit takes it on a passage into the inner solar system. (Not to scale.)

Comet Structure and Composition

Comets grow tails only as they enter the solar system, where they are heated by the warmth of the Sun. Figure 9.8 shows the anatomy of a comet when it is in the inner solar system, and Figure 9.9 shows how this anatomy takes shape along the comet's orbital path. Far from the Sun, the comet is completely frozen. If you could see it, the comet would look like a large "dirty snowball"—a chunk of ice mixed with rocky dust and some more complex chemicals. We call this chunk of ice the **nucleus** of the comet. Comet nuclei are typically a few kilometers across.

As a comet accelerates toward the Sun, its surface temperature increases, and ices begin to sublimate into gas that easily escapes the comet's weak gravity. Some of the escaping gas drags away dust particles from the nucleus, and the gas and dust create a huge, dusty atmosphere called a **coma**. The coma is far larger than the nucleus it surrounds. The coma grows as the comet continues into the inner solar system, and some of the gas and dust is pushed away from the Sun, forming the comet's tails.

When a comet nears the Sun, its ices can sublimate into gas and carry off dust, creating a coma and long tails.

Comets have two visible tails, and each can be hundreds of millions of kilometers in length. The **plasma tail** consists of gas escaping from the coma. Ultraviolet light from the Sun ionizes the gas, and the solar wind then carries this gas straight outward from the Sun at speeds of hundreds of kilometers per second. That is why the plasma tail extends almost directly away from the Sun at all times. The **dust tail** is made of dust-size particles escaping from the coma. These particles are not affected by the solar wind and instead are pushed away from the Sun by the much weaker pressure of sunlight itself (*radiation pressure*). The dust tail therefore points generally away from the Sun, but has a slight curve back in the direction the comet came from.

After the comet loops around the Sun and begins to head back outward, sublimation declines, the coma dissipates, and the tails disappear. Nothing happens until the comet again comes sunward—in a century, a millennium, a million years, or perhaps never. Comets that do return eventually use up their ices, some crumbling before our eyes (Figure 9.10)

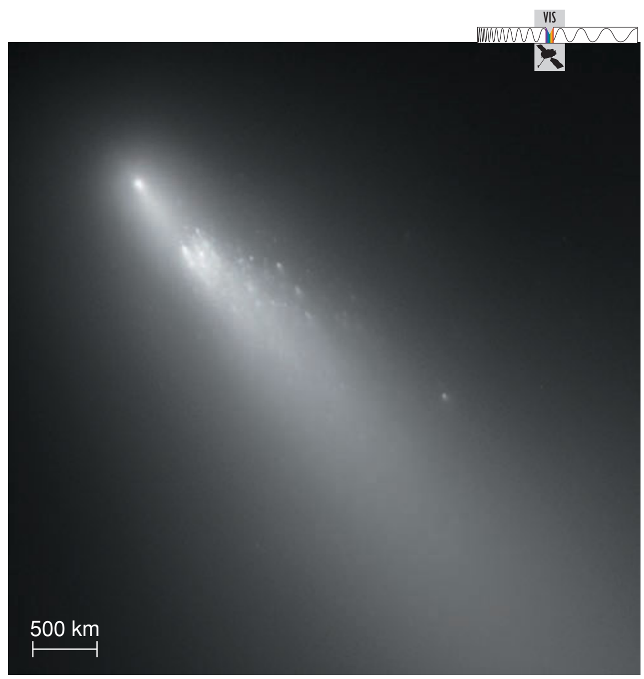


Figure 9.10

One possible fate for a comet is disintegration, as the ice binding the comet together is used up. This photo shows how a comet fragment (one of dozens that made up Comet Schwassmann-Wachmann 3) crumbled as it passed Earth in 2006.

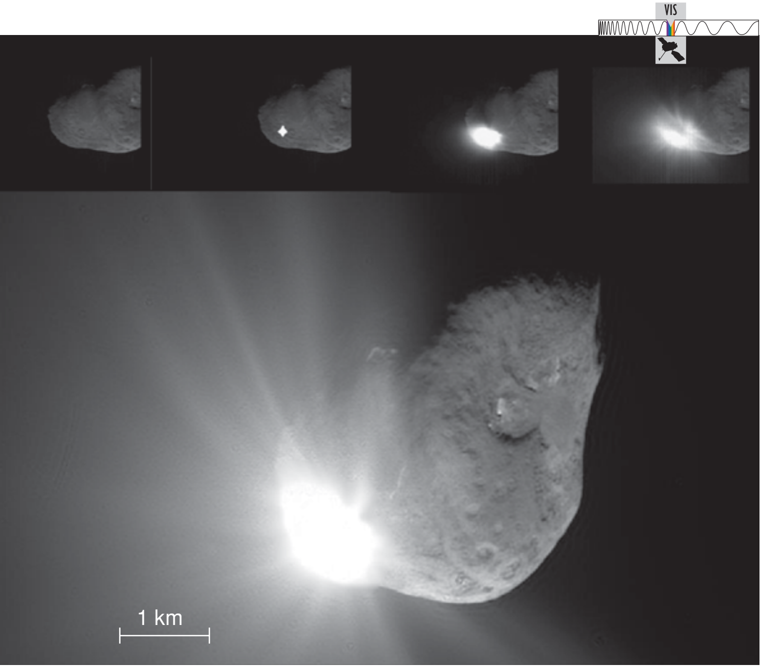


Figure 9.11 MA interactive photo

These photos were taken by the *Deep Impact* spacecraft as its 370-kilogram impactor crashed into Comet Tempel 1. The entire sequence, which starts just before impact at the upper left, unfolded over just 67 seconds.

and others becoming inactive nuclei. In 2007, the inactive Comet Holmes came briefly back to life, perhaps because of a comet-quake that occurred when the comet cooled and contracted as it receded from the Sun.

In the past, all our data about comets came from images and spectroscopy of their tails and comas. Recently, however, spacecraft missions to comets have begun to provide us with much more detailed information. We now have our first sample of actual comet material for laboratory study. In 2004, NASA's *Stardust* spacecraft used a material called aerogel to capture dust particles from Comet Wild 2 (pronounced "vilt two"). The aerogel was then sealed in a re-entry capsule, which the main spacecraft ejected on a return trajectory to Earth. Scientists are still puzzling over the composition of some of the comet dust, which indicates that it must have formed in the inner solar system and somehow became mixed in with other cometary materials that formed in the outer solar system.

NASA's *Deep Impact* mission offered an even closer look at a comet. On July 4, 2005, a 370-kilogram impactor slammed into Comet Tempel 1 at 37,000 kilometers per hour as the main spacecraft followed behind to record the event (Figure 9.11). The impactor penetrated many meters into a relatively soft and porous surface, vaporized from the heat of the collision, and ejected a huge plume of dust and gas. In an example of space age recycling, NASA redirected the *Deep Impact* spacecraft on an orbit to revisit Comet Tempel 1 in 2011 to study the interior exposed by the impact. Scientists are also looking forward to data from the European Space Agency's *Rosetta* mission, on track for a 2014 landing on comet Churyumov-Gerasimenko, which is now approaching the Sun.

Comet Tails and Meteor Showers Comets also eject sand- to pebble-size particles that are too big to be affected by either the solar wind or sunlight. These particles essentially form a third, invisible tail that follows the comet around its orbit. They are also the particles responsible for most meteors and meteor showers.

We see a meteor light up the sky when one of these small particles (or a similar-size particle from an asteroid) burns up in our atmosphere. The sand- to pebble-size particles are much too small to be seen themselves, but they enter the atmosphere at such high speeds that they make the surrounding air glow with heat. It is this glow that we see as the brief but brilliant flash of a meteor. The small particles are vaporized by the heat and never reach the ground. You can typically see a few meteors each hour on any clear night.

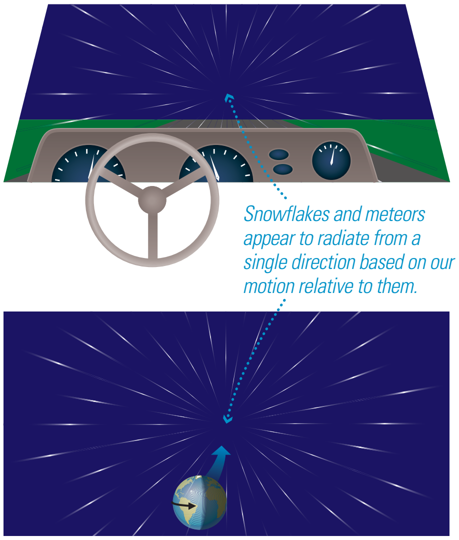
A comet ejects small particles that follow it around in its orbit and cause meteor showers when Earth crosses the comet's orbit.

Comet dust is sprinkled throughout the inner solar system, but the "third tails" of ejected particles make the dust much more concentrated along the orbits of comets. This dust rains down on our planet whenever we cross a comet's orbit, producing a **meteor shower**. They recur at about the same time each year because the orbiting Earth passes through a particular comet's orbit at the same time each year. For example, the meteor shower known as the *Perseids* occurs on about August 12 each year, when Earth passes through the orbit of comet Swift–Tuttle. Table 9.1 lists major annual meteor showers and their parent comet, if known.

If you go outside during one of the annual meteor showers, you may see dozens of meteors per hour. The meteors generally appear to radiate from a particular direction in the sky, for essentially the same reason that snow or heavy rain seems to come from a particular direction in front of a moving car (Figure 9.12). Because more meteors hit Earth from the

Table 9.1 *Major Annual Meteor Showers*

Shower Name	Approximate Date	Associated Comet
Quadrantids	January 3	?
Lyrids	April 22	Thatcher
Eta Aquarids	May 5	Halley
Delta Aquarids	July 28	?
Perseids	August 12	Swift–Tuttle
Orionids	October 22	Halley
Taurids	November 3	Encke
Leonids	November 17	Tempel–Tuttle
Geminids	December 14	Phaeton
Ursids	December 23	Tuttle



a Meteors appear to radiate from a particular point in the sky for the same reason that we see snow or heavy rain come from a single point in front of a moving car.

b This digital composite photo, taken near Uluru (also known as Ayers Rock) in Australia during the 2001 Leonids meteor shower, shows meteors as streaks of light.

Figure 9.12

The geometry of meteor showers.

front than from behind (just as more snow hits the front windshield of a moving car), meteor showers are best observed in the predawn sky, when part of the sky faces in the direction of Earth's motion.

see it for yourself Try to observe the next meteor shower (see Table 9.1); be prepared with an expendable star chart, a marker, and a dim (preferably red) flashlight. Each time you see a meteor, record its path on your star chart. Record at least a dozen meteors, and try to determine the "radiant" of the shower—that is, the constellation from which the meteors appear to radiate. Does the meteor shower live up to its name?

• Where do comets come from?

Comets that repeatedly visit the inner solar system, like Halley's Comet, cannot last long on the time scale of our solar system. A comet loses a small fraction of its material on every pass around the Sun, so there is nothing left after just a few hundred passages. The comets that humans have seen in the skies cannot be the same ones that passed overhead when dinosaurs or earlier life forms inhabited Earth. So where do comets come from?

We've already stated that comets come from the outer solar system, but we can be much more specific. By analyzing the orbits of comets that pass close to the Sun, scientists learned that there are two major "reservoirs" of comets in the outer solar system.

Most comets that visit the inner solar system follow orbits that seem almost random. They do not orbit the Sun in the same direction as the planets, and their elliptical orbits have random orientations. Moreover, their orbits show that they come from far beyond the orbits of the planets—sometimes nearly a quarter of the distance to the nearest star. These comets must come plunging sunward from a vast, spherical region of space that scientists call the **Oort cloud** (after astronomer Jan Oort;

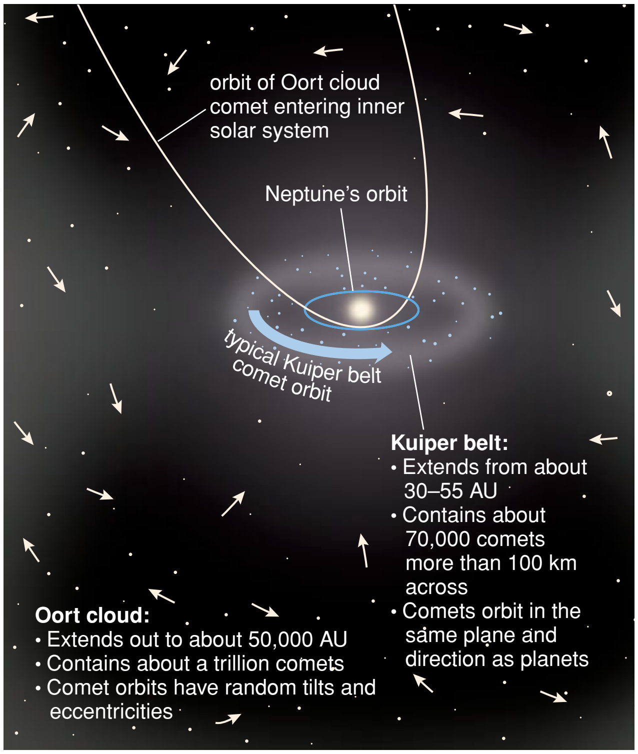


Figure 9.13

The comets we occasionally see in the inner solar system come from two major reservoirs in the outer solar system: the Kuiper belt and the Oort cloud.

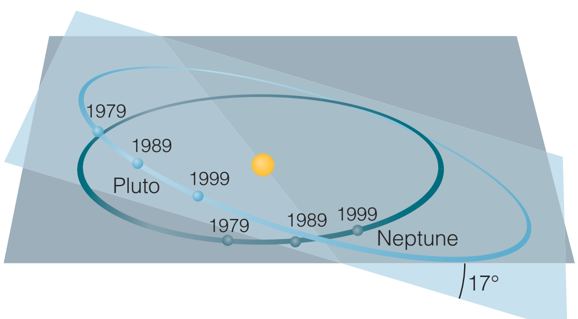


Figure 9.14 MA interactive figure

Pluto's orbit is significantly elliptical and tilted relative to the ecliptic. It comes closer to the Sun than Neptune for 20 years in each 248-year orbit, as was the case between 1979 and 1999. There's no danger of a collision, however, thanks to an orbital resonance in which Neptune completes three orbits for every two of Pluto's orbits.

rhymes with "court"). Be sure to note that the Oort cloud is not a cloud of gas but rather a collection of many individual comets. Based on the number of Oort cloud comets that enter the inner solar system each year, we conclude that the Oort cloud must contain about a trillion (10^{12}) comets.

The comets we occasionally see in the inner solar system come from two major reservoirs of comets in the outer solar system: the *Kuiper belt* and the *Oort cloud.*

A smaller number of the comets that visit the inner solar system have a pattern to their orbits. They travel around the Sun in the same direction and in nearly the same plane as the planets, and their elliptical orbits carry them no more than about twice as far from the Sun as Neptune. These comets must come from a ring of comets that orbit the Sun beyond the orbit of Neptune. This ring is usually called the **Kuiper belt** (after astronomer Gerald Kuiper; rhymes with "piper"). Figure 9.13 contrasts the general features of the Kuiper belt and the Oort cloud.

The Origin of the Oort Cloud and the Kuiper Belt How did comets end up in these far-flung regions of the solar system? The only answer that makes scientific sense comes from thinking about what happened to the icy, leftover planetesimals that roamed the region in which the jovian planets formed.

The leftover planetesimals that cruised the spaces between Jupiter, Saturn, Uranus, and Neptune were doomed to suffer either a collision or a close gravitational encounter with one of the young jovian planets. The planetesimals that escaped being swallowed up tended to be flung off in all directions. (Recall that when a small object passes near a large planet, the planet is hardly affected but the small object may be flung off at high speed **[Section 4.4]**.) Some may have been cast away at such high speeds that they completely escaped the solar system and now drift through interstellar space. The rest ended up with orbits at very large average distances from the Sun, becoming the comets of the Oort cloud. The random directions in which these comets were flung explain why the Oort cloud is roughly spherical in shape. Oort cloud comets are so far from the Sun that they can be nudged by the gravity of nearby stars, and even by the mass of the galaxy as a whole. These nudges further randomize their orbits, preventing some of them from ever returning to the solar system and sending others plummeting toward the Sun.

Kuiper belt comets orbit in the region in which they formed, just beyond Neptune's orbit. The more distant Oort cloud contains comets that once orbited among the jovian planets.

Beyond the orbit of Neptune, the icy planetesimals were much less likely to be cast off by gravitational encounters. Instead, they remained in orbits going in the same directions as planetary orbits and concentrated relatively near the ecliptic plane. These are the comets of the donut-shaped Kuiper belt. In other words, the comets of the Kuiper belt seem to have originated farther from the Sun than the comets of the Oort cloud, even though the Kuiper belt comets now reside much closer. Kuiper belt comets can be nudged by the gravity of the jovian planets through orbital resonances, sending some on close passes through the inner solar system.

9.3 Pluto: Lone Dog No More

Pluto seemed a misfit among the planets almost since the day it was discovered in 1930. Its 248-year orbit is more elliptical and more inclined to the ecliptic plane than that of the first eight planets (Figure 9.14). In fact, Pluto sometimes comes closer to the Sun than Neptune, although there is no danger of collision: Neptune orbits the Sun precisely three times for every two Pluto orbits, and this stable orbital resonance means that Neptune is always a safe distance away whenever Pluto approaches its orbit. Neptune and Pluto will probably continue their dance of avoidance until the end of the solar system.

Pluto's composition and orbit indicate that it is essentially a large comet of the Kuiper belt.

As we learned more about Pluto, it proved to be a misfit among the planets in size and composition as well: It is far smaller than even the terrestrial planets, and its ice-rich composition fits neither the terrestrial nor jovian categories. These seeming oddities long made Pluto seem like a lone dog of the outer solar system. But it is not: We now know that Pluto is part of a vast pack of similar objects—essentially large comets—that orbit in its region of the solar system. In fact, Pluto is not even the largest member of this pack.

• How big can a comet be?

We've known since the 1950s that many of the comets that visit the inner solar system come from the reservoir that we call the Kuiper belt. We've also known that Pluto orbits the Sun near the middle of this reservoir. Scientists now realize that Pluto's location is no mere coincidence, but rather evidence of an astonishing fact: Some of the objects that populate the Kuiper belt are far larger than any of the comets that we ever see in the inner solar system.

All the comets we've observed in the inner solar system are fairly small, with nuclei no larger than about 20 kilometers across. This shouldn't be surprising based on our understanding of comet origins, because only relatively small objects are likely to have their orbits changed enough to send them from the Kuiper belt or Oort cloud into the inner solar system. But it made scientists wonder: Given that the comets we see are rare and relatively small visitors from distant reaches of the solar system, could these outer realms hold much larger objects as well?

According to our understanding of solar system formation, the icy planetesimals of the Kuiper belt should have been able to continue their accretion as long as other icy particles were nearby. In principle, one of these planetesimals could have grown large enough to become the seed of a fifth jovian planet, beyond Neptune, but that did not occur—probably because the density of material was too low at this great distance from the Sun. Nevertheless, it's reasonable to think that many of these planetesimals grew to hundreds or even thousands of kilometers in diameter.

Discovering Large Iceballs Finding such large, icy objects requires powerful telescope technology. Trying to see a 1000-kilometer iceball at Pluto's distance from Earth is equivalent to looking for a snowball the size of your fist that is 600 kilometers away (and in dim light, too). Aside from Pluto, the first large objects in the Kuiper belt were discovered in the early 1990s. The discoveries have come at a rapid pace ever since.

As astronomers surveyed more and more of the sky in search of large, icy objects, the record size seemed to rise with each passing year. In 2002, the record was set by an object named *Quaoar* (pronounced "kwa-o-whar"), which is more than half the diameter of Pluto. Two objects discovered in 2004—Sedna and Orcus—are between two-thirds and three-quarters of Pluto's size. It seemed only a matter of time until scientists would find an object larger than Pluto, and the time came in 2005, when Caltech astronomer Michael Brown announced the discovery of the object now named Eris (Figure 9.15). Eris is named for a

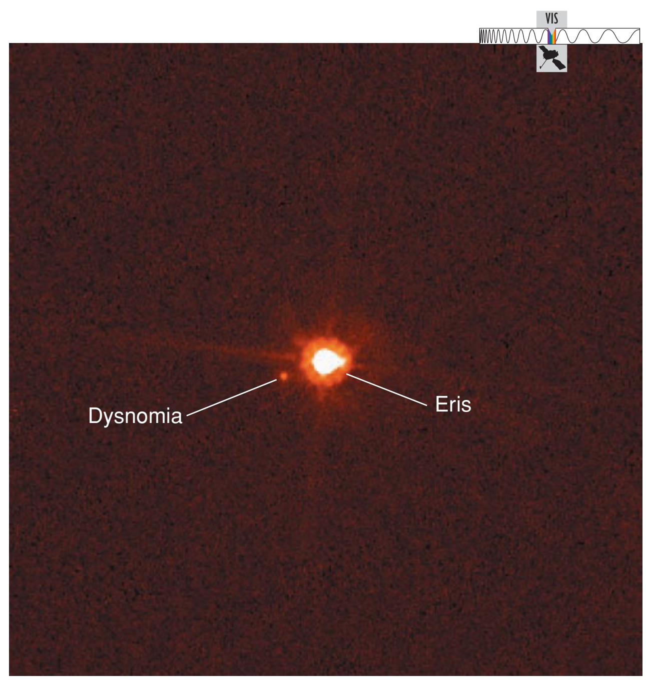


Figure 9.15

Eris and its moon, photographed by the Hubble Space Telescope.

Figure 9.16

Artist paintings of the largest known objects of the Kuiper belt (as of 2010), along with their known moons, shown to scale with Earth for comparison. Pluto, Eris, Makemake, and Haumea officially qualify as dwarf planets, and others may yet join the list. The paintings are guesses about appearance, since the Kuiper belt objects have not been photographed with high resolution. The dwarf planet Ceres is included for comparison at the lower left.

Greek goddess who caused strife among humans (an allusion to the arguments its discovery caused about the definition of *planet*). Eris even has a moon of its own, named Dysnomia, the mythological daughter of Eris and a goddess of lawlessness.

Eris, discovered in 2005, is about 5% larger than Pluto, making it the largest known member of the Kuiper belt.

Eris currently lies about twice as far as Pluto from the Sun. Its 557-year orbit is inclined to the ecliptic plane more than twice as much as Pluto's, and it is so eccentric that it must sometimes come closer to the Sun than Pluto. Observations indicate that Eris is about 5% larger and 27% more massive than Pluto. Pluto has therefore fallen to second place in the rankings of large objects in the Kuiper belt, and it could fall further, though by 2010, most of the sky had been carefully searched for large Kuiper belt objects.

Classifying Pluto and Its Siblings What should we call Pluto, Eris, and the other big iceballs (Figure 9.16)? The terminology has been a topic of much debate, but the science behind it seems clear. By 2010, more than 1100 icy objects had been directly observed in the Kuiper belt, allowing scientists to infer that the region contains at least 70,000 objects more than 100 kilometers across and many more that are smaller. The new Pan-STARRS telescopes should discover tens of thousands of them. The smaller ones are easy to refer to as comets, but the larger ones pose a classification challenge, as evidenced by the fact that Pluto was generally considered a planet from the time of its discovery in 1930 until 2006, when the International Astronomical Union (IAU) demoted Pluto to *dwarf planet*.

Under the new classification scheme (see Special Topic, page 12), Pluto, Eris, Makemake, and Haumea all qualify as *dwarf planets* because they are big enough to be round but have not cleared their orbital neighborhoods. (In the case of Haumea, it is actually oblong, rather than round, because of its high rotation rate.) Indeed, although the distances between individual objects in the Kuiper belt are quite large on average (tens of millions of kilometers), many of these objects share the same orbital periods and distances. Dozens of other objects of the Kuiper belt may also qualify as dwarf planets, though further observations will be needed to establish whether these objects are really round.

In terms of composition, Pluto, Eris, and all the other large objects of the Kuiper belt are essentially large comets.

Regardless of what we call them, all the objects of the Kuiper belt—from the smallest boulders to the largest dwarf planets—probably share the same basic composition of ice and rock. In other words, they are all essentially comets of different sizes. That is why we often refer to all of them as *comets* of the Kuiper belt. However, some astronomers object to calling objects "comets" if they never venture into the inner solar system and show tails; therefore, you may also hear these objects referred to as *Kuiper Belt Objects* (*KBOs*) or *Trans-Neptunian Objects* (*TNOs*).

• What are Pluto and other large objects of the Kuiper belt like?

Although Pluto, Eris, and other similar objects are large compared to most comets of the Kuiper belt, they are quite small compared to any of the terrestrial or jovian planets. These small sizes, combined with their great distances, make them difficult to study. Even our best photographs show little more than fuzzy blobs. As a result, we generally know little about these objects besides their orbits and the fact that their reflectivities and spectra suggest that they have ice-rich compositions. To understand these objects a little better, let's first consider Pluto and then turn our attention to the rest.

Pluto We've had more time to study Pluto than any other object of the Kuiper belt, but the most important reason we've been able to learn a lot about Pluto is its relatively large moon, Charon. Pluto also has two much smaller moons, discovered in 2005 (Figure 9.17a).

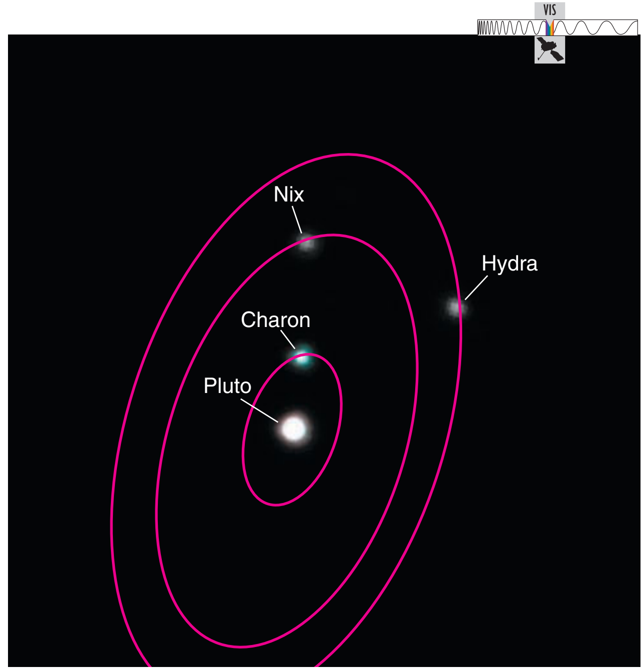
Remember that we can determine an object's mass only if we can observe its gravitational effect on some other object. As a result, we could only estimate Pluto's mass until Charon's discovery in 1978. Charon's orbital characteristics then allowed us to find the combined Pluto–Charon mass using Newton's version of Kepler's third law **[Section 4.4]**.

More precise data came from some good luck in timing: From 1985 to 1990, Pluto and Charon happened to be aligned in a way that made them eclipse each other every few days as seen from Earth—something that won't happen again for more than 100 years. Detailed analysis of brightness variations during these eclipses allowed the calculation of accurate sizes, masses, and densities for both Pluto and Charon. These measurements confirmed that Pluto and Charon are both made of ice mixed with rock—just like comets. The eclipse data even allowed astronomers to construct rough maps of Pluto's surface markings, which have not yet been explained. More recent images show that Pluto's surface is being altered, probably due to seasonal changes, which on Pluto are affected both by axis tilt and by changing distance from the Sun (Figure 9.17b).

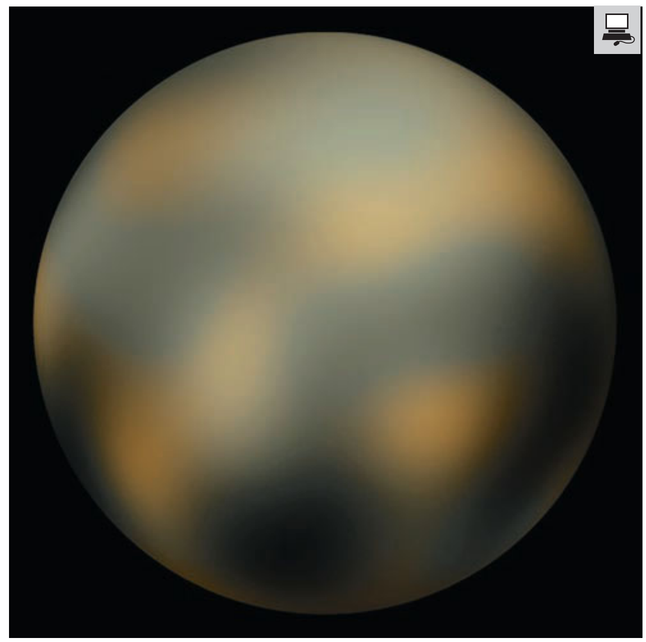
Curiously, Pluto is slightly higher in density than Charon. This has led astronomers to guess that Charon might have been created by a *giant impact* similar to the one thought to have formed our Moon **[Section 6.4]**. A large comet may have crashed into Pluto and blasted away its low-density outer layers. The debris could have then formed a ring of debris around Pluto, with the material eventually accreting to make its three moons. The impact may also explain why Pluto's rotation axis is tipped almost on its side.

Pluto is very cold, with an average temperature of only 40 K, as we would expect at its great distance from the Sun. Nevertheless, Pluto currently has a thin atmosphere of nitrogen and other gases formed by sublimation of surface ices. The atmosphere should gradually refreeze onto the surface as Pluto's 248-year orbit carries it farther from the Sun, although recent observations have puzzled astronomers by showing the opposite effect.

Despite the cold, the view from Pluto would be stunning. Charon would dominate the sky, appearing almost 10 times larger in angular size than our Moon appears from Earth. Pluto and Charon's mutual tidal pulls long ago made them rotate synchronously with each other **[Section 4.4]**, so that Charon is visible from only one side of Pluto and always shows the same face to Pluto. This synchronous rotation also means that Pluto's "day" is the same length as Charon's "month" (orbital period) of 6.4 Earth days. Viewed from Pluto's surface, Charon neither rises nor sets but hangs motionless as it cycles through its phases every 6.4 days. The Sun would appear more than a thousand times fainter than it appears here on Earth and would be no larger in angular size than Jupiter appears in our skies.



a Pluto and its moons, photographed by the Hubble Space Telescope with orbital paths drawn in.



b The surface of Pluto in approximately true color, based on a computer-processed series of Hubble Space Telescope images, each just a few pixels across. Comparison with images taken 8 years earlier reveals changes in surface markings, which may be due to the gradual change in seasons on Pluto.

Figure 9.17

Pluto's great distance and small size make it difficult to study.

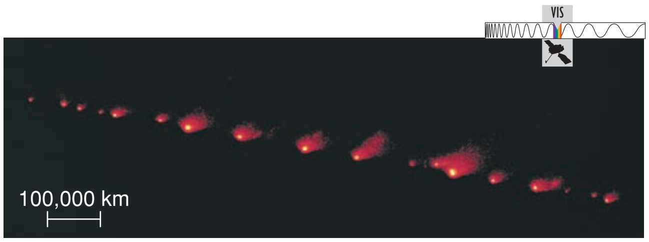
see it for yourself Charon is both relatively large compared to Pluto and relatively close to it. But this doesn't do justice to the visual impact Charon would have in Pluto's sky. Let your head stand for Pluto, and find a round object about 5 centimeters across to represent Charon. Place it 2 meters away. How does this compare to the angular size of our Moon, which is about as large as your pinky fingernail held at arm's length?

Other Kuiper Belt Objects We don't know much about other large comets of the Kuiper belt, but because they all probably formed in the same region of the solar system, we expect them to be similar in nature and composition to Pluto and Charon. Evidence of similarities comes from careful study of orbits. Like Pluto, many Kuiper belt comets have stable orbital resonances with Neptune. In fact, hundreds of Kuiper belt comets have the same orbital period and average distance from the Sun as Pluto itself. Besides Pluto and Eris, several other Kuiper belt comets are also known to have moons, and in those cases we can use Newton's version of Kepler's third law **[Section 4.4]** to calculate their masses and then infer their densities. The results confirm that these objects have comet-like compositions of ice and rock.

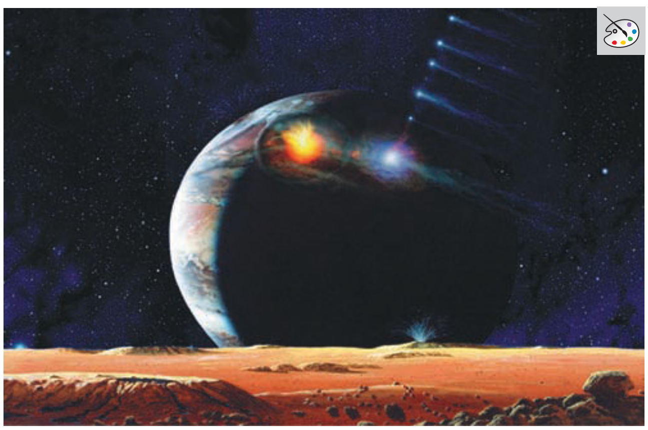
Pluto and other larger Kuiper belt objects are smaller, icier, and more distant than any of the planets. They can have moons, atmospheres, and possibly geological activity.

We should learn much more about the objects of the Kuiper belt beginning in 2015, when the *New Horizons* spacecraft will fly by Pluto and hopefully continue on to fly past one or two other Kuiper belt comets. Meanwhile, if you think back to what we learned about jovian moons in Chapter 8, you'll realize that we probably already have close-up photos of at least one *former* member of the Kuiper belt: Neptune's moon Triton (see Figure 8.27). Like Triton, it's possible that Pluto and other large Kuiper belt comets are geologically active.

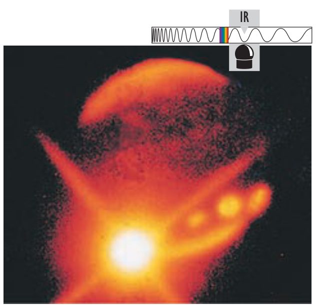
think about it Despite the heated debate about the IAU's 2006 definition of *planet*, no alternatives were presented at the group's 2009 meeting. Do you think the definition should be reconsidered? How do you think planets should be defined, and how many planets would the solar system have under your definition?



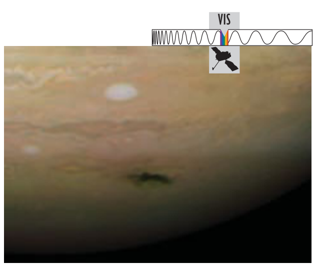
a Jupiter's tidal forces ripped apart the single comet nucleus of SL9 into a chain of smaller nuclei.



b This painting shows how the SL9 impacts might have looked from the surface of Io. The impacts occurred on Jupiter's night side.



c This infrared photo shows the brilliant glow of a rising fireball from the impact of one SL9 nucleus in 1994. Jupiter is the round disk, with the impact occurring near the lower left.



d The black spot in this Hubble Space Telescope photo is a scar from the impact of an unknown object that struck Jupiter in July 2009.

Figure 9.18

The impacts of Comet Shoemaker–Levy 9 on Jupiter gave astronomers their first direct view of a cosmic collision. Jupiter was struck again in 2009, though only the aftermath was observed, not the collision itself.

9.4 Cosmic Collisions: Small Bodies versus the Planets

The hordes of small bodies orbiting the Sun are slowly shrinking in number through collisions with the planets and ejection from the solar system. Many more roamed the solar system in the days of the heavy bombardment, when most impact craters formed **[Section 6.4]**. Plenty of small bodies still remain, however, and cosmic collisions still occur on occasion. These collisions have had important effects on Earth and other planets.

• Have we ever witnessed a major impact?

Modern scientists have never witnessed a major impact on a solid world, but in 1994 we were privileged to witness one on Jupiter. This dramatic event was the impact of a comet named *Shoemaker–Levy 9*, or *SL9* for short. Rather than having a single nucleus, SL9 consisted of a string of comet nuclei (Figure 9.18a). Apparently, tidal forces from Jupiter ripped apart a single comet nucleus during a previous close pass by the planet. Chains of craters observed on some of Jupiter's moons provide evidence that similar breakups of comets near Jupiter have occurred in the past.

Comet impacts on Jupiter remind us that catastrophic collisions still happen.

Comet SL9 was discovered more than a year before its impact on Jupiter, and orbital calculations told astronomers precisely when the impact would occur. When the impacts began, they were observed with nearly every major telescope in existence, as well as by spacecraft that were in position to get a view. Each of the individual comet nuclei crashed into Jupiter with an energy equivalent to that of a million hydrogen bombs (Figure 9.18b, c). Nuclei barely a kilometer across left scars larger than all of Earth. The scars lasted for months before Jupiter's strong winds finally erased them from view.

The SL9 impacts allowed scientists to study both the impact process and material splashed out from deep inside Jupiter. Scientists felt quite fortunate, because estimates suggested that impacts as large as that of SL9 occur only about once in a thousand years. Astronomers were therefore surprised when another impact occurred on Jupiter in 2009. This impact was first noticed by an amateur astronomer from Australia, who reported a new "dark spot" on Jupiter that was soon recognized as the aftermath of an unseen impact (Figure 9.18d). And two amateur astronomers independently recorded images of an even smaller impact event in 2010. Astronomers are still not sure if these recent events signify that Jupiter impacts are more common than previously thought, or if improved monitoring of Jupiter can now capture smaller impact events, which occur more frequently than impacts of SL9's magnitude. If such violent impacts can happen on other planets in our lifetime, could they also happen on Earth?

• Did an impact kill the dinosaurs?

There's no doubt that major impacts have occurred on Earth in the past: Geologists have identified more than 150 impact craters on our planet. So before we consider whether an impact might occur in our lifetimes, it's worth examining the potential consequences if it did. Clearly, an impact could cause widespread physical damage. But a growing body of evidence, accumulated over the past three decades, suggests that an impact can do much more—in some cases, large impacts may have altered the entire course of evolution.

In 1978, while analyzing geological samples collected in Italy, a scientific team led by father-and-son team Luis and Walter Alvarez made a startling discovery. They found that a thin layer of dark sediments deposited about 65 million years ago—about the time the dinosaurs went extinct—was unusually rich in the element iridium. Iridium is a metal that is rare on Earth's surface (because it sank to Earth's core with other metals during differentiation) but common in meteorites. Subsequent studies found the same iridium-rich layer in 65-million-year-old sediments around the world (Figure 9.19). The Alvarez team suggested a stunning hypothesis: The extinction of the dinosaurs was caused by the impact of an asteroid or comet.

In fact, the death of the dinosaurs was only a small part of the biological devastation that seems to have occurred 65 million years ago. The fossil record suggests that up to 99% of all living organisms died around that time and that up to 75% of all existing *species* were driven to extinction. This event was clearly a **mass extinction**—the rapid extinction of a large fraction of all living species. Could it really have been caused by an impact?

Figure 9.19

Around the world, sedimentary rock layers dating to 65 million years ago share the evidence of the impact of a comet or asteroid. Fossils of dinosaurs and many other species appear only in rocks below the iridium-rich layer.

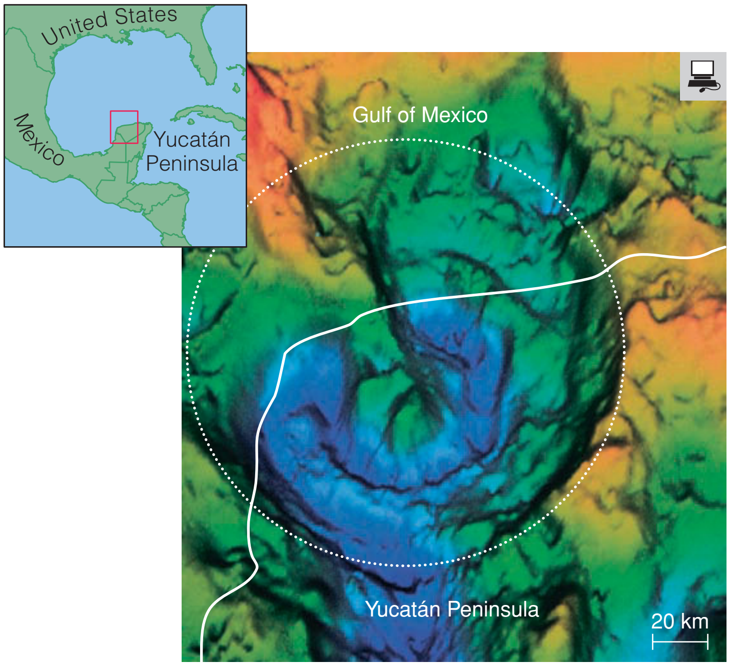


Figure 9.20

This computer-generated image, based on measurements of small local variations in the strength of gravity, shows an impact crater about 200 kilometers across (dashed circle). The crater straddles the coast of Mexico's Yucatán Peninsula (see inset).

There's still some scientific controversy about whether the impact was the sole cause of the mass extinction or just one of many causes, but there's little doubt that a major impact coincided with the death of the dinosaurs. In addition to the evidence within the sediments, scientists have identified a 65-million-year-old crater (Figure 9.20), apparently created by the impact of an asteroid or a comet measuring about 10 kilometers across. Astronomers have also found evidence that the breakup of a 170-kilometer asteroid 160 million years ago may have created a fragment that struck Earth a hundred million years later.

An iridium-rich sediment layer and an impact crater on the Mexican coast show that a large impact occurred at the time the dinosaurs died out, 65 million years ago.

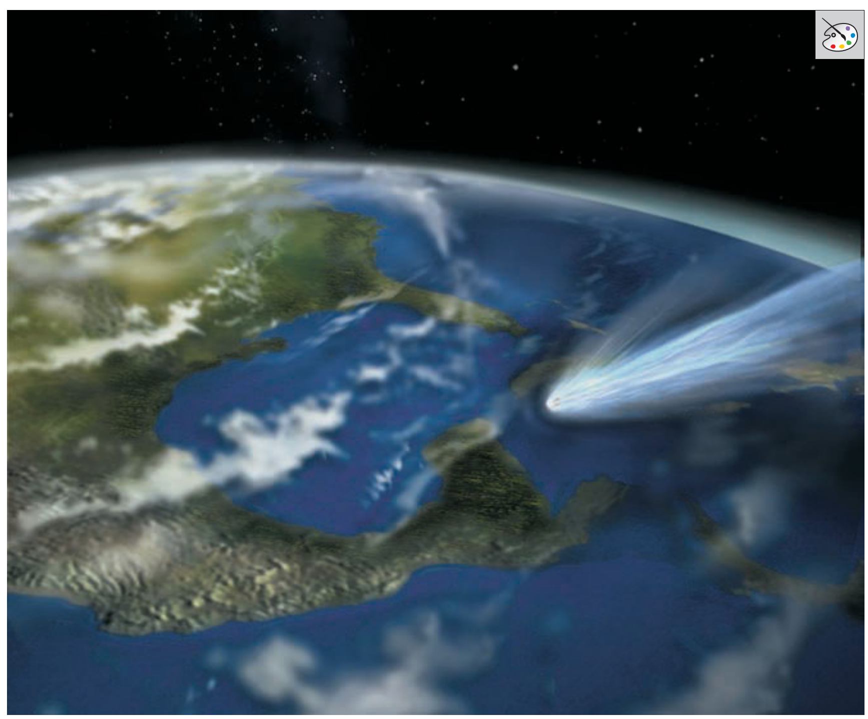
If an impact was indeed the cause of the mass extinction, here's how it probably happened. On that fateful day some 65 million years ago, the asteroid or comet slammed into Mexico with the force of a hundred million hydrogen bombs (Figure 9.21). North America may have been devastated immediately. Hot debris from the impact rained around the rest of the world, igniting fires that killed many more living organisms.

The longer-term effects were even more severe. Dust and smoke remained in the atmosphere for weeks to months, blocking sunlight and causing temperatures to fall as if Earth were experiencing a harsh global winter. The reduced sunlight would have stopped photosynthesis for up to a year, killing large numbers of species throughout the food chain. Acid rain may have been another by-product, killing vegetation and acidifying lakes around the world. Chemical reactions in the atmosphere probably produced nitrous oxides and other compounds that dissolved in the oceans and killed marine organisms.

Perhaps the most astonishing fact is not that 75% of all species died but that 25% *survived*. Among the survivors were a few small mammals. These mammals may have survived in part because they lived in underground burrows and managed to store enough food to outlast the global winter that immediately followed the impact.

Figure 9.21

This painting shows an asteroid or comet moments before its impact on Earth, some 65 million years ago. The impact probably caused the extinction of the dinosaurs, and if it hadn't occurred, the dinosaurs might still rule Earth today.



The evolutionary impact of the extinctions was profound. For 180 million years, dinosaurs had diversified into a wide variety of species, while most mammals (which had arisen at almost the same time as the dinosaurs) had generally remained small and rodent-like. With the dinosaurs gone, mammals became the new kings of the planet. Over the next 65 million years, small mammals rapidly evolved into an assortment of much larger mammals—ultimately including us.

• Is the impact threat a real danger or just media hype?

The dinosaur extinction is only one of several known mass extinctions in Earth's past, and some of the others also seem to coincide with past impacts. Given that impacts have altered the course of life on Earth in the past, could a future impact endanger our own survival? Hollywood seems to take the threat seriously and has made several feature movies about it. Should we take it seriously, too?

Space is filled with plenty of objects that could hit our planet. As of 2010, astronomers had identified nearly 7000 near-Earth asteroids, of which more than 1000 were classified as potentially hazardous. The threat from comets is lower, but their high speeds would give us less time to prepare for an impact.

The threat of a major impact is undoubtedly real, but the chance of a large impact in our lifetime is quite small. Geological data show that impacts large enough to cause mass extinctions happen many tens of millions of years apart on average. We're far more likely to do ourselves in than to be done in by a large asteroid or comet.

Smaller impacts can be expected more frequently. While such impacts would not wipe out our civilization, they could kill thousands or millions of people. We know of one close call in modern times. In 1908, a tremendous explosion occurred over Tunguska, Siberia (Figure 9.22). The explosion, estimated to have released energy equivalent to that of several atomic bombs, is thought to have been caused by a small asteroid less than 40 meters across. If the asteroid had exploded over a major city instead of Siberia, it would have been the worst natural disaster in human history. A less devastating impact occurred in 2007, when eyewitnesses saw a bright fireball streak across the mid-day sky near Carancas, Peru. A stony meteorite about 1–2 meters across slammed into the ground and excavated a crater 15 meters across (Figure 9.23). The impact spewed debris more than 300 meters and shattered windows as far away as a kilometer.

Impacts will certainly occur in the future, and while the chance of a major impact in our lifetimes is small, the effects could be devastating.

Figure 9.24 shows how often, on average, we expect Earth to be hit by objects of different sizes. Notice that objects large enough to cause mass extinctions come tens of millions of years apart. Objects of the size that caused the Tunguska event probably strike our planet every few hundred years or so. That's a level of threat that we cannot discount. Nevertheless, these rare events are unlikely to strike populated areas. After all, most of Earth's surface is ocean, and even on land humans are concentrated in relatively small urban areas.

If we were to find an asteroid or a comet on a collision course with Earth, could we do anything about it? Many people have proposed schemes to save Earth by using nuclear weapons or other means to

Figure 9.22

This photo shows forests burned and flattened by the 1908 impact over Tunguska, Siberia. Atmospheric friction caused the small asteroid to explode completely before it hit the ground, so it left no impact crater.

Figure 9.23

The impact crater made by a 1–2 meter stony meteorite near Carancas, Peru, in 2007. The crater filled with groundwater soon after the impact.

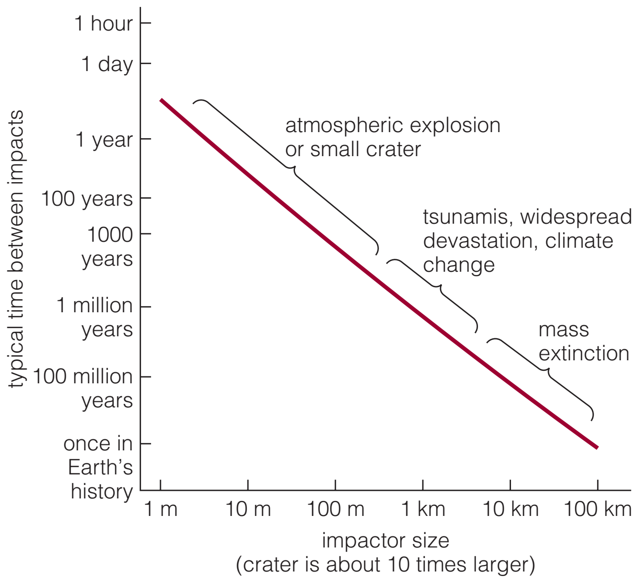


Figure 9.24

This graph shows that larger objects (asteroids or comets) hit the Earth less frequently than smaller ones. The labels describe the effects of impacts of different sizes.

demolish or divert an incoming asteroid, but no one knows whether current technology is up to the task. We can only hope that the threat doesn't become a reality before we're ready.

think about it Study Figure 9.24. Based on the frequency of impacts large enough to cause serious damage, do you think we should be spending time and resources to counter the impact threat? Or should we focus resources on other threats first? Defend your opinion.

• How do other planets affect impact rates and life on Earth?

Ancient people imagined that the mere movement of planets relative to the visible stars in our sky could somehow have an astrological influence on our lives. Although scientists no longer give credence to this ancient superstition, we now know that planets can have a real effect on life on Earth. By catapulting asteroids and comets in Earth's direction, other planets have caused cosmic collisions that have helped shape Earth's destiny.

Jupiter and the other jovian planets have had the greatest effects because of their influence on the small bodies of the solar system. As we saw earlier in this chapter, Jupiter disturbed the orbits of rocky planetesimals outside Mars's orbit, preventing a planet from forming and instead creating the asteroid belt. The jovian planets ejected icy planetesimals to create the distant Oort cloud of comets, and orbital resonances with Neptune shape the orbits of many comets in the Kuiper belt. Ultimately, every asteroid or comet that has impacted Earth since the end of the heavy bombardment was in some sense sent our way by the influence of Jupiter or one of the other jovian planets. Figure 9.25 summarizes the ways the jovian planets have controlled the motions of asteroids and comets.

Nearly every asteroid or comet that has ever struck Earth was in some sense sent our way by the influence of the jovian planets.

We thereby find a deep connection between the jovian planets and the survival of life on Earth. If Jupiter did not exist, the threat from asteroids might be much smaller, since the objects that make up the asteroid belt might instead have become part of a planet. On the other hand, the threat from comets might be much greater: Jupiter probably ejected more comets to the Oort cloud than any other jovian planet, and without Jupiter, those comets might have remained dangerously close to Earth. Of course, even if Jupiter has protected us from impacts, it's not clear whether that has been good or bad for life overall. The dinosaurs appear to have suffered from an impact, but the same impact may have paved the way for our existence. So while some scientists argue that more impacts would have damaged life on Earth, others argue that more impacts might have sped up evolution.

The role of Jupiter has led some scientists to wonder whether we could exist if our solar system had been laid out differently. Could it be that civilizations can arise only in solar systems that happen to have a Jupiter-like planet in a Jupiter-like orbit? No one yet knows the answer to this question. What we do know is that Jupiter has had profound effects on life on Earth and will continue to have effects in the future.

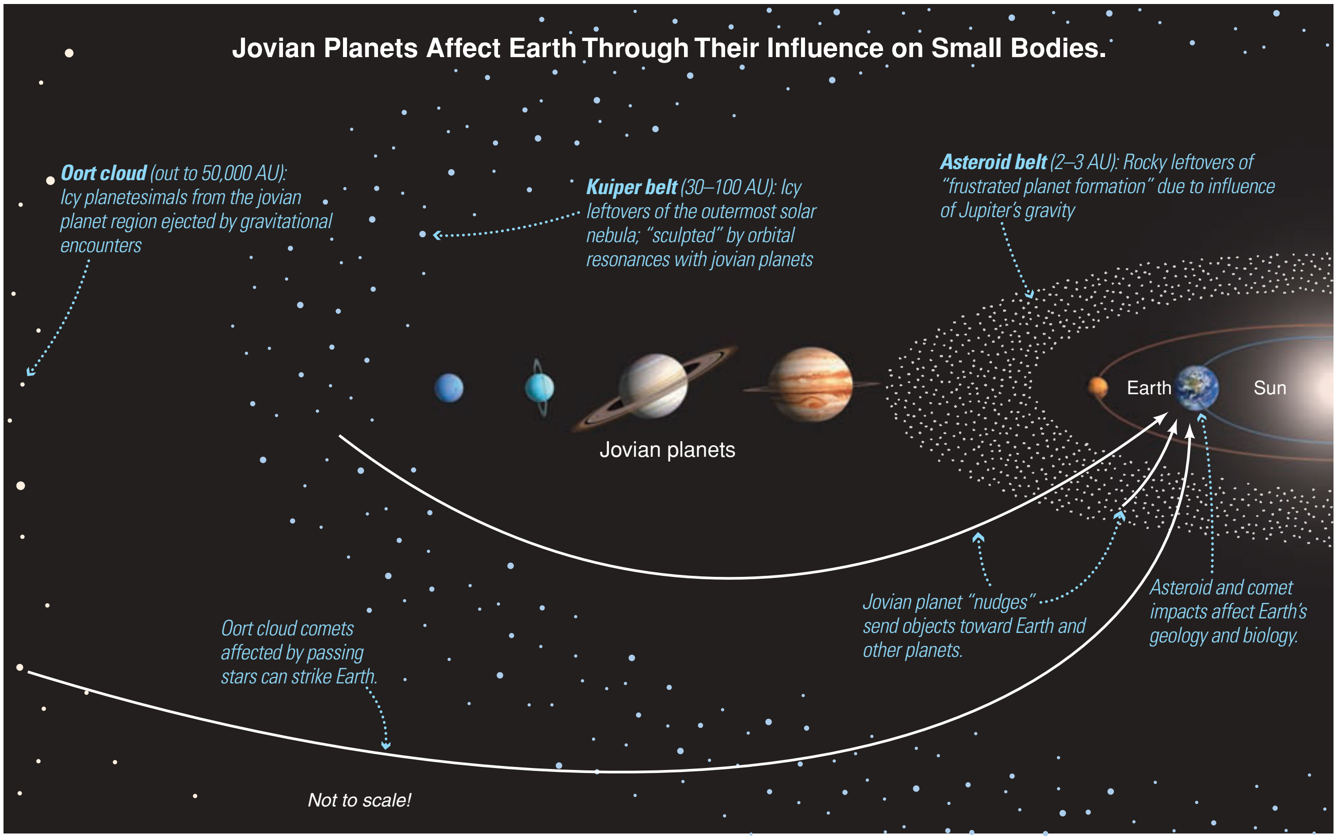


Figure 9.25

The connections between the jovian planets, small bodies, and Earth. The gravity of the jovian planets helped shape both the asteroid belt and the Kuiper belt, and the Oort cloud consists of comets ejected from the jovian planet region by gravitational encounters with these large planets. Ongoing gravitational influences can send asteroids or comets heading toward Earth.

the big picture

Putting Chapter 9 into Perspective

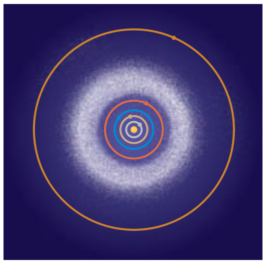
In this chapter we concluded our study of the solar system by focusing on its smallest objects, finding that these objects can have big consequences. Keep in mind the following "big picture" ideas:

- Asteroids, comets, and meteorites may be small compared to planets, but they provide much of the evidence that has helped us understand how the solar system formed.
- The small bodies are subject to the gravitational influences of the largest. The jovian planets shaped the asteroid belt, the Kuiper belt, and the Oort cloud, and they continue to nudge objects onto collision courses with the planets.
- Pluto, once considered a "misfit" among the planets, is now viewed as just one of many moderately sized objects in the Kuiper belt. In terms of composition, the dwarf planets Pluto and Eris—along with other similar objects—are essentially comets of unusually large size.
- Collisions not only bring meteorites and leave impact craters but also can profoundly affect life on Earth. An impact probably wiped out the dinosaurs, and future impacts pose a threat that we cannot ignore.

summary of key concepts

9.1 Asteroids and Meteorites

• Why is there an asteroid belt?



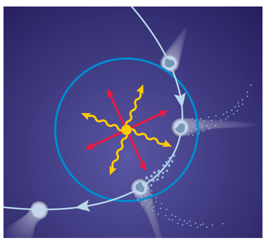
Orbital resonances with Jupiter disrupted the orbits of planetesimals in the asteroid belt, preventing them from accreting into a terrestrial planet. Many were ejected, but some remained and make up the asteroid belt today. Most asteroids in other regions of the inner solar system crashed into one of the planets.

• How are meteorites related to asteroids?

Most **meteorites** are pieces of asteroids. **Primitive meteorites** are essentially unchanged since the birth of the solar system. **Processed meteorites** are fragments of larger asteroids that underwent differentiation.

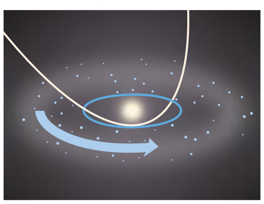
9.2 Comets

• How do comets get their tails?



Comets are icy leftovers from the era of planet formation, and most orbit far from the Sun. If a comet approaches the Sun, its **nucleus** heats up and its ice sublimates into gas. The escaping gases carry along some dust, forming a **coma** and two tails: a **plasma tail** of ionized gas and a **dust tail**. Larger particles can also escape, causing **meteor showers** on Earth.

• Where do comets come from?



Comets come from two reservoirs: the **Kuiper belt** and the **Oort cloud**. The Kuiper belt comets still reside in the region beyond Neptune in which they formed. The Oort cloud comets formed between the jovian planets and were kicked out to a great distance by gravitational encounters with these planets.

9.3 Pluto: Lone Dog No More

• How big can a comet be?

In the Kuiper belt, icy planetesimals were able to grow to hundreds or thousands of kilometers in size. The recently discovered Eris is the largest known of these objects and Pluto is the second largest.

• What are Pluto and other large objects of the Kuiper belt like?

Like smaller comets, these objects are ice-rich in composition. They orbit the Sun roughly between the orbit of Neptune and twice that distance from the Sun. Their orbits tend to be more elliptical and more inclined to the ecliptic plane than those of the terrestrial and jovian planets. Many share orbital resonances with Neptune. A few have moons, including Pluto.

9.4 Cosmic Collisions: Small Bodies Versus the Planets

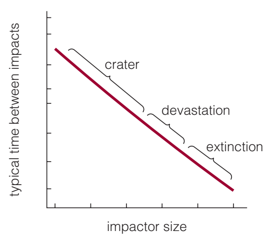
• Have we ever witnessed a major impact?

In 1994, we observed the fragmented Comet Shoemaker–Levy 9 impacting Jupiter, scarring its atmosphere for months. In 2009, we saw the aftermath of another impact on Jupiter.

• Did an impact kill the dinosaurs?

It may not have been the sole cause, but a major impact clearly coincided with the **mass extinction** in which the dinosaurs died out, about 65 million years ago. Sediments from this era contain iridium and other evidence of an impact, and an impact crater of the same age lies along the coast of Mexico.

• Is the impact threat a real danger or just media hype?



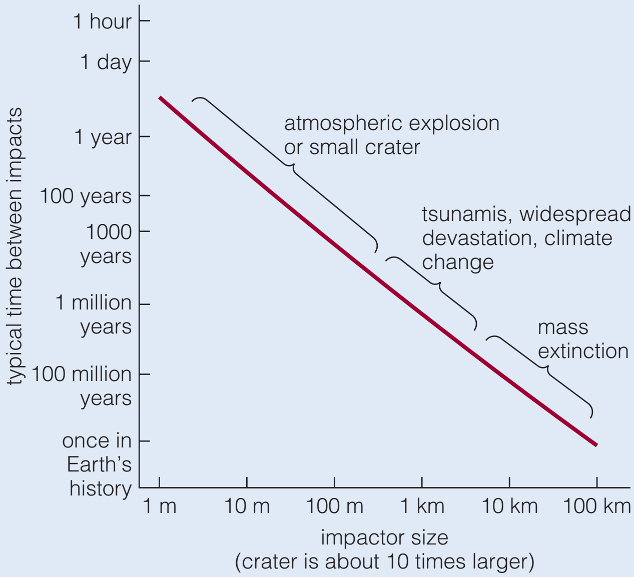
Impacts certainly pose a threat, though the probability of a major impact in our lifetimes is fairly low. Impacts like the Tunguska event may occur every few hundred years and would be catastrophic if they struck populated areas.

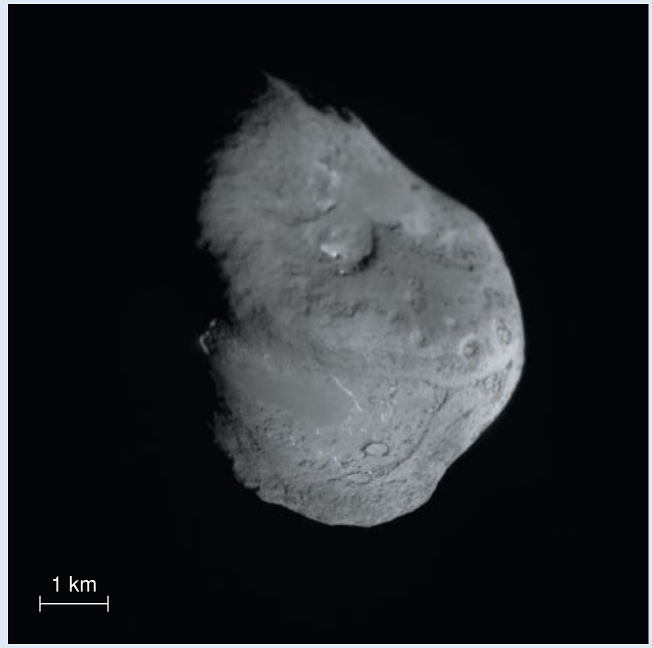
• How do other planets affect impact rates and life on Earth?

Impacts are always linked in at least some way to the gravitational influences of Jupiter and the other jovian planets. These influences have shaped the asteroid belt, the Kuiper belt, and the Oort cloud and continue to determine when an object is flung our way.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 9 Visual Quiz at www.masteringastronomy.com.





The graph above (from Figure 9.24) shows how often impacts occur for objects of different sizes. The photo above shows comet Tempel 1 moments before the *Deep Impact* spacecraft crashed into it.

1. Estimate comet Tempel 1's diameter, using the scale bar in the photo above.
2. According to the graph above, how frequently do objects the size of comet Tempel 1 strike Earth?
   a. once in Earth's history
   b. about once every hundred million years
   c. about once every million years
   d. about once every thousand years
3. According to the graph, what kind of damage would this object cause if it hit our planet?
   a. mass extinction
   b. widespread devastation and climate change
   c. atmospheric explosion or a small crater
4. The Meteor Crater in Arizona is about 1.2 kilometers across. According to the graph, about how big was the object that made this crater? (*Note*: Be sure to read the axis labels carefully.)
   a. 1 meter b. 10 meters
   c. 100 meters d. 1 kilometer
5. How often do objects big enough to create craters like the Meteor Crater impact Earth?
   a. once in Earth's history
   b. about once every ten thousand years
   c. about once every few million years
   d. about once every day, but most burn up in the atmosphere or land in the ocean

exercises and problems

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Briefly explain why comets, asteroids, and meteorites are so useful in helping us understand the history of the solar system.
2. How does the largest asteroid compare in size to the planets? How does the total mass of all asteroids compare to the mass of a terrestrial world?
3. Where is the *asteroid belt* located, and why? Briefly explain how orbital resonances with Jupiter have affected the asteroid belt.
4. What is the difference between a *meteor* and a *meteorite?* How can we distinguish a meteorite from a terrestrial rock?
5. Distinguish between *primitive meteorites* and *processed meteorites* in terms of both composition and origin.
6. What does a comet look like when it is far from the Sun? How does its appearance change when it is near the Sun? What happens to comets that make many passes near the Sun?
7. What produces the *coma* and tails of a comet? What is the *nucleus?* Why do tails point away from the Sun?

8. Explain how meteor showers are linked to comets. Why do meteor showers recur at about the same time each year?
9. Describe the *Kuiper belt* and *Oort cloud* in terms of their locations and the orbits of comets within them. How did comets come to exist in these two regions?
10. How large are the largest objects in the Kuiper belt? How many qualify—or may qualify—as *dwarf planets*? In what sense are all these objects really just large comets?
11. Briefly describe Pluto and Charon. How do Eris and other large Kuiper belt objects compare to Pluto and Charon?
12. Briefly describe the impact of comet Shoemaker–Levy 9 on Jupiter.
13. Briefly describe the evidence suggesting that an impact caused the mass extinction that killed off the dinosaurs. How might the impact have led to the mass extinction?
14. How often should we expect impacts of various sizes on Earth? How serious a threat do we face from these impacts?

Test Your Understanding

Surprising Discoveries?

Consider the following hypothetical discoveries. (These are not real discoveries.) In light of what you've learned about the formation of our solar system, decide whether each discovery should be considered reasonable or surprising. Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

15. A small asteroid that orbits within the asteroid belt has an active volcano.
16. Scientists discover a meteorite that, based on radiometric dating, is 7.9 billion years old.
17. An object that resembles a comet in size and composition is discovered orbiting in the inner solar system.
18. Studies of a large object in the Kuiper belt reveal that it is made almost entirely of rocky (as opposed to icy) material.
19. Astronomers discover a previously unknown comet that will be brightly visible in our night sky about 2 years from now.
20. A mission to Pluto finds that it has lakes of liquid water on its surface.
21. Geologists discover a crater from a 5-kilometer object that impacted Earth more than 100 million years ago.
22. Archaeologists learn that the fall of ancient Rome was caused in large part by an asteroid impact in Asia.
23. Astronomers discover three objects with the same average distance from the Sun (and the same orbital period) as Pluto.
24. Astronomers discover an asteroid with an orbit suggesting that it will impact the Earth in the year 2064.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

25. The asteroid belt lies between the orbits of (a) Earth and Mars. (b) Mars and Jupiter. (c) Jupiter and Saturn.
26. Jupiter nudges the asteroids through the influence of (a) tidal forces. (b) orbital resonances. (c) magnetic fields.
27. Can an asteroid be pure metal? (a) No, all asteroids contain rock. (b) Yes, it must have formed where only metal could condense in the solar nebula. (c) Yes, it must have been the core of a shattered asteroid.
28. Did a large terrestrial planet ever form in the region of the asteroid belt? (a) No, because there was never enough mass there. (b) No, because Jupiter prevented one from accreting. (c) Yes, but it was shattered by a giant impact.
29. What does Pluto most resemble? (a) a terrestrial planet (b) a jovian planet (c) a comet
30. How big an object causes a typical shooting star? (a) a grain of sand or a small pebble (b) a boulder (c) an object the size of a car
31. Which have the most elliptical and tilted orbits? (a) asteroids (b) Kuiper belt comets (c) Oort cloud comets
32. Which are thought to have formed farthest from the Sun? (a) asteroids (b) Kuiper belt comets (c) Oort cloud comets
33. About how often does a 1-kilometer object strike Earth? (a) every year (b) every million years (c) every billion years
34. What would happen if a 1-kilometer object struck Earth? (a) It would break up in the atmosphere without causing widespread damage. (b) It would cause widespread devastation and climate change. (c) It would cause a mass extinction.

Process of Science

35. *The Pluto Debate.* Research the decision to reclassify Pluto as a dwarf planet. In your opinion, is this a good example of the application of the scientific process? Does it exhibit the hallmarks of science described in Chapter 3? Compare your conclusions to opinions you find about the debate, and describe how you think astronomers should handle similar debates in the future.
36. *Life or Death Astronomy.* In most cases, the study of the solar system has little direct effect on our lives. But the discovery of an asteroid or comet on a collision course with Earth is another matter. How should the standards for verifiable observations described in Chapter 3 apply in this case? Is the potential danger so great that any astronomer with evidence of an impending impact should spread the word as soon as possible? Or is the potential for panic so great that even higher standards of verification ought to be applied? What kind of review process, if any, would you set in place? Who should be informed of an impact threat, and when?
37. *Unanswered Questions.* NASA has two missions en route to dwarf planets: *New Horizons* to Pluto, and the *Dawn* mission to Ceres and Vesta. Do a Web search to identify one important but still unanswered question about these destinations, and write two or three paragraphs discussing how one of these missions might answer this question. Be as specific as possible, focusing on the type of evidence necessary to answer the question and how the evidence could be gathered. What are the benefits of finding an answer to this question?

Group Work Exercise

38. *Assessing Impact Danger*. Your task in this exercise is to assess the risks we face on Earth from meteorite and comet impacts. Before you begin, assign the following roles to the people in your group: *Scribe* (collects data and takes notes on the group's activities), *Proposer* (proposes hypotheses and explanations of the data), *Skeptic* (points out weaknesses in the hypotheses and explanations), *Moderator* (leads group discussion and makes sure everyone contributes). Each person should write down the answers from each part of the exercise.
    a. Estimate the odds that human civilization will be destroyed by an impact during your lifetime. The *Moderator* should lead a discussion about how to go about making such an estimate. As a group, determine the kinds of information you would need, develop a method for making the estimate, and write down your method.
    b. *Scribe* analyzes Figure 9.24, determines whether it contains any of the necessary information, and shares his or her findings with the group.
    c. *Proposer* uses the group's method to estimate the probability that civilization will be destroyed by an impact during your lifetime, which you can assume to be 100 years for the purpose of this exercise. *Skeptic* should check *Proposer's* work.

d. Estimate the probability that an impact will cause widespread devastation somewhere on Earth during your lifetime. *Moderator* should lead the discussion about how to make this estimate. *Scribe* should gather the information from Figure 9.24. *Proposer* should do the calculation, and *Skeptic* should check *Proposer's* work.

e. Finding near-Earth asteroids early greatly increases our chances of deflecting them. Given the probabilities from parts (c) and (d) and considering the damage these events would cause, decide as a group how much money per year should be spent on finding near-Earth asteroids and explain your reasoning.

Investigate Further

Short-Answer/Essay Questions

39. *The Role of Jupiter.* Suppose that Jupiter had never existed. Describe at least three ways in which our solar system would be different, and clearly explain why.
40. *Life Story of an Iron Atom.* Imagine that you are an iron atom in a processed meteorite made mostly of iron. Tell the story of how you got to Earth, beginning from the time you were part of the gas in the solar nebula 4.6 billion years ago. Include as much detail as possible. Your story should be scientifically accurate but also creative and interesting
41. *Asteroids vs. Comets.* Contrast the compositions and locations of comets and asteroids, and explain in your own words why they have turned out differently.
42. *Comet Tails.* Describe in your own words why comets have tails. Why do most comets have two distinct visible tails, and why do the tails go in different directions? Why is the third, invisible tail of small pebbles of interest to us on Earth?
43. *Oort Cloud vs. Kuiper Belt.* Explain in your own words how and why there are two different reservoirs of comets. Be sure to discuss where the two groups of comets formed, and what kinds of orbits they travel on.
44. *Project: Dirty Snowballs.* If there is snow where you live or study, make a dirty snowball. (The ice chunks that form behind tires work well.) How much dirt does it take to darken snow? Find out by allowing your dirty snowball to melt in a container and measuring the approximate proportions of water and dirt afterward. What do your results tell you about comet composition?

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

45. *Adding Up Asteroids.* It's estimated that there are a million asteroids 1 kilometer across or larger. If a million asteroids 1 kilometer across were all combined into one object, how big would it be? How many 1-kilometer asteroids would it take to make an object as large as the Earth? (*Hint:* You can assume they're spherical. The equation for the volume of a sphere is $\left(\frac{4}{3}\right)\pi r^3$, where r is the radius—not the diameter.)
46. *Impact Energies.* A relatively small impact crater 20 kilometers in diameter could be made by a comet 2 kilometers in diameter traveling at 30 kilometers (30,000 meters) per second.
    a. Assume that the comet has a total mass of 4.2×10^{12} kilograms. What is its total kinetic energy? (*Hint:* The kinetic energy is equal to $\frac{1}{2}mv^2$, where m is the comet's mass and v is its speed. If you use mass in kilograms and velocity in meters per second, the answer for kinetic energy will have units of joules.)
    b. Convert your answer from part (a) to an equivalent in megatons of TNT, the unit used for nuclear bombs. Comment on the degree of devastation the impact of such a comet could cause if it struck a populated region on Earth. (*Hint:* One megaton of TNT releases 4.2×10^{15} joules of energy.)
47. *The "Near Miss" of Toutatis.* The 5-kilometer asteroid Toutatis passed a mere 1.5 million kilometers from Earth in 2004. Suppose Toutatis were destined to pass *somewhere* within 3 million kilometers of Earth. Calculate the probability that this "somewhere" would have meant that it slammed into Earth. Based on your result, do you think it is fair to call the 2004 passage a "near miss"? Explain. (*Hint:* You can calculate the probability by imagining a dartboard of radius 3 million kilometers in which the bull's-eye has Earth's radius, 6378 kilometers.)
48. *Room to Roam.* It's estimated that there are a trillion comets in the Oort cloud, which extends out to about 50,000 AU. What is the total volume of the Oort cloud in cubic AU? How much space does each comet have in cubic AU, on average? Take the cube root of the average volume per comet to find their typical spacing in AU. (*Hints:* For this calculation, you can assume the Oort cloud fills the whole sphere out to 50,000 AU. The equation for the volume of a sphere is $\left(\frac{4}{3}\right)\pi r^3$, where r is the radius.)
49. *Dust Accumulation.* A few hundred tons of comet and asteroid dust are added to Earth daily from the millions of meteors that enter our atmosphere. Estimate the time it would take for Earth to get 0.1% heavier at this rate. Is this mass accumulation significant for Earth as a planet? Explain.

Discussion Questions

50. *Rise of the Mammals.* Suppose the impact 65 million years ago had not occurred. How do you think our planet would be different? Do you think that mammals still would eventually have come to dominate Earth? Would we be here? Defend your opinions.
51. *How Should Kids Count Planets?* The new definitions that have officially demoted Pluto from planet to dwarf planet have many educational implications. For example, many children learn songs in school that refer to "nine planets" and Pluto. How would you recommend that school teachers deal with the new definitions? Be sure to consider the fact that while these definitions have "official" status today (from the International Astronomical Union), it is possible that they may change again in the future.
52. *Reducing the Impact Threat.* Based on your own opinion of how the impact threat compares to other threats, how much money and resources do you think should be used to alleviate it? What types of programs would you support? (Examples include programs to search for objects that could strike Earth, to develop defensive tactics against impacts, or to build physical defenses.) Defend your opinions.

Web Projects

53. *Recent Asteroid and Comet Missions.* Learn about the goals and status of the *NEAR, Stardust,* or *Hayabusa* mission. What did it accomplish? Write a one- to two-page summary of your findings.
54. *Future Asteroid and Comet Missions.* Learn about another proposed space mission to study asteroids or comets, such as *Dawn* or *Rosetta*. For the mission you choose, write a short report about its plans, goals, and prospects for success.
55. *The New Horizons Mission to Pluto.* The *New Horizons* mission is more than halfway to Pluto. What are its goals? What has it done so far? Summarize your findings in a few paragraphs.
56. *Impact Hazards.* Many groups are searching for near-Earth asteroids that might impact the Earth. They use the *Torino Scale* to evaluate the possible danger posed by an asteroid, based on our knowledge of its orbit. What is this scale? What object has reached the highest level on this scale? What were the estimated chances of impact by that object, and when was it expected?