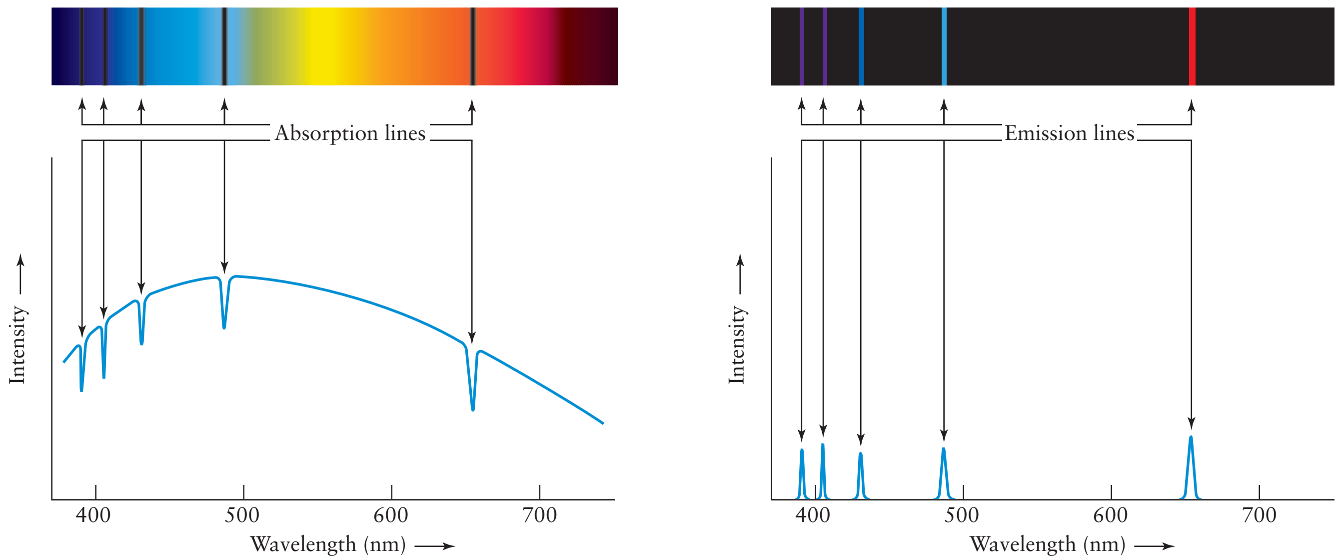


(a) Two representations of an absorption line spectrum

(b) Two representations of an emission line spectrum

Figure 6-21

Two Ways to Represent Spectra When a CCD is placed at the focus of a spectrograph, it records the rainbow-colored spectrum. A computer program can be used to convert the recorded data into a graph of intensity versus wavelength. **(a)** Absorption lines appear as dips on such a graph, while **(b)** emission lines appear as peaks. The dark absorption lines and bright emission lines in this example are the Balmer lines of hydrogen (see Section 5-8).

of the comparison spectrum are known from laboratory experiments and can therefore serve as reference markers. (See Figure 5-17, which shows the spectrum of the Sun and a comparison spectrum of iron.)

When the exposure is finished, electronic equipment measures the charge that has accumulated in each pixel. These data are used to graph light intensity against wavelength. Dark absorption lines in the spectrum appear as depressions or valleys on the graph, while bright emission lines appear as peaks. Figure 6-21 compares two ways of exhibiting spectra with absorption lines and emission lines. Later in this book we shall see spectra presented in both these ways.

6-6 A radio telescope uses a large concave dish to reflect radio waves to a focus

For thousands of years, all the information that astronomers gathered about the universe was based on ordinary visible light. In the twentieth century, however, astronomers first began to explore the nonvisible electromagnetic radiation coming from astronomical objects. In this way they have discovered aspects of the cosmos that are forever hidden to optical telescopes.

Observing at radio wavelengths reveals aspects of the universe hidden from ordinary telescopes

Astronomers have used ultraviolet light to map the outer regions of the Sun and the clouds of Venus, and used infrared radiation to see new stars and perhaps new planetary systems in the process of formation. By detecting radio waves from Jupiter and Saturn, they have mapped the intense magnetic fields that surround those giant planets; by detecting curious bursts of X rays from space, they have learned about the utterly alien conditions in the vicinity of a black hole. It is no exaggeration to say that today's astronomers learn as much about the universe using telescopes for nonvisible wavelengths as they do using visible light.

Radio Astronomy

Radio waves were the first part of the electromagnetic spectrum beyond the visible to be exploited for astronomy. This happened as a result of a research project seemingly unrelated to astronomy. In the early 1930s, Karl Jansky, a young electrical engineer at Bell Telephone Laboratories, was trying to locate what was causing interference with the then-new transatlantic radio link. By 1932, he realized that one kind of radio noise is strongest when the constellation Sagittarius is high in the sky. The center of our Galaxy is located in the direction of Sagittarius, and Jansky concluded that he was detecting radio waves from an astronomical source.

At first only Grote Reber, a radio engineer living in Illinois, took up Jansky's research. In 1936 Reber built in his backyard the first **radio telescope,** a radio-wave detector dedicated to astronomy. He modeled his design after an ordinary reflecting telescope, with a parabolic metal "dish" (reflecting antenna) measuring 31 ft (10 m) in diameter and a radio receiver at the focal point of the dish.

Reber spent the years from 1938 to 1944 mapping radio emissions from the sky at wavelengths of 1.9 m and 0.63 m. He found radio waves coming from the entire Milky Way, with the greatest emission from the center of the Galaxy. These results, together with the development of improved radio technology during World War II, encouraged the growth of radio astronomy and the construction of new radio telescopes around the world. Radio observatories are as common today as major optical observatories.

Modern Radio Telescopes

Like Reber's prototype, a typical modern radio telescope has a large parabolic dish (Figure 6-22). An antenna tuned to the desired frequency is located at the focus (like the prime focus design for optical reflecting telescopes shown in Fig. 6-11*a*). The incoming signal is relayed from the antenna to amplifiers and recording instruments, typically located in a room at the base of the telescope's pier.

CAUTION! The radio telescope in Figure 6-22 looks like a radar dish but is used in a different way. In radar, the dish is used to send out a narrow beam of radio waves. If this beam encounters an object like an airplane, some of the radio waves will be reflected back to the radar dish and detected by a receiver at the focus of the dish. Thus, a radar dish looks for radio waves *reflected* by distant objects. By contrast, a radio telescope is designed to receive radio waves *emitted* by objects in space.

Many radio telescope dishes, like the one in Figure 6-22, have visible gaps in them like a wire mesh. This does not affect their reflecting power because the holes are much smaller than the wavelengths of the radio waves. The same idea is used in the design of microwave ovens. The glass window in the oven door would allow the microwaves to leak out, so the window is covered by a metal screen with small holes. These holes are much smaller than the 12.2-cm (4.8-in.) wavelength of the microwaves, so the screen reflects the microwaves back into the oven.

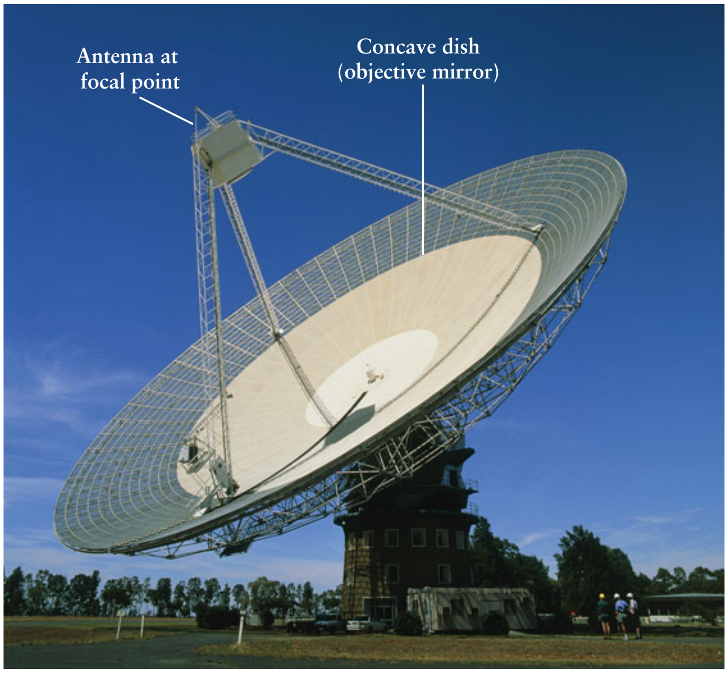


Figure 6-22 R I **V** U X G

A Radio Telescope The dish of the Parkes radio telescope in New South Wales, Australia, is 64 m (210 ft) in diameter. Radio waves reflected from the dish are brought to a focus and collected by an antenna at the focal point. (David Nunuk/Photo Researchers)

Radio Telescopes: Limits to Angular Resolution

One great drawback of early radio telescopes was their very poor angular resolution. Recall from Section 6-3 that angular resolution is the smallest angular separation between two stars that can just barely be distinguished as separate objects. Unlike visible light, radio waves are only slightly affected by turbulence in the atmosphere, so the limitation on the angular resolution of a radio telescope is diffraction. The problem is that diffraction-limited angular resolution is directly proportional to the wavelength being observed: The longer the wavelength, the larger (and hence worse) the angular resolution and the fuzzier the image. (See the formula for angular resolution θ in Section 6-3.) As an example, a 1-m radio telescope detecting radio waves of 5-cm wavelength has 100,000 times poorer angular resolution than a 1-m optical telescope. Because radio radiation has very long wavelengths, small radio telescopes can produce only blurry, indistinct images.

VIDEO 6.1

A very large radio telescope can produce a somewhat sharper radio image, because as the diameter of the telescope increases, the angular resolution decreases. In other words, the bigger the dish, the better the resolution. For this reason, most modern radio telescopes have dishes more than 30 m (100 ft) in diameter. This is also useful for increasing light-gathering power, because radio signals from astronomical objects are typically very weak in comparison with the intensity of visible light. But even the largest single radio dish in existence, the 305-m (1000-ft) Arecibo radio telescope in Puerto Rico, cannot come close to the resolution of the best optical instruments.

To improve angular resolution at radio wavelengths, astronomers combine observations from two or more widely separated telescopes using the interferometry technique that we described in Section 6-3. This is much easier than for visible or infrared light because radio signals can be carried over electrical wires. Consequently, two radio telescopes observing the same astronomical object can be hooked together, even if they are separated by many kilometers. As for visible light, the resulting angular resolution is that of a single telescope whose diameter is equal to the baseline, or separation between the telescopes.

One of the largest arrangements of radio telescopes for interferometry is the Very Large Array (VLA), located in the desert near Socorro, New Mexico (Figure 6-23). The VLA consists of 27 parabolic dishes, each 25 m (82 ft) in diameter. These 27 telescopes are arranged along the arms of a gigantic Y that covers an area 27 km (17 mi) in diameter. By pointing all 27 telescopes at the same object and combining the 27 radio signals, this system can produce radio views of the sky with an angular resolution as small as 0.05 arcsec, comparable to that of the very best optical telescopes.

WEB LINK 6.6

Figure 6-23 R I V U X G

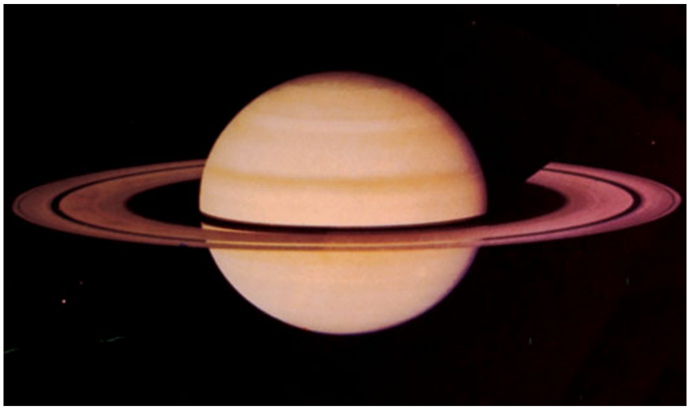
The Very Large Array (VLA) The 27 radio telescopes of the VLA in central New Mexico are arranged along the arms of a Y. The north arm of the array is 19 km long; the southwest and southeast arms are each 21 km long. By spreading the telescopes out along the legs and combining the signals received, the VLA can give the same angular resolution as a single dish many kilometers in radius. (Courtesy of NRAO/AUI)

WEB LINK 6.7

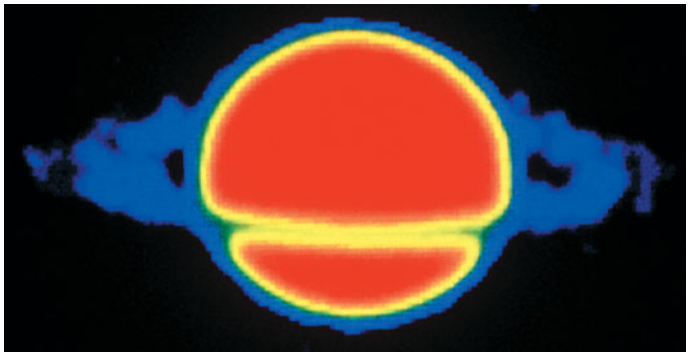
Dramatically better angular resolution can be obtained by combining the signals from radio telescopes at different observatories thousands of kilometers apart. This technique is called **very-long-baseline interferometry (VLBI).** VLBI is used by a system called the Very Long Baseline Array (VLBA), which consists of ten 25-meter dishes at different locations between Hawaii and the Caribbean. Although the ten dishes are not physically connected, they are all used to observe the same object at the same time. The data from each telescope are recorded electronically and processed later. By carefully synchronizing the ten recorded signals, they can be combined just as if the telescopes had been linked together during the observation. With the VLBA, features smaller than 0.001 arcsec can be distinguished at radio wavelengths. This angular resolution is 100 times better than a large optical telescope with adaptive optics.

Even better angular resolution can be obtained by adding radio telescopes in space; the baseline is then the distance from the VLBA to the orbiting telescope. The first such space radio telescope, the Japanese HALCA spacecraft, operated from 1997 to 2003. Orbiting at a maximum distance of 21,400 km (13,300 mi) above the Earth's surface, HALCA gave a baseline three times longer—and thus an angular resolution three times better—than can be obtained with Earthbound telescopes alone. Successors to HALCA may be placed in orbit after 2010.

Figure 6-24 shows how optical and radio images of the same object can give different and complementary kinds of information. The visible-light image of Saturn (Figure 6-24*a*) shows clouds in the planet's atmosphere and the structure of the rings.



(a) R I V U X G



(b) R I V U X G

Figure 6-24

Optical and Radio Views of Saturn **(a)** This picture was taken by a spacecraft 18 million kilometers from Saturn. The view was produced by sunlight reflecting from the planet's cloudtops and rings. **(b)** This VLA image shows radio emission from Saturn at a wavelength of 2 cm. In this false-color image, the most intense radio emission is shown in red, the least intense in blue. Yellow and green represent intermediate levels of radio intensity; black indicates no detectable radio emission. Note the radio "shadow" caused by Saturn's rings where they lie in front of the planet. (a: NASA; b: Image courtesy of NRAO/AUI)

Like the visible light from the Moon, the light used to make this image is just reflected sunlight. By contrast, the false-color radio image of Saturn (Figure 6-24*b*) is a record of waves *emitted* by the planet and its rings. Analyzing such images provides information about the structure of Saturn's atmosphere and rings that could never be obtained from a visible-light image such as Figure 6-24*a*.

6-7 Telescopes in orbit around the Earth detect radiation that does not penetrate the atmosphere

The many successes of radio astronomy show the value of observations at nonvisible wavelengths. But the Earth's atmo-

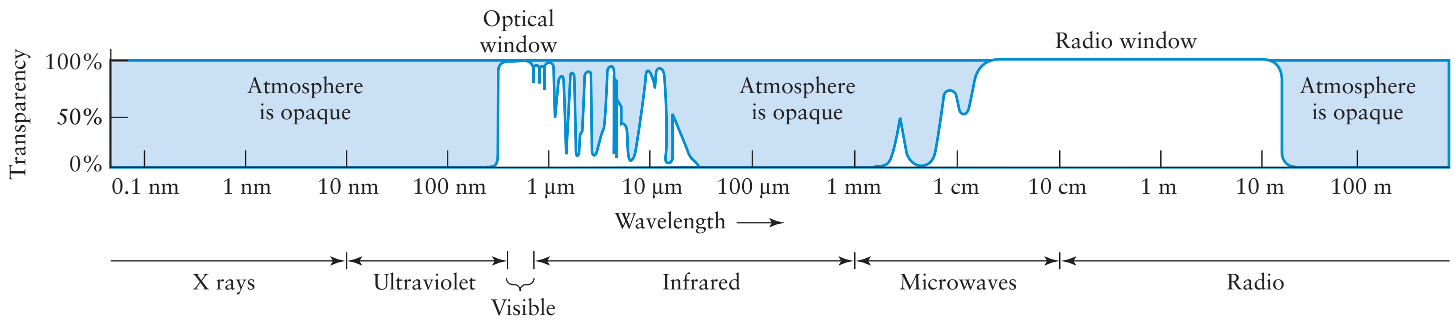


Figure 6-25

The Transparency of the Earth's Atmosphere This graph shows the percentage of radiation that can penetrate the Earth's atmosphere at different wavelengths. Regions in which the curve is high are called "windows," because the atmosphere is relatively transparent at those wavelengths. There are also three wavelength ranges in which the atmosphere is opaque and the curve is near zero: at wavelengths less than about 290 nm, which are absorbed by atmospheric oxygen and nitrogen; between the optical and radio windows, due to absorption by water vapor and carbon dioxide; and at wavelengths longer than about 20 m, which are reflected back into space by ionized gases in the upper atmosphere.

sphere is opaque to many wavelengths. Other than visible light and radio waves, very little radiation from space manages to penetrate the air we breathe. To overcome this, astronomers have placed a variety of telescopes in orbit.

Space telescopes make it possible to study the universe across the entire electromagnetic spectrum

Figure 6-25 shows the transparency of the Earth's atmosphere to different wavelengths of electromagnetic radiation. The atmosphere is most transparent in two wavelength regions, the **optical window** (which includes the entire visible spectrum) and the **radio window** (which includes part, but not all, of the radio spectrum). There are also several relatively transparent regions at infrared wavelengths between 1 and 40 μm. Infrared radiation within these wavelength intervals can penetrate the Earth's atmosphere somewhat and can be detected with ground-based telescopes. This wavelength range is called the *near-infrared,* because it lies just beyond the red end of the visible spectrum.

Infrared Astronomy

Water vapor is the main absorber of infrared radiation from space, which is why infrared observatories are located at sites with exceptionally low humidity. The site must also be at high altitude to get above as much of the atmosphere's water vapor as possible. One site that meets both criteria is the summit of Mauna Kea in Hawaii, shown in Figure 6-16. (The complete lack of vegetation on the summit attests to its extreme dryness.) Some of the telescopes on Mauna Kea are designed exclusively for detecting infrared radiation. Others, such as the Keck I and Keck II telescopes, are used for both visible and near-infrared observations (see Figure 6-18).

WEB LINK 6.8 Even at the elevation of Mauna Kea, water vapor in the atmosphere restricts the kinds of infrared observations that astronomers can make. This situation can be improved by carrying telescopes on board high-altitude balloons or aircraft. But the ultimate solution is to place a telescope in Earth's orbit and radio its data back to astronomers on the ground. The first such orbiting infrared observatory, the Infrared Astronomical Satellite (IRAS), was launched in 1983. During its nine-month mission, IRAS used its 57-cm (22-in.) telescope to map almost the entire sky at wavelengths from 12 to 100 μm.

The IRAS data revealed the presence of dust disks around nearby stars. Planets are thought to coalesce from disks of this kind, so this was the first concrete (if indirect) evidence that there might be planets orbiting other stars. The dust that IRAS detected is warm enough to emit infrared radiation but too cold to emit much visible light, so it remained undetected by ordinary optical telescopes. IRAS also discovered distant, ultraluminous galaxies that emit almost all their radiation at infrared wavelengths.

In 1995 the Infrared Space Observatory (ISO), a more advanced 60-cm reflector with better light detectors, was launched into orbit by the European Space Agency. During its 2½-year mission, ISO made a number of groundbreaking observations of very distant galaxies and of the thin, cold material between the stars of our own Galaxy. Like IRAS, ISO had to be cooled by liquid helium to temperatures just a few degrees above absolute zero. Had this not been done, the infrared blackbody radiation from the telescope itself would have outshone the infrared radiation from astronomical objects. The ISO mission came to an end when the last of the helium evaporated into space.

WEB LINK 6.9 At the time of this writing the largest orbiting infrared observatory is the Spitzer Space Telescope, an 85-cm infrared telescope designed to survey the infrared sky with unprecedented resolution (Figure 6-26). Placed in orbit in 2003, the Spitzer Space Telescope is being used to study the formation of new stars, probe the inner structure of galaxies, and examine the first galaxies that formed after the Big Bang. The images that open this chapter illustrate how Spitzer can reveal aspects of astronomical objects that are hidden from visible-light telescopes.

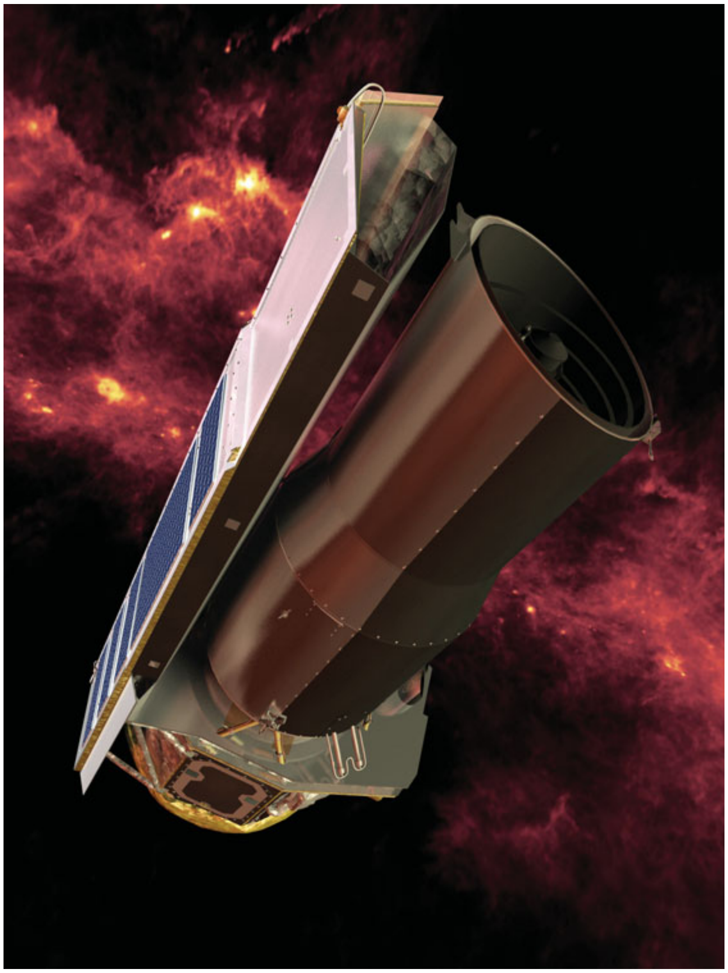


Figure 6-26 R I V U X G

The Spitzer Space Telescope Launched in 2003, this is the largest infrared telescope ever placed in space. Its 85-cm objective mirror and three science instruments, kept cold by 360 liters of liquid helium, enable the Spitzer Space Telescope to observe the universe at wavelengths from 3 to 180 μm. The background to this illustration of the telescope is a false-color Spitzer image of the Milky Way and the constellation Orion at 100 μm, showing emission from warm interstellar dust. (NASA/JPL-Caltech)

Ultraviolet Astronomy

Astronomers are also very interested in observing at ultraviolet wavelengths. These observations can reveal a great deal about hot stars, ionized clouds of gas between the stars, and the Sun's high-temperature corona (see Section 3-5), all of which emit copious amounts of ultraviolet light. The spectrum of ultraviolet sunlight reflected from a planet can also reveal the composition of the planet's atmosphere. However, Earth's atmosphere is opaque to ultraviolet light except for the narrow *near-ultraviolet* range, which extends from about 400 nm (the violet end of the visible spectrum) down to 300 nm.

To see shorter-wavelength *far-ultraviolet* light, astronomers must again make their observations from space. The first ultraviolet telescope was placed in orbit in 1962, and several others have since followed it into space. Small rockets have also lifted ultraviolet cameras briefly above the Earth's atmosphere. Figure 6-27 shows an ultraviolet view of the constellation Orion, along with infrared and visible views.

WEB LINK 6.10

The Far Ultraviolet Spectroscopic Explorer (FUSE), which went into orbit in 1999, specializes in measuring spectra at wavelengths from 90 to 120 nm. Highly ionized oxygen atoms, which can exist only in an extremely high-temperature gas, have a characteristic spectral line in this range. By looking for this spectral line in various parts of the sky, FUSE has confirmed that our Milky Way Galaxy (Section 1-4) is surrounded by an immense "halo" of gas at temperatures in excess of 200,000 K. Only an ultraviolet telescope could have detected this "halo," which is thought to have been produced by exploding stars called supernovae (Section 1-3).

The Hubble Space Telescope

Infrared and ultraviolet satellites give excellent views of the heavens at selected wavelengths. But since the 1940s astronomers had dreamed of having one large telescope that could be operated at any wavelength from the near-infrared through the visible range and out into the ultraviolet. This is the mission of the Hubble Space Telescope (HST), which was placed in a 600-km-high orbit by the space shuttle *Discovery* in 1990 (Figure 6-28). HST has a 2.4-meter (7.9-ft) objective mirror and was designed to observe at wavelengths from 115 nm to 1 μm. Like most ground-based telescopes, HST uses a CCD to record images. (In fact, the development of HST helped drive advances in CCD technology.) The images are then radioed back to Earth in digital form.

The great promise of HST was that from its vantage point high above the atmosphere, its angular resolution would be limited only by diffraction. But soon after HST was placed in orbit, astronomers discovered that a manufacturing error had caused the telescope's objective mirror to suffer from spherical aberration. The mirror should have been able to concentrate 70% of a star's light into an image with an angular diameter of 0.1 arcsec. Instead, only 20% of the light was focused into this small area. The remainder was smeared out over an area about 1 arcsec wide, giving images little better than those achieved at major ground-based observatories.

On an interim basis, astronomers used only the 20% of incoming starlight that was properly focused and, with computer processing, discarded the remaining poorly focused 80%. This was practical only for brighter objects on which astronomers could afford to waste light. But many of the observing projects scheduled for HST involved extremely dim galaxies and nebulae.

These problems were resolved by a second space shuttle mission in 1993. Astronauts installed a set of small secondary mirrors whose curvature exactly compensated for the error in curvature of the primary mirror. Once these were in place, HST was able to make truly sharp images of extremely faint objects. Astronomers have used the repaired HST to make discoveries about the nature of planets, the evolution of stars, the inner

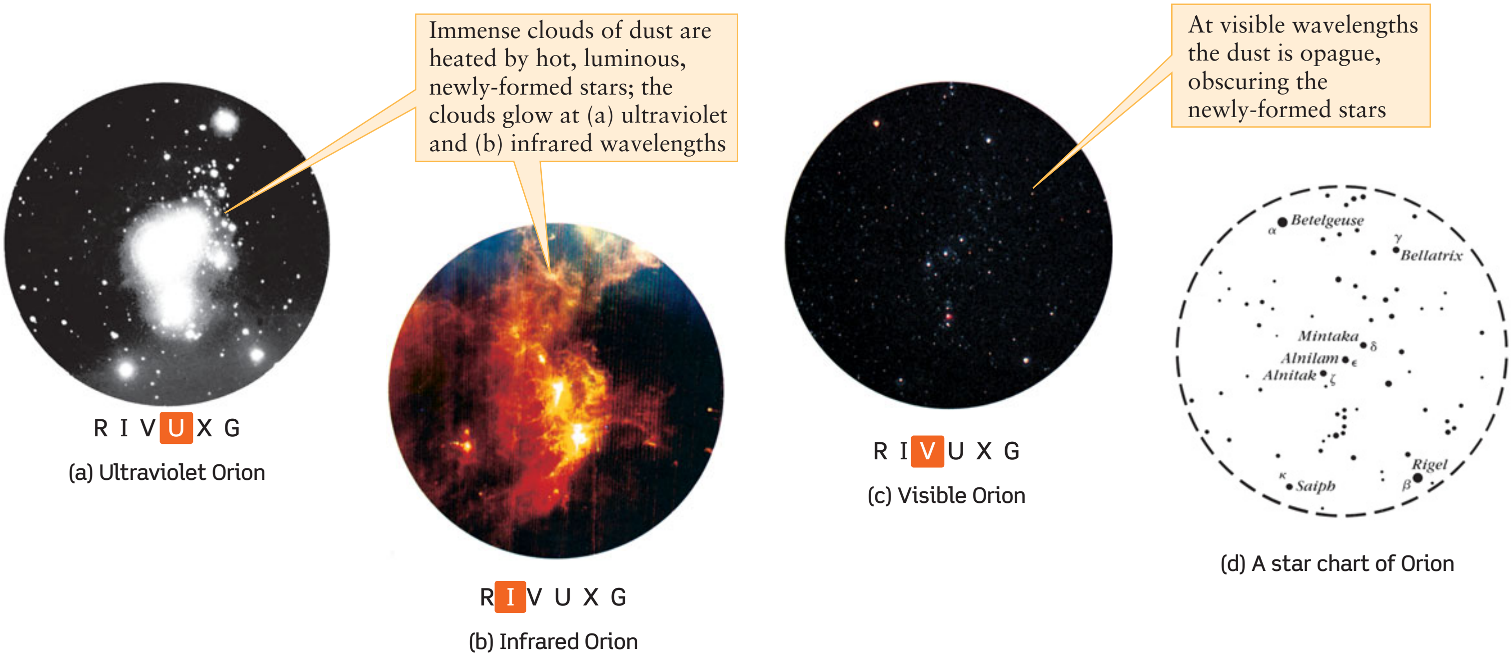


Figure 6-27

Orion Seen at Ultraviolet, Infrared, and Visible Wavelengths **(a)** An ultraviolet view of the constellation of Orion was obtained during a brief rocket flight in 1975. This 100-s exposure covers the wavelength range 125–200 nm. **(b)** The false-color view from the Infrared Astronomical Satellite displays emission at different wavelengths in different colors: red for 100-μm radiation, green for 60-μm radiation, and blue for 12-μm radiation. Compare these images with **(c)** an ordinary visible-light photograph and (d) a star chart of Orion. (a: G. R. Carruthers, Naval Research Laboratory; b: NASA; c: R. C. Mitchell, Central Washington University)

WEB LINK 6.11

Figure 6-28 R I V U X G

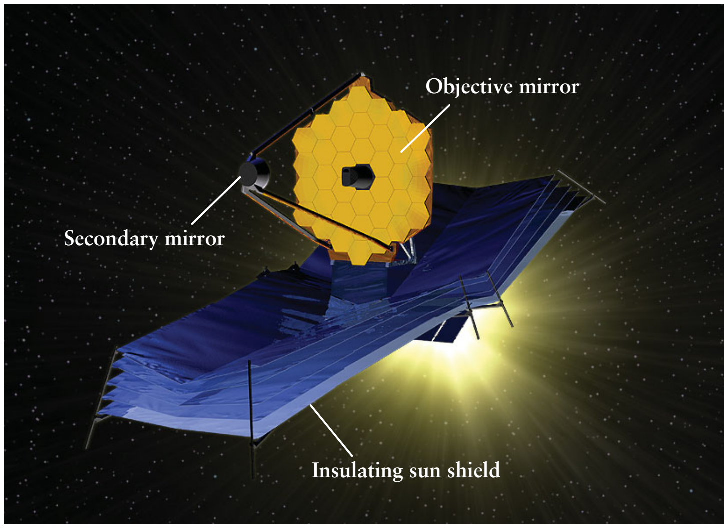
The Hubble Space Telescope The largest telescope yet placed in orbit, HST is a joint project of NASA and the European Space Agency (ESA). HST has helped discover new moons of Pluto, probed the formation of stars, and found evidence that the universe is now expanding at a faster rate than several billion years ago. This photograph was taken from the space shuttle *Discovery* during a 1997 mission to service HST. (NASA) workings of galaxies, and the expansion of the universe. You will see many HST images in later chapters.

WEB LINK 6.12

The success of HST has inspired plans for its larger successor, the James Webb Space Telescope or JWST (Figure 6-29). Planned for a 2013 launch, JWST will observe at visible and infrared wavelengths from 600 nm to 28 μm. With its 6.5-m objective mirror—2.5 times the diameter of the HST objective mirror, with six times the light-gathering power—JWST will study faint objects such as planetary systems forming around other stars and galaxies near the limit of the observable universe. Unlike HST, which is in a relatively low-altitude orbit around the Earth, JWST will orbit the Sun some 1.5 million km beyond the Earth. In this orbit the telescope's view will not be blocked by the Earth. Furthermore, by remaining far from the radiant heat of the Earth it will be easier to keep JWST at the very cold temperatures required by its infrared detectors.

X-Ray Astronomy

Space telescopes have also made it possible to explore objects whose temperatures reach the almost inconceivable values of 10^6 to 10^8 K. Atoms in such a high-temperature gas move so fast that when they collide, they emit X-ray photons of very high energy and very short wavelengths less than 10 nm. X-ray telescopes designed to detect these photons must be placed in orbit, since Earth's atmosphere is totally opaque at these wavelengths.



ANIMATION 6.3

Figure 6-29

The James Webb Space Telescope (JWST) The successor to the Hubble Space Telescope, JWST will have an objective mirror 6.5 m (21 ft) in diameter. Like many Earthbound telescopes, JWST will be of Cassegrain design (see Figures 6-11*b* and 6-14*b*). Rather than using liquid helium to keep the telescope and instruments at the low temperatures needed to observe at infrared wavelengths, JWST will keep cool using a multilayer sunshield the size of two tennis courts. (Courtesy of Northrop Grumman Space Technology)

CAUTION! X-ray telescopes work on a very different principle from the X-ray devices used in medicine and dentistry. If you have your foot "X rayed" to check for a broken bone, a piece of photographic film (or an electronic detector) sensitive to X rays is placed under your foot and an X-ray beam is directed at your foot from above. The radiation penetrates through soft tissue but not through bone, so the bones cast an "X-ray shadow" on the film. A fracture will show as a break in the shadow. X-ray telescopes, by contrast, do *not* send beams of X rays toward astronomical objects in an attempt to see inside them. Rather, these telescopes detect X rays that the objects emit on their own.

Astronomers got their first quick look at the X-ray sky from brief rocket flights during the late 1940s. These observations confirmed that the Sun's corona (see Section 3-5) is a source of X rays, and must therefore be at a temperature of millions of kelvins. In 1962 a rocket experiment revealed that objects beyond the solar system also emit X rays.

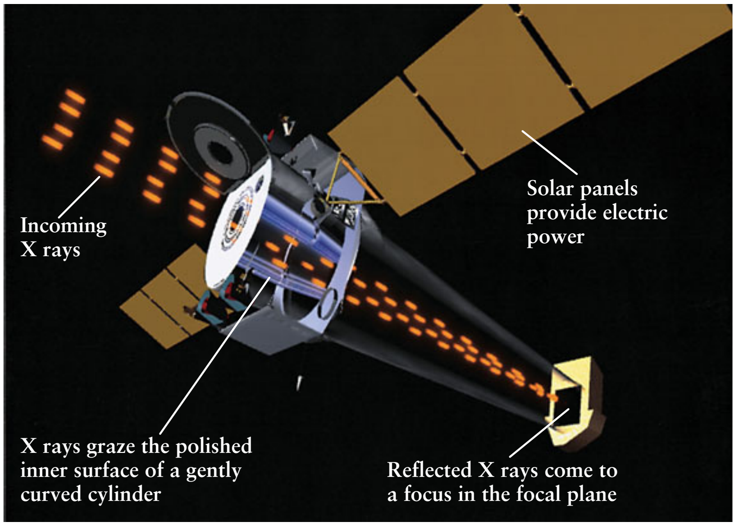
Since 1970, a series of increasingly sensitive and sophisticated X-ray observatories have been placed in orbit, including NASA's Einstein Observatory, the European Space Agency's Exosat, and the German-British-American ROSAT. These telescopes have shown that other stars also have high-temperature coronae, and have found hot, X-ray-emitting gas clouds so immense that hundreds of galaxies fit inside them. They also discovered unusual stars that emit X rays in erratic bursts. These bursts are now thought to be coming from heated gas swirling around a small but massive object—possibly a black hole.

X-ray astronomy took a quantum leap forward in 1999 with the launch of NASA's Chandra X-ray Observatory and the European Space Agency's XMM-Newton. Named for the Indian-American astrophysicist Subrahmanyan Chandrasekhar, Chandra can view the X-ray sky with an angular resolution of 0.5 arcsec (Figure 6-30*a*). This is comparable to the best ground-based optical telescopes, and more than a thousand times better than the resolution of the first orbiting X-ray telescope. Chandra can also measure X-ray spectra 100 times more precisely than any previous spacecraft and can detect variations in X-ray emissions on time scales as short as 16 microseconds. This latter capability is essential for understanding how X-ray bursts are produced around black holes.

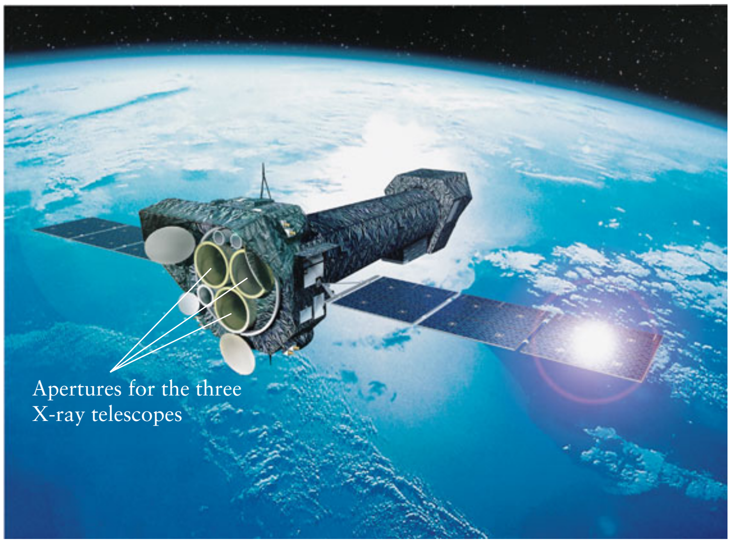
XMM-Newton (for *X*-ray *M*ulti-mirror *M*ission) is actually three X-ray telescopes that all point in the same direction (Figure 6-30*b*). Their combined light-gathering power is five times greater than that of Chandra, which makes XMM-Newton able to observe fainter objects. (For reasons of economy, the mirrors were not ground as precisely as those on Chandra, so the angular resolution of XMM-Newton is only about 6 arcseconds.) It also carries a small but highly capable telescope for ultraviolet and visible observations. Hot X-ray sources are usually accompanied by cooler material that radiates at these longer wavelengths, so XMM-Newton can observe these hot and cool regions simultaneously.

Gamma-Ray Astronomy

Gamma rays, the shortest-wavelength photons of all, help us to understand phenomena even more energetic than those that pro-



(a) Chandra X-ray Observatory



(b) XMM-Newton

WEB LINK 6.13

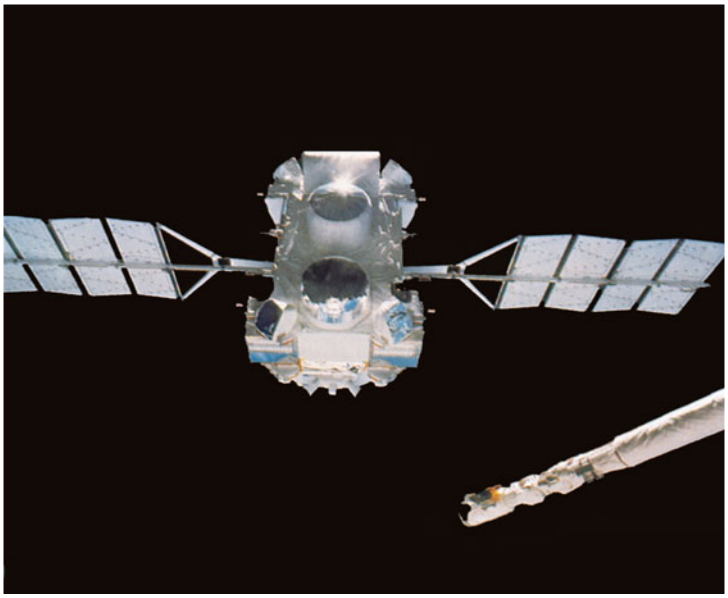
Figure 6-30

Two Orbiting X-Ray Observatories **(a)** X rays are absorbed by ordinary mirrors like those used in optical reflectors, but they can be reflected if they graze the mirror surface at a very shallow angle. In the Chandra X-ray Observatory, X rays are focused in this way onto a focal plane 10 m (33 ft) behind the mirror. **(b)** XMM-Newton is about the same size as Chandra, and its three X-ray telescopes form images in the same way. (a: NASA/Chandra X-ray Observatory Center/ Smithsonian Astrophysical Observatory; b: D. Ducros/European Space Agency)

duce X rays. As an example, when a massive star explodes into a supernova, it produces radioactive atomic nuclei that are strewn across interstellar space. Observing the gamma rays emitted by these nuclei helps astronomers understand the nature of supernova explosions.

Like X rays, gamma rays do not penetrate Earth's atmosphere, so space telescopes are required. One of the most important gamma-ray telescopes placed in orbit to date is the Compton Gamma Ray Observatory (CGRO), shown in Figure 6-31. One particularly important task for CGRO was the study of gamma-ray bursts, which are brief, unpredictable, and very intense flashes of gamma rays that are found in all parts of the sky. By analyzing data from CGRO and other orbiting observatories, astronomers have shown that the sources of these gamma-ray bursts are billions of light-years away. For these bursts to be visible across such great distances, their sources must be among the most energetic objects in the universe. By combining these gamma-ray observations with images made by optical telescopes, astronomers have found that at least some of the gamma-ray bursts emanate from stars that explode catastrophically. Since the CGRO mission ended in 2000, more advanced gamma-ray telescopes, including the European Space Agency's INTEGRAL (International Gamma-Ray Astrophysics Laboratory), have taken its place.

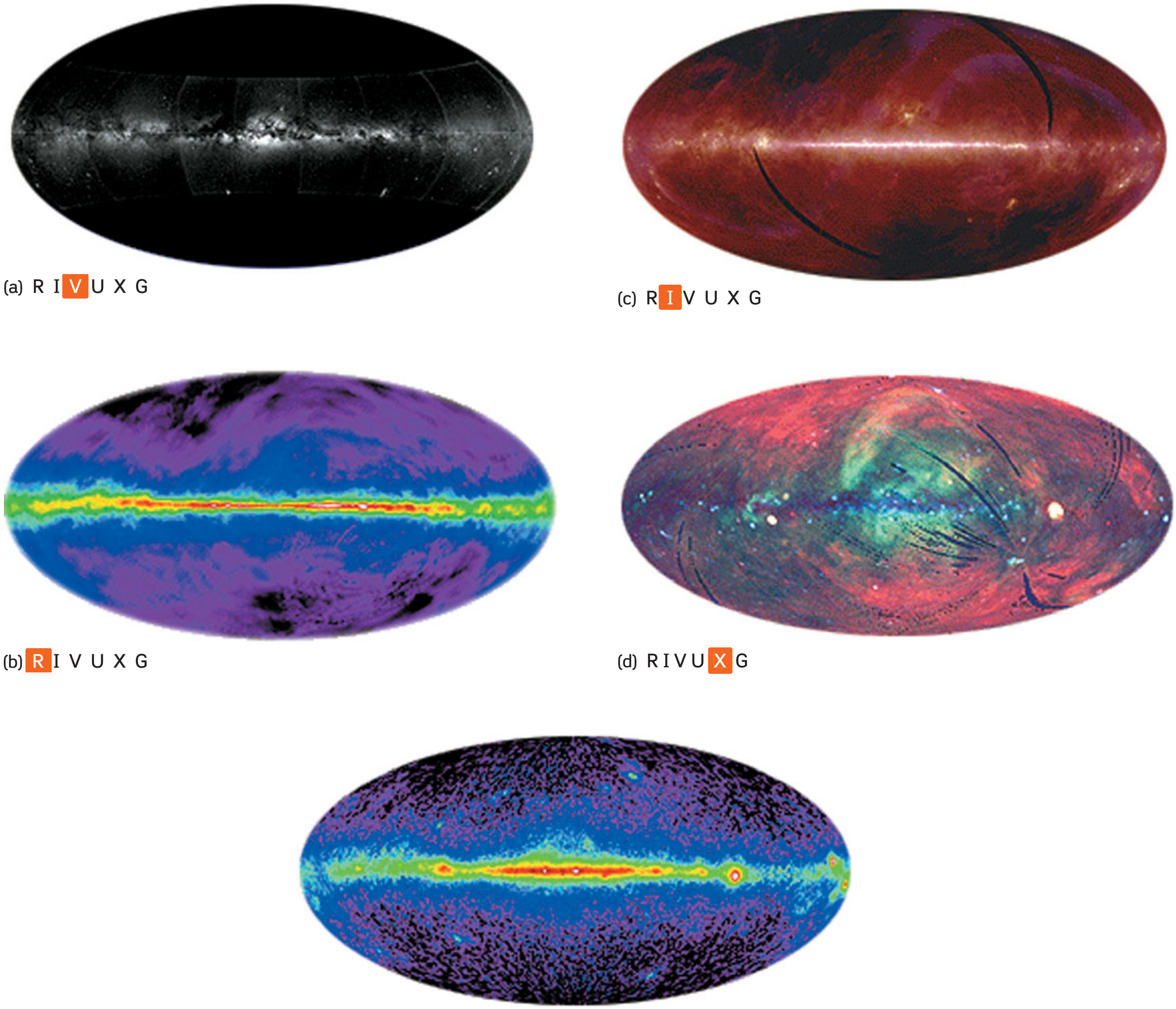
The *Cosmic Connections* figure shows the wavelengths at which Earth-orbiting telescopes are particularly useful, as well as summarizing the design of refracting and reflecting Earth-based telescopes. The advantages and benefits of Earth-orbiting observatories cannot be overemphasized. We are no longer limited to the narrow ranges of whatever wavelengths manage to leak through our shimmering, hazy atmosphere (Figure 6-32). For the first time, we are really *seeing* the universe.



WEB LINK 6.14

Figure 6-31 R I V U X G

The Compton Gamma Ray Observatory (CGRO) This photograph shows the Compton Observatory being deployed from the space shuttle *Atlantis* in 1991. Named in honor of Arthur Holly Compton, an American scientist who made important discoveries about gamma rays, CGRO carried four different gamma-ray detectors. When its mission ended in 2000, CGRO disintegrated as it reentered our atmosphere. (NASA)



(a) R I V U X G

(c) R I V U X G

(b) R I V U X G

(d) R I V U X G

(e) R I V U X G

WEB LINK 6.15

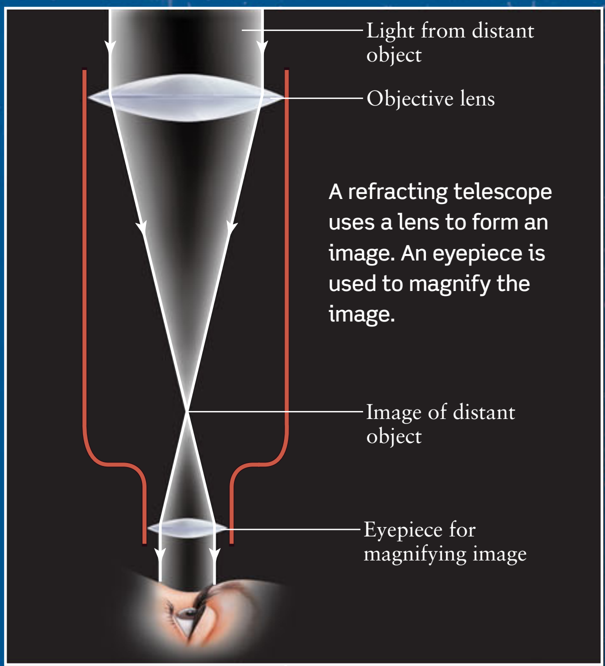
Figure 6-32

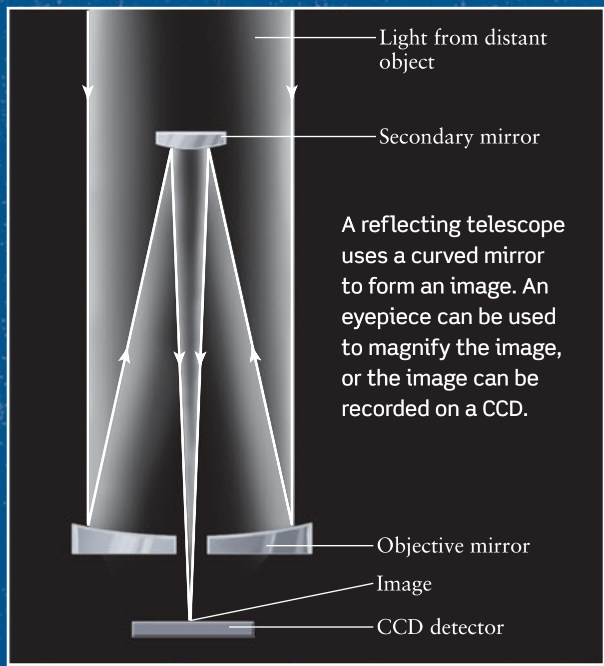
The Entire Sky at Five Wavelength Ranges These five views show the entire sky at visible, radio, infrared, X-ray, and gamma-ray wavelengths. The entire celestial sphere is mapped onto an oval, with the Milky Way stretching horizontally across the center. The black crescents in the infrared and X-ray images are where data are missing. (GSFC/NASA) **(a)** In the visible view the constellation Orion is at the right, Sagittarius in the middle, and Cygnus toward the left. Many of the dark areas along the Milky Way are locations where interstellar dust is sufficiently thick to block visible light. **(b)** The radio view shows the sky at a wavelength of 21 cm. This wavelength is emitted by hydrogen atoms in interstellar space. The brightest regions (shown in red) are in the plane of the Milky Way, where the hydrogen is most concentrated. **(c)** The infrared view from IRAS shows emission at 100 μm, 60 μm, and 12 μm. Most of the emission is from dust particles in the plane of the Milky Way that have been warmed by starlight. **(d)** The X-ray view from ROSAT shows wavelengths of 0.8 nm (blue), 1.7 nm (green), and 5.0 nm (red), corresponding to photon energies of 1500, 750, and 250 eV. Extremely high temperature gas emits these X rays. The white regions, which emit strongly at all X-ray wavelengths, are remnants of supernovae. **(e)** The gamma-ray view from the Compton Gamma Ray Observatory includes all wavelengths less than about 1.2×10^{-5} nm (photon energies greater than 10^{8} eV). The diffuse radiation from the Milky Way is emitted when fast-moving subatomic particles collide with the nuclei of atoms in interstellar gas clouds. The bright spots above and below the Milky Way are distant, extremely energetic galaxies.

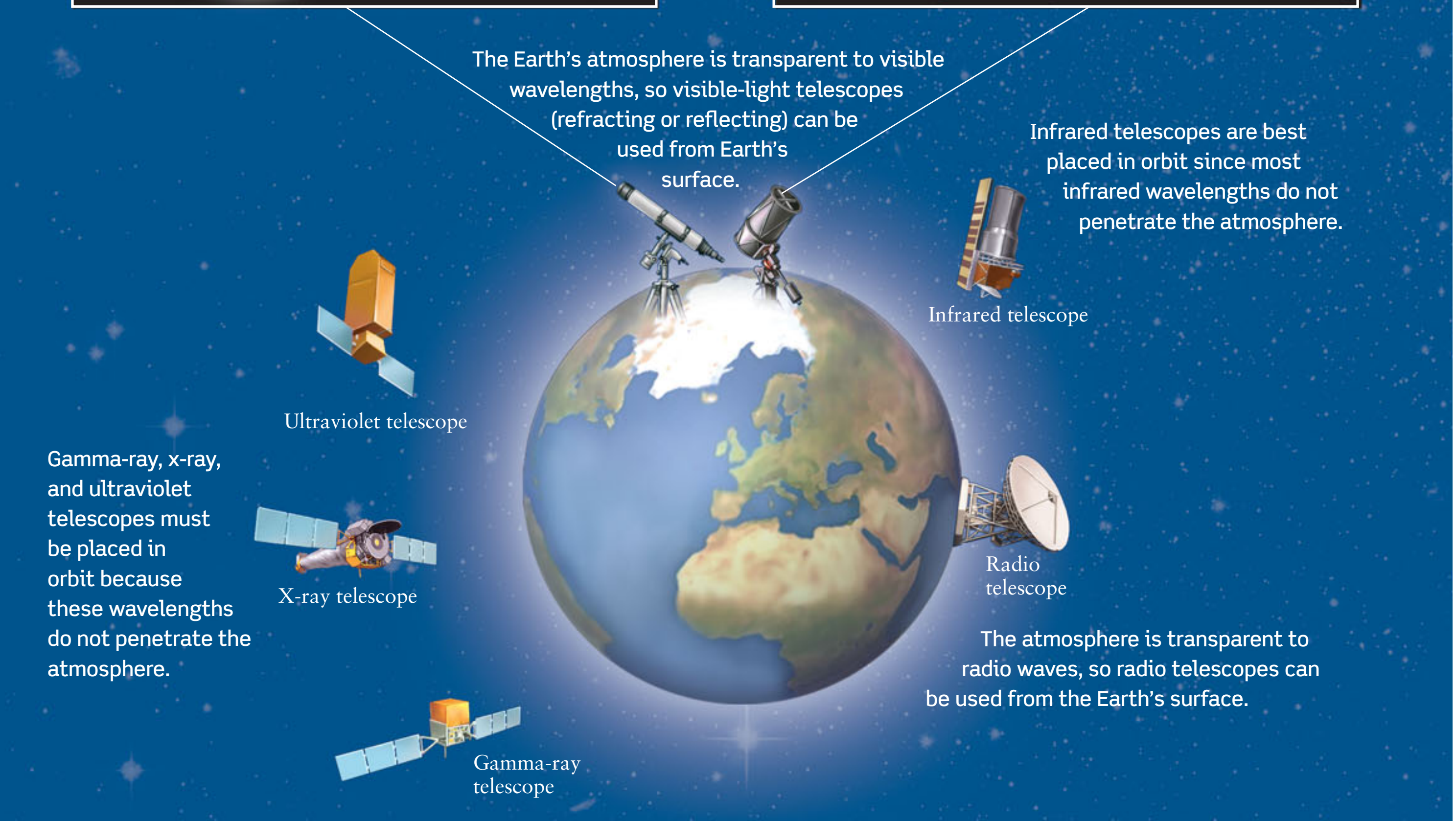
COSMIC CONNECTIONS

Telescopes Across the EM Spectrum

Today, telescopes can view the universe in every range of electromagnetic radiation, although some must be above Earth's atmosphere to receive radiation without interference.







Key Words

active optics, p. 140
adaptive optics, p. 140
angular resolution, p. 139
baseline, p. 140
Cassegrain focus, p. 137
charge-coupled device (CCD), p. 142
chromatic aberration, p. 134
coma, p. 138
coudé focus, p. 137
diffraction, p. 139
diffraction grating, p. 143
eyepiece lens, p. 131
false color, p. 140
focal length, p. 130
focal plane, p. 131
focal point, p. 130
focus (of a lens or mirror), p. 130
imaging, p. 142
interferometry, p. 140
lens, p. 129
light-gathering power, p. 132
light pollution, p. 141
magnification (magnifying power), p. 132
medium (*plural* media), p. 130
Newtonian reflector, p. 136
objective lens, p. 131
objective mirror (primary mirror), p. 135
optical telescope, p. 129
optical window (in the Earth's atmosphere), p. 147
photometry, p. 142
pixel, p. 142
prime focus, p. 136
radio telescope, p. 144
radio window (in the Earth's atmosphere), p. 147
reflecting telescope (reflector), p. 135
reflection, p. 134
refracting telescope (refractor), p. 131
refraction, p. 130
seeing disk, p. 139
spectrograph, p. 143
spectroscopy, p. 143
spherical aberration, p. 137
very-long-baseline interferometry (VLBI), p. 146

Key Ideas

Refracting Telescopes: Refracting telescopes, or refractors, produce images by bending light rays as they pass through glass lenses.

• Chromatic aberration is an optical defect whereby light of different wavelengths is bent in different amounts by a lens.

• Glass impurities, chromatic aberration, opacity to certain wavelengths, and structural difficulties make it inadvisable to build extremely large refractors.

Reflecting Telescopes: Reflecting telescopes, or reflectors, produce images by reflecting light rays to a focus point from curved mirrors.

• Reflectors are not subject to most of the problems that limit the useful size of refractors.

Angular Resolution: A telescope's angular resolution, which indicates ability to see fine details, is limited by two key factors.

• Diffraction is an intrinsic property of light waves. Its effects can be minimized by using a larger objective lens or mirror.

• The blurring effects of atmospheric turbulence can be minimized by placing the telescope atop a tall mountain with very smooth air. They can be dramatically reduced by the use of adaptive optics and can be eliminated entirely by placing the telescope in orbit.

Charge-Coupled Devices: Sensitive light detectors called charge-coupled devices (CCDs) are often used at a telescope's focus to record faint images.

Spectrographs: A spectrograph uses a diffraction grating to form the spectrum of an astronomical object.

Radio Telescopes: Radio telescopes use large reflecting dishes to focus radio waves onto a detector.

• Very large dishes provide reasonably sharp radio images. Higher resolution is achieved with interferometry techniques that link smaller dishes together.

Transparency of the Earth's Atmosphere: The Earth's atmosphere absorbs much of the radiation that arrives from space.

• The atmosphere is transparent chiefly in two wavelength ranges known as the optical window and the radio window. A few wavelengths in the near-infrared also reach the ground.

Telescopes in Space: For observations at wavelengths to which the Earth's atmosphere is opaque, astronomers depend on telescopes carried above the atmosphere by rockets or spacecraft.

• Satellite-based observatories provide new information about the universe and permit coordinated observation of the sky at all wavelengths.

Questions

Review Questions

1. Describe refraction and reflection. Explain how these processes enable astronomers to build telescopes.
2. Explain why a flat piece of glass does not bring light to a focus while a curved piece of glass can.
3. Explain why the light rays that enter a telescope from an astronomical object are essentially parallel.
4. With the aid of a diagram, describe a refracting telescope. Which dimensions of the telescope determine its light-gathering power? Which dimensions determine the magnification?
5. What is the purpose of a telescope eyepiece? What aspect of the eyepiece determines the magnification of the image? In what circumstances would the eyepiece not be used?
6. Do most professional astronomers actually look through their telescopes? Why or why not?
7. Quite often advertisements appear for telescopes that extol their magnifying power. Is this a good criterion for evaluating telescopes? Explain your answer.
8. What is chromatic aberration? For what kinds of telescopes does it occur? How can it be corrected?
9. With the aid of a diagram, describe a reflecting telescope. Describe four different ways in which an astronomer can access the focal plane.
10. Explain some of the disadvantages of refracting telescopes compared to reflecting telescopes.
11. What kind of telescope would you use if you wanted to take a color photograph entirely free of chromatic aberration? Explain your answer.
12. Explain why a Cassegrain reflector can be substantially shorter than a refractor of the same focal length.

13. No major observatory has a Newtonian reflector as its primary instrument, whereas Newtonian reflectors are extremely popular among amateur astronomers. Explain why this is so.
14. What is spherical aberration? How can it be corrected?
15. What is diffraction? Why does it limit the angular resolution of a telescope? What other physical phenomenon is often a more important restriction on angular resolution?
16. What is active optics? What is adaptive optics? Why are they useful? Would either of these be a good feature to include on a telescope to be placed in orbit?
17. Explain why combining the light from two or more optical telescopes can give dramatically improved angular resolution.
18. What is light pollution? What effects does it have on the operation of telescopes? What can be done to minimize these effects?
19. What is a charge-coupled device (CCD)? Why have CCDs replaced photographic film for recording astronomical images?
20. What is a spectrograph? Why do many astronomers regard it as the most important device that can be attached to a telescope?
21. What are the advantages of using a diffraction grating rather than a prism in a spectrograph?
22. Compare an optical reflecting telescope and a radio telescope. What do they have in common? How are they different?
23. Why can radio astronomers make observations at any time during the day, whereas optical astronomers are mostly limited to observing at night? (*Hint:* Does your radio work any better or worse in the daytime than at night?)
24. Why are radio telescopes so large? Why does a single radio telescope have poorer angular resolution than a large optical telescope? How can the resolution be improved by making simultaneous observations with several radio telescopes?
25. What are the optical window and the radio window? Why isn't there an X-ray window or an ultraviolet window?
26. Why is it necessary to keep an infrared telescope at a very low temperature?
27. How are the images made by an X-ray telescope different from those made by a medical X-ray machine?
28. Why must astronomers use satellites and Earth-orbiting observatories to study the heavens at X-ray and gamma-ray wavelengths?

Advanced Questions

Questions preceded by an asterisk (*) involve topics discussed in the Boxes.

> **Problem-solving tips and tools**
>
> You may find it useful to review the small-angle formula discussed in Box 1-1. The area of a circle is proportional to the square of its diameter. Data on the planets can be found in the appendices at the end of this book. Section 5-2 discusses the relationship between frequency and wavelength. Box 6-1 gives examples of how to calculate magnifying power and light-gathering power.

29. Show by means of a diagram why the image formed by a simple refracting telescope is upside down.
30. Ordinary photographs made with a telephoto lens make distant objects appear close. How does the focal length of a telephoto lens compare with that of a normal lens? Explain your reasoning.
31. The observing cage in which an astronomer can sit at the prime focus of the 5-m telescope on Palomar Mountain is about 1 m in diameter. Calculate what fraction of the incoming starlight is blocked by the cage.
32. (**a**) Compare the light-gathering power of the Keck I 10.0-m telescope with that of the Hubble Space Telescope (HST), which has a 2.4-m objective mirror. (**b**) What advantages does Keck I have over HST? What advantages does HST have over Keck I?
33. Suppose your Newtonian reflector has an objective mirror 20 cm (8 in.) in diameter with a focal length of 2 m. What magnification do you get with eyepieces whose focal lengths are (**a**) 9 mm, (**b**) 20 mm, and (**c**) 55 mm? (**d**) What is the telescope's diffraction-limited angular resolution when used with orange light of wavelength 600 nm? (**e**) Would it be possible to achieve this angular resolution if you took the telescope to the summit of Mauna Kea? Why or why not?
34. Several groups of astronomers are making plans for large ground-based telescopes. (**a**) What would be the diffraction-limited angular resolution of a telescope with a 40-meter objective mirror? Assume that yellow light with wavelength 550 nm is used. (**b**) Suppose this telescope is placed atop Mauna Kea. How will the actual angular resolution of the telescope compare to that of the 10-meter Keck I telescope? Assume that adaptive optics is not used.
35. The Hobby-Eberly Telescope (HET) at the McDonald Observatory in Texas has a spherical mirror, which is the least expensive shape to grind. Consequently, the telescope has spherical aberration. Explain why this doesn't affect the usefulness of HET for spectroscopy. (The telescope is not used for imaging.)
36. The four largest moons of Jupiter are roughly the same size as our Moon and are about 628 million (6.28×10^8) kilometers from Earth at opposition. What is the size in kilometers of the smallest surface features that the Hubble Space Telescope (resolution of 0.1 arcsec) can detect? How does this compare with the smallest features that can be seen on the Moon with the unaided human eye (resolution of 1 arcmin)?
37. The Hubble Space Telescope (HST) has been used to observe the galaxy M100, some 70 million light-years from Earth. (**a**) If the angular resolution of the HST image is 0.1 arcsec, what is the diameter in light-years of the smallest detail that can be discerned in the image? (**b**) At what distance would a U.S. dime (diameter 1.8 cm) have an angular size of 0.1 arcsec? Give your answer in kilometers.
38. At its closest to Earth, Pluto is 28.6 AU from Earth. Can the Hubble Space Telescope distinguish any features on Pluto? Justify your answer using calculations.
39. The Institute of Space and Astronautical Science in Japan proposes to place a radio telescope into an even higher orbit than the HALCA telescope. Using this telescope in concert with ground-based radio-telescopes, baselines as long as

25,000 km may be obtainable. Astronomers want to use this combination to study radio emission at a frequency of 43 GHz from the molecule silicon monoxide, which is found in the interstellar clouds from which stars form. (1 GHz = 1 gigahertz = 10^9 Hz.) (**a**) What is the wavelength of this emission? (**b**) Taking the baseline to be the effective diameter of this radio-telescope array, what angular resolution can be achieved?

40. The mission of the Submillimeter Wave Astronomy Satellite (SWAS), launched in 1998, was to investigate interstellar clouds within which stars form. One of the frequencies at which it observed these clouds is 557 GHz (1 GHz = 1 gigahertz = 10^9 Hz), characteristic of the emission from interstellar water molecules. (**a**) What is the wavelength (in meters) of this emission? In what part of the electromagnetic spectrum is this? (**b**) Why was it necessary to use a satellite for these observations? (**c**) SWAS had an angular resolution of 4 arcminutes. What was the diameter of its primary mirror?

41. To search for ionized oxygen gas surrounding our Milky Way Galaxy, astronomers aimed the ultraviolet telescope of the FUSE spacecraft at a distant galaxy far beyond the Milky Way. They then looked for an ultraviolet spectral line of ionized oxygen in that galaxy's spectrum. Were they looking for an emission line or an absorption line? Explain.

42. A sufficiently thick interstellar cloud of cool gas can absorb low-energy X rays but is transparent to high-energy X rays and gamma rays. Explain why both part *b* and part *d* of Figure 6-32 reveal the presence of cool gas in the Milky Way. Could you infer the presence of this gas from the visible-light image in Figure 6-32*a*? Explain.

Discussion Questions

43. If you were in charge of selecting a site for a new observatory, what factors would you consider important?

44. Discuss the advantages and disadvantages of using a small telescope in Earth's orbit versus a large telescope on a mountaintop.

Web/e-Book Questions

45. Several telescope manufacturers build telescopes with a design called a "Schmidt-Cassegrain." These use a correcting lens in an arrangement like that shown in Figure 6-13*c*. Consult advertisements on the World Wide Web to see the appearance of these telescopes and find out their cost. Why do you suppose they are very popular among amateur astronomers?

46. The Large Zenith Telescope (LZT) in British Columbia, Canada, uses a 5.0-m *liquid* mirror made of mercury. Use the World Wide Web to investigate this technology. How can a liquid metal be formed into the necessary shape for a telescope mirror? What are the advantages of a liquid mirror? What are the disadvantages?

47. Three of the telescopes shown in Figure 6-16—the James Clerk Maxwell Telescope (JCMT), the Caltech Submillimeter Observatory (CSO), and the Submillimeter Array (SMA)—are designed to detect radiation with wavelengths close to 1 mm. Search for current information about JCMT, CSO, and SMA on the World Wide Web. What kinds of celestial objects emit radiation at these wavelengths? What can astronomers see using JCMT, CSO, and SMA that cannot be observed at other wavelengths? Why is it important that they be at high altitude? How large are the primary mirrors used in JCMT, CSO, and SMA? What are the differences among the three telescopes? Which can be used in the daytime? What recent discoveries have been made using JCMT, CSO, or SMA?

48. In 2003 an ultraviolet telescope called GALEX (Galaxy Evolution Explorer) was placed into orbit. Use the World Wide Web to learn about GALEX and its mission. What aspects of galaxies was GALEX designed to investigate? Why is it important to make these observations using ultraviolet wavelengths?

49. At the time of this writing, NASA's plans for the end of the Hubble Space Telescope's mission were uncertain. Consult the Space Telescope Science Institute Web site to learn about plans for HST's final years of operation. Are future space shuttle missions planned to service HST? If so, what changes will be made to HST on such missions? What will become of HST at the end of its mission lifetime?

50. NASA and the European Space Agency (ESA) have plans to launch a number of advanced space telescopes. These include Herschel, the Wide-Field Infrared Survey Explorer (WISE), the Gamma-ray Large Area Space Telescope (GLAST), the Space Interferometry Mission (SIM), and the X-ray Evolving Universe Spectroscopy (XEUS) mission. Search the World Wide Web for information about at least two of these. What are the scientific goals of these projects? What is unique about each telescope? What advantages would they have over existing ground-based or orbiting telescopes? What kind of orbit will each telescope be in? When will each be launched and placed in operation?

AIMM 6.1

51. Telescope Magnification. Access the Active Integrated Media Module "Telescope Magnification" in Chapter 6 of the *Universe* Web site or eBook. A common telescope found in department stores is a 3-inch (76-mm) diameter refractor that boasts a magnification of 300 times. Use the magnification calculator to determine the magnifications that are achieved by using each of the following commonly found eyepieces on that telescope: Eyepiece A with focal length 40 mm; Eyepiece B with focal length 25 mm; Eyepiece C with focal length 12 mm; and Eyepiece D with focal length 2.5 mm.

Activities

Observing Projects

52. Obtain a telescope during the daytime along with several eyepieces of various focal lengths. If you can determine the telescope's focal length, calculate the magnifying powers of the eyepieces. Focus the telescope on some familiar object, such as a distant lamppost or tree. **DO NOT FOCUS ON THE SUN! Looking directly at the Sun can cause blindness.** Describe the image you see through the telescope. Is it upside down? How does the image move as you slowly and gently shift the telescope left and right or up and down? Examine the eyepieces, noting their focal lengths. By changing the eyepieces, examine the distant object under different magnifications. How do the field of view and the quality of the image change as you go from low power to high power?

53. On a clear night, view the Moon, a planet, and a star through a telescope using eyepieces of various focal lengths and known magnifying powers. (To determine the locations in the sky of the Moon and planets, you may want to use the *Starry Night Enthusiast*™ program on the CD-ROM that comes with certain printed copies of this book. You may also want to consult such magazines as *Sky & Telescope* and *Astronomy* or their Web sites.) In what way does the image seem to degrade as you view with increasingly higher magnification? Do you see any chromatic aberration? If so, with which object and which eyepiece is it most noticeable?

54. Many towns and cities have amateur astronomy clubs. If you are so inclined, attend a "star party" hosted by your local club. People who bring their telescopes to such gatherings are delighted to show you their instruments and take you on a telescopic tour of the heavens. Such an experience can lead to a very enjoyable, lifelong hobby.

STARRY NIGHT **55.** The field of view of a typical small telescope for amateur astronomers is about 30 arcminutes, or 30′. (Many research telescopes have much smaller fields of view. For instance, the widest field of view available to the Hubble Space Telescope is only 3.4 arcminutes.) Use the *Starry Night Enthusiast*™ program to simulate the view that such a telescope provides of various celestial objects. First display the entire celestial sphere (select **Guides > Atlas** in the **Favourites** menu). Open the **Find** pane (select **Find . . .** under the **Edit** menu or click the **Find** tab on the left side of the view window). Click on the magnifying glass icon at the left-hand side of the edit box at the top of the Find pane and select the **Orbiting Objects** item from the drop-down menu that appears. This will bring up a list of Solar System objects in the Find pane. For each of the following objects, (i) the Moon, (ii) Jupiter, and (iii) Saturn, double-click on the name of the object in the Find pane to center it in the view. Use the zoom controls (+ and − buttons) at the right-hand end of the toolbar to adjust the field of view to approximately 30 arcminutes. (You can display an indication of this specific field of view on the sky by opening the **FOV (Field of View)** pane on the left side of the window and clicking on **Other > 30 Arcminutes.**) Describe how much detail you can see on each object. Open the Find pane again. Click on the magnifying glass icon on the left-hand side of the edit box at the top of the Find pane and select Messier Objects from the drop-down menu that appears. From the list of Messier Objects that populates the Find pane, double-click the entry for "M31 (Andromeda Galaxy)" to center this object in the view. Again, use the zoom controls to adjust the field of view to approximately 30 arcminutes. Describe how much detail you can see for this object.

STARRY NIGHT **56.** Use the *Starry Night Enthusiast*™ program to explore the concept of angular resolution. Click the **Find** tab to the left of the main view window to open the Find pane. Click on the magnifying glass icon at the left-hand side of the edit box at the top of the Find pane and select the **Orbiting Objects** item from the drop-down menu that appears. This will bring up a list of Solar System objects in the Find pane. Double-click the entry labeled **The Moon.** You can zoom in and zoom out using the **Zoom** buttons at the right side of the toolbar. You can also rotate the Moon by putting the mouse cursor over the image, holding down the mouse button and the **Shift** key on the keyboard, and moving the mouse. (On a two-button mouse, hold down the left mouse button.) (**a**) What is the size of the smallest detail that you can see? (You will have to make measurements on the screen using a ruler and compare it to the diameter of the Moon, which is 3476 km.) (**b**) The angular resolution of the Hubble Space Telescope (HST) is 0.1 arcsec. How far away from the Moon could HST be and still be able to resolve details as small as you determined in part (a)? Give your answer in kilometers and in astronomical units (AU).

Collaborative Exercises

57. Stand up and have everyone in your group join hands, making as large a circle as possible. If a telescope mirror were built as big as your circle, what would be its diameter? What would be your telescope's diffraction-limited angular resolution for blue light? Would atmospheric turbulence have a noticeable effect on the angular resolution?

58. Are there enough students in your class to stand and join hands and make two large circles that recreate the sizes of the two Keck telescopes? Explain how you determined your answer.

7

Comparative Planetology I: Our Solar System

WEB LINK 7.1 March 10, 2006: The *Mars Reconnaissance Orbiter* spacecraft arrives at Mars (artist's impression). (JPL/NASA)

Fifty years ago, astronomers knew precious little about the worlds that orbit the Sun. Even the best telescopes provided images of the planets that were frustratingly hazy and indistinct. Of asteroids, comets, and the satellites of the planets, we knew even less.

Today, our knowledge of the solar system has grown exponentially, due almost entirely to robotic spacecraft. (The illustration shows an artist's impression of one such robotic explorer, the *Mars Reconnaissance Orbiter* spacecraft, as it approached Mars in 2006.) Spacecraft have been sent to fly past all the planets at close range, revealing details unimagined by astronomers of an earlier generation. We have landed spacecraft on the Moon, Venus, and Mars and dropped a probe into the immense atmosphere of Jupiter. This is truly the golden age of solar system exploration.

In this chapter we paint in broad outline our present understanding of the solar system. We will see that the planets come in a variety of sizes and chemical compositions. There is also rich variety among the moons of the planets and among smaller bodies we call asteroids, comets, and trans-Neptunian objects. We will investigate the nature of craters on the Moon and other worlds of the solar system. And by exploring the magnetic fields of planets, we will be able to peer inside the Earth and other worlds and learn about their interior compositions.

An important reason to study the solar system is to search for our own origins. In Chapter 8 we will see how astronomers have used evidence from the present-day solar system to understand how the Sun, the Earth, and the other planets formed some four and a half billion years ago, and how they have evolved since then. But for now, we invite you to join us on a guided tour of the worlds that orbit our Sun.

7-1 The solar system has two broad categories of planets: Earthlike and Jupiterlike

Each of the planets that orbit the Sun is unique. Only Earth has liquid water and an atmosphere breathable by humans; only Venus has a perpetual cloud layer made of sulfuric acid droplets; and only Jupiter has immense storm systems that persist for centuries. But there are also striking similarities among planets.

Learning Goals

By reading the sections of this chapter, you will learn

7-1 The important differences between the two broad categories of planets: terrestrial and Jovian

7-2 The similarities and differences among the large planetary satellites, including Earth's Moon

7-3 How the spectrum of sunlight reflected from a planet reveals the composition of its atmosphere and surface

7-4 Why some planets have atmospheres and others do not

7-5 The categories of the many small bodies that also orbit the Sun

7-6 How craters on a planet or satellite reveal the age of its surface and the nature of its interior

7-7 Why a planet's magnetic field indicates a fluid interior in motion

7-8 How the diversity of the solar system is a result of its origin and evolution

Volcanoes are found not only on Earth but also on Venus and Mars; rings encircle Jupiter, Saturn, Uranus, and Neptune; and impact craters dot the surfaces of Mercury, Venus, Earth, and Mars, showing that all of these planets have been bombarded by interplanetary debris.

We can understand the most important similarities and differences among the planets by comparing their orbits, masses, and diameters

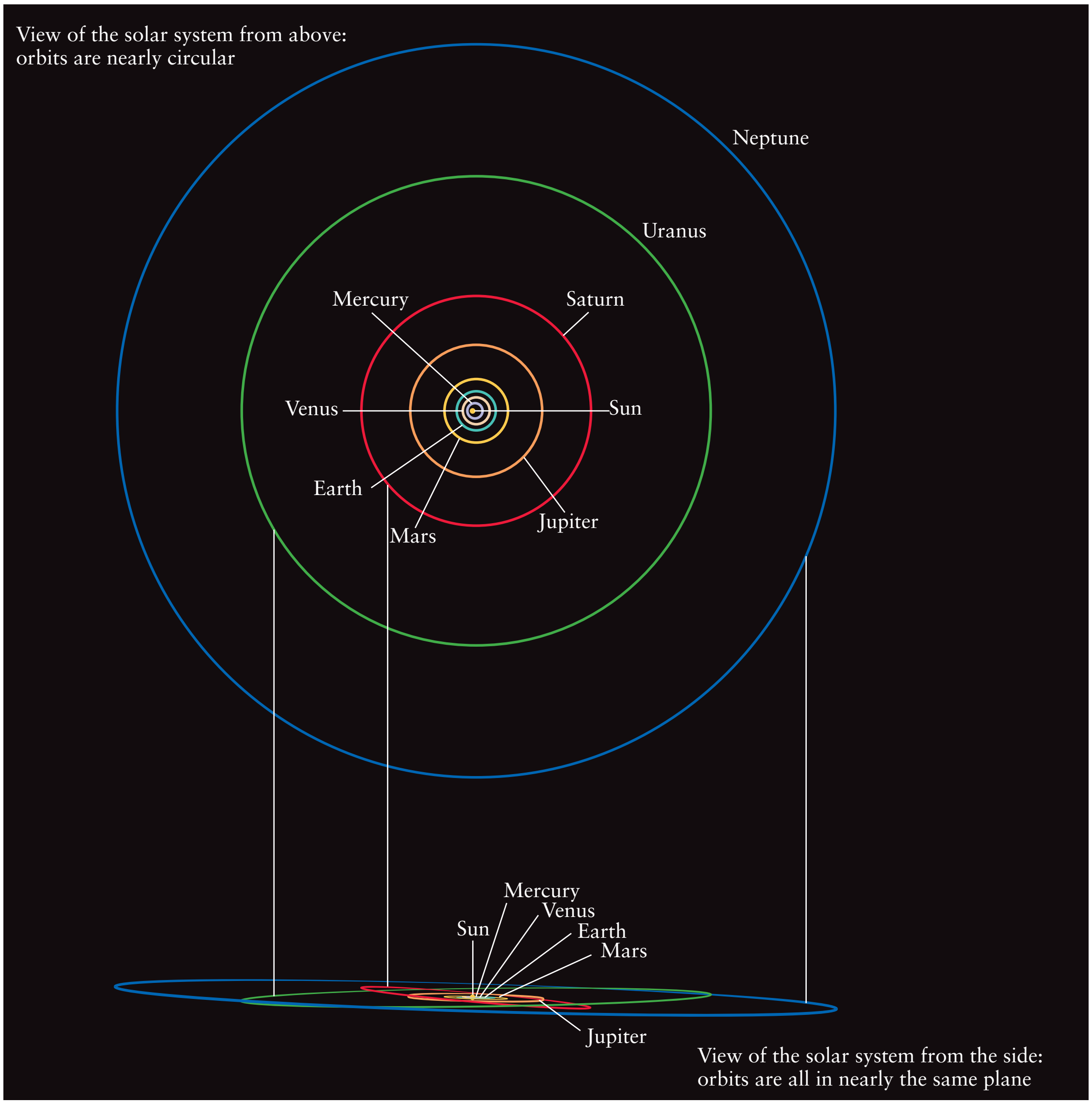
How can we make sense of the many similarities and differences among the planets? An important step is to organize our knowledge of the planets in a systematic way. There are two useful ways to do this. First, we can contrast the orbits of different planets around the Sun; and second, we can compare the planets' physical properties such as diameter, mass, average density, and chemical composition.

Comparing the Planets: Orbits

The planets fall naturally into two classes according to the sizes of their orbits. As Figure 7-1 shows, the orbits of the four inner planets (Mercury, Venus, Earth, and Mars) are crowded in close to the Sun. In contrast, the orbits of the next four planets (Jupiter, Saturn, Uranus, and Neptune) are widely spaced at great distances from the Sun. Table 7-1 lists the orbital characteristics of these eight planets.

CAUTION! While Figure 7-1 shows the orbits of the planets, it does not show the planets themselves. The reason is simple: If Jupiter, the largest of the planets, were to be drawn to the same scale as the rest of this figure, it would be a dot just 0.0002 cm across—about $^1/_{300}$ of the width of a human hair and far too small to be seen without a microscope. The planets themselves are *very* small compared to the distances between them. Indeed, while an airliner traveling at 1000 km/h (620 mi/h) can fly around the Earth in less than two days, at this speed it would take 17 *years* to fly from the Earth to the Sun. The solar system is a very large and very empty place!

Most of the planets have orbits that are nearly circular. As we learned in Section 4-4, Kepler discovered in the seventeenth



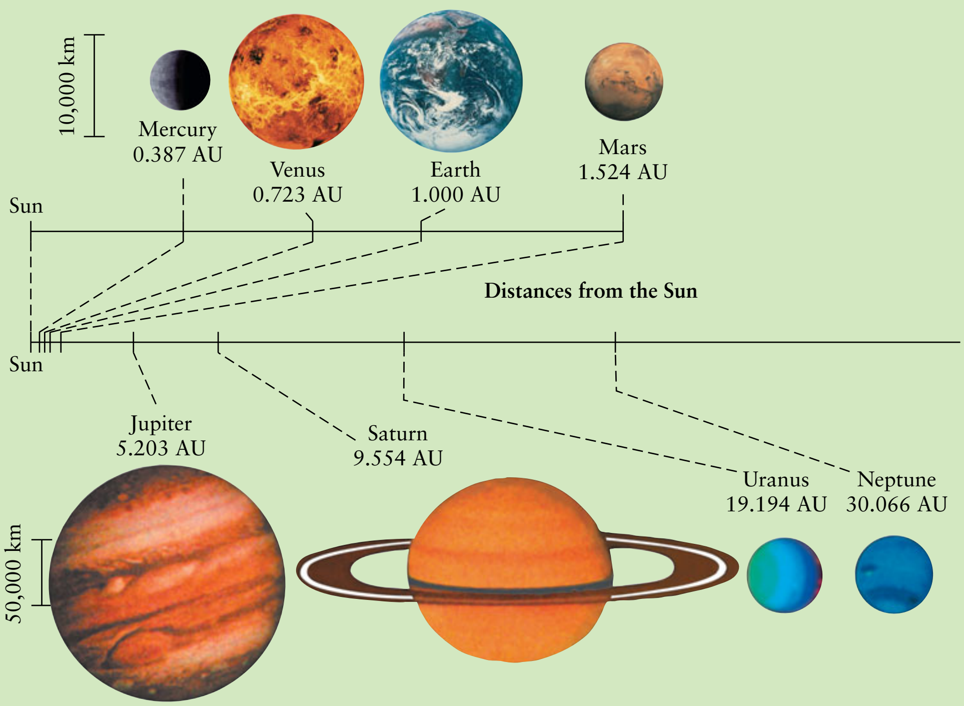
ANIMATION 7.1

Figure 7-1
The Solar System to Scale This scale drawing shows the orbits of the planets around the Sun. The four inner planets are crowded in close to the Sun, while the four outer planets orbit the Sun at much greater distances. On the scale of this drawing, the planets themselves would be much smaller than the diameter of a human hair and too small to see.

WEB LINK 7.2

Table 7-1 Characteristics of the Planets

	The Inner (Terrestrial) Planets			
	Mercury	Venus	Earth	Mars
Average distance from Sun (10^6 km)	57.9	108.2	149.6	227.9
Average distance from Sun (AU)	0.387	0.723	1.000	1.524
Orbital period (years)	0.241	0.615	1.000	1.88
Orbital eccentricity	0.206	0.007	0.017	0.093
Inclination of orbit to the ecliptic	7.00°	3.39°	0.00°	1.85°
Equatorial diameter (km)	4880	12,104	12,756	6794
Equatorial diameter (Earth = 1)	0.383	0.949	1.000	0.533
Mass (kg)	3.302×10^{23}	4.868×10^{24}	5.974×10^{24}	6.418×10^{23}
Mass (Earth = 1)	0.0553	0.8150	1.0000	0.1074
Average density (kg/m^3)	5430	5243	5515	3934



R I V U X G
(NASA)

	The Outer (Jovian) Planets			
	Jupiter	Saturn	Uranus	Neptune
Average distance from Sun (10^6 km)	778.3	1429	2871	4498
Average distance from Sun (AU)	5.203	9.554	19.194	30.066
Orbital period (years)	11.86	29.46	84.10	164.86
Orbital eccentricity	0.048	0.053	0.043	0.010
Inclination of orbit to the ecliptic	1.30°	2.48°	0.77°	1.77°
Equatorial diameter (km)	142,984	120,536	51,118	49,528
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883
Mass (kg)	1.899×10^{27}	5.685×10^{26}	8.682×10^{25}	1.024×10^{26}
Mass (Earth = 1)	317.8	95.16	14.53	17.15
Average density (kg/m^3)	1326	687	1318	1638

century that these orbits are actually ellipses. Astronomers denote the elongation of an ellipse by its *eccentricity* (see Figure 4-10*b*). The eccentricity of a circle is zero, and indeed most of the eight planets (with the notable exception of Mercury) have orbital eccentricities that are very close to zero.

If you could observe the solar system from a point several astronomical units (AU) above the Earth's north pole, you would see that all the planets orbit the Sun in the same counterclockwise direction. Furthermore, the orbits of the eight planets all lie in nearly the same plane. In other words, these orbits are inclined at only slight angles to the plane of the ecliptic, which is the plane of the Earth's orbit around the Sun (see Section 2-5). What is more, the plane of the Sun's equator is very closely aligned with the orbital planes of the planets. As we will see in Chapter 8, these near-alignments are not a coincidence. They provide important clues about the origin of the solar system.

Not included in Figure 7-1 or Table 7-1 is Pluto, which is in an even larger orbit than Neptune. Until the late 1990s, Pluto was generally regarded as the ninth planet. But in light of recent discoveries many astronomers now consider Pluto to be simply one member of a large collection of *trans-Neptunian objects* that orbit far from the Sun. These all orbit the Sun in the same direction as the planets, though many of them have orbits that are steeply inclined to the plane of the ecliptic and have high eccentricities (that is, the orbits are quite elongated and noncircular). We will discuss trans-Neptunian objects, along with other small bodies that orbit the Sun, in Section 7-5.

Comparing the Planets: Physical Properties

When we compare the physical properties of the planets, we again find that they fall naturally into two classes—four small inner planets and four large outer ones. The four small inner planets are called **terrestrial planets** because they resemble the Earth (in Latin, *terra*). They all have hard, rocky surfaces with mountains, craters, valleys, and volcanoes. You could stand on the surface of any one of them, although you would need a protective spacesuit on Mercury, Venus, or Mars. The four large outer planets are called **Jovian planets** because they resemble Jupiter. (Jove was another name for the Roman god Jupiter.) An attempt to land a spacecraft on the surface of any of the Jovian planets would be futile, because the materials of which these planets are made are mostly gaseous or liquid. The visible "surface" features of a Jovian planet are actually cloud formations in the planet's atmosphere. The photographs in Figure 7-2 show the distinctive appearances of the two classes of planets.

The most apparent difference between the terrestrial and Jovian planets is their *diameters*. You can compute the diameter of a planet if you know its angular diameter as seen from Earth and its distance from Earth. For example, on March 16, 2007, Venus was 1.97×10^8 km from Earth and had an angular diameter of 12.7 arcsec. Using the small-angle formula from Box 1-1, we can calculate the diameter of Venus to be 12,100 km (7520 mi). Similar calculations demonstrate that the Earth, with its diameter of about 12,756 km (7926 mi), is the largest of the four inner, terrestrial planets. In sharp contrast, the four outer, Jovian planets are much larger than the terrestrial planets. First place goes to Jupiter, whose equatorial diameter is more than 11 times that of the Earth. On the other end of the scale, Mercury's diameter is less than two-fifths that of the Earth. Figure 7-2 shows the Sun and the planets drawn to the same scale. The diameters of the planets are given in Table 7-1.

The *masses* of the terrestrial and Jovian planets are also dramatically different. If a planet has a satellite, you can calculate the planet's mass from the satellite's period and semimajor axis by using Newton's form of Kepler's third law (see Section 4-7 and Box 4-4). Astronomers have also measured the mass of each planet by sending a spacecraft to pass near the planet. The planet's gravitational pull (which is proportional to its mass) deflects the spacecraft's path, and the amount of deflection tells us the planet's mass. Using these techniques, astronomers have found that the four Jovian planets have masses that are tens or hundreds of times greater than the mass of any of the terrestrial planets. Again, first place goes to Jupiter, whose mass is 318 times greater than the Earth's.

Once we know the diameter and mass of a planet, we can learn something about what that planet is made of. The trick is to calculate the planet's **average density**, or mass divided by vol-

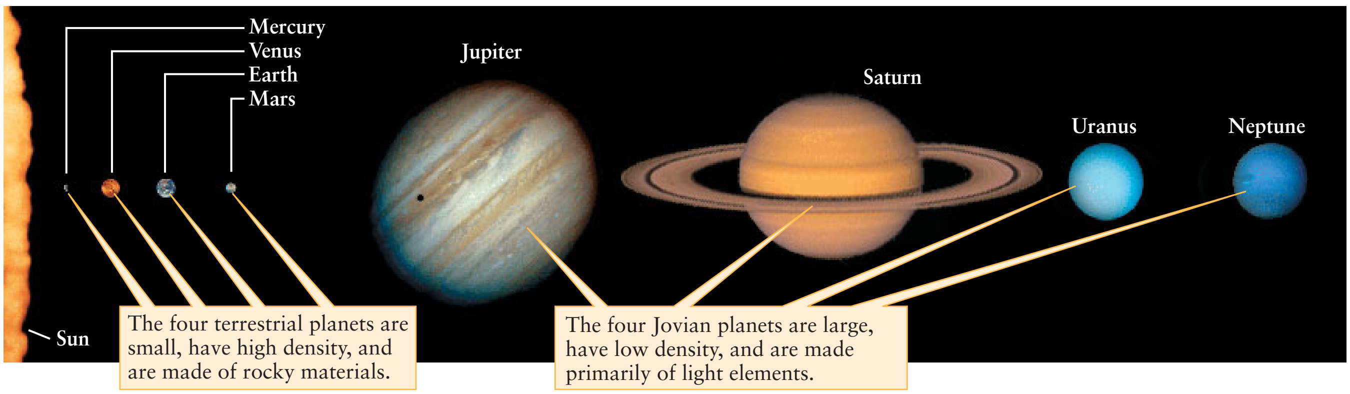


Figure 7-2 R I V U X G

The Planets to Scale This figure shows the planets from Mercury to Neptune to the same scale. The four terrestrial planets have orbits nearest the Sun, and the Jovian planets are the next four planets from the Sun. (Calvin J. Hamilton and NASA/JPL)

BOX 7-1 The Heavens on the Earth

Average Density

Average density—the mass of an object divided by that object's volume—is a useful quantity for describing the differences between planets in our solar system. This same quantity has many applications here on Earth.

A rock tossed into a lake sinks to the bottom, while an air bubble produced at the bottom of a lake (for example, by the air tanks of a scuba diver) rises to the top. These are examples of a general principle: An object sinks in a fluid if its average density is greater than that of the fluid, but rises if its average density is less than that of the fluid. The average density of water is 1000 kg/m^3, which is why a typical rock (with an average density of about 3000 kg/m^3) sinks, while an air bubble (average density of about 1.2 kg/m^3) rises.

At many summer barbecues, cans of soft drinks are kept cold by putting them in a container full of ice. When the ice melts, the cans of diet soda always rise to the top, while the cans of regular soda sink to the bottom. Why is this? The average density of a can of diet soda—which includes water, flavoring, artificial sweetener, and the trapped gas that makes the drink fizzy—is slightly less than the density of water, and so the can floats. A can of regular soda contains sugar instead of artificial sweetener, and the sugar is a bit heavier than the sweetener. The extra weight is just enough to make the average density of a can of regular soda slightly more than that of water, making the can sink. (You can test these statements for yourself by putting unopened cans of diet soda and regular soda in a sink or bathtub full of water.)

The concept of average density provides geologists with important clues about the early history of the Earth. The average density of surface rocks on Earth, about 3000 kg/m^3, is less than the Earth's average density of 5515 kg/m^3. The simplest explanation is that in the ancient past, the Earth was completely molten throughout its volume, so that low-density materials rose to the surface and high-density materials sank deep into the Earth's interior in a process called *chemical differentiation*. This series of events also suggests that the Earth's core must be made of relatively dense materials, such as iron and nickel. A tremendous amount of other geological evidence has convinced scientists that this picture is correct.

ume, measured in kilograms per cubic meter (kg/m^3). The average density of any substance depends in part on that substance's composition. For example, air near sea level on Earth has an average density of 1.2 kg/m^3, water's average density is 1000 kg/m^3, and a piece of concrete has an average density of 2000 kg/m^3. Box 7-1 describes some applications of the idea of average density to everyday phenomena on Earth.

The four inner, terrestrial planets have very high average densities (see Table 7-1); the average density of the Earth, for example, is 5515 kg/m^3. By contrast, a typical rock found on the Earth's surface has a lower average density, about 3000 kg/m^3. Thus, the Earth must contain a large amount of material that is denser than rock. This information provides our first clue that terrestrial planets have dense iron cores.

In sharp contrast, the outer, Jovian planets have quite low densities. Saturn has an average density less than that of water. This information strongly suggests that the giant outer planets are composed primarily of light elements such as hydrogen and helium. All four Jovian planets probably have large cores of mixed rock and highly compressed water buried beneath low-density outer layers tens of thousands of kilometers thick.

We can conclude that the following general rule applies to the planets:

The terrestrial planets are made of rocky materials and have dense iron cores, which gives these planets high average densities. The Jovian planets are composed primarily of light elements such as hydrogen and helium, which gives these planets low average densities.

7-2 Seven large satellites are almost as big as the terrestrial planets

All the planets except Mercury and Venus have satellites. More than 140 satellites are known: Earth has one (the Moon), Mars has two, Jupiter has at least 62, Saturn at least 43, Uranus at least 24, and Neptune at least 13. Dozens of other small satellites probably remain to be discovered as our telescope technology continues to improve. Like the terrestrial planets, all of the satellites of the planets have solid surfaces.

The various moons of the planets are not simply copies of the Earth's Moon

You can see that there is a striking difference between the terrestrial planets, with few or no satellites, and the Jovian planets, each of which has so many moons that it resembles a solar system in miniature. In Chapter 8 we will explore this and other evidence that the Jovian planets formed in a manner similar to the solar system as a whole, but on a smaller scale.

Of the known satellites, seven are roughly as big as the planet Mercury. Table 7-2 lists these satellites and shows them to the same scale. Note that the Earth's Moon and Jupiter's satellites Io and Europa have relatively high average densities, indicating that these satellites are made primarily of rocky materials. By contrast, the average densities of Ganymede, Callisto, Titan, and Triton are all relatively low. Planetary scientists conclude that the interiors of these four satellites also contain substantial amounts of water ice, which is less dense than rock. (In Section 7-4 we

WEB LINK 7.3

Table 7-2 The Seven Giant Satellites

	Moon	Io	Europa	Ganymede	Callisto	Titan	Triton
Parent planet	Earth	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Diameter (km)	3476	3642	3130	5268	4806	5150	2706
Mass (kg)	7.35×10^{22}	8.93×10^{22}	4.80×10^{22}	1.48×10^{23}	1.08×10^{23}	1.34×10^{23}	2.15×10^{22}
Average density (kg/m^3)	3340	3530	2970	1940	1850	1880	2050
Substantial atmosphere?	No	No	No	No	No	Yes	No

R I V U X G

(NASA/JPL/Space Science Institute)

will learn about types of frozen "ice" made of substances other than water.)

CAUTION! Water ice may seem like a poor material for building a satellite, since the ice you find in your freezer can easily be cracked or crushed. But under high pressure, such as is found in the interior of a large satellite, water ice becomes as rigid as rock. (It also becomes denser than the ice found in ice cubes, although not as dense as rock.) Note that water ice is an important constituent only for satellites in the outer solar system, where the Sun is far away and temperatures are very low. For example, the surface temperature of Titan is a frigid 95 K (−178°C = −288°F). In Section 7-4 we will learn more about the importance of temperature in determining the composition of a planet or satellite.

The satellites listed in Table 7-2 are actually unusually large. Most of the known satellites have diameters less than 2000 km, and many are just a few kilometers across.

Interplanetary spacecraft have made many surprising and fascinating discoveries about the satellites of the solar system. We now know that Jupiter's satellite Io is the most geologically active world in the solar system, with numerous geyserlike volcanoes that continually belch forth sulfur-rich compounds. The fractured surface of Europa, another of Jupiter's large satellites, suggests that a worldwide ocean of liquid water may lie beneath its icy surface. Saturn's largest satellite, Titan, has an atmosphere nearly twice as dense as the Earth's atmosphere, with a perpetual haze layer that gives it a featureless appearance (see the photographs in Table 7-2).

7-3 Spectroscopy reveals the chemical composition of the planets

As we have seen, the average densities of the planets and satellites give us a crude measure of their **chemical compositions**—that is, what substances they are made of. For example, the low average density of the Moon (3340 kg/m^3) compared with the Earth (5515 kg/m^3) tells us that the Moon contains relatively little iron or other dense metals. But to truly understand the nature of the planets and satellites, we need to know their chemical compositions in much greater detail than we can learn from average density alone.

The light we receive from a planet or satellite is reflected sunlight—but with revealing differences in its spectrum

The most accurate way to determine chemical composition is by directly analyzing samples taken from a planet's atmosphere and soil. Unfortunately, of all the planets and satellites, we have such direct information only for the Earth and the three worlds on which spacecraft have landed—Venus, the Moon, and Mars. In all other cases, astronomers must analyze sunlight reflected from the distant planets and their satellites. To do that, astronomers bring to bear one of their most powerful tools, **spectroscopy**, the systematic study of spectra and spectral lines. (We discussed spectroscopy in Sections 5-6 and 6-5.)

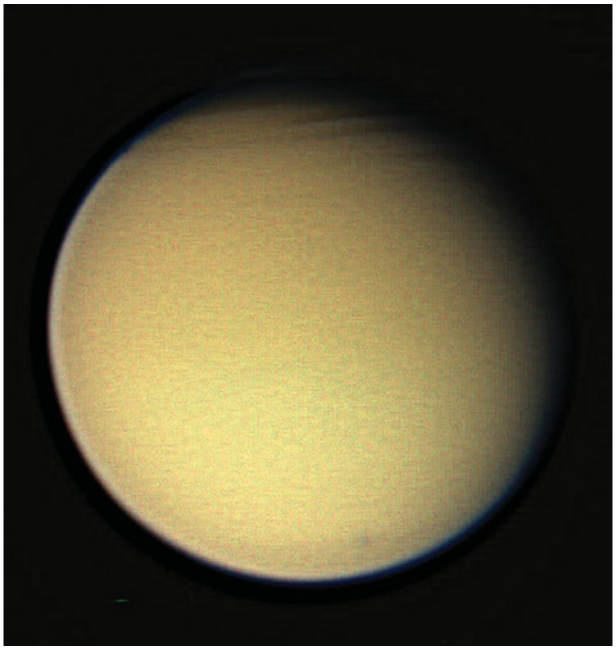
Determining Atmospheric Composition

Spectroscopy is a sensitive probe of the composition of a planet's *atmosphere*. If a planet has an atmosphere, then sunlight reflected from that planet must have passed through its atmosphere. During this passage, some of the wavelengths of sunlight will have been absorbed. Hence, the spectrum of this reflected sunlight will have dark absorption lines. Astronomers look at the particular wavelengths absorbed and the amount of light absorbed at those wavelengths. Both of these depend on the kinds of chemicals present in the planet's atmosphere and the abundance of those chemicals.

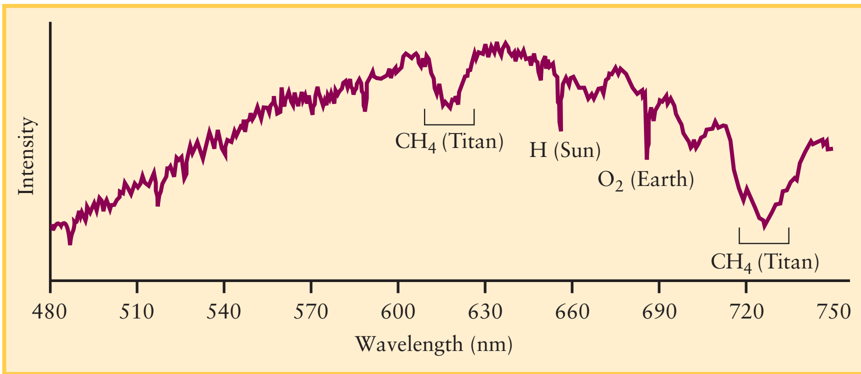
For example, astronomers have used spectroscopy to analyze the atmosphere of Saturn's largest satellite, Titan (see Figure 7-3*a* and Table 7-2). The graph in Figure 7-3*b* shows the spectrum of visible sunlight reflected from Titan. (We first saw this method of displaying spectra in Figure 6-21.) The dips in this curve of intensity versus wavelength represent absorption lines. However, not all of these absorption lines are produced in the atmosphere of Titan (Figure 7-3*c*). Before reaching Titan, light from the Sun's glowing surface must pass through the Sun's hydrogen-rich atmosphere. This produces the hydrogen absorption line in Figure 7-3*b* at a wavelength of 656 nm. After being reflected from Titan, the light must pass through the Earth's atmosphere before reaching the telescope; this is where the oxygen absorption line in Figure 7-3*b* is produced. Only the two dips near 620 nm and 730 nm are caused by gases in Titan's atmosphere.

These two absorption lines are caused not by individual atoms in the atmosphere of Titan but by atoms combined to form molecules. (We introduced the idea of molecules in Section 5-6.) Molecules, like atoms, also produce unique patterns of lines in the spectra of astronomical objects. The absorption lines in Figure 7-3*b* indicate the presence in Titan's atmosphere of molecules of methane (CH_4, a molecule made of one carbon atom and four hydrogen atoms). This shows that Titan is a curious place indeed, because on Earth, methane is a rather rare substance that is the primary ingredient in natural gas! When we examine other planets and satellites with atmospheres, we find that all of their spectra have absorption lines of molecules of various types.

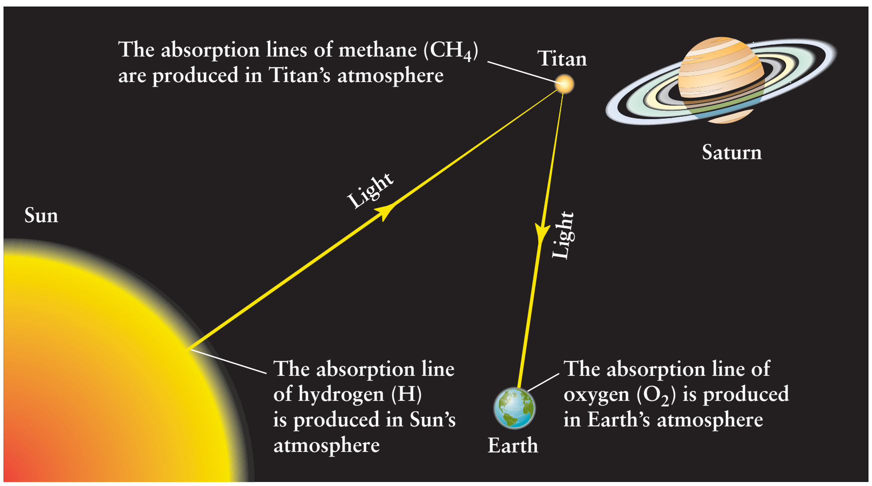
In addition to visible-light measurements such as those shown in Figure 7-3*b*, it is very useful to study the *infrared* and *ultraviolet* spectra of planetary atmospheres. Many molecules have much stronger spectral lines in these nonvisible wavelength bands than in the visible. As an example, the ultraviolet spectrum of Titan shows that nitrogen molecules (N_2) are the dominant constituent of Titan's atmosphere. Furthermore, Titan's infrared spectrum



(a) Saturn's satellite Titan



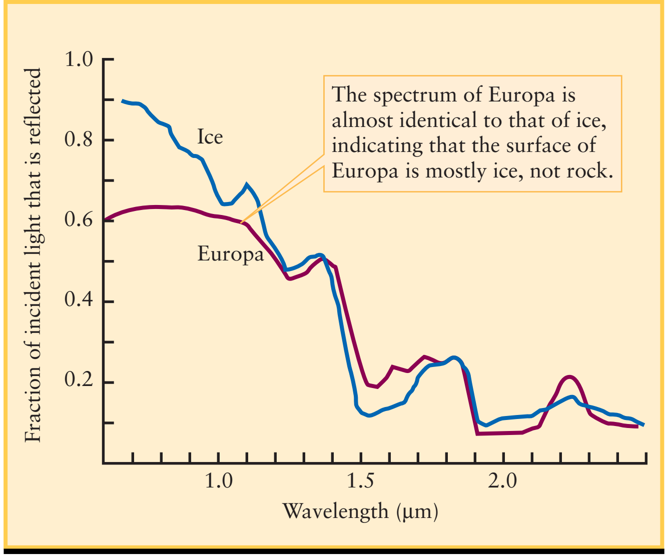
(b) The spectrum of sunlight reflected from Titan



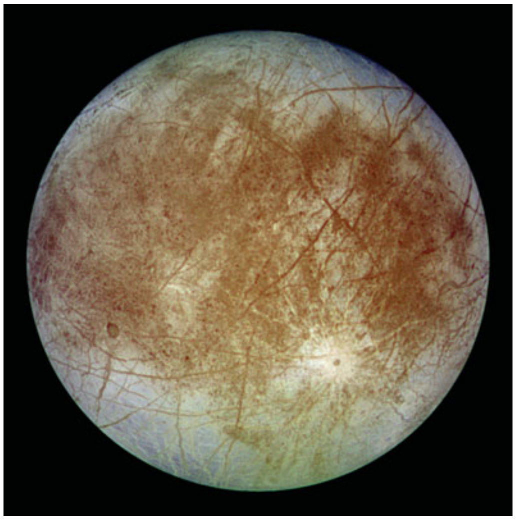
(c) Interpreting Titan's spectrum

Figure 7-3 R I V U X G

Analyzing a Satellite's Atmosphere through its Spectrum **(a)** Titan is the only satellite in the solar system with a substantial atmosphere. **(b)** The dips in the spectrum of sunlight reflected from Titan are due to absorption by hydrogen atoms (H), oxygen molecules (O_2), and methane molecules (CH_4). Of these, only methane is actually present in Titan's atmosphere. **(c)** This illustration shows the path of the light that reaches us from Titan. To interpret the spectrum of this light as shown in (b), astronomers must account for the absorption that takes place in the atmospheres of the Sun and Earth. (a: NASA/JPL/Space Science Institute)



(a) The spectum of light reflected from Europa R I V U X G



(b) Jupiter's moon Europa

WEB LINK 7.4

Figure 7-4

Analyzing a Satellite's Surface from Its Spectrum
(a) Unlike Titan (Figure 7-3*a*), Jupiter's satellite Europa has no atmosphere. **(b)** Infrared light from the Sun that is reflected from the surface of Europa, has almost exactly the same spectrum as sunlight reflected from ordinary water ice.

includes spectral lines of a variety of molecules that contain carbon and hydrogen, indicating that Titan's atmosphere has a very complex chemistry. None of these molecules could have been detected by visible light alone. Since the Earth's atmosphere is largely opaque to infrared and ultraviolet wavelengths (see Section 6-7), telescopes in space are important tools for these spectroscopic studies of the solar system.

It is a testament to the power of spectroscopy that when the robotic spacecraft *Huygens* landed on Titan in 2005, its onboard instruments confirmed the presence of methane and nitrogen in Titan's atmosphere—just as had been predicted years before by spectroscopic observations.

Determining Surface Composition

Spectroscopy can also provide useful information about the *solid surfaces* of planets and satellites without atmospheres. When light shines on a solid surface, some wavelengths are absorbed while others are reflected. (For example, a plant leaf absorbs red and violet light but reflects green light—which is why leaves look green.) Unlike a gas, a solid illuminated by sunlight does not produce sharp, definite spectral lines. Instead, only broad absorption features appear in the spectrum. By comparing such a spectrum with the spectra of samples of different substances on Earth, astronomers can infer the chemical composition of the surface of a planet or satellite.

As an example, Figure 7-4*a* shows Jupiter's satellite Europa (see Table 7-2), and Figure 7-4*b* shows the infrared spectrum of light reflected from the surface of Europa. Because this spectrum is so close to that of water ice—that is, frozen water—astronomers conclude that water ice is the dominant constituent of Europa's surface. (We saw in Section 7-2 that water ice cannot be the dominant constituent of Europa's *interior,* because this satellite's density is too high.)

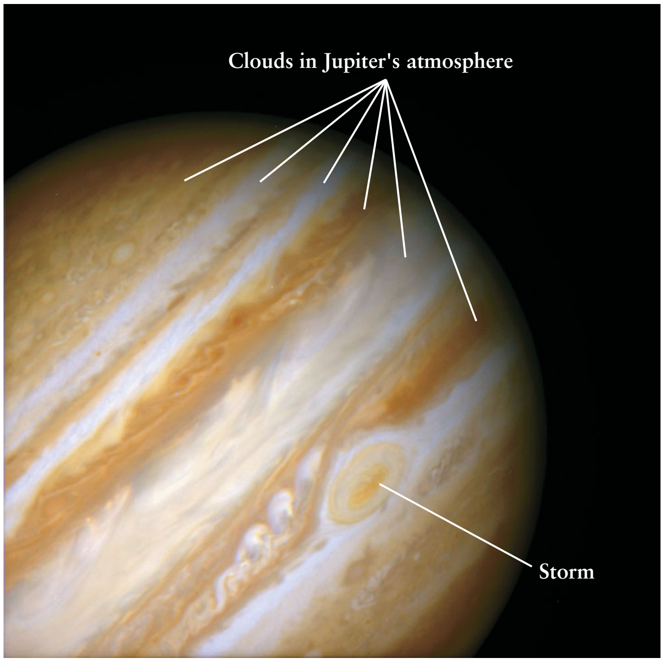
Unfortunately, spectroscopy tells us little about what the material is like just below the surface of a satellite or planet. For this purpose, there is simply no substitute for sending a spacecraft to a planet and examining its surface directly.

7-4 The Jovian planets are made of lighter elements than the terrestrial planets

Spectroscopic observations from Earth and spacecraft show that the outer layers of the Jovian planets are composed primarily of the lightest gases, hydrogen and helium (see Box 5-5). In contrast, chemical analysis of soil samples from Venus, Earth, and Mars demonstrate that the terrestrial planets are made mostly of heavier elements, such as iron, oxygen, silicon, magnesium, nickel, and sulfur. Spacecraft images such as Figure 7-5 and Figure 7-6 only hint at these striking differences in chemical composition, which are summarized in Table 7-3.

Differences in distance from the Sun, and hence in temperature, explain many distinctions between terrestrial and Jovian planets

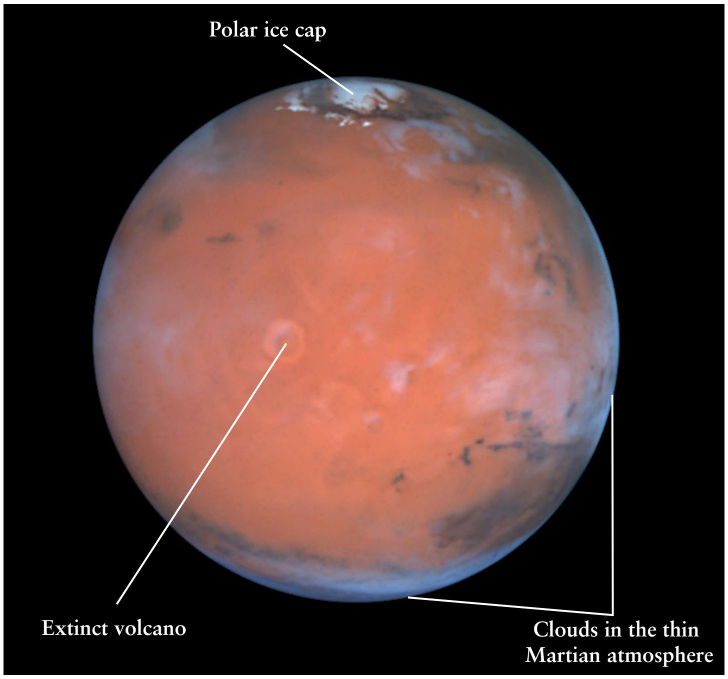
Temperature plays a major role in determining whether the materials of which planets are made exist as solids, liquids, or gases. Hydrogen (H_2) and helium (He) are gaseous except at extremely low temperatures and extraordinarily high pressures. By contrast, rock-forming substances such as iron and silicon are solids except



WEB LINK 7.5

Figure 7-5 R I V U X G

A Jovian Planet This Hubble Space Telescope image gives a detailed view of Jupiter's cloudtops. Jupiter is composed mostly of the lightest elements, hydrogen and helium, which are colorless; the colors in the atmosphere are caused by trace amounts of other substances. The giant storm at lower right, called the Great Red Spot, has been raging for more than 300 years. (Space Telescope Science Institute/JPL/NASA)



WEB LINK 7.6

Figure 7-6 R I V U X G

A Terrestrial Planet Mars is composed mostly of heavy elements such as iron, oxygen, silicon, magnesium, nickel, and sulfur. The planet's red surface can be seen clearly in this Hubble Space Telescope image because the Martian atmosphere is thin and nearly cloudless. Olympus Mons, the extinct volcano to the left of center, is nearly 3 times the height of Mount Everest. (Space Telescope Science Institute/JPL/NASA)

at temperatures well above 1000 K. (You may want to review the discussion of temperature scales in Box 5-1.) Between these two extremes are substances such as water (H_2O), carbon dioxide (CO_2), methane (CH_4), and ammonia (NH_3), which solidify at low temperatures (from below 100 to 300 K) into solids called **ices.** (In astronomy, frozen water is just one kind of "ice.") At somewhat higher temperatures, they can exist as liquids or gases. For example, clouds of ammonia ice crystals are found in the cold upper atmosphere of Jupiter, but within Jupiter's warmer interior, ammonia exists primarily as a liquid.

CAUTION! The Jovian planets are sometimes called "gas giants." It is true that their primary constituents, including hydrogen, helium, ammonia, and methane, are gases under normal conditions on Earth. But in the interiors of these planets, pressures are so high that these substances are *liquids*, not gases. The Jovian planets might be better described as "liquid giants"!

As you might expect, a planet's surface temperature is related to its distance from the Sun. The four inner planets are quite warm. For example, midday temperatures on Mercury may climb to 700 K (= 427°C = 801°F), and during midsummer on Mars, it is sometimes as warm as 290 K (= 17°C = 63°F). The outer planets, which receive much less solar radiation, are cooler. Typical temperatures range from about 125 K (= –148°C = –234°F) in Jupiter's upper atmosphere to about 55 K (= –218°C = –360°F) at the tops of Neptune's clouds.

How Temperature Affects Atmospheres

The higher surface temperatures of the terrestrial planets help to explain the following observation: The atmospheres of the terrestrial planets contain virtually *no* hydrogen molecules or helium atoms.

Table 7-3 Comparing Terrestrial and Jovian Planets

	Terrestrial Planets	Jovian Planets
Distance from the Sun	Less than 2 AU	More than 5 AU
Size	Small	Large
Composition	Mostly rocky materials containing iron, oxygen, silicon, magnesium, nickel, and sulfur	Mostly light elements such as hydrogen and helium
Density	High	Low

BOX 7-2 Tools of the Astronomer's Trade

Kinetic Energy, Temperature, and Whether Planets Have Atmospheres

A moving object possesses energy as a result of its motion. The faster it moves, the more energy it has. Energy of this type is called **kinetic energy.** If an object of mass m is moving with a speed v, its kinetic energy E_k is given by

Kinetic energy

$$E_k = \frac{1}{2} mv^2$$

E_k = kinetic energy of an object

m = mass of object

v = speed of object

This expression for kinetic energy is valid for all objects, both big and small, from atoms and molecules to planets and stars, as long as their speeds are slow in relation to the speed of light. If the mass is expressed in kilograms and the speed in meters per second, the kinetic energy is expressed in joules (J).

EXAMPLE: An automobile of mass 1000 kg driving at a typical freeway speed of 30 m/s (= 108 km/h = 67 mi/h) has a kinetic energy of

$$E_k = \frac{1}{2}(1000 \times 30^2) = 450{,}000 \text{ J} = 4.5 \times 10^5 \text{ J}$$

Consider a gas, such as the atmosphere of a star or planet. Some of the gas atoms or molecules will be moving slowly, with little kinetic energy, while others will be moving faster and have more kinetic energy. The temperature of the gas is a direct measure of the *average* amount of kinetic energy per atom or molecule. The hotter the gas, the faster atoms or molecules move, on average, and the greater the average kinetic energy of an atom or molecule.

If the gas temperature is sufficiently high, typically several thousand kelvins, molecules move so fast that when they collide with one another, the energy of the collision can break the molecules apart into their constituent atoms. Thus, the Sun's atmosphere, where the temperature is 5800 K, consists primarily of individual hydrogen atoms rather than hydrogen molecules. By contrast, the hydrogen atoms in the Earth's atmosphere (temperature 290 K) are combined with oxygen atoms into molecules of water vapor (H_2O).

The physics of gases tells us that in a gas of temperature T (in kelvins), the average kinetic energy of an atom or molecule is

Kinetic energy of a gas atom or molecule

$$E_k = \frac{3}{2} kT$$

E_k = average kinetic energy of a gas atom or molecule, in joules

$k = 1.38 \times 10^{-23}$ J/K

T = temperature of gas, in kelvins

The quantity k is called the Boltzmann constant. Note that the higher the gas temperature, the greater the average kinetic energy of an atom or molecule of the gas. This average kinetic energy becomes zero at absolute zero, or $T = 0$, the temperature at which molecular motion is at a minimum.

At a given temperature, all kinds of atoms and molecules will have the same average kinetic energy. But the average *speed* of a given kind of atom or molecule depends on its mass. To see this, note that the average kinetic energy of a gas atom or molecule can be written in two equivalent ways:

$$E_k = \frac{1}{2} mv^2 = \frac{3}{2} kT$$

where v represents the average speed of an atom or molecule in a gas with temperature T. Rearranging this equation, we obtain

Average speed of a gas atom or molecule

$$v = \sqrt{\frac{3kT}{m}}$$

v = average speed of a gas atom or molecule, in m/s

$k = 1.38 \times 10^{-23}$ J/K

T = temperature of gas, in kelvins

m = mass of the atom or molecule, in kilograms

For a given gas temperature, the greater the mass of a given type of gas atom or molecule, the slower its average

Instead, the atmospheres of Venus, Earth, and Mars are composed of heavier molecules such as nitrogen (N_2, 14 times more massive than a hydrogen molecule), oxygen (O_2, 16 times more massive), and carbon dioxide (22 times more massive). To understand the connection between surface temperature and the absence of hydrogen and helium, we need to know a few basic facts about gases.

The temperature of a gas is directly related to the speeds at which the atoms or molecules of the gas move: The higher the gas temperature, the greater the speed of its atoms or molecules. Furthermore, for a given temperature, lightweight atoms and molecules move more rapidly than heavy ones. On the four inner, terrestrial planets, where atmospheric temperatures are high, low-speed. (The value of v given by this equation is actually slightly higher than the average speed of the atoms or molecules in the gas, but it is close enough for our purposes here. If you are studying physics, you may know that v is actually the root-mean-square speed.)

EXAMPLE: What is the average speed of the oxygen molecules that you breathe at a room temperature of 20°C (= 68°F)?

Situation: We are given the temperature of a gas and are asked to find the average speed of the gas molecules.

Tools: We use the relationship $v = \sqrt{3kT/m}$, where T is the gas temperature in kelvins and m is the mass of a single oxygen molecule in kilograms.

Answer: To use the equation to calculate the average speed v, we must express the temperature T in kelvins (K) rather than degrees Celsius (°C). As we learned in Box 5-1, we do this by adding 273 to the Celsius temperature, so 20°C becomes (20 + 273) = 293 K. The mass m of an oxygen molecule is not given, but from a reference book you can find that the mass of an oxygen *atom* is 2.66×10^{-26} kg. The mass of an oxygen molecule (O_2) is twice the mass of an oxygen atom, or $2(2.66 \times 10^{-26}\text{ kg}) = 5.32 \times 10^{-26}$ kg. Thus, the average speed of an oxygen molecule in 20°C air is

$$v = \sqrt{\frac{3(1.38 \times 10^{-23})(293)}{5.32 \times 10^{-26}}} = 478 \text{ m/s} = 0.478 \text{ km/s}$$

Review: This is about 1700 kilometers per hour, or about 1100 miles per hour. Hence, atoms and molecules move rapidly in even a moderate-temperature gas.

In some situations, atoms and molecules in a gas may be moving so fast that they can overcome the attractive force of a planet's gravity and escape into interplanetary space. The minimum speed that an object at a planet's surface must have in order to permanently leave the planet is called the planet's **escape speed.** The escape speed for a planet of mass M and radius R is given by

$$v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

where $G = 6.67 \times 10^{-11}$ N m^2/kg^2 is the universal constant of gravitation.

The accompanying table gives the escape speed for the Sun, the planets, and the Moon. For example, to get to another planet, a spacecraft must leave Earth with a speed greater than 11.2 km/s (25,100 mi/h).

A good rule of thumb is that a planet can retain a gas if the escape speed is at least 6 times greater than the average speed of the molecules in the gas. (Some molecules are moving slower than average, and others are moving faster, but very few are moving more than 6 times faster than average.) In such a case, very few molecules will be moving fast enough to escape from the planet's gravity.

EXAMPLE: Consider the Earth's atmosphere. We saw that the average speed of oxygen molecules is 0.478 km/s at room temperature. The escape speed from the Earth (11.2 km/s) is much more than 6 times the average speed of the oxygen molecules, so the Earth has no trouble keeping oxygen in its atmosphere.

A similar calculation for hydrogen molecules (H_2) gives a different result, however. At 293 K, the average speed of a hydrogen molecule is 1.9 km/s. Six times this speed is 11.4 km/s, which is slightly higher than the escape speed from the Earth. Thus, the Earth does not retain hydrogen in its atmosphere. Any hydrogen released into the air slowly leaks away into space. On Jupiter, by contrast, the escape speed is so high that even the lightest gases such as hydrogen are retained in its atmosphere. But on Mercury the escape speed is low and the temperature high (so that gas molecules move faster), so Mercury cannot retain any significant atmosphere at all.

Object	Escape speed (km/s)
Sun	618
Mercury	4.3
Venus	10.4
Earth	11.2
Moon	2.4
Mars	5.0
Jupiter	59.5
Saturn	35.5
Uranus	21.3
Neptune	23.5

mass hydrogen molecules and helium atoms move so swiftly that they can escape from the relatively weak gravity of these planets. Hence, the atmospheres that surround the terrestrial planets are composed primarily of more massive, slower-moving molecules such as CO_2, N_2, O_2, and water vapor (H_2O). On the four Jovian planets, low temperatures and relatively strong gravity prevent even lightweight hydrogen and helium gases from escaping into space, and so their atmospheres are much more extensive. The combined mass of Jupiter's atmosphere, for example, is about a million (10^6) times greater than that of the Earth's atmosphere. This is comparable to the mass of the entire Earth! Box 7-2 describes more about the ability of a planet's gravity to retain gases.

7-5 Small chunks of rock and ice also orbit the Sun

In addition to the eight planets, many smaller objects orbit the Sun. These fall into three broad categories: asteroids, which are rocky objects found in the inner solar system; trans-Neptunian objects, which are found beyond Neptune in the outer solar system and contain both rock and ice; and comets, which are mixtures of rock and ice that originate in the outer solar system but can venture close to the Sun.

The smaller bodies of the solar system contain important clues about its origin and evolution

Asteroids

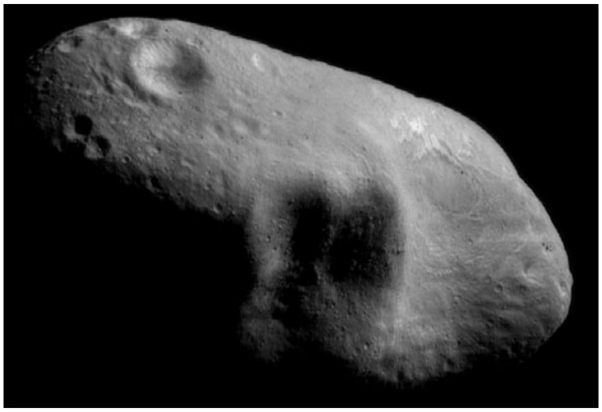
Within the orbit of Jupiter are hundreds of thousands of rocky objects called **asteroids.** There is no sharp dividing line between planets and asteroids, which is why asteroids are also called **minor planets.** The largest asteroid, Ceres, has a diameter of about 900 km. The next largest, Pallas and Vesta, are each about 500 km in diameter. Still smaller ones, like the asteroid shown in close-up in Figure 7-7, are increasingly numerous. Hundreds of thousands of kilometer-sized asteroids are known, and there are probably hundreds of thousands more that are boulder-sized or smaller. All of these objects orbit the Sun in the same direction as the planets.

Most (although not all) asteroids orbit the Sun at distances of 2 to 3.5 AU. This region of the solar system between the orbits of Mars and Jupiter is called the **asteroid belt.**

CAUTION! One common misconception about asteroids is that they are the remnants of an ancient planet that somehow broke apart or exploded, like the fictional planet Krypton in the comic book adventures of Superman. In fact, the combined mass of the asteroids is less than that of the Moon, and they were probably never part of any planet-sized body. The early solar system is thought to have been filled with asteroidlike objects, most of which were incorporated into the planets. The "leftover" objects that missed out on this process make up our present-day population of asteroids.

Trans-Neptunian Objects

While asteroids are the most important small bodies in the inner solar system, the outer solar system is the realm of the **trans-Neptunian objects.** As the name suggests, these are small bodies whose orbits lie beyond the orbit of Neptune. The first of these to be discovered (1930) was Pluto, with a diameter of only 2274 km. This is larger than any asteroid, but smaller than any planet or any of the satellites listed in Table 7-2. The orbit of Pluto has a greater semimajor axis (39.54 AU), is more steeply inclined to the ecliptic (17.15°), and has a greater eccentricity (0.250) than that of any of the planets (Figure 7-8). In fact, Pluto's noncircular orbit sometimes takes it nearer the Sun than Neptune. (Happily, the orbits of Neptune and Pluto are such that they will never collide.) Pluto's density is only 2000 kg/m^3, about the same as Neptune's moon Triton, shown in Table 7-2. Hence, its composition is thought to be a mixture of about 70% rock and 30% ice.



WEB LINK 7.7 **Figure 7-7** R I V U X G
An Asteroid The asteroid shown in this image, 433 Eros, is only 33 km (21 mi) long and 13 km (8 mi) wide—about the same size as the island of Manhattan. Because Eros is so small, its gravity is too weak to have pulled it into a spherical shape. This image was taken in March 2000 by *NEAR Shoemaker,* the first spacecraft to orbit around and land on an asteroid. (*NEAR* Project, Johns Hopkins University, Applied Physics Laboratory, and NASA)

Since 1992 astronomers have discovered more than 900 other trans-Neptunian objects, and are discovering more each year. Like asteroids, all trans-Neptunian objects orbit the Sun in the same direction as the planets. A handful of trans-Neptunian objects are comparable in size to Pluto; at least one, Eris, is even larger than Pluto, as well as being in an orbit that is much larger, more steeply inclined, and more eccentric (Figure 7-8). Table 7-4 lists the seven largest trans-Neptunian objects known as of this writing. (Note that Charon is actually a satellite of Pluto.)

Just as most asteroids lie in the asteroid belt, most trans-Neptunian objects orbit within a band called the **Kuiper belt** (pronounced "ki-per") that extends from 30 AU to 50 AU from the Sun and is centered on the plane of the ecliptic. Like asteroids, many more trans-Neptunian objects remain to be discovered: astronomers estimate that there are 35,000 or more such objects with diameters greater than 100 km. If so, the combined mass of all trans-Neptunian objects is comparable to the mass of Jupiter, and is several hundred times greater than the combined mass of all the asteroids found in the inner solar system.

Like asteroids, trans-Neptunian objects are thought to be debris left over from the formation of the solar system. In the inner regions of the solar system, rocky fragments have been able to endure continuous exposure to the Sun's heat, but any ice originally present would have evaporated. Far from the Sun, ice has survived for billions of years. Thus, debris in the solar system naturally divides into two families (asteroids and trans-Neptunian objects), which can be arranged according to distance from the Sun, just like the two categories of planets (terrestrial and Jovian).

Comets

Two objects in the Kuiper belt can collide if their orbits cross each other. When this happens, a fragment a few kilometers across can be knocked off one of the colliding objects and be diverted into an elongated orbit that brings it close to the Sun. Such small

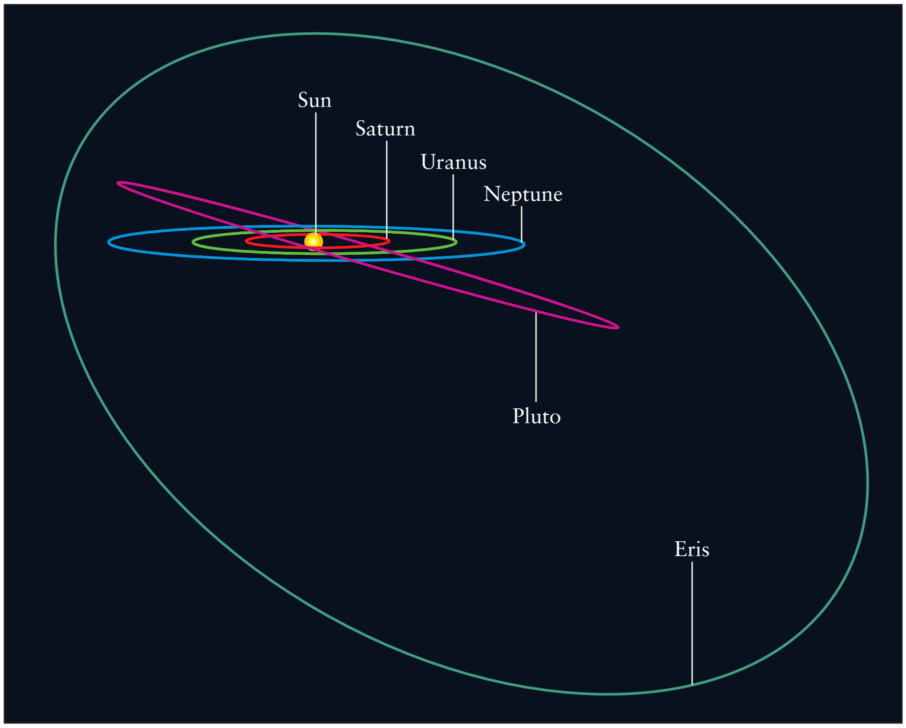


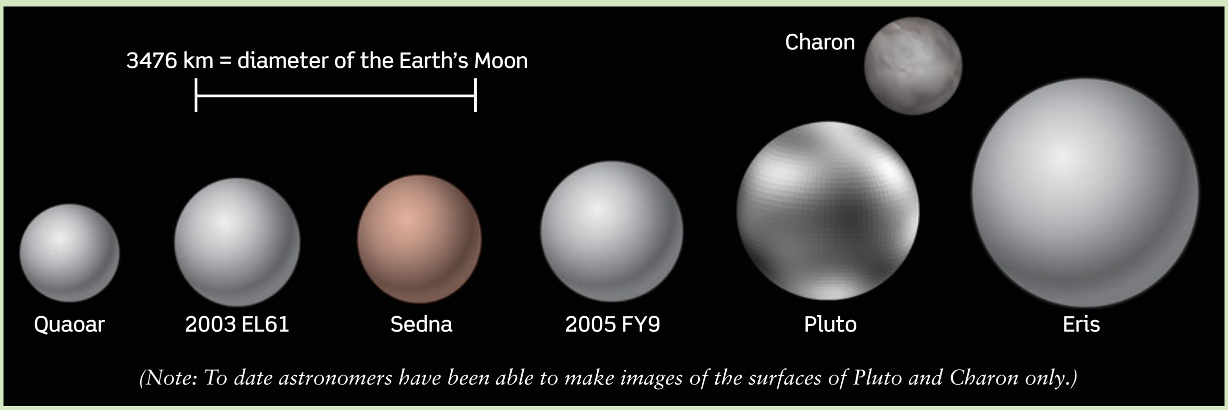
Figure 7-8

Trans-Neptunian Objects Pluto and Eris are the two largest trans-Neptunian objects, small worlds of rock and ice that orbit beyond Neptune. Unlike the orbits of the planets, the orbits of these two objects are steeply inclined to the ecliptic: Pluto's orbit is tilted by about 17°, and that of Eris is tilted by 44°.

WEB LINK 7.8

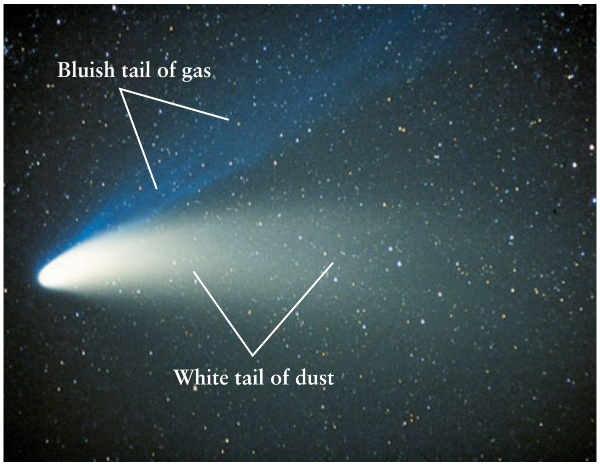
Table 7-4 Seven Large Trans-Neptunian Objects

	Quaoar	2003 EL61	Sedna	2005 FY9	Pluto	Charon (satellite of Pluto)	Eris
Average distance from Sun (AU)	43.54	43.34	489	45.71	39.54	39.54	67.67
Orbital period (years)	287	285	10,800	309	248.6	248.6	557
Orbital eccentricity	0.035	0.189	0.844	0.155	0.250	0.250	0.442
Inclination of orbit to the ecliptic	8.0°	28.2°	11.9°	29.0°	17.15°	17.15°	44.2°
Approximate diameter (km)	1250	1500	1600	1800	2274	1190	2900



R I V U X G

(Images of Pluto and Charon: Alan Stern, Southwest Research Institute; Marc Buie, Lowell Observatory; NASA; and ESA)



WEB LINK 7.9

Figure 7-9 R I V U X G

A Comet This photograph shows Comet Hale-Bopp as it appeared in April 1997. The solid part of a comet like this is a chunk of dirty ice a few tens of kilometers in diameter. When a comet passes near the Sun, solar radiation vaporizes some of the icy material, forming a bluish tail of gas and a white tail of dust. Both tails can extend for tens of millions of kilometers. (Richard J. Wainscoat, University of Hawaii)

objects, each a combination of rock and ice, are called **comets.** When a comet comes close enough to the Sun, the Sun's radiation vaporizes some of the comet's ices, producing long flowing tails of gas and dust particles (Figure 7-9). Astronomers deduce the composition of comets by studying the spectra of these tails.

CAUTION! Science-fiction movies and television programs sometimes show comets tearing across the night sky like a rocket. That would be a pretty impressive sight—but that is not what comets look like. Like the planets, comets orbit the Sun. And like the planets, comets move hardly at all against the background of stars over the course of a single night (see Section 4-1). If you are lucky enough to see a bright comet, it will not zoom dramatically from horizon to horizon. Instead, it will seem to hang majestically among the stars, so you can admire it at your leisure.

Some comets appear to originate from locations far beyond the Kuiper belt. The source of these is thought to be a swarm of comets that forms a spherical "halo" around the solar system called the **Oort cloud.** This hypothesized "halo" extends to 50,000 AU from the Sun (about one-fifth of the way to the nearest other star). Because the Oort cloud is so distant, it has not yet been possible to detect objects in the Oort cloud directly.

7-6 Cratering on planets and satellites is the result of impacts from interplanetary debris

One of the great challenges in studying planets and satellites is how to determine their internal structures. Are they solid or liquid inside? If there is liquid in the interiors, is the liquid calm or in agitated motion? Because planets are opaque, we cannot see directly into their interiors to answer these questions. But we can gather important clues about the interiors of terrestrial planets and satellites by studying the extent to which their surfaces are covered with craters (Figure 7-10). To see how this is done, we first need to understand where craters come from.

Scientists study craters on a planet or satellite to learn the age and geologic history of the surface

The Origin of Craters

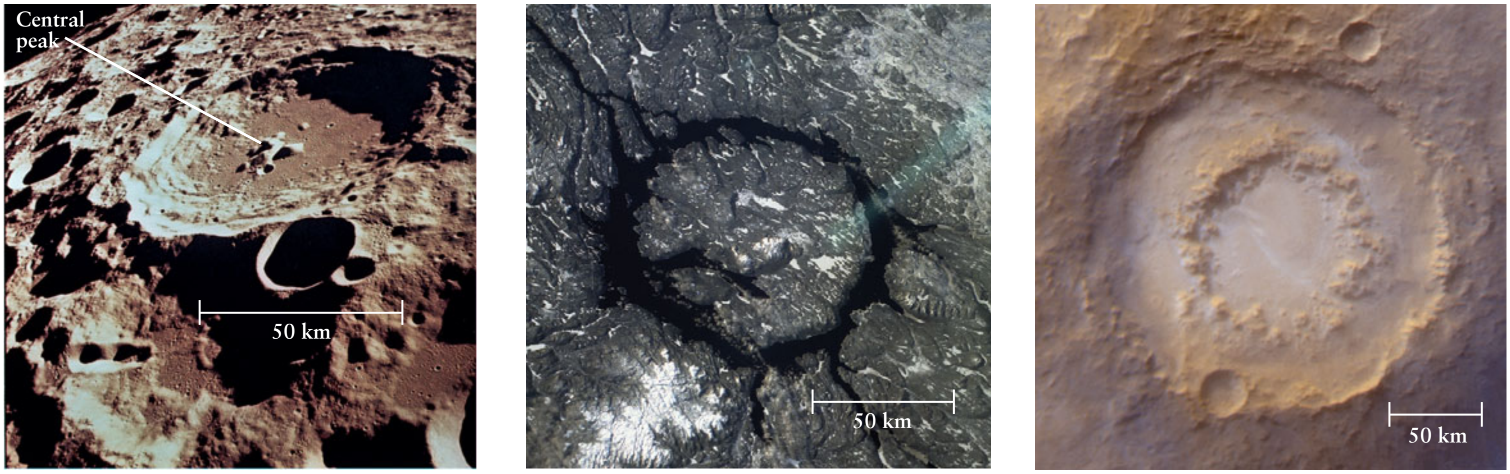
The planets orbit the Sun in roughly circular orbits. But many asteroids and comets are in more elongated orbits. Such an elongated orbit can put these small objects on a collision course with a planet or satellite. If the object collides with a Jovian planet, it is swallowed up by the planet's thick atmosphere. (Astronomers actually saw an event of this kind in 1994, when a comet crashed into Jupiter.) But if the object collides with the solid surface of a terrestrial planet or a satellite, the result is an **impact crater** (see Figure 7-10). Such impact craters, found throughout the solar system, offer stark evidence of these violent collisions.

The easiest way to view impact craters is to examine the Moon through a telescope or binoculars. Some 30,000 lunar craters are visible, with diameters ranging from 1 km to several hundred km. Close-up photographs from lunar orbit have revealed millions of craters too small to be seen from Earth (Figure 7-10*a*). These smaller craters are thought to have been caused by impacts of relatively small objects called **meteoroids,** which range in size from a few hundred meters across to the size of a pebble or smaller. Meteoroids are the result of collisions between asteroids, whose orbits sometimes cross. The chunks of rock that result from these collisions go into independent orbits around the Sun, which can lead them to collide with the Moon or another world.

When German astronomer Franz Gruithuisen proposed in 1824 that lunar craters were the result of impacts, a major sticking point was the observation that nearly all craters are circular. If craters were merely gouged out by high-speed rocks, a rock striking the Moon in any direction except straight downward would have created a noncircular crater. A century after Gruithuisen, it was realized that a meteoroid colliding with the Moon generates a shock wave in the lunar surface that spreads out from the point of impact. Such a shock wave produces a circular crater no matter what direction the meteoroid was moving. (In a similar way, the craters made by artillery shells are almost always circular.) Many of the larger lunar craters also have a central peak, which is characteristic of a high-speed impact (see Figure 7-10*a*). Craters made by other processes, such as volcanic action, would not have central peaks of this sort.

Comparing Cratering on Different Worlds

Not all planets and satellites show the same amount of cratering. The Moon is heavily cratered over its entire surface, with craters on top of craters, as shown in Figure 7-10*a*. On Earth, by contrast, craters are very rare: Geologists have identified fewer than 200 impact craters on our planet (Figure 7-10*b*). Our understanding is that both the Earth and the Moon formed at nearly the same time and have been bombarded at comparable rates over



(a) A crater on the Moon (b) A crater on the Earth (c) A crater on Mars

WEB LINK 7.10

Figure 7-10 R I **V** U X G

Impact Craters These images, all taken from spacecraft, show impact craters on three different worlds. **(a)** The Moon's surface has craters of all sizes. The large crater near the middle of this image is about 80 km (50 miles) in diameter, equal to the length of San Francisco Bay. **(b)** Manicouagan Reservoir in Quebec is the relic of a crater formed by an impact more than 200 million years ago. The crater was eroded over the ages by the advance and retreat of glaciers, leaving a ring lake 100 km (60 miles) across. **(c)** Lowell Crater in the southern highlands of Mars is 201 km (125 miles) across. Like the image of the Moon in part (a), there are craters on top of craters. Note the light-colored frost formed by condensation of carbon dioxide from the Martian atmosphere. (a: NASA; b: JSC/NASA; c: NASA/JPL/MSSS)

their history. Why, then, are craters so much rarer on the Earth than on the Moon?

The answer is that the Earth is a *geologically active* planet: the continents slowly change their positions over eons, new material flows onto the surface from the interior (as occurs in a volcanic eruption), and old surface material is pushed back into the interior (as occurs off the coast of Chile, where the ocean bottom is slowly being pushed beneath the South American continent). These processes, coupled with erosion from wind and water, cause craters on Earth to be erased over time. The few craters found on Earth today must be relatively recent, since there has not yet been time to erase them.

The Moon, by contrast, is geologically *inactive*. There are no volcanoes and no motion of continents (and, indeed, no continents). Furthermore, the Moon has neither oceans nor an atmosphere, so there is no erosion as we know it on Earth. With none of the processes that tend to erase craters on Earth, the Moon's surface remains pockmarked with the scars of billions of years of impacts.

In order for a planet to be geologically active, its interior must be at least partially molten. This is necessary so that continents can slide around on the underlying molten material and so that molten lava can come to the surface, as in a volcanic eruption. Hence, we would expect geologically inactive (and hence heavily cratered) worlds like the Moon to have less molten material in their interiors than does the Earth. Investigations of these inactive worlds bear this out. But *why* is the Moon's interior less molten than the Earth's?

ANALOGY To see one simple answer to this question, notice that a large turkey or roast taken from the oven will stay warm inside for hours, but a single meatball will cool off much more rapidly. The reason is that the meatball has more surface area relative to its volume, and so it can more easily lose heat to its surroundings. A planet or satellite also tends to cool down as it emits electromagnetic radiation into space (see Section 5-3); the smaller the planet or satellite, the greater its surface area relative to its volume, and the more readily it can radiate away heat (Figure 7-11). Both the Earth and Moon were probably completely molten when they first formed, but because the Moon (diameter 3476 km) is so much smaller than the Earth (diameter 12,756 km), it has lost much of its internal heat and has a much more solid interior.

Cratering Measures Geologic Activity

By considering these differences between the Earth and the Moon, we have uncovered a general rule for worlds with solid surfaces:

The smaller the terrestrial world, the less internal heat it is likely to have retained, and, thus, the less geologic activity it will display on its surface. The less geologically active the world, the older and hence more heavily cratered its surface.

This rule means that we can use the amount of cratering visible on a planet or satellite to estimate the age of its surface and how geologically active it is. As an example, Mercury has a heavily cratered surface, which means that the surface is very old. This accords with Mercury being the smallest of the terrestrial planets (see Table 7-1): Due to its small size, it has lost the internal heat required to sustain geologic activity. On Venus, by comparison, there are only about a thousand craters larger than a few kilometers in diameter, many more than have been found on Earth but only a small fraction of the number on the Moon or Mercury. Venus is only slightly smaller than the Earth, and it has enough internal heat to power the geologic activity required to erase most of its impact craters.

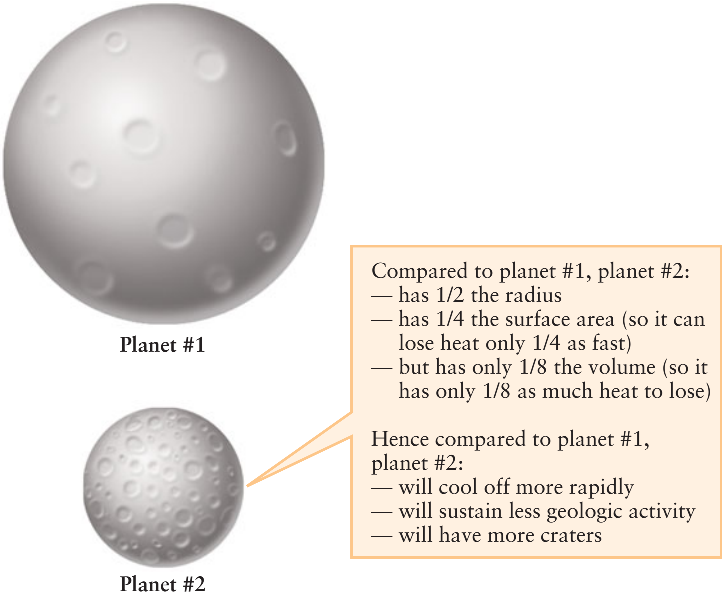


Figure 7-11

Planet Size and Cratering Of these two hypothetical planets, the smaller one (#2) has less volume and less internal heat, as well as less surface area from which to radiate heat into space. But the *ratio* of surface area to volume is greater for the smaller planet. Hence, the smaller planet will lose heat faster, have a colder interior, and be less geologically active. It will also have a more heavily cratered surface, since it takes geologic activity to erase craters.

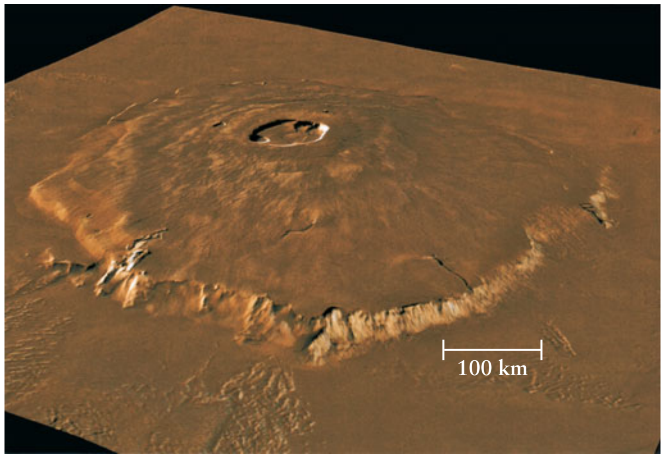


Figure 7-12 R I V U X G

A Martian Volcano Olympus Mons is the largest of the inactive volcanoes of Mars and the largest volcano in the solar system. The base of Olympus Mons measures 600 km (370 mi) in diameter, and the scarps (cliffs) that surround the base are 6 km (4 mi) high. The caldera, or volcanic crater, at the summit is approximately 70 km across, large enough to contain the state of Rhode Island. This view was creating by combining a number of images taken from Mars orbit. (© Calvin J. Hamilton)

Mars is an unusual case, in that extensive cratering (Figure 7-10*c*) is found only in the higher terrain; the lowlands of Mars are remarkably smooth and free of craters. Thus, it follows that the Martian highlands are quite old, while the lowlands have a younger surface from which most craters have been erased. Considering the planet as a whole, the amount of cratering on Mars is intermediate between that on Mercury and the Earth. This agrees with our general rule, because Mars is intermediate in size between Mercury and Earth. The interior of Mars was once hotter and more molten than it is now, so that geologic processes were able to erase some of the impact craters. A key piece of evidence that supports this picture is that Mars has a number of immense volcanoes (Figure 7-12). These were active when Mars was young, but as this relatively small planet cooled down and its interior solidified, the supply of molten material to the volcanoes from the Martian interior was cut off. As a result, all of the volcanoes of Mars are now inactive.

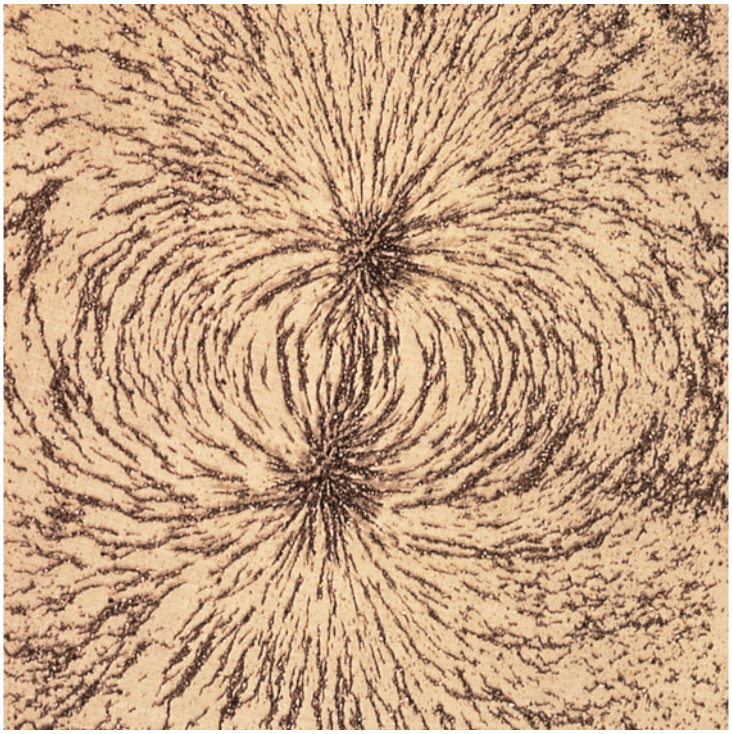
As for all rules, there are limitations and exceptions to the rule relating a world's size to its geologic activity. One limitation is that the four terrestrial planets all have slightly different compositions, which affects the types and extent of geologic activity that can take place on their surfaces. This also complicates the relationship between the number of craters and the age of the surface. An important exception to our rule is Jupiter's satellite Io, which, despite its small size, is the most volcanic world in the solar system (see Section 7-2). Something must be supplying Io with energy to keep its interior hot; this turns out to be Jupiter, which exerts powerful tides on Io as it moves in a relatively small orbit around its planet. These tides cause Io to flex like a ball of clay being kneaded between your fingers, and this flexing heats up the satellite's interior. But despite these limitations and exceptions, the relationships between a world's size, internal heat, geologic activity, and amount of cratering are powerful tools for understanding the terrestrial planets and satellites.

7-7 A planet with a magnetic field indicates a fluid interior in motion

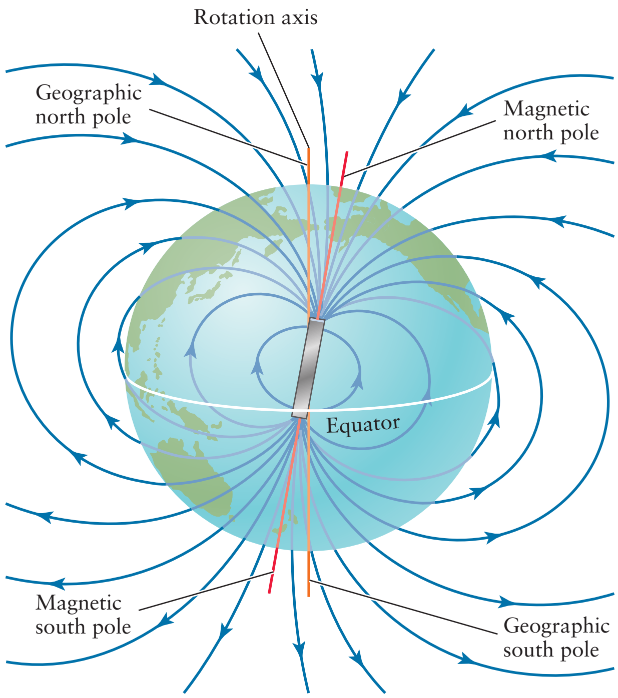
The amount of impact cratering on a terrestrial planet or satellite provides indirect evidence about whether the planet or satellite has a molten interior. But another, more direct tool for probing the interior of *any* planet or satellite is an ordinary compass, which senses the magnetic field outside the planet or satellite. Magnetic field measurements prove to be an extremely powerful way to investigate the internal structure of a world without having to actually dig into its interior. To illustrate how this works, consider the behavior of a compass on Earth.

By studying the magnetic field of a planet or satellite, scientists can learn about that world's interior motions

The needle of a compass on Earth points north because it aligns with the Earth's *magnetic field*. Such fields arise whenever electrically charged particles are in motion. For example, a loop of wire carrying an electric current generates a magnetic field in the space around it. The magnetic field that surrounds an ordinary bar magnet (Figure 7-13*a*) is created by the motions of negatively charged electrons within the iron atoms of which the magnet is made. The Earth's magnetic field is similar to that of a bar magnet, as Figure 7-13*b* shows. The consensus among geolo-



(a)



(b)

Figure 7-13

The Magnetic Fields of a Bar Magnet and of the Earth **(a)** This picture was made by placing a piece of paper on top of a bar magnet, then spreading iron filings on the paper. The pattern of the filings show the magnetic field lines, which appear to stream from one of the magnet's poles to the other. **(b)** The Earth's magnetic field lines have a similar pattern. Although the Earth's field is produced in a different way—by electric currents in the liquid portion of our planet's interior—the field is much the same as if there were a giant bar magnet inside the Earth. This "bar magnet" is not exactly aligned with the Earth's rotation axis, which is why the magnetic north and south poles are not at the same locations as the true, or geographic, poles. A compass needle points toward the north magnetic pole, not the true north pole. (a: Jules Bucher/Photo Researchers)

gists is that this magnetic field is caused by the motion of the liquid portions of the Earth's interior. Because this molten material (mostly iron) conducts electricity, these motions give rise to electric currents, which in turn produce the Earth's magnetic field. Our planet's rotation helps to sustain these motions and hence the magnetic field. This process for producing a magnetic field is called a **dynamo.**

CAUTION! While the Earth's magnetic field is similar to that of a giant bar magnet, you should not take this picture too literally. The Earth is *not* simply a magnetized ball of iron. In an iron bar magnet, the electrons of different atoms orbit their nuclei in the same general direction, so that the magnetic fields generated by individual atoms add together to form a single, strong field. But at temperatures above 770°C (1418°F = 1043 K), the orientations of the electron orbits become randomized. The fields of individual atoms tend to cancel each other out, and the iron loses its magnetism. Geological evidence shows that almost all of the Earth's interior is hotter than 770°C, so the iron there cannot be extensively magnetized. The correct picture is that the Earth acts as a dynamo: The liquid iron carries electric currents, and these currents create the Earth's magnetic field.

If a planet or satellite has a mostly solid interior, then the dynamo mechanism cannot work: Material in the interior cannot flow, there are no electric currents, and the planet or satellite does not generate a magnetic field. One example of this is the Moon. As we saw in Section 7-6, the extensive cratering of the lunar surface indicates that the Moon has no geologic activity and must therefore have a mostly solid interior. Measurements made during the *Apollo* missions, in which 12 humans visited the lunar surface between 1969 and 1972, showed that the present-day Moon indeed has no global magnetic field. However, careful magnetic measurements of lunar rocks returned by the *Apollo* astronauts indicate that the Moon *did* have a weak magnetic field when the rocks solidified. These rocks, like the rest of the lunar surface, are very old. Hence, in the distant past the Moon may have had a small amount of molten iron in its interior that acted as a dynamo. This material presumably solidified at least partially as the Moon cooled, so that the lunar magnetic field disappeared.

We have now identified another general rule about planets and satellites:

A planet or satellite with a global magnetic field has liquid material in its interior that conducts electricity and is in motion, generating the magnetic field.

Thus, by studying the magnetic field of a planet or satellite, we can learn about that world's interior. This explains why many spacecraft carry devices called **magnetometers** to measure magnetic fields. Magnetometers are often placed on a long boom extending outward from the body of the spacecraft (Figure 7-14). This isolates them from the magnetic fields produced by electric currents in the spacecraft's own circuitry.

Measurements made with magnetometers on spacecraft have led to a number of striking discoveries. For example, it has been found that Mercury has a planetwide magnetic field like the Earth's, although it is only about 1% as strong as the Earth's field. Mercury has a heavily cratered surface and hence little or no geologic activity, which by itself would suggest that the planet's interior is mostly solid. The magnetic field measurements show that *some* of Mercury's interior must be in the liquid state to act as a dynamo. By contrast, Venus has no measurable planetwide magnetic field, even though the paucity of craters on its surface indicates the presence of geologic activity and hence a hot interior of the planet. One possible reason for the lack of a magnetic field on Venus is that the planet turns on its axis very slowly, taking 243 days for a complete rotation. Because of this slow rotation, the fluid material within the planet is hardly agitated at all, and so may not move in the fashion that generates a magnetic field.

Like Venus, Mars has no planetwide magnetic field. But the magnetometer aboard the *Mars Global Surveyor* spacecraft, which went into orbit around Mars in 1997, found magnetized regions in the cratered highlands of the Martian southern hemisphere (Figure 7-15). As we saw in Section 7-6, these portions of the Martian surface are very old, and so would have formed when the planet's interior was still hot and molten. Electric currents in the flowing molten material could then produce a planetwide magnetic field. As surface material cooled and solidified, it became magnetized by the planetwide field, and this material has retained its magnetization over the eons. *Mars Global Surveyor* has not found magnetized areas in the younger terrain of the lowlands. Hence, the planetwide Martian magnetic field must have shut off by the time the lowland terrain formed.

The most intense planetary magnetic field in the solar system is that of Jupiter: at the tops of Jupiter's clouds, the magnetic field is about 14 times stronger than the field at the Earth's surface. It is thought that Jupiter's field, like the Earth's, is produced by a dynamo acting deep within the planet's interior. Unlike the Earth, however, Jupiter is composed primarily of hydrogen and helium, not substances like iron that conduct electricity. How, then, can Jupiter have a dynamo that generates such strong magnetic fields?

To answer this question, recall from Section 5-8 that a hydrogen atom consists of a single proton orbited by a single electron. Deep inside Jupiter, the pressure is so great and hydrogen atoms are squeezed so close together that electrons can hop from one atom to another. This hopping motion creates an electric current, just as the ordered movement of electrons in the copper wires of a flashlight constitutes an electric current. In other words, the highly compressed hydrogen deep inside Jupiter behaves like an electrically conducting metal; thus, it is called **liquid metallic hydrogen.**

Laboratory experiments show that hydrogen becomes a liquid metal when the pressure is more than about 1.4 million times ordinary atmospheric pressure on Earth. Recent calculations suggest that this transition occurs about 7000 km below Jupiter's cloudtops. Most of the planet's enormous bulk lies below this level, so there is a tremendous amount of liquid metallic hydrogen within Jupiter. Since Jupiter rotates rapidly—a "day" on Jupiter is just less than 10 hours long—this liquid metal moves rapidly, generating the planet's powerful magnetic field. Saturn

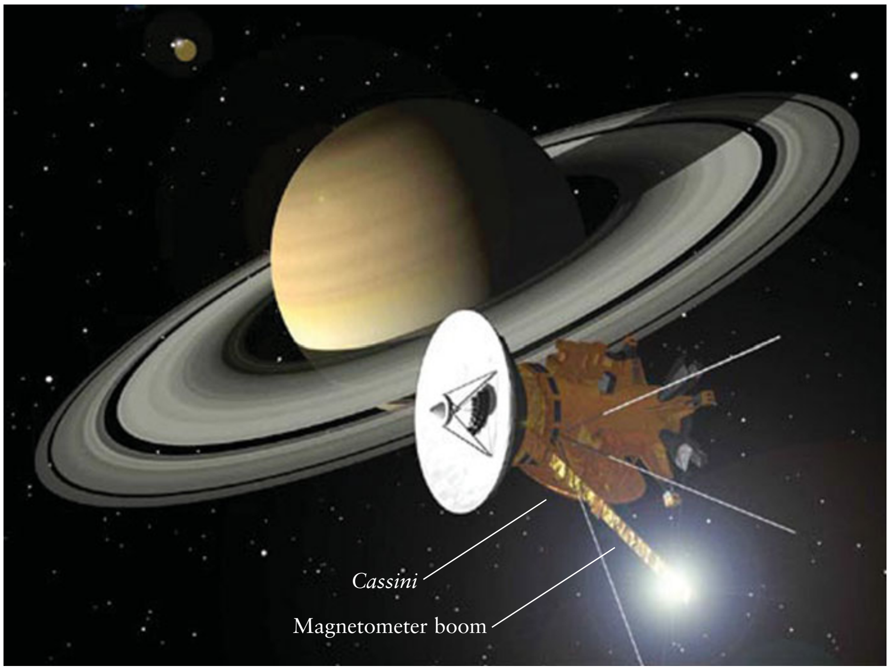


Figure 7-14

Probing the Magnetic Field of Saturn This illustration depicts the *Cassini* spacecraft as it entered orbit around Saturn on July 1, 2004. In addition to telescopes for observing Saturn and its satellites, *Cassini* carries a magnetometer for exploring Saturn's magnetic field. The magnetometer is located on the long boom that extends down and to the right from the body of the spacecraft. (The glow at the end of the boom is the reflection of the Sun.) (JPL/NASA)

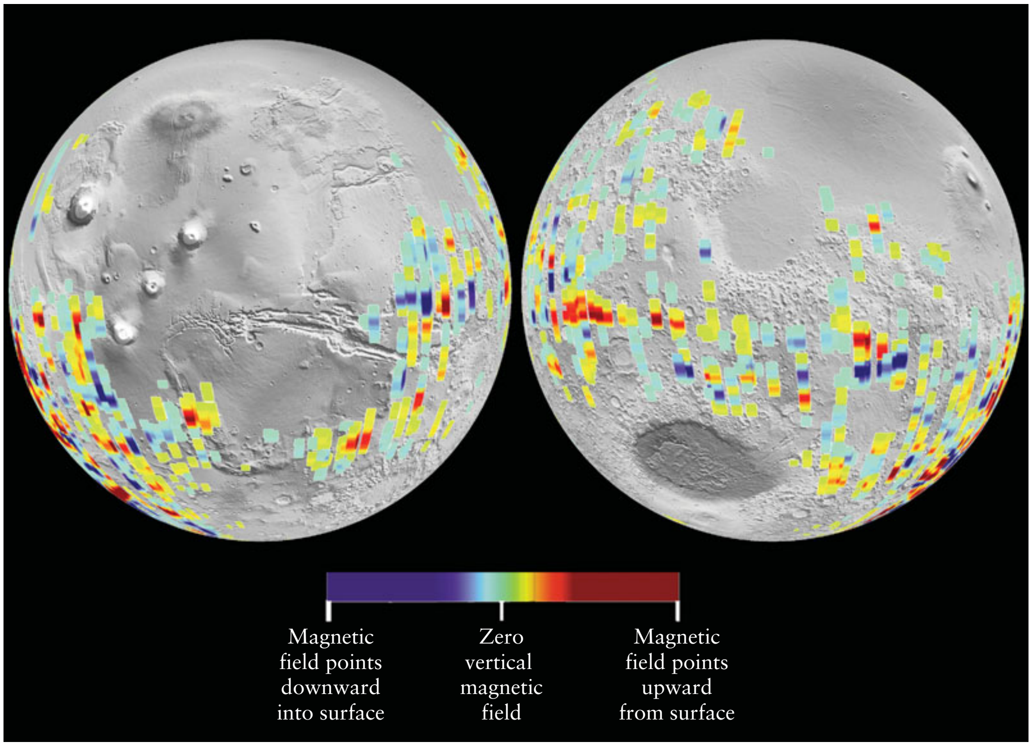


Figure 7-15

Relic Magnetism on Mars Portions of the highlands of Mars became magnetized during the period early in Martian history when the planet had an extensive magnetic field. The planetwide field has long since disappeared, but certain surface regions remained magnetized. The false colors in this illustration indicate the direction and strength of the field at different locations on Mars superimposed on images of the two Martian hemispheres. (MGS Magnetometer Team, GSFC/NASA)

also has a magnetic field produced by dynamo action in liquid metallic hydrogen. (The field is weaker than Jupiter's because Saturn is a smaller planet with less internal pressure, so there is less of the liquid metal available.)

Uranus and Neptune also have magnetic fields, but they cannot be produced in the same way: Because these planets are relatively small, the internal pressure is not great enough to turn liquid hydrogen into a metal. Instead, it is thought that both Uranus and Neptune have large amounts of liquid water in their interiors and that this water has molecules of ammonia and other substances dissolved in it. (The fluid used for washing windows has a similar chemical composition.) Under the pressures found in this interior water, the dissolved molecules lose one or more electrons and become electrically charged (that is, they become ionized; see Section 5-8). Water is a good conductor of electricity when it has such electrically charged molecules dissolved in it, and electric currents in this fluid are probably the source of the magnetic fields of Uranus and Neptune.

7-8 The diversity of the solar system is a result of its origin and evolution

Our brief tour of the solar system has revealed its almost dizzying variety. No two planets are alike, satellites come in all sizes, the extent of cratering varies from one terrestrial planet to another, and the magnetic fields of different planets vary dramatically in their strength and in how they are produced. (The *Cosmic Connections* figure that closes this chapter summarizes these properties of the planets.) All of this variety leads us to a simple yet profound question: *Why* are the planets and satellites of the solar system so different from each other?

The similarities and differences among the planets can be logically explained by a model of the solar system's origin and evolution

Among humans, the differences from one individual to another result from heredity (the genetic traits passed on from an individual's parents) and environment (the circumstances under which the individual matures to an adult). As we will find in the fzollowing chapter, much the same is true for the worlds of the solar system.

In Chapter 8 we will see evidence that the entire solar system shares a common "heredity," in that the planets, satellites, comets, asteroids, and the Sun itself formed from the same cloud of interstellar gas and dust. The composition of this cloud was shaped by cosmic processes, including nuclear reactions that took place within stars that died long before our solar system was formed. We will see how different planets formed in different environments depending on their distance from the Sun and will discover how these environmental variations gave rise to the planets and satellites of our present-day solar system. And we will see how we can test these ideas of solar system origin and evolution by studying planetary systems orbiting other stars.

Our journey through the solar system is just beginning. In this chapter we have explored space to examine the variety of the present-day solar system; in Chapter 8 we will journey through time to see how our solar system came to be.

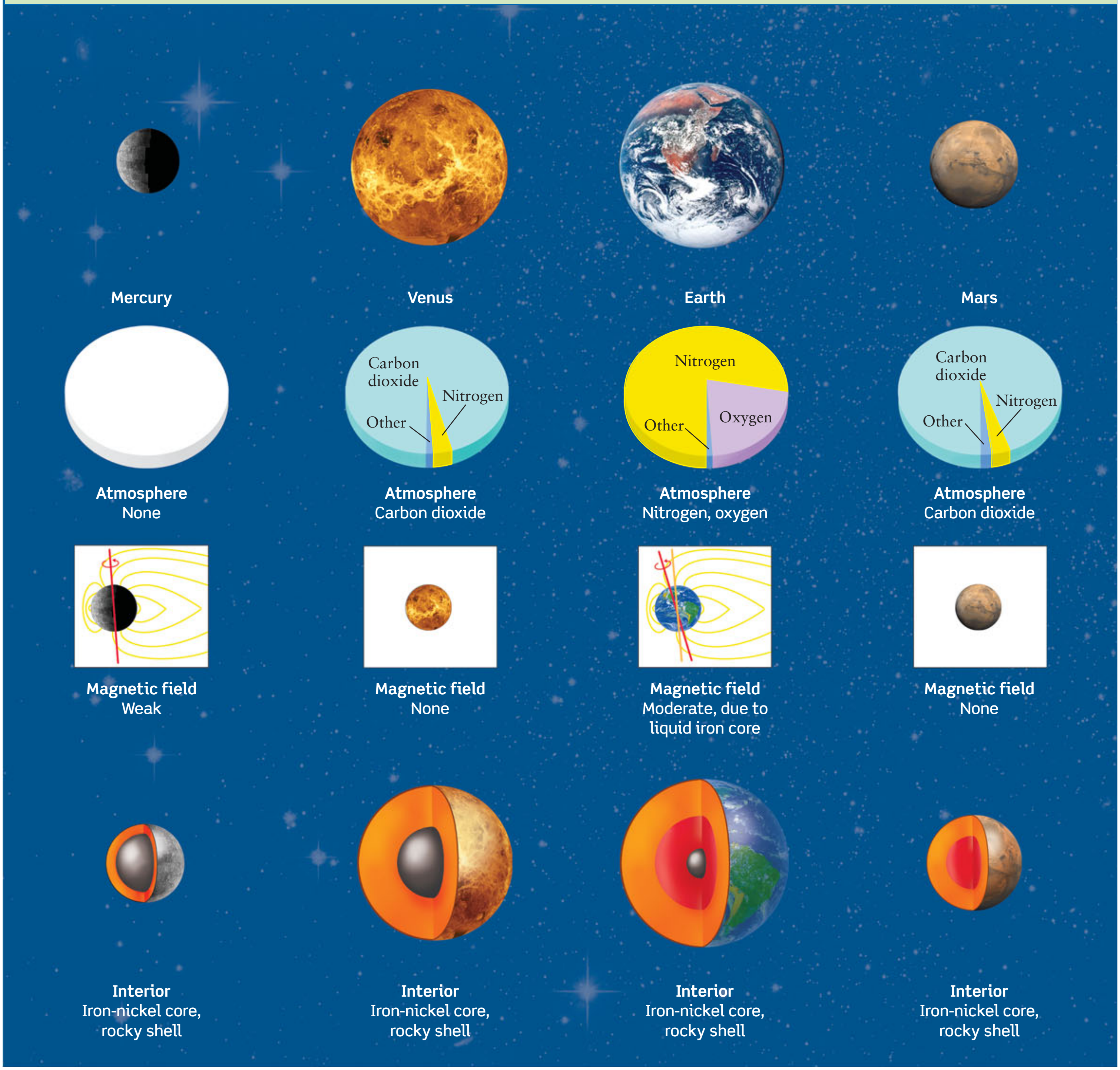
COSMIC CONNECTIONS

Characteristics of the Planets

The Inner (Terrestrial) Planets

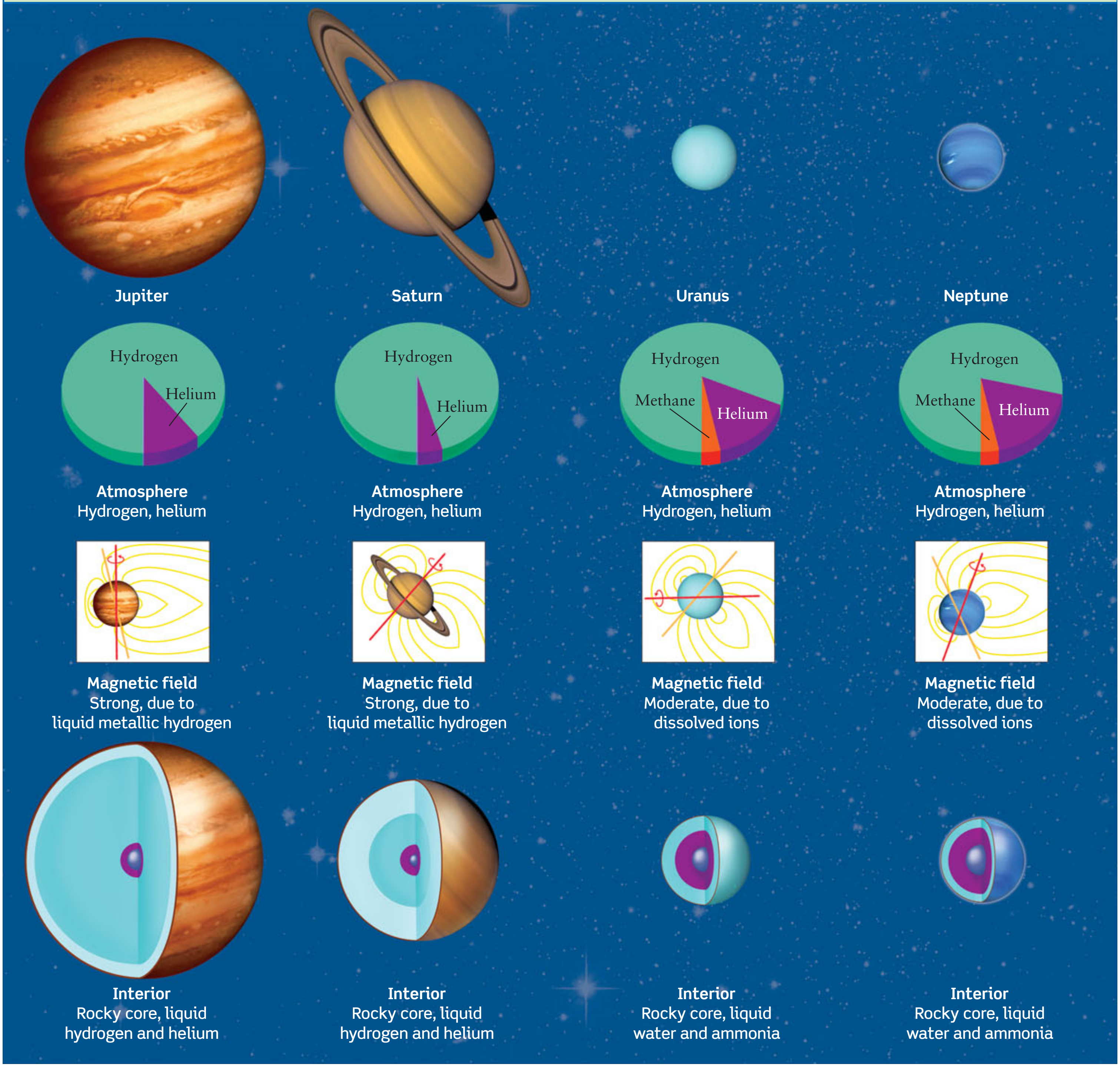
Close to the Sun - Small diameter, small mass - High density

	Mercury	Venus	Earth	Mars
Average distance from Sun (AU)	0.387	0.723	1.000	1.524
Equatorial diameter (Earth = 1)	0.383	0.949	1.000	0.533
Mass (Earth = 1)	0.0553	0.8150	1.0000	0.1074
Average density (kg/m^3)	5430	5243	5515	3934



The Outer (Jovian) Planets Far from the Sun - Large diameter, large mass - Low density

	Jupiter	Saturn	Uranus	Neptune
Average distance from Sun (AU)	5.203	9.554	19.194	30.066
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883
Mass (Earth = 1)	317.8	95.16	14.53	17.15
Average density (kg/m^3)	1326	687	1318	1638



Key Words

Terms preceded by an asterisk (*) are discussed in the Boxes.

asteroid, p. 170
asteroid belt, p. 170
average density, p. 162
chemical composition, p. 164
comet, p. 172
dynamo, p. 175
*escape speed, p. 169
ices, p. 167
impact crater, p. 172
Jovian planet, p. 162
*kinetic energy, p. 168
Kuiper belt, p. 170
liquid metallic hydrogen, p. 176
magnetometer, p. 176
meteoroid, p. 172
minor planet, p. 170
Oort cloud, p. 172
spectroscopy, p. 164
terrestrial planet, p. 162
trans-Neptunian object, p. 170

Key Ideas

Properties of the Planets: All of the planets orbit the Sun in the same direction and in almost the same plane. Most of the planets have nearly circular orbits.

• The four inner planets are called terrestrial planets. They are relatively small (with diameters of 5000 to 13,000 km), have high average densities (4000 to 5500 kg/m^3), and are composed primarily of rocky materials.

• The four giant outer planets are called Jovian planets. They have large diameters (50,000 to 143,000 km) and low average densities (700 to 1700 kg/m^3) and are composed primarily of light elements such as hydrogen and helium.

Satellites and Small Bodies in the Solar System: Besides the planets, the solar system includes satellites of the planets, asteroids, comets, and trans-Neptunian objects.

• Seven large planetary satellites (one of which is the Moon) are comparable in size to the planet Mercury. The remaining satellites of the solar system are much smaller.

• Asteroids are small, rocky objects, while comets and trans-Neptunian objects are made of ice and rock. All are remnants left over from the formation of the planets.

• Most asteroids are found in the asteroid belt between the orbits of Mars and Jupiter, and most trans-Neptunian objects lie in the Kuiper belt outside the orbit of Neptune. Pluto is one of the largest members of the Kuiper belt.

Spectroscopy and the Composition of the Planets: Spectroscopy, the study of spectra, provides information about the chemical composition of objects in the solar system.

• The spectrum of a planet or satellite with an atmosphere reveals the atmosphere's composition. If there is no atmosphere, the spectrum indicates the composition of the surface.

• The substances that make up the planets can be classified as gases, ices, or rock, depending on the temperatures at which they solidify.

Impact Craters: When an asteroid, comet, or meteoroid collides with the surface of a terrestrial planet or satellite, the result is an impact crater.

• Geologic activity renews the surface and erases craters, so a terrestrial world with extensive cratering has an old surface and little or no geologic activity.

• Because geologic activity is powered by internal heat, and smaller worlds lose heat more rapidly, as a general rule smaller terrestrial worlds are more extensively cratered.

Magnetic Fields and Planetary Interiors: Planetary magnetic fields are produced by the motion of electrically conducting liquids inside the planet. This mechanism is called a dynamo. If a planet has no magnetic field, that is evidence that there is little such liquid material in the planet's interior or that the liquid is not in a state of motion.

• The magnetic fields of terrestrial planets are produced by metals such as iron in the liquid state. The stronger fields of the Jovian planets are generated by liquid metallic hydrogen or by water with ionized molecules dissolved in it.

Questions

Review Questions

1. Do all the planets orbit the Sun in the same direction? Are all of the orbits circular?
2. What are the characteristics of a terrestrial planet?
3. What are the characteristics of a Jovian planet?
4. What is meant by the average density of a planet? What does the average density of a planet tell us?
5. In what ways are the largest satellites similar to the terrestrial planets? In what ways are they different? Which satellites are the largest?
6. The absorption lines in the spectrum of a planet or satellite do not necessarily indicate the composition of the planet or satellite's atmosphere. Why not?
7. What are the differences in chemical composition between the terrestrial and Jovian planets?
8. Why are hydrogen and helium abundant in the atmospheres of the Jovian planets but present in only small amounts in the Earth's atmosphere?
9. What is an asteroid? What is a trans-Neptunian object? In what ways are these minor members of the solar system like or unlike the planets?
10. What are the asteroid belt, the Kuiper belt, and the Oort cloud? Where are they located? How do the objects found in these three regions compare?
11. In what ways is Pluto similar to a terrestrial planet? In what ways is it different?
12. What is the connection between comets and the Kuiper belt? Between comets and the Oort cloud?
13. What is one piece of evidence that impact craters are actually caused by impacts?

14. What is the relationship between the extent to which a planet or satellite is cratered and the amount of geologic activity on that planet or satellite?
15. How do we know that the surface of Venus is older than the Earth's surface but younger than the Moon's surface?
16. Why do smaller worlds retain less of their internal heat?
17. How does the size of a terrestrial planet influence the amount of cratering on the planet's surface?
18. How is the magnetic field of a planet different from that of a bar magnet? Why is a large planet more likely to have a magnetic field than a small planet?
19. Could you use a compass to find your way around Venus? Why or why not?
20. If Mars has no planetwide magnetic field, why does it have magnetized regions on its surface?
21. What is liquid metallic hydrogen? Why is it found only in the interiors of certain planets?

Advanced Questions

Questions preceded by an asterisk (*) involve topics discussed in the Boxes.

> **Problem-solving tips and tools**
>
> The volume of a sphere of radius r is $4\pi r^3/3$, and the surface area of a sphere of radius r is $4\pi r^2$. The surface area of a circle of radius r is πr^2. The average density of an object is its mass divided by its volume. To calculate escape speeds, you will need to review Box 7-2. Be sure to use the same system of units (meters, seconds, kilograms) in all your calculations involving escape speeds, orbital speeds, and masses. Appendix 6 gives conversion factors between different sets of units, and Box 5-1 has formulas relating various temperature scales.

22. Mars has two small satellites, Phobos and Deimos. Phobos circles Mars once every 0.31891 day at an average altitude of 5980 km above the planet's surface. The diameter of Mars is 6794 km. Using this information, calculate the mass and average density of Mars.
23. Figure 7-3 shows the spectrum of Saturn's largest satellite, Titan. Can you think of a way that astronomers can tell which absorption lines are due to Titan's atmosphere and which are due to the atmospheres of the Sun and Earth? Explain.

*24. (**a**) Find the mass of a hypothetical spherical asteroid 2 km in diameter and composed of rock with average density 2500 kg/m^3. (**b**) Find the speed required to escape from the surface of this asteroid. (**c**) A typical jogging speed is 3 m/s. What would happen to an astronaut who decided to go for a jog on this asteroid?

*25. The hypothetical asteroid described in Question 24 strikes the Earth with a speed of 25 km/s. (**a**) What is the kinetic energy of the asteroid at the moment of impact? (**b**) How does this energy compare with that released by a 20-kiloton nuclear weapon, like the device that destroyed Hiroshima, Japan, on August 6, 1945? (*Hint:* 1 kiloton of TNT releases 4.2×10^{12} joules of energy.)

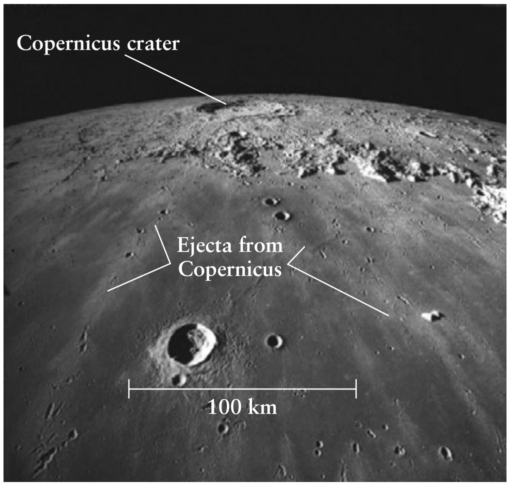
*26. Suppose a spacecraft landed on Jupiter's moon Europa (see Table 7-2), which moves around Jupiter in an orbit of radius 670,900 km. After collecting samples from the satellite's surface, the spacecraft prepares to return to Earth. (**a**) Calculate the escape speed from Europa. (**b**) Calculate the escape speed from Jupiter at the distance of Europa's orbit. (**c**) In order to begin its homeward journey, the spacecraft must leave Europa with a speed greater than either your answer to (a) or your answer to (b). Explain why.

*27. A hydrogen atom has a mass of 1.673×10^{-27} kg, and the temperature of the Sun's surface is 5800 K. What is the average speed of hydrogen atoms at the Sun's surface?

*28. The Sun's mass is 1.989×10^{30} kg, and its radius is 6.96×10^8 m. (**a**) Calculate the escape speed from the Sun's surface. (**b**) Using your answer to Question 27, explain why the Sun has lost very little hydrogen over its entire 4.56-billion-year history.

*29. Saturn's satellite Titan has an appreciable atmosphere, yet Jupiter's satellite Ganymede—which is about the same size and mass as Titan—has no atmosphere. Explain why there is a difference.

30. The distance from the asteroid 433 Eros (Figure 7-7) to the Sun varies between 1.13 and 1.78 AU. (**a**) Find the period of Eros's orbit. (**b**) Does Eros lie in the asteroid belt? How can you tell?
31. Imagine a trans-Neptunian object with roughly the same mass as Earth but located 50 AU from the Sun. (**a**) What do you think this object would be made of? Explain your reasoning. (**b**) On the basis of this speculation, assume a reasonable density for this object and calculate its diameter. How many times bigger or smaller than Earth would it be?
32. Consider a hypothetical trans-Neptunian object located 100 AU from the Sun. (**a**) What would be the orbital period (in years) of this object? (**b**) There are 360 degrees in a circle, and 60 arcminutes in a degree. How long would it take this object to move 1 arcminute across the sky? (**c**) Trans-Neptunian objects are discovered by looking for "stars" that move on the celestial sphere. Use your answer from part (b) to explain why these discoveries require patience. (**d**) Discovering trans-Neptunian objects also requires large telescopes equipped with sensitive detectors. Explain why.
33. The surfaces of Mercury, the Moon, and Mars are riddled with craters formed by the impact of space debris. Many of these craters are billions of years old. By contrast, there are only a few conspicuous craters on the Earth's surface, and these are generally less than 500 million years old. What do you suppose explains the difference?
34. During the period of most intense bombardment by space debris, a new 1-km-radius crater formed somewhere on the Moon about once per century. During this same period, what was the probability that such a crater would be created within 1 km of a certain location on the Moon during a 100-year period? During a 10^6-year period? (*Hint:* If you drop a coin onto a checkerboard, the probability that the coin will land on any particular one of the board's 64 squares is $^1/_{64}$.)



R I V U X G

(Courtesy of USRA)

35. When an impact crater is formed, material (called *ejecta*) is sprayed outward from the impact. (The accompanying photograph of the Moon shows light-colored ejecta extending outward from the crater Copernicus.) While ejecta are found surrounding the craters on Mercury, they do not extend as far from the craters as do ejecta on the Moon. Explain why, using the difference in surface gravity between the Moon (surface gravity = 0.17 that on Earth) and Mercury (surface gravity = 0.38 that on Earth).
36. Mercury rotates once on its axis every 58.646 days, compared to 1 day for the Earth. Use this information to argue why Mercury's magnetic field should be much smaller than the Earth's.
37. Suppose *Mars Global Surveyor* had discovered magnetized regions in the lowlands of Mars. How would this discovery have affected our understanding of the evolution of the Martian interior?
38. Liquid metallic hydrogen is the source of the magnetic fields of Jupiter and Saturn. Explain why liquid metallic hydrogen cannot be the source of the Earth's magnetic field.

Discussion Questions

*39. There are no asteroids with an atmosphere. Discuss why not.
40. The *Galileo* spacecraft that orbited Jupiter from 1995 to 2003 discovered that Ganymede (Table 7-2) has a magnetic field twice as strong as that of Mercury. Does this discovery surprise you? Why or why not?

Web/eBook Questions

41. Search the World Wide Web for information about impact craters on Earth. Where is the largest crater located? How old is it estimated to be? Which crater is closest to where you live?

STARRY NIGHT

42. **Determining Terrestrial Planet Orbital Periods.** Access the animation "Planetary Orbits" in Chapter 7 of the *Universe* Web site or eBook. Focus on the motions of the inner planets at the last half of the animation. Using the stop and start buttons, determine how many days it takes Mars, Venus, and Mercury to orbit the Sun once if Earth takes approximately 365 days.

Activities

Observing Projects

43. Use a telescope or binoculars to observe craters on the Moon. Make a drawing of the Moon, indicating the smallest and largest craters that you can see. Can you estimate their sizes? For comparison, the Moon as a whole has a diameter of 3476 km. *Hint:* You can see craters most distinctly when the Moon is near first quarter or third quarter (see Figure 3-2). At these phases, the Sun casts long shadows across the portion of the Moon in the center of your field of view, making the variations in elevation between the rims and centers of craters easy to identify. You can determine the phase of the Moon by looking at a calendar or the weather page of the newspaper, by using the *Starry Night Enthusiast*™ program, or on the World Wide Web.

ANIMATION 7.1

44. Use the *Starry Night Enthusiast*™ program to examine magnified images of the terrestrial planets Mercury, Venus, Earth, and Mars and the asteroid Ceres. In the **Favourites** menu, under the **Solar System** submenu, select the desired planet. This will place you in the position of an astronaut orbiting above the surface of the planet. The astronaut's spacesuit and feet are shown in the foreground in this view but can be removed by clicking on **View > Feet.** To show the planet as we see it from Earth, we need to show its atmosphere. Select **Solar System > Planets-Moons . . .** in the **Options** menu. In the Planets-Moons Options dialog that pops up, click on the **Show atmosphere** checkbox to turn this option on and then click the **OK** button. The mouse icon will change to the **location scroller** when moved over the planet. You can use this scroller to rotate the image to see different views of the planet. This is equivalent to flying around the planet at a fixed distance. Follow the above steps to examine each planet and asteroid from different viewpoints and describe each planet's appearance. From what you observe in each case, is there any way of knowing whether you are looking at a planet's surface or at complete cloud cover over the planet? Which planet or planets have clouds? Which planet or asteroid shows the heaviest cratering? Which of these planets show evidence of liquid water?

STARRY NIGHT

45. Use the *Starry Night Enthusiast*™ program to examine the Jovian planets Jupiter, Saturn, Uranus, and Neptune. Select each of these planets from the **Solar System** submenu in the **Favourites** menu. If you desire, you can remove the image of the astronaut's feet by selecting **Feet** in the **View** menu. Position the mouse cursor over the planet and click and drag the image to examine the planet from different views. Describe each planet's appearance. Which has the greatest color contrast in its cloud tops? Which has the least color contrast? What can

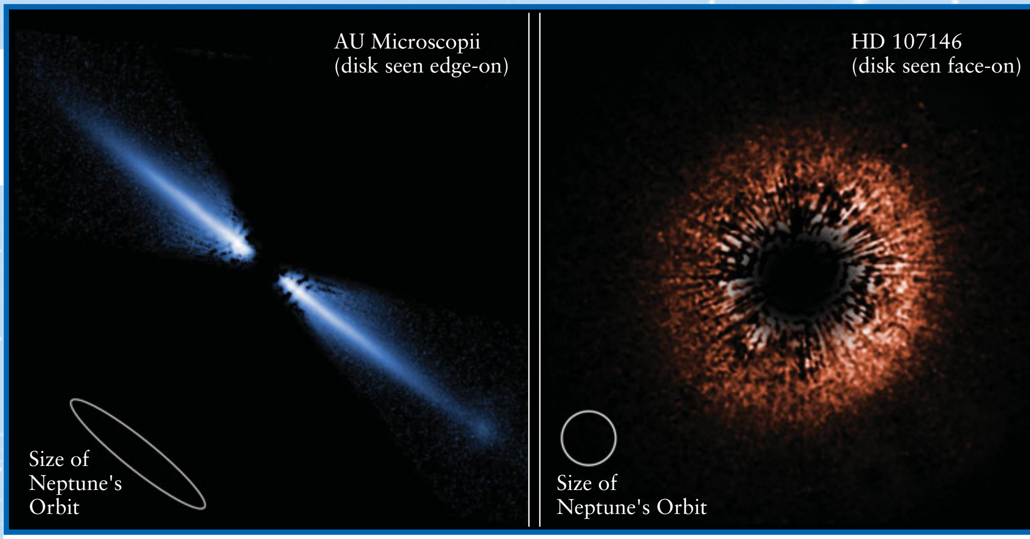
you say about the thickness of Saturn's rings compared to their diameter?

46. Use the ***Deep Space Explorer™*** program to examine the Jovian planets Jupiter, Saturn, Uranus, and Neptune. In the left-hand part of the window, under the heading **Solar System** select **Explore.** Then click on the name of each planet to view it in detail. You can zoom in and zoom out using the buttons at the upper left of the window (an upward-pointing triangle and a downward-pointing triangle). You can also rotate the planet by putting the mouse cursor over the image of the planet or asteroid, holding down the mouse button, and moving the mouse. (On a two-button mouse, hold down the left mouse button.) Describe each planet's appearance. Which has the greatest color contrast in its cloudtops? Which has the least color contrast? What can you say about the thickness of Saturn's rings compared to their diameter?

This page intentionally left blank

8

Comparative Planetology II: The Origin of Our Solar System



WEB LINK 8.1

R I V U X G

Planets are thought to form within the disks surrounding young stars such as these. Neptune's orbit, shown for scale, is about 60 AU across. (NASA, ESA, D. R. Ardila (JHU), D. A. Golimowski (JHU), J. E. Krist (STScI/JPL), M. Clampin (NASA/GSFC), J. P. Williams (UH/IfA), J. P. Blakeslee (JHU), H. C. Ford (JHU), G. F. Hartig (STScI), G. D. Illingworth (UCO-Lick) and the ACS Science Team)

What did our solar system look like before the planets were fully formed? The answer may lie in these remarkable images from the Hubble Space Telescope. Each image shows an immense disk of gas and dust centered on a young star. (In each image the light from the star itself was blocked out within the telescope to make the rather faint disk more visible.) Astronomers strongly suspect that in its infancy our own Sun was surrounded by a disk of this kind and that the planets coalesced from it.

In this chapter we will examine the evidence that led astronomers to this picture of the origin of the planets. We will see how the abundances of different chemical elements in the solar system indicate that the Sun and planets formed from a thin cloud of interstellar matter some 4.56 billion years ago, an age determined by measuring the radioactivity of meteorites. We will learn how the nature of planetary orbits gives important clues to what happened as this cloud contracted and how evidence from meteorites reveals the chaotic conditions that existed within the cloud. And we will see how this cloud eventually evolved into the solar system that we see today.

In the past few years astronomers have been able to test this picture of planetary formation by examining disks around young stars (like the ones in the accompanying images). Most remarkably of all, they have discovered planets in orbit around dozens of other stars. These recent observations provide valuable information about how our own system of planets came to be.

8-1 Any model of solar system origins must explain the present-day Sun and planets

How did the Sun and planets form? In other words, where did the solar system come from? This question has tantalized astronomers for centuries. Our goal in this chapter is to examine

Learning Goals

By reading the sections of this chapter, you will learn

8-1 The key characteristics of the solar system that must be explained by any theory of its origins

8-2 How the abundances of chemical elements in the solar system and beyond explain the sizes of the planets

8-3 How we can determine the age of the solar system by measuring abundances of radioactive elements

8-4 Why scientists think the Sun and planets all formed from a cloud called the solar nebula

8-5 How the solar nebula model explains the formation of the terrestrial planets

8-6 Two competing models for the origin of the Jovian planets

8-7 How astronomers test the solar nebula model by observing planets around other stars

Table 8-1 Three Key Properties of Our Solar System

Any theory of the origin of the solar system must be able to account for these properties of the planets.

Property 1: *Sizes and compositions of terrestrial planets versus Jovian planets*	The terrestrial planets, which are composed primarily of rocky substances, are relatively small, while the Jovian planets, which are composed primarily of hydrogen and helium, are relatively large (see Sections 7-1 and 7-4).
Property 2: *Directions and orientations of planetary orbits*	All of the planets orbit the Sun in the same direction, and all of their orbits are in nearly the same plane (see Section 7-1).
Property 3: *Sizes of terrestrial planet orbits versus Jovian planet orbits*	The terrestrial planets orbit close to the Sun, while the Jovian planets orbit far from the Sun (see Section 7-1).

our current understanding of how the solar system came to be—that is, our current best *theory* of the origin of the solar system.

Recall from Section 1-1 that a theory is not merely a set of wild speculations, but a self-consistent collection of ideas that must pass the test of providing an accurate description of the real world. Since no humans were present to witness the formation of the planets, scientists must base their theories of solar system origins on their observations of the present-day solar system. (In an analogous way, paleontologists base their understanding of the lives of dinosaurs on the evidence provided by fossils that have survived to the present day.) In so doing, they are following the steps of the scientific method that we described in Section 1-1.

What key attributes of the solar system should guide us in building a theory of solar system origins? Among the many properties of the planets that we discussed in Chapter 7, three of the most important are listed in Table 8-1.

Any theory that attempts to describe the origin of the solar system must be able to explain how these attributes came to be. We begin by considering what Property 1 tells us; we will return to Properties 2 and 3 and the orbits of the planets later in this chapter.

8-2 The cosmic abundances of the chemical elements are the result of how stars evolve

The small sizes of the terrestrial planets compared to the Jovian planets (Property 1 in Table 8-1) suggest that some chemical elements are quite common in our solar system, while others are quite rare. The tremendous masses of the Jovian planets—Jupiter alone has more mass than all of the other planets combined—means that the elements of which they are made, primarily hydrogen and helium, are very abundant. The Sun, too, is made almost entirely of hydrogen and helium: Its average density of 1410 kg/m^3 is in the same range as the densities of the Jovian planets (see Table 7-1), and its absorption spectrum (see Figure 5-12) shows the dominance of hydrogen and helium in the Sun's atmosphere. Hydrogen, the most abundant element, makes up nearly three-quarters of the combined mass of the Sun and planets. Helium is the second most abundant element. Together, hydrogen and helium account for about 98% of the mass of all the material in the solar system. All of the other chemical elements are relatively rare; combined, they make up the remaining 2% (Figure 8-1).

The terrestrial planets are small because they are made of less abundant elements

The dominance of hydrogen and helium is not merely a characteristic of our local part of the universe. By analyzing the spectra of stars and galaxies, astronomers have found essentially the same pattern of chemical abundances out to the farthest distance attainable by the most powerful telescopes. Hence, the vast majority of the atoms in the universe are hydrogen and helium atoms. The elements that make up the bulk of the Earth—mostly iron, oxygen, and silicon—are relatively rare in the universe as a whole, as are the elements of which living organisms are made—carbon, oxygen, nitrogen, and phosphorus, among others. (You may find

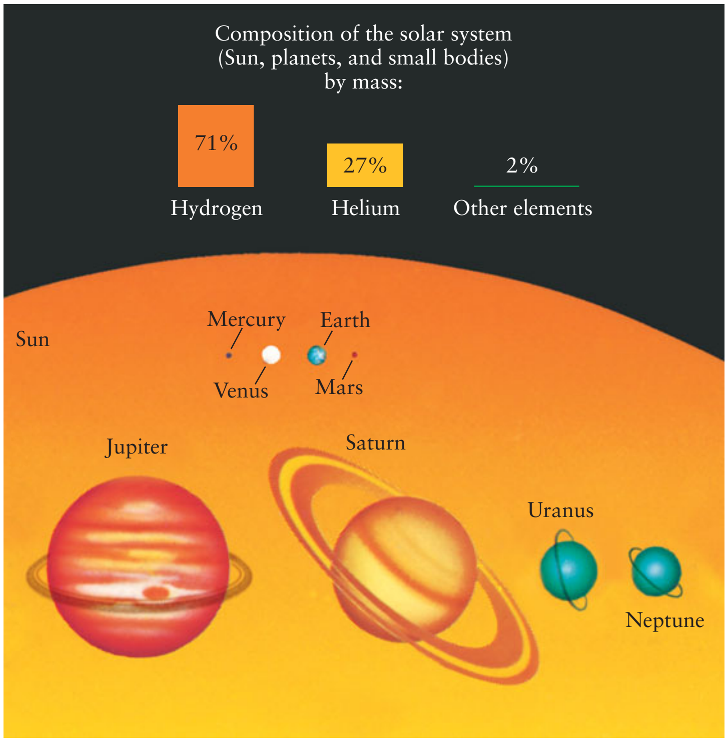


Figure 8-1

Composition of the Solar System Hydrogen and helium make up almost all of the mass of our solar system. Other elements such as carbon, oxygen, nitrogen, iron, gold, and uranium constitute only 2% of the total mass.

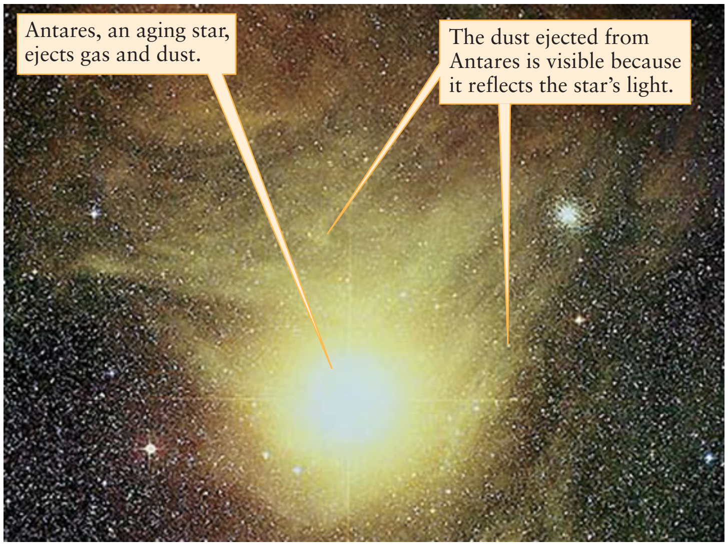


Figure 8-2 R I V U X G

A Mature Star Ejecting Gas and Dust The star Antares is shedding material from its outer layers, forming a thin cloud around the star. We can see the cloud because some of the ejected material has condensed into tiny grains of dust that reflect the star's light. (Dust particles in the air around you reflect light in the same way, which is why you can see them within a shaft of sunlight in a darkened room). Antares lies some 600 light-years from Earth in the constellation Scorpio. (David Malin/Anglo-Australian Observatory)

it useful to review the periodic table of the elements, described in Box 5-5.)

The Origin of the Elements and Cosmic "Recycling"

There is a good reason for this overwhelming abundance of hydrogen and helium. A wealth of evidence has led astronomers to conclude that the universe began some 13.7 billion years ago with a violent event called the Big Bang (see Section 1-4). Only the lightest elements—hydrogen and helium, as well as tiny amounts of lithium and perhaps beryllium—emerged from the enormously high temperatures following this cosmic event. All the heavier elements were manufactured by stars later, either by thermonuclear fusion reactions deep in their interiors or by the violent explosions that mark the end of massive stars. Were it not for these processes that take place only in stars, there would be no heavy elements in the universe, no planet like our Earth, and no humans to contemplate the nature of the cosmos.

Because our solar system contains heavy elements, it must be that at least some of its material was once inside other stars. But how did this material become available to help build our solar system? The answer is that near the ends of their lives, stars cast much of their matter back out into space. For most stars this process is a comparatively gentle one, in which a star's outer layers are gradually expelled. Figure 8-2 shows a star losing material in this fashion. This ejected material appears as the cloudy region, or **nebulosity** (from *nubes,* Latin for "cloud"), that surrounds the star and is illuminated by it. A few stars eject matter much more dramatically at the very end of their lives, in a spectacular detonation called a *supernova,* which blows the star apart (see Figure 1-6).

No matter how it escapes, the ejected material contains heavy elements dredged up from the star's interior, where they were formed. This material becomes part of the **interstellar medium,** a tenuous collection of gas and dust that pervades the spaces between the stars. As different stars die, they increasingly enrich the interstellar medium with heavy elements. Observations show that new stars form as condensations in the interstellar medium (Figure 8-3). Thus, these new stars have an adequate supply of heavy elements from which to develop a system of planets, satellites, comets, and asteroids. Our own solar system must have formed from enriched material in just this way. Thus, our solar system contains "recycled" material that was produced long ago inside a now-dead star. This "recycled" material includes all of the carbon in your body, all of the oxygen that you breathe, and all of the iron and silicon in the soil beneath your feet.

The Abundances of the Elements

Stars create different heavy elements in different amounts. For example, oxygen (as well as carbon, silicon, and iron) is readily produced in the interiors of massive stars, whereas gold (as well as silver, platinum, and uranium) is created only under special

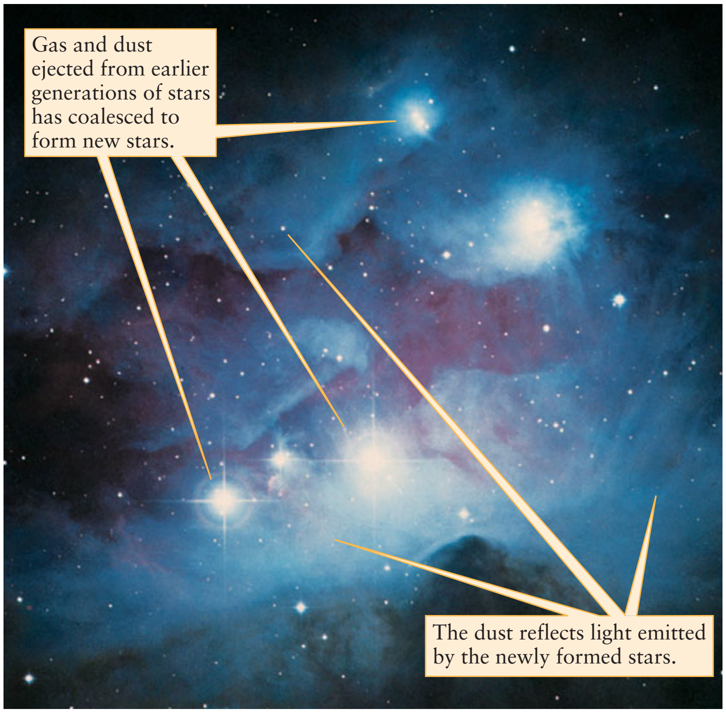


Figure 8-3 R I V U X G

New Stars Forming from Gas and Dust Unlike Figure 8-2, which depicts an old star that is ejecting material into space, this image shows young stars in the constellation Orion (the Hunter) that have only recently formed from a cloud of gas and dust. The bluish, wispy appearance of the cloud (called NGC 1973-1975-1977) is caused by starlight reflecting off interstellar dust grains within the cloud (see Box 5-4). The grains are made of heavy elements produced by earlier generations of stars. (David Malin/Anglo-Australian Observatory)

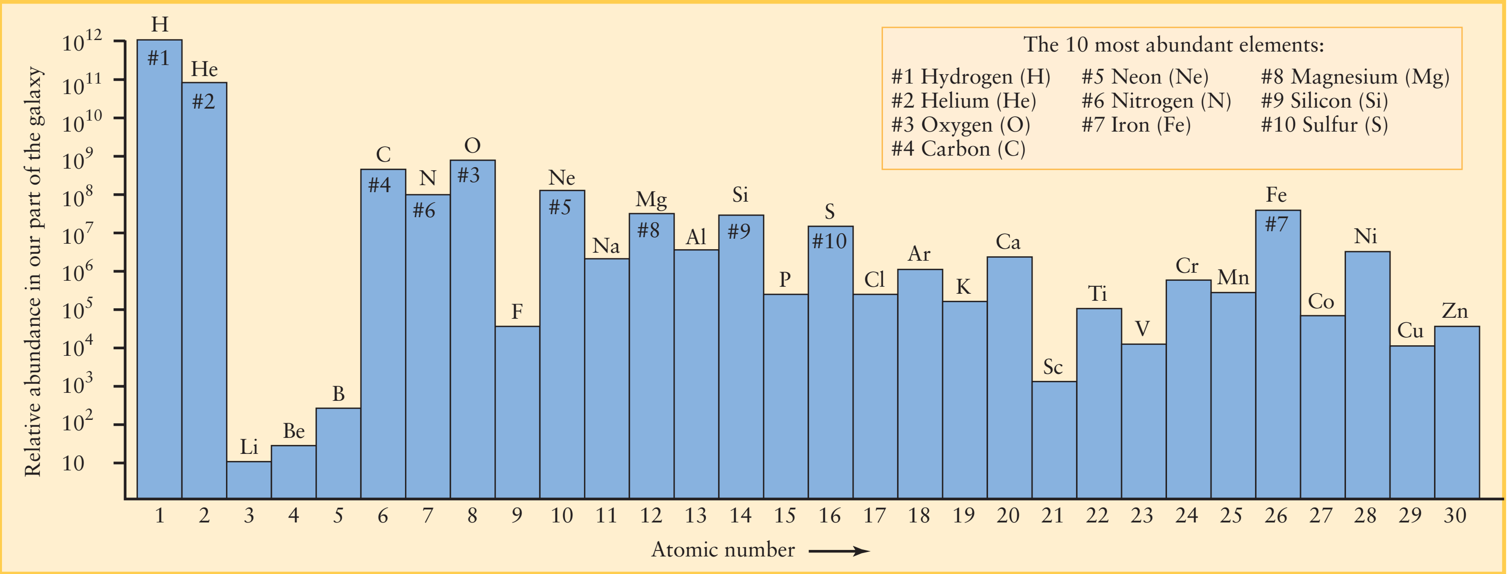


Figure 8-4

Abundances of the Lighter Elements This graph shows the abundances in our part of the Galaxy of the 30 lightest elements (listed in order of increasing atomic number) compared to a value of 10^{12} for hydrogen. The inset lists the 10 most abundant of these elements, which are also indicated in the graph. Notice that the vertical scale is not linear; each division on the scale corresponds to a tenfold increase in abundance. All elements heavier than zinc (Zn) have abundances of fewer than 1000 atoms per 10^{12} atoms of hydrogen.

circumstances. Consequently, gold is rare in our solar system and in the universe as a whole, while oxygen is relatively abundant (although still much less abundant than hydrogen or helium).

A convenient way to express the relative abundances of the various elements is to say how many atoms of a particular element are found for every trillion (10^{12}) hydrogen atoms. For example, for every 10^{12} hydrogen atoms in space, there are about 100 billion (10^{11}) helium atoms. From spectral analysis of stars and chemical analysis of Earth rocks, Moon rocks, and bits of interplanetary debris called meteorites, scientists have determined the relative abundances of the elements in our part of the Milky Way Galaxy today. Figure 8-4 shows the relative abundances of the 30 lightest elements, arranged in order of their **atomic numbers.** An element's atomic number is the number of protons in the nucleus of an atom of that element. It is also equal to the number of electrons orbiting the nucleus (see Box 5-5). In general, the greater the atomic number of an atom, the greater its mass.

CAUTION! Figure 8-1 shows that our solar system has 2.6 times (71% versus 27%) as much hydrogen than helium by *mass*, while Figure 8-4 shows that there is about 10 times as much hydrogen than helium by *number of atoms*. The explanation of this seeming inconsistency is that a helium atom has about 4 times the mass of a hydrogen atom, which makes helium more important on a per-mass basis than on a per-number basis.

The inset in Figure 8-4 lists the 10 most abundant elements. Note that even oxygen (chemical symbol O), the third most abundant element, is quite rare relative to hydrogen (H) and helium (He): There are only 8.5×10^8 oxygen atoms for each 10^{12} hydrogen atoms and each 10^{11} helium atoms. Expressed another way, for each oxygen atom in our region of the Milky Way Galaxy, there are about 1200 hydrogen atoms and 120 helium atoms.

In addition to the 10 most abundant elements listed in Figure 8-3, five elements are moderately abundant: sodium (Na), aluminum (Al), argon (Ar), calcium (Ca), and nickel (Ni). These elements have abundances in the range of 10^6 to 10^7 relative to the standard 10^{12} hydrogen atoms. Most of the other elements are much rarer. For example, for every 10^{12} hydrogen atoms in the solar system, there are only six atoms of gold.

The small cosmic abundances of elements other than hydrogen and helium help to explain why the terrestrial planets are so small (Property 1 in Table 8-1). Because the heavier elements required to make a terrestrial planet are rare, only relatively small planets can form out of them. By contrast, hydrogen and helium are so abundant that it was possible for these elements to form large Jovian planets.

8-3 The abundances of radioactive elements reveal the solar system's age

The heavy elements can tell us even more about the solar system: They also help us determine its age. The particular heavy elements that provide us with this information are *radioactive*. Their atomic nuclei are unstable because they contain too many protons or too many neutrons. A radioactive nucleus therefore ejects particles until it becomes stable. In doing so, a nucleus may change from one element to another. Physicists refer to this transmutation as **radioactive decay.** For example, a radioactive form of the element rubidium (atomic number 37) decays into the element strontium (atomic number 38) when one of the neutrons in the rubidium nucleus decays into a proton and an electron (which is ejected from the nucleus).

Our solar system, which formed 9 billion years after the Big Bang, is a relative newcomer in the universe

Experiment shows that each type of radioactive nucleus decays at its own characteristic rate, which can be measured in the laboratory. This observation is the key to a technique called **radioactive dating,** which is used to determine the ages of rocks. If a rock contained a certain amount of radioactive rubidium when it first formed, over time more and more of the atoms of rubidium within the rock will decay into strontium atoms. The ratio of the number of strontium atoms the rock contains to the number of rubidium atoms it contains then gives a measure of the age of the rock. Box 8-1 describes radioactive dating in more detail.

Dating the Solar System

Scientists have applied techniques of radioactive dating to rocks taken from all over the Earth. The results show that most rocks are tens or hundreds of millions of years old, but that some rocks are as much as 4 billion (4×10^9) years old. These results confirm that geologic processes have produced new surface material over the Earth's history, as we concluded from the small number of impact craters found on Earth (see Section 7-6). They also show that the Earth is at least 4×10^9 years old.

Radioactive dating has also been applied to rock samples brought back from the Moon by the *Apollo* astronauts. The oldest *Apollo* specimen, collected from one of the most heavily cratered and hence most ancient regions of the Moon, is 4.5×10^9 years old. But the oldest rocks found anywhere in the solar system are **meteorites,** bits of interplanetary debris that survive passing through the Earth's atmosphere and land on our planet's surface (Figure 8-5). Radioactive dating of meteorites reveals that they are all nearly the *same* age, about 4.56 billion years old. The absence of any younger or older meteorites indicates that these are all remnants of objects that formed at the same time in the early solar system. We conclude that the age of the oldest meteorites, about 4.56×10^9 years, is the age of the solar system itself. Note that this almost inconceivably long span of time is only about one-third of the current age of the universe, 13.7×10^9 years.

Thus, by studying the abundances of radioactive elements, we are led to a remarkable insight: Some 4.56 billion years ago, a collection of hydrogen, helium, and heavy elements came together to form the Sun and all of the objects that orbit around it. All of those heavy elements, including the carbon atoms in your body and the oxygen atoms that you breathe, were created and cast off by stars that lived and died long before our solar system formed, during the first 9 billion years of the universe's existence. We are literally made of star dust.

Figure 8-5 R I V U X G

A Meteorite Although it resembles an ordinary Earth rock, this is actually a meteorite that fell from space. The proof of its extraterrestrial origin is the meteorite's surface, which shows evidence of having been melted by air friction as it entered our atmosphere at 40,000 km/h (25,000 mi/h). Meteorites are the oldest objects in the solar system. (Ted Kinsman/Photo Researchers, Inc.)

8-4 The Sun and planets formed from a solar nebula

We have seen how processes in the Big Bang and within ancient stars produced the raw ingredients of our solar system. But given these ingredients, how did they combine to make the Sun and planets? Astronomers have developed a variety of models for the origin of the solar system. The test of these models is whether they explain the properties of the present-day system of Sun and planets.

Astronomers see young stars that may be forming planets today in the same way that our solar system did billions of years ago

The Failed Tidal Hypothesis

Any model of the origin of the solar system must explain why all the planets orbit the Sun in the same direction and in nearly the same plane (Property 2 in Table 8-1). One model that was devised explicitly to address this issue was the *tidal hypothesis,* proposed in the early 1900s. As we saw in Section 4-8, two nearby planets, stars, or galaxies exert tidal forces on each other that cause the objects to elongate. In the tidal hypothesis, another star happened to pass close by the Sun, and the star's tidal forces drew a long filament out of the Sun. The filament material would then go into orbit around the Sun, and all of it would naturally orbit in the same direction and in the same plane. From this filament the planets would condense. However, it was shown in the 1930s that tidal forces strong enough to pull a filament out of the Sun would cause the filament to disperse before it could condense into planets. Hence, the tidal hypothesis cannot be correct.

BOX 8-1 Tools of the Astronomers Trade

Radioactive Dating

How old are the rocks found on the Earth and other planets? Are rocks found at different locations the same age or of different ages? How old are meteorites? Questions like these are important to scientists who wish to reconstruct the history of our solar system. But simply looking at a rock cannot tell us whether it was formed a thousand years, a million years, or a billion years ago. Fortunately, most rocks contain trace amounts of radioactive elements such as uranium. By measuring the relative abundances of various radioactive isotopes and their decay products within a rock, scientists can determine the rock's age.

As we saw in Box 5-5, every atom of a particular element has the same number of protons in its nucleus. However, different isotopes of the same element have different numbers of neutrons in their nuclei. For example, the common isotopes of uranium are ^{235}U and ^{238}U. Each isotope of uranium has 92 protons in its nucleus (correspondingly, uranium is element 92 in the periodic table; see Box 5-5). However, a ^{235}U nucleus contains 143 neutrons, whereas a ^{238}U nucleus has 146 neutrons.

A radioactive nucleus with too many protons or too many neutrons is unstable; to become stable, it *decays* by ejecting particles until it becomes stable. If the number of protons (the atomic number) changes in this process, the nucleus changes from one element to another.

Some radioactive isotopes decay rapidly, while others decay slowly. Physicists find it convenient to talk about the decay rate in terms of an isotope's **half-life.** The half-life of an isotope is the time interval in which one-half of the nuclei decay. For example, the half-life of ^{238}U is 4.5 billion (4.5×10^9) years. This means that if you start out with 1 kg of ^{238}U, after 4.5 billion years you will have only $\frac{1}{2}$ kg of ^{238}U remaining; the other $\frac{1}{2}$ kg will have turned into other elements. If you want another half-life, so that a total of 9.0 billion years has elapsed, only $\frac{1}{4}$ kg of ^{238}U—one-half of one-half of the original amount—will remain. Several isotopes useful for determining the ages of rocks are listed in the accompanying table.

To see how geologists date rocks, consider the slow conversion of radioactive rubidium (^{87}Rb) into strontium (^{87}Sr). (The periodic table in Box 5-5 shows that the atomic numbers for these elements are 37 for rubidium and 38 for strontium, so in the decay a neutron is transformed into a proton. In this process an electron is ejected from the nucleus.) Over the years, the amount of ^{87}Rb in a rock decreases, while the amount of ^{87}Sr increases. Because the ^{87}Sr appears in the rock due to radioactive decay, this isotope is called *radiogenic*. Dating the rock is not simply a matter of measuring its ratio of rubidium to strontium, however, because the rock already had some strontium in it when it was formed. Geologists must therefore determine how much fresh strontium came from the decay of rubidium after the rock's formation.

To do this, geologists use as a reference another isotope of strontium whose concentration has remained constant. In this case, they use ^{86}Sr, which is stable and is not created by radioactive decay; it is said to be *nonradiogenic*. Dating a rock thus entails comparing the ratio of radiogenic and nonradiogenic strontium (^{87}Sr/^{86}Sr) in the rock to the ratio of radioactive rubidium to nonradiogenic strontium (^{87}Rb/^{86}Sr). Because the half-life for converting ^{87}Rb into ^{87}Sr is known, the rock's age can then be calculated from these ratios (see the table).

Radioactive isotopes decay with the same half-life no matter where in the universe they are found. Hence, scientists have used the same techniques to determine the ages of rocks from the Moon and of meteorites.

Original Radioactive Isotope	Final Stable Isotope	Half-Life (Years)	Range of Ages that Can Be Determined (Years)
Rubidium (^{87}Rb)	Strontium (^{87}Sr)	47.0 billion	10 million–4.56 billion
Uranium (^{238}U)	Lead (^{206}Pb)	4.5 billion	10 million–4.56 billion
Potassium (^{40}K)	Argon (^{40}Ar)	1.3 billion	50,000–4.56 billion
Carbon (^{14}C)	Nitrogen (^{14}N)	5730	100–70,000

The Successful Nebular Hypothesis

An entirely different model is now thought to describe the most likely series of events that led to our present solar system (Figure 8-6). The central idea of this model dates to the late 1700s, when the German philosopher Immanuel Kant and the French scientist Pierre-Simon de Laplace turned their attention to the manner in which the planets orbit the Sun. Both concluded that the arrangement of the orbits—all in the same direction and in nearly the same plane—could not be mere coincidence. To explain the orbits, Kant and Laplace independently proposed that our entire solar system, including the Sun as well as all of its planets and satellites, formed from a vast, rotating cloud of gas and dust called the **solar nebula** (Figure 8-6*a*). This model is called the **nebular hypothesis.**

The consensus among today's astronomers is that Kant and Laplace were exactly right. In the modern version of the nebular hypothesis, at the outset the solar nebula was similar in character to the nebulosity shown in Figure 8-3 and had a mass somewhat greater than that of our present-day Sun.

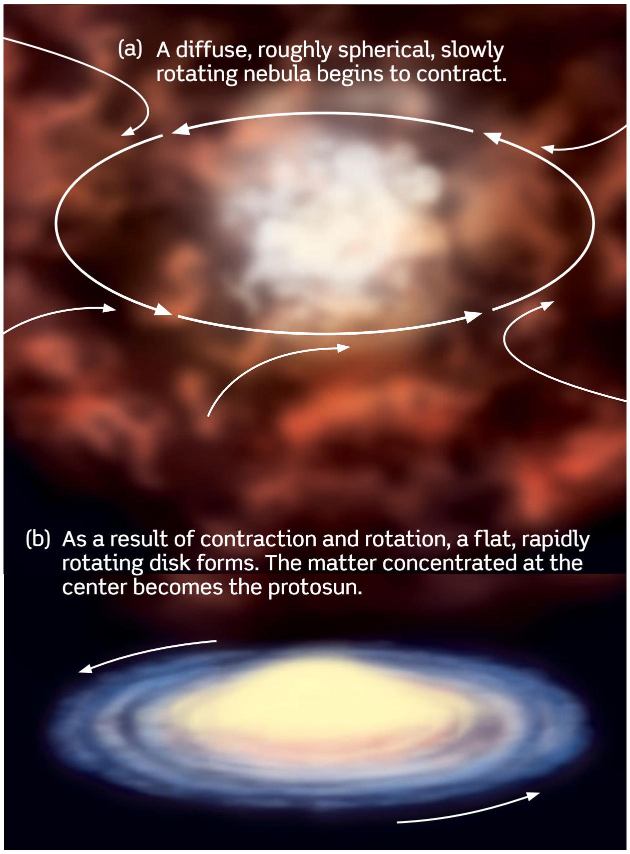


Figure 8-6

The Birth of the Solar System **(a)** A cloud of interstellar gas and dust begins to contract because of its own gravity. **(b)** As the cloud flattens and spins more rapidly around its rotation axis, a central condensation develops that evolves into a glowing protosun. The planets will form out of the surrounding disk of gas and dust.

Each part of the nebula exerted a gravitational attraction on the other parts, and these mutual gravitational pulls tended to make the nebula contract. As it contracted, the greatest concentration of matter occurred at the center of the nebula, forming a relatively dense region called the **protosun.** As its name suggests, this part of the solar nebula eventually developed into the Sun. The planets formed from the much sparser material in the outer regions of the solar nebula. Indeed, the mass of all the planets together is only 0.1% of the Sun's mass.

Evolution of the Protosun

When you drop a ball, the gravitational attraction of the Earth makes the ball fall faster and faster as it falls; in the same way, material falling inward toward the protosun would have gained speed. As this fast-moving material ran into the protosun, the energy of the collision was converted into thermal energy, causing the temperature deep inside the solar nebula to climb. This process, in which the gravitational energy of a contracting gas cloud is converted into thermal energy, is called **Kelvin-Helmholtz contraction,** after the nineteenth-century physicists who first described it.

As the newly created protosun continued to contract and become denser, its temperature continued to climb as well. After about 10^5 (100,000) years, the protosun's surface temperature stabilized at about 6000 K, but the temperature in its interior kept increasing to ever higher values as the central regions of the protosun became denser and denser. Eventually, after perhaps 10^7 (10 million) years had passed since the solar nebula first began to contract, the gas at the center of the protosun reached a density of about 10^5 kg/m^3 (a hundred times denser than water) and a temperature of a few million kelvins (that is, a few times 10^6 K). Under these extreme conditions, nuclear reactions that convert hydrogen into helium began in the protosun's interior. When this happened, the energy released by these reactions stopped the contraction and a true star was born. Nuclear reactions continue to the present day in the interior of the Sun and are the source of all the energy that the Sun radiates into space.

The Protoplanetary Disk

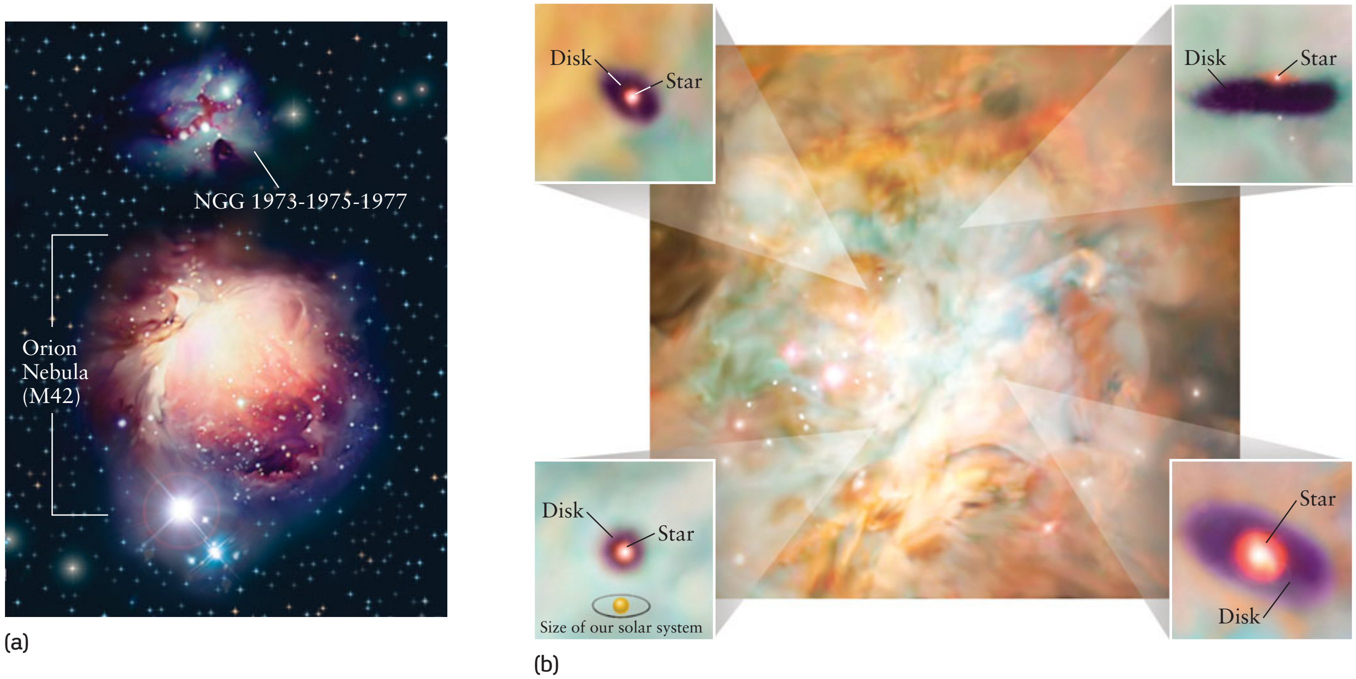
If the solar nebula had not been rotating at all, everything would have fallen directly into the protosun, leaving nothing behind to form the planets. Instead, the solar nebula must have had an overall slight rotation, which caused its evolution to follow a different path. As the slowly rotating nebula collapsed inward, it would naturally have tended to rotate faster. This relationship between the size of an object and its rotation speed is an example of a general principle called the **conservation of angular momentum.**

ANALOGY Figure skaters make use of the conservation of angular momentum. When a spinning skater pulls her arms and legs in close to her body, the rate at which she spins automatically increases (Figure 8-7). Even if you are not a figure skater,

(a) (b)

Figure 8-7 R I V U X G

Conservation of Angular Momentum A figure skater who **(a)** spins slowly with her limbs extended will naturally speed up when **(b)** she pulls her limbs in. In the same way, the solar nebula spun more rapidly as its material contracted toward the center of the nebula. (AP Photo/Amy Sancetta)



VIDEO 8.1

Figure 8-8 R I V U X G

Protoplanetary Disks (a) The Orion Nebula is a star-forming region located some 1500 light-years from Earth. It is the middle "star" in Orion's "sword" (see Figure 2-2*a*). The smaller, bluish nebula is the object shown in Figure 8-3. **(b)** This view of the center of the Orion Nebula is a mosaic of Hubble Space Telescope images. The four insets are false-color close-ups of four protoplanetary disks that lie within the nebula. A young, recently formed star is at the center of each disk. (The disk at upper right is seen nearly edge-on.) The inset at the lower left shows the size of our own solar system for comparison. (a: Anglo-Australian Observatory image by David Malin; b: C. R. O'Dell and S. K. Wong, Rice University; NASA)

you can demonstrate this by sitting on an office chair. Sit with your arms outstretched and hold a weight, like a brick or a full water bottle, in either hand. Now use your feet to start your body and the chair rotating, lift your feet off the ground, and then pull your arms inward. Your rotation will speed up quite noticeably.

As the solar nebula began to rotate more rapidly, it also tended to flatten out (Figure 8-6*b*). From the perspective of a particle rotating along with the nebula, it felt as though there were a force pushing the particle away from the nebula's axis of rotation. (Likewise, passengers on a spinning carnival ride seem to feel a force pushing them outward and away from the ride's axis of rotation.) This apparent force was directed opposite to the inward pull of gravity, and so it tended to slow the contraction of material toward the nebula's rotation axis. But there was no such effect opposing contraction in a direction parallel to the rotation axis. Some 10^5 (100,000) years after the solar nebula first began to contract, it had developed the structure shown in Figure 8-5*b*, with a rotating, flattened disk surrounding what will become the protosun. This disk is called the **protoplanetary disk** or **proplyd,** since planets formed from its material. This model explains why their orbits all lie in essentially the same plane and why they all orbit the Sun in the same direction.

There were no humans to observe these processes taking place during the formation of the solar system. But Earth astronomers have seen disks of material surrounding other stars that formed only recently. These, too, are called protoplanetary disks, because it is thought that planets can eventually form from these disks around other stars. Hence, these disks are planetary systems that are still "under construction." By studying these disks around other stars, astronomers are able to examine what our solar nebula may have been like some 4.56×10^9 years ago.

WEB LINK 8.5

Figure 8-8 shows a number of protoplanetary disks in the Orion Nebula, a region of active star formation. A star is visible at the center of each disk, which reinforces the idea that our Sun began to shine before the planets were fully formed. (The images that open this chapter show even more detailed views of disks surrounding young stars.) A study of 110 young stars in the Orion Nebula detected protoplanetary disks around 56 of them, which suggests that systems of planets may form around a substantial fraction of stars. Later in this chapter we will see direct evidence for planets that have formed around stars other than the Sun.

8-5 The terrestrial planets formed by the accretion of planetesimals

We have seen how the solar nebula would have contracted to form a young Sun with a protoplanetary disk rotating around it. But how did the material in this disk form into planets? And why are terrestrial planets in the inner solar system, while the giant Jovian planets are in the outer solar system (Property 3 in Table 8-1)? In this section and the next we will see how the nebular hypothesis provides answers to these questions.

Rocky planets formed in the inner solar nebula as a consequence of the high temperatures close to the protosun

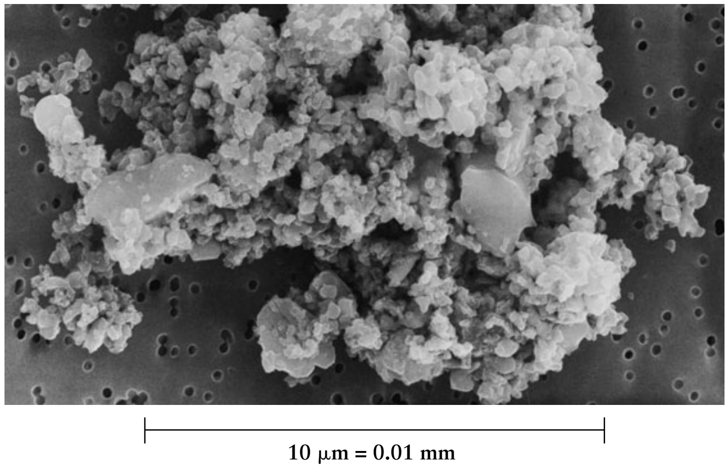
Temperatures in the Solar Nebula

To understand how the planets, asteroids, and comets formed, we must look at the conditions that prevailed within the solar nebula. The density of material in the part of the nebula outside the protosun was rather low, as was the pressure of the nebula's gas. If the pressure is sufficiently low, a substance cannot remain in the liquid state, but must end up as either a solid or a gas. For a given pressure, what determines whether a certain substance is a solid or a gas is its **condensation temperature.** If the temperature of a substance is above its condensation temperature, the substance is a gas; if the temperature is below the condensation temperature, the substance solidifies into tiny specks of dust or snowflakes. You can often see similar behavior on a cold morning. The air temperature can be above the condensation temperature of water, while the cold windows of parked cars may have temperatures below the condensation temperature. Thus, water molecules in the air remain as a gas (water vapor) but form solid ice particles (frost) on the car windows.

Substances such as water (H_2O), methane (CH_4), and ammonia (NH_3) have low condensation temperatures, ranging from 100 to 300 K. Rock-forming substances have much higher condensation temperatures, in the range from 1300 to 1600 K. The gas cloud from which the solar system formed had an initial temperature near 50 K, so all of these substances could have existed in solid form. Thus, the solar nebula would have been populated by an abundance of small ice particles and solid dust grains like the one shown in Figure 8-9. (Recall from Section 7-4 that "ice" can refer to frozen CO_2, CH_4, or NH_3, as well as frozen water.) But hydrogen and helium, the most abundant elements in the solar nebula, have condensation temperatures so near absolute zero that these substances always existed as gases during the creation of the solar system. You can best visualize the initial state of the solar nebula as a thin gas of hydrogen and helium strewn with tiny dust particles.

This state of affairs changed as the central part of the solar nebula underwent Kelvin-Helmholtz contraction to form the protosun. During this phase, the protosun was actually quite a bit more luminous than the present-day Sun, and it heated the innermost part of the solar nebula to temperatures above 2000 K. Meanwhile, temperatures in the outermost regions of the solar nebula remained below 50 K.

Figure 8-10 shows the probable temperature distribution in the solar nebula at this stage in the formation of our solar system. In the inner regions of the solar nebula, water, methane, and ammonia were vaporized by the high temperatures. Only materials with high condensation temperatures could have remained solid. Of these materials, iron, silicon, magnesium, and sulfur were particularly abundant, followed closely by aluminum, calcium, and nickel. (Most of these elements were present in the form of oxides, which are chemical compounds containing oxygen. These compounds also have high condensation temperatures.) In contrast, ice particles and ice-coated dust grains were able to survive in the cooler, outer portions of the solar nebula.



WEB LINK 8.6

Figure 8-9

A Grain of Cosmic Dust This highly magnified image shows a microscopic dust grain that came from interplanetary space. It entered Earth's upper atmosphere and was collected by a high-flying aircraft. Dust grains of this sort are abundant in star-forming regions like that shown in Figure 8-3. These tiny grains were also abundant in the solar nebula and served as the building blocks of the planets. (Donald Brownlee, University of Washington)

Planetesimals, Protoplanets, and Terrestrial Planets

ANIMATION 8.1

In the inner part of the solar nebula, the grains of high-condensation-temperature materials would have

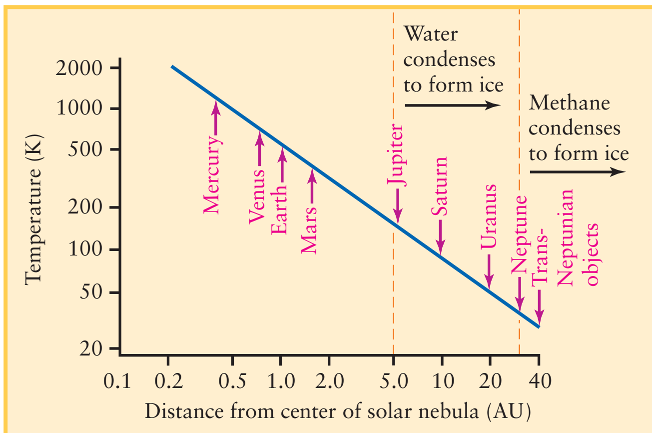


Figure 8-10

Temperature Distribution in the Solar Nebula This graph shows how temperatures probably varied across the solar nebula as the planets were forming. Note the general decline in temperature with increasing distance from the center of the nebula. Beyond 5 AU from the center of the nebula, temperatures were low enough for water to condense and form ice; beyond 30 AU, methane (CH_4) could also condense into ice.

collided and merged into small chunks. Initially, electric forces—that is, chemical bonds—held these chunks together, in the same way that chemical bonds hold an ordinary rock together. Over a few million years, these chunks coalesced into roughly 10^9 asteroidlike objects called **planetesimals,** with diameters of a kilometer or so. These were large enough to be held together by the gravitational attraction of the different parts of the planetesimal for each other. During the next stage, gravitational attraction between the planetesimals caused them to collide and accumulate into still-larger objects called **protoplanets,** which were roughly the size and mass of our Moon. This accumulation of material to form larger and larger objects is called **accretion.** During the final stage, these Moon-sized protoplanets collided to form the inner planets. This final episode must have involved some truly spectacular, world-shattering collisions.

In the inner solar nebula only materials with high condensation temperatures could form dust grains and hence protoplanets, so the result was a set of planets made predominantly of materials such as iron, silicon, magnesium, and nickel, and their oxides. This is just the composition of the present-day terrestrial planets.

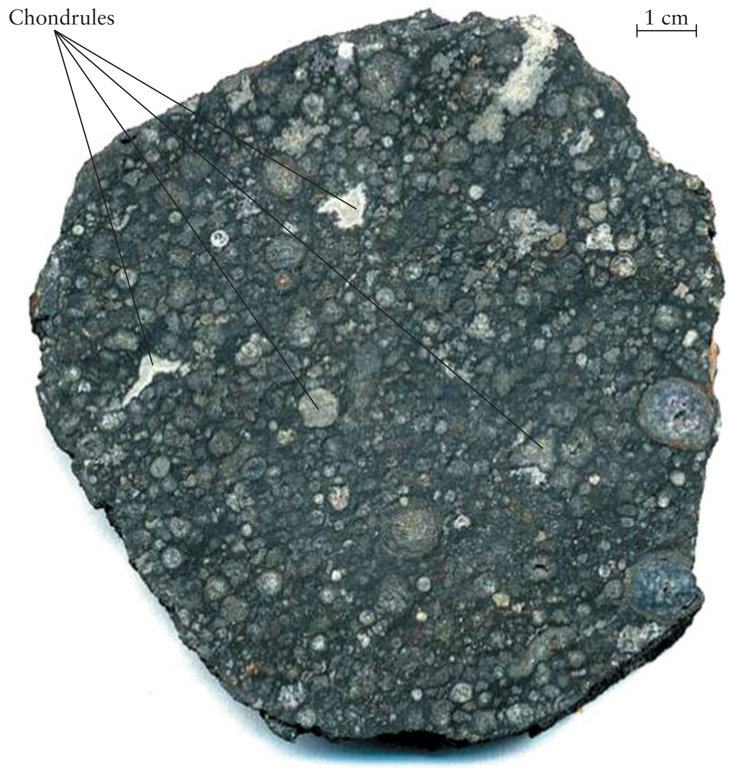
At first the material that coalesced to form protoplanets in the inner solar nebula remained largely in solid form, despite the high temperatures close to the protosun. But as the protoplanets grew, they were heated by the violent impacts of planetesimals as well as the decay of radioactive elements such as uranium, and this heat caused melting. Thus, the terrestrial planets began their existence as spheres of at least partially molten rocky materials. Material was free to move within these molten spheres, so the denser, iron-rich minerals sank to the centers of the planets while the less dense silicon-rich minerals floated to their surfaces. This process is called **chemical differentiation** (see Box 7-1). In this way the terrestrial planets developed their dense iron cores. We saw in Section 7-7 that this electrically conductive iron gives rise to the magnetic fields of the terrestrial planets.

Because the materials that went into the terrestrial planets are relatively scarce, these planets ended up having relatively small mass and hence relatively weak gravity. As a result, these terrestrial protoplanets were unable to capture any of the hydrogen or helium in the solar nebula to form atmospheres (see Box 7-2). The thin envelopes of atmosphere that encircle Venus, Earth, and Mars evolved much later as trapped gases were released from the molten interiors of these planets.

The Evidence of Chondrules

Important clues about the evolution of the inner solar system come from studies of meteorites, which, as we saw in Section 8-3, are the oldest solid objects known in the solar system. Many of these are fragments of planetesimals that were never incorporated into the planets. Most meteorites contain not only dust grains but also **chondrules,** which are small, glassy, roughly spherical blobs (Figure 8-11). (The "ch" in "chondrule" is pronounced as in "chord.") Liquids tend to form spherical drops (like drops of water), so the shape of chondrules shows that they were once molten.

Attempts to produce chondrules in the laboratory show that the blobs must have melted suddenly, then solidified over the space of only an hour or so. This means they could not have been melted by the temperature of the inner solar nebula, which would have remained high for hundreds of thousands of years after the formation of the protosun. Instead, chondrules must have been produced by sudden, high-energy events that quickly melted material and then permitted it to cool. These events were probably shock waves propagating through the gas of the solar nebula, like the sonic booms produced by an airplane traveling faster than sound. The sheer number of chondrules suggests that such shock waves occurred throughout the inner solar nebula over a period of more than 10^6 years. The words "cloud" and "nebula" may suggest material moving in gentle orbits around the protosun; the existence of chondrules suggests that conditions in the inner solar nebula were at times quite violent.



WEB LINK 8.7

Figure 8-11 R I V U X G

Chondrules This is a cross-section of a meteorite that landed in Chihuahua, Mexico in 1969. The light-colored spots are individual chondrules that range in size from a few millimeters to a few tenths of a millimeter. Many of the chondrules are coated with dust grains like the one shown in Figure 8-8. (The R. N. Hartman Collection)

Simulating the Formation of Planets

Astronomers use computer simulations to learn how the inner planets could have formed from planetesimals. A computer is programmed to simulate a large number of particles circling a newborn sun along orbits dictated by Newtonian mechanics. As the simulation proceeds, the particles coalesce to form larger objects, which in turn collide to form planets. By performing a variety of simulations, each beginning with somewhat different numbers of planetesimals in different orbits, it is possible to see what kinds of planetary systems would have been created under different initial conditions. Such studies demonstrate that a wide range of initial conditions ultimately lead to basically the same result in the

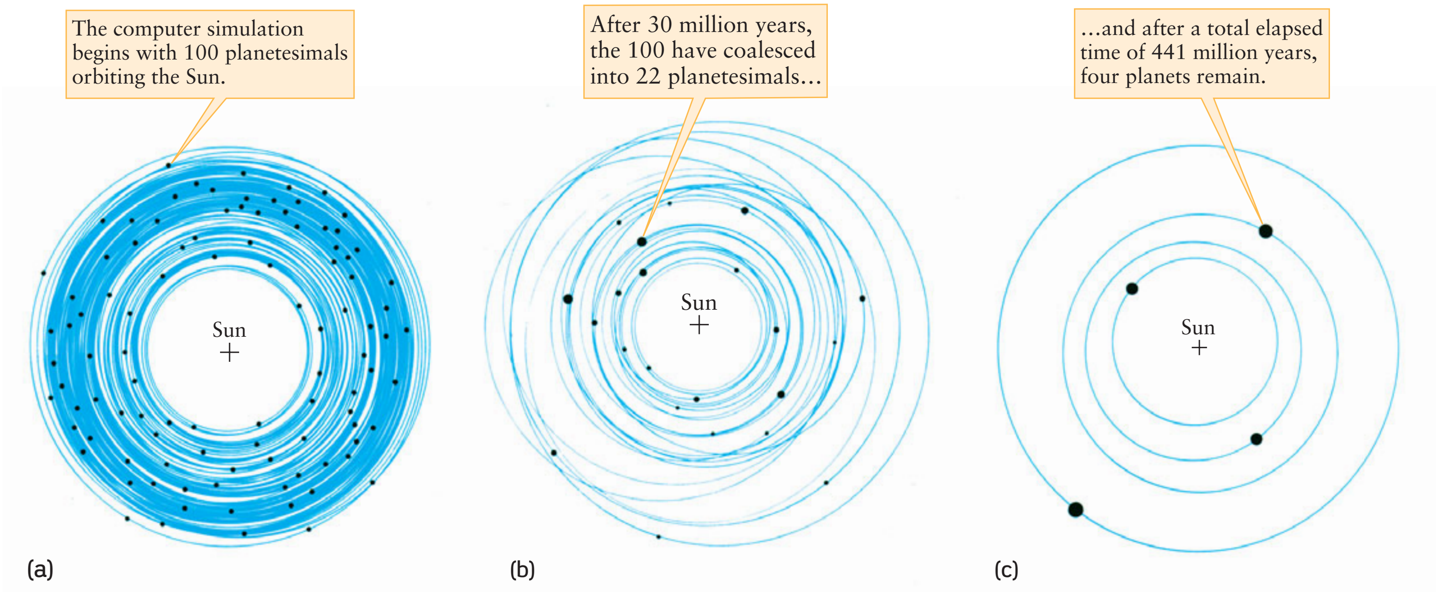


Figure 8-12

Accretion of the Terrestrial Planets These three drawings show the results of a computer simulation of the formation of the inner planets. In this simulation, the inner planets were essentially formed after 150 million years. (Adapted from George W. Wetherill)

inner solar system: Accretion continues for roughly 10^8 (100 million) years and typically forms four or five terrestrial planets with orbits between 0.3 and 1.6 AU from the Sun.

Figure 8-12 shows one particular computer simulation. The calculations began with 100 planetesimals, each having a mass of 1.2×10^{23} kg. This choice ensures that the total mass (1.2×10^{25} kg) equals the combined mass of the four terrestrial planets (Mercury through Mars) plus their satellites. The initial orbits of planetesimals are inclined to each other by angles of less than 5° to simulate a thin layer of particles orbiting the protosun.

After an elapsed time simulating 30 million (3×10^7) years, the 100 original planetesimals have merged into 22 protoplanets (Figure 8-9*b*). After 79 million (7.9×10^7) years, these have combined into 11 larger protoplanets. Nearly another 100 million (10^8) years elapse before further mergers leave just six growing protoplanets. Finally, Figure 8-9*c* shows four planets following nearly circular orbits after a total elapsed time of 441 million (4.41×10^8) years. In this particular simulation, the fourth planet from the Sun ends up being the most massive; in our own solar system, the third planet (Earth) is the most massive of the terrestrial planets. Note that due to collisions, the four planets in the simulation end up in orbits that are nearly circular, just like the orbits of most of the planets in our solar system.

8-6 Gases in the outer solar nebula formed the Jovian planets, whose gravitational influence gave rise to the small bodies of the solar system

We have seen how the high temperatures in the inner solar nebula led to the formation of the small, rocky terrestrial planets. To explain the very different properties of the Jovian planets, we need to consider the conditions that prevailed in the relatively cool outer regions of the solar nebula. Two leading models explain how the Jovian planets could have formed there.

Low temperatures in the outer solar nebula made it possible for planets to grow to titanic size

The Core Accretion Model

Like the inner planets, the outer planets may have begun to form by the accretion of planetesimals. The key difference is that ices as well as rocky grains were able to survive in the outer regions of the solar nebula, where temperatures were relatively low (see Figure 8-10). The elements of which ices are made are much more abundant than those that form rocky grains. Thus, much more solid material would have been available to form planetesimals in the outer solar nebula than in the inner part. As a result, solid objects several times larger than any of the terrestrial planets could have formed in the outer solar nebula. Each such object, made up of a mixture of ices and rocky material, could have become the core of a Jovian planet and served as a "seed" around which the rest of the planet eventually grew.

Thanks to the lower temperatures in the outer solar system, gas atoms (principally hydrogen and helium) were moving relatively slowly and so could more easily be captured by the strong gravity of these massive cores (see Box 7-2). Thus, the core of a Jovian protoplanet could have captured an envelope of gas as it continued to grow by accretion. This picture is called the **core accretion model** for the origin of the Jovian planets.

Calculations based on the core accretion model suggest that both rocky materials and gas slowly accumulated for several million years, until the masses of the core and the envelope became equal. From that critical moment on, the envelope pulled in all the gas it could get, dramatically increasing the protoplanet's mass and size. This runaway growth of the protoplanet would have continued until all the available gas was used up. The result was a huge planet with an enormously thick, hydrogen-rich envelope surrounding a rocky core with 5 to 10 times the mass of the Earth. This scenario could have occurred at four different distances from the Sun, thus creating the four Jovian planets.

In the core accretion model, Uranus and Neptune probably did not form at their present locations, respectively about 19 and 30 AU from the Sun. The solar nebula was too sparse at those distances to allow these planets to have grown to the present-day sizes. Instead, it is thought that Uranus and Neptune formed between 4 and 10 AU from the Sun, but were flung into larger orbits by gravitational interactions with Jupiter.

The Disk Instability Model

An alternative model for the origin of the Jovian planets, the **disk instability model,** suggests that they formed directly from the gas of the solar nebula. If the gas of the outer solar nebula was not smooth but clumpy, a sufficiently large and massive clump of gas could begin to collapse inward all on its own, like the protosun but on a smaller scale. Such a large clump would attract other gas, forming a very large planet of hydrogen and helium within just a few hundreds or thousands of years.

In the disk instability model the rocky core of a Jovian planet is *not* the original nucleus around which the planet grew; rather, it is the result of planetesimals and icy dust grains that were drawn gravitationally into the planet and then settled at the planet's center. Another difference is that in the disk instability model it is possible for Uranus and Neptune to have formed in their present-day orbits, since they would have grown much more rapidly than would be possible in the core accretion model.

Planetary scientists are actively researching whether the core accretion model or the disk instability model is the more correct description of the formation of the Jovian planets. In either case, we can explain why the terrestrial planets formed in the inner solar system while the Jovian planets formed in the outer solar system. Figure 8-13 summarizes our overall picture of the formation of the terrestrial and Jovian planets.

The Origin of Jovian Satellites and Small Bodies

Like the terrestrial planets, the Jovian planets were quite a bit hotter during their formation than they are today. A heated gas expands, so these gas-rich planets must also have been much larger than at present. As each planet cooled and contracted, it would have formed a disk like a solar nebula in miniature (see Figure 8-6). Many of the satellites of the Jovian planets, including those shown in Table 7-2, are thought to have formed from ice particles and dust grains within these disks.

Jupiter, the most massive of the planets, was almost certainly the first to form. This may explain why there are asteroids, trans-Neptunian objects, and comets (see Section 7-5). Jupiter's tremendous mass would have exerted strong gravitational forces on any nearby planetesimals. Some would have been sent crashing into the Sun, while others would have been sent crashing into the terrestrial planets to form impact craters (see Section 7-6). Still others would have been ejected completely from the solar system. Only a relatively few rocky planetesimals survived to produce the present-day population of asteroids. Indeed, the mass of all known asteroids combined is less than the mass of the Moon.

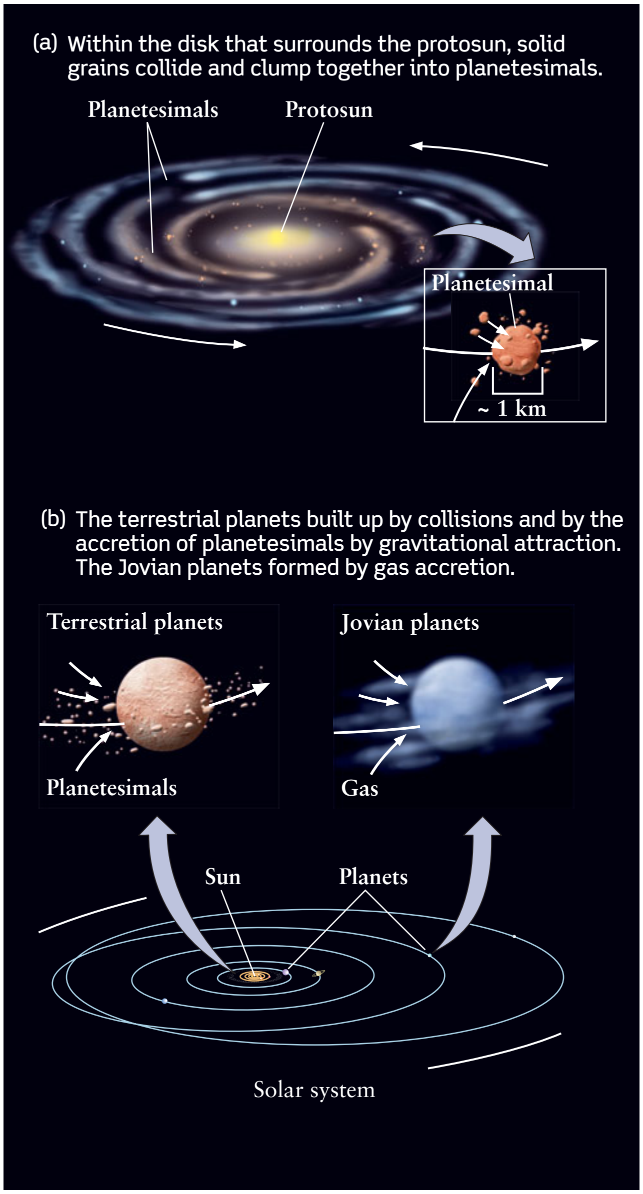
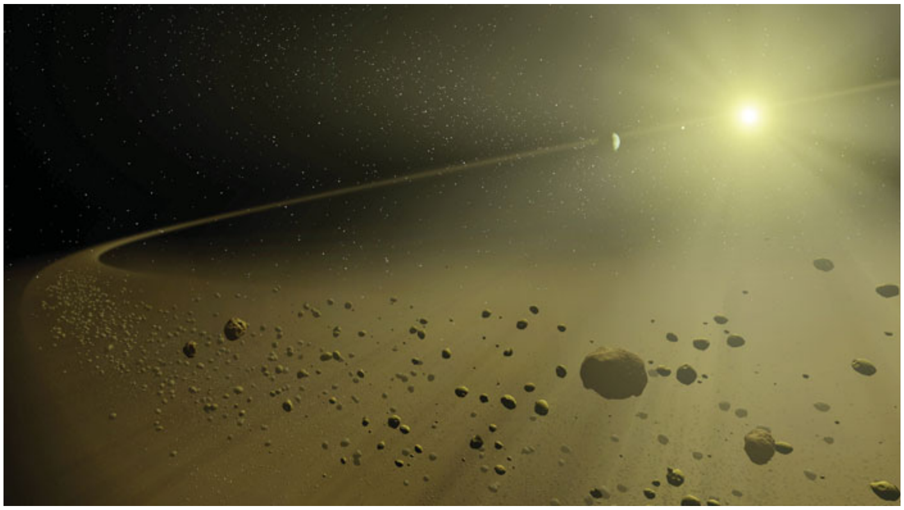


Figure 8-13
Terrestrial Versus Jovian Planet Formation
(a) Planetesimals about 1 km in size formed in the solar nebula from small dust grains sticking together. **(b)** Planetesimals in the inner solar system grouped together to form the terrestrial planets, as in Figure 8-12. In the outer solar system, the Jovian planets may have begun as terrestrial-like planets that accumulated massive envelopes of hydrogen and helium. Alternatively, the Jovian planets may have formed directly from the gas of the solar nebula.

By contrast, trans-Neptunian objects (including Pluto and the other objects shown in Table 7-4) began as icy planetesimals beyond the orbit of Jupiter. The strong gravitational forces from all of the Jovian planets pushed these into orbits even further from the Sun, forming the immense ring of the Kuiper belt (Figure 8-14). The images that open this chapter show two young stars surrounded by dusty disks, one seen



ANIMATION 8.4

Figure 8-14

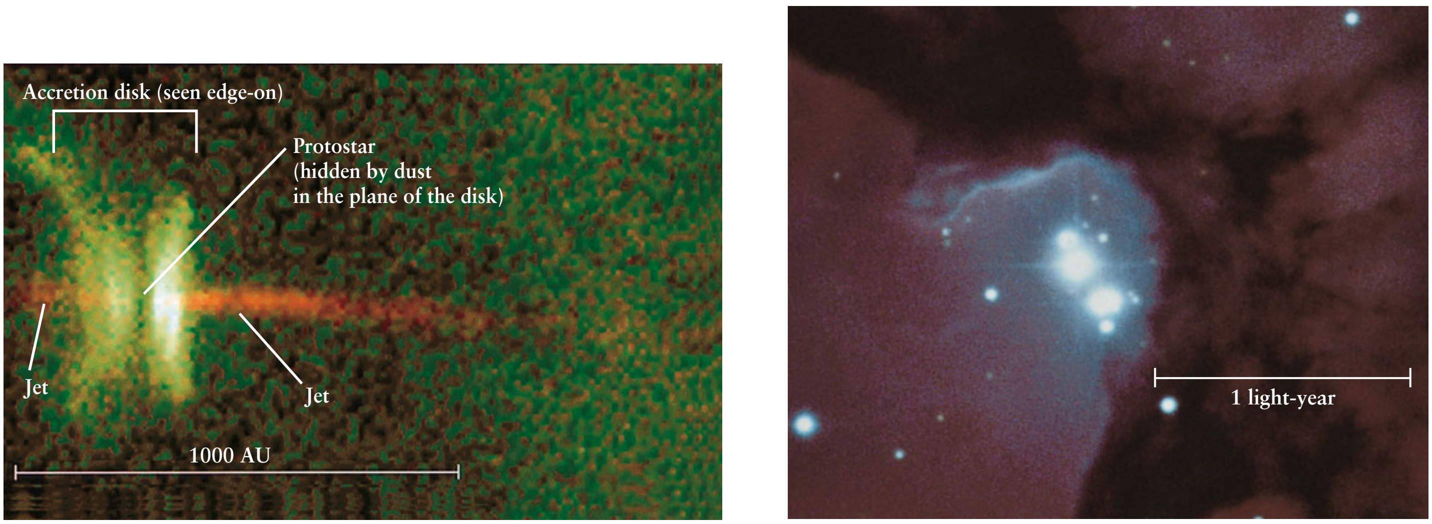
The Kuiper Belt: A Dusty Debris Ring The gravitational influence of the Jovian planets pushed small, icy objects to the outer reaches of the solar system beyond Neptune. The result shown in this artist's conception is the Kuiper belt, a ring populated by trans-Neptunian objects like Pluto, icy planetesimals, and dust particles. (NASA/JPL-Caltech/T. Pyle, SSC)

edge-on and the other seen face-on, that resemble the Kuiper belt. As we saw in Section 7-5, the combined mass of all trans-Neptunian objects is hundreds of times larger than that of the asteroid belt, in part because the materials that form ices are much more abundant than those that form rock.

Some of the smaller icy objects are thought to have been pushed as far as 50,000 AU from the Sun, forming a spherical "halo" around the solar system called the Oort cloud. From time to time one of the smaller chunks of ice and rock from either the Kuiper belt or the Oort cloud is deflected into the inner solar system. If one of these chunks comes close enough to the Sun, it begins to evaporate, producing a visible tail and appearing as a comet (see Figure 7-9).

The Final Stages of Solar System Evolution

While the planets, satellites, asteroids, and comets were forming, the protosun was also evolving into a full-fledged star with nuclear reactions occurring in its core (see Section 1-3). The time required for this to occur was about 10^8 years, roughly the same as that required for the formation of the terrestrial planets. Before the onset of nuclear reactions, however, the young Sun probably expelled a substantial portion of its mass into space (Figure 8-15).



(a) Jets from a young star

(b) Winds from young stars

WEB LINK 8.8

Figure 8-15 R I V U X G

Jets and Winds from Young Stars **(a)** This protostar in the constellation Taurus (the Bull) is ejecting matter in two immense jets directed perpendicular to the plane of the accretion disk. Red denotes light emitted by hot ionized gas in the jet, while green denotes starlight scattered by dust particles in the disk. **(b)** An outpouring of particles and radiation from the surfaces of these young stars has carved out a cavity in the surrounding dusty material. The stars lie within the Trifid Nebula in the constellation Sagittarius (the Archer). The scale of this image is about 100 times greater than that of image (a). (a: C. Burrows, the WFPC-2 Investigation Definition Team, and NASA; b: David Malin/Anglo-Australian Observatory)

Magnetic fields within the solar nebula would have funneled a portion of the nebula's mass into oppositely directed **jets** along the rotation axis of the nebula. Figure 8-15*a* shows one such jet emanating from a young star.

In addition, instabilities within the young Sun would have caused it to eject its tenuous outermost layers into space. This brief but intense burst of mass loss, observed in many young stars across the sky, is called a **T Tauri wind,** after the star in the constellation Taurus (the Bull) where it was first identified (see Figure 8-15*b*). Each of the protoplanetary disks in Figure 8-8 has a T Tauri star at its center. (The present-day Sun also loses mass from its outer layers in the form of high-speed electrons and protons, a flow called the **solar wind.** But this is minuscule compared with a T Tauri wind, which causes a star to lose mass 10^6 to 10^7 times faster than in the solar wind.)

With the passage of time, the combined effects of jets, the T Tauri wind, and accretion onto the planets would have swept the solar system nearly clean of gas and dust. With no more interplanetary material to gather up, the planets would have stabilized at roughly their present-day sizes, and the formation of the solar system would have been complete.

The *Cosmic Connections* figure summarizes our modern-day picture of the origin of our solar system. Prior to 1995 the only fully formed planetary system to which we could apply this model was our own. As we will see in the next section, astronomers can now further test this model on an ever-growing number of planets known to orbit other stars.

8-7 A variety of observational techniques reveal planets around other stars

If planets formed around our Sun, have they formed around other stars? That is, are there **extrasolar planets** orbiting stars other than the Sun? Our model for the formation of the planets would seem to suggest so. This model is based on the laws of physics and chemistry, which to the best of our understanding are the same throughout the universe. The discovery of a set of planets orbiting another star, with terrestrial planets in orbit close to the star and Jovian planets orbiting farther away, would be a tremendous vindication of our theory of solar system formation. It would also tell us that our planetary system is not unique in the universe. Because at least one planet in our solar system—the Earth—has the ability to support life, perhaps other planetary systems could also harbor living organisms.

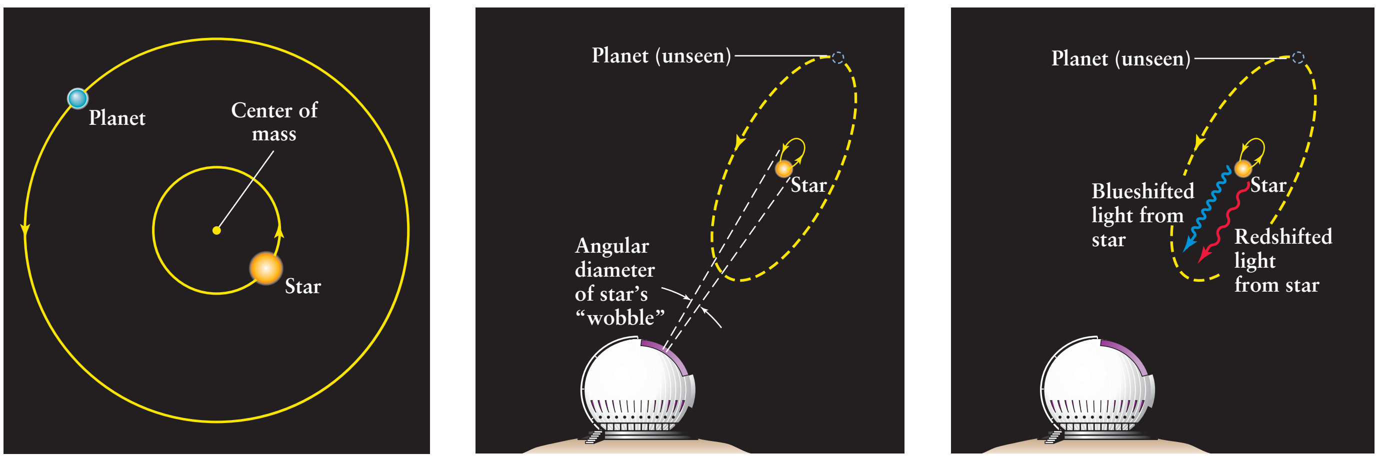
Several stars are known to have systems of two or more planets, but none of these resemble our own solar system

Since 1995 astronomers have in fact discovered about 200 planets orbiting stars other than the Sun. However, none of these is a terrestrial planet. Most of them are more massive than Jupiter, and some are in eccentric, noncircular orbits quite unlike planetary orbits in our solar system. To appreciate how remarkable these discoveries are, we must look at the process that astronomers go through to search for extrasolar planets.

Searching for Extrasolar Planets

It is very difficult to make direct observations of planets orbiting other stars. The problem is that planets are small and dim compared with stars; at visible wavelengths, the Sun is 10^9 times brighter than Jupiter and 10^{10} times brighter than the Earth. A hypothetical planet orbiting a distant star, even a planet 10 times larger than Jupiter, would be lost in the star's glare as seen through even the largest telescope on Earth.

Instead, indirect methods are used to search for extrasolar planets. One very powerful method is to search for stars that appear to "wobble" (Figure 8-16). If a star has a planet, it is not



(a) A star and its planet (b) The astrometric method (c) The radial velocity method

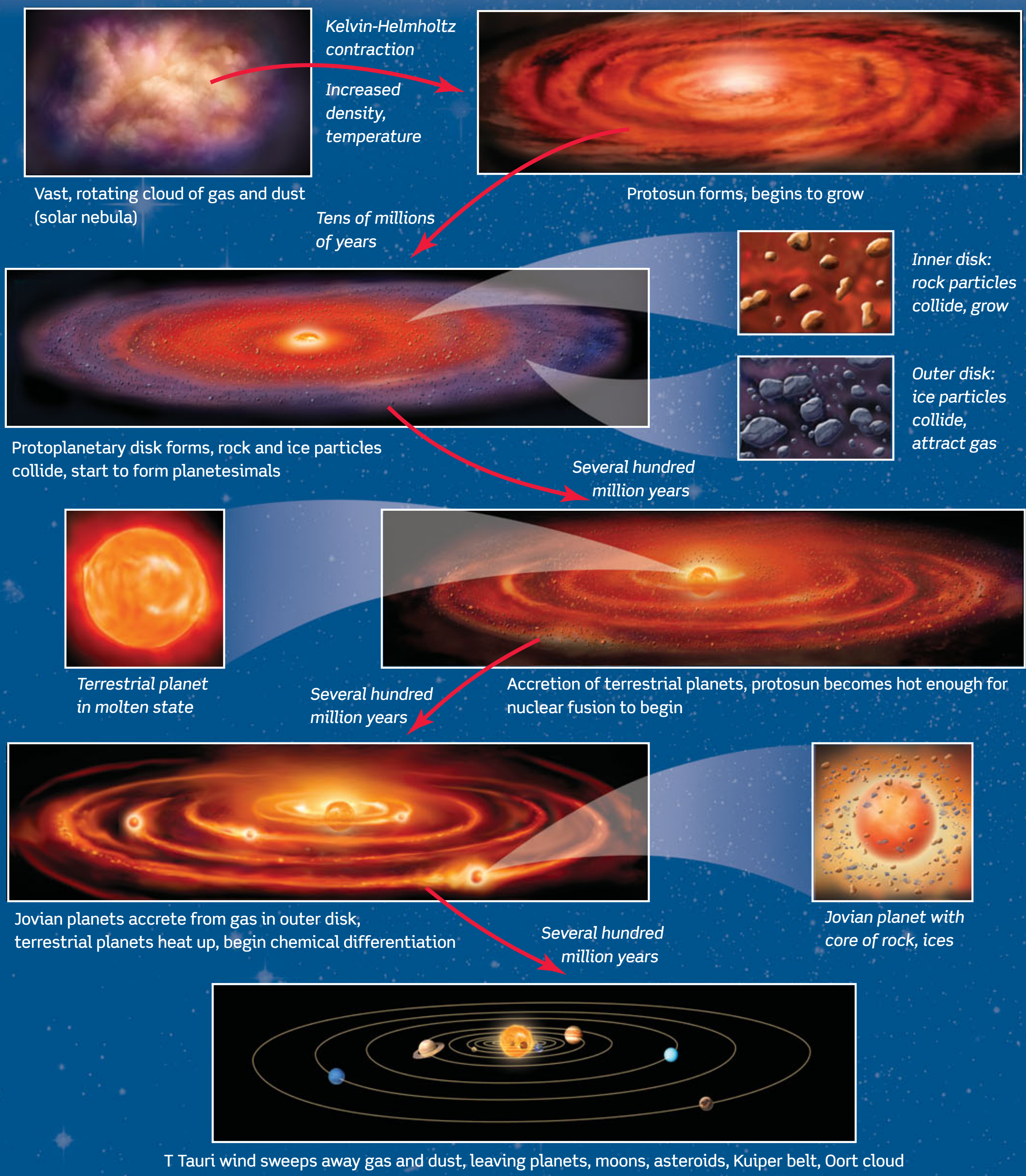
Figure 8-16

Detecting a Planet by Measuring Its Parent Star's Motion
(a) A planet and its star both orbit around their common center of mass, always staying on opposite sides of this point. Even if the planet cannot be seen, its presence can be inferred if the star's motion can be detected. **(b)** The astrometric method of detecting the unseen planet involves making direct measurements of the star's orbital motion. **(c)** In the radial velocity method, astronomers measure the Doppler shift of the star's spectrum as it moves alternately toward and away from the Earth. The amount of Doppler shift determines the size of the star's orbit, which in turn tells us about the unseen planet's orbit.

COSMIC CONNECTIONS

An overview of our present-day understanding of how the solar system formed.

Formation of the Solar System



quite correct to say that the planet orbits the star. Rather, both the planet and the star move in elliptical orbits around a point called the **center of mass.** Imagine the planet and the star as sitting at opposite ends of a very long seesaw; the center of mass is the point where you would have to place the fulcrum in order to make the seesaw balance. Because of the star's much greater mass, the center of mass is much closer to the star than to the planet. Thus, while the planet may move in an orbit that is hundreds of millions of kilometers across, the star will move in a much smaller orbit (Figure 8-16*a*).

As an example, the Sun and Jupiter both orbit their common center of mass with an orbital period of 11.86 years. (Jupiter has more mass than the other eight planets put together, so it is a reasonable approximation to consider the Sun's wobble as being due to Jupiter alone.) Jupiter's orbit has a semimajor axis of 7.78×10^8 km, while the Sun's orbit has a much smaller semimajor axis of 742,000 km. The Sun's radius is 696,000 km, so the Sun slowly wobbles around a point not far outside its surface. If astronomers elsewhere in the Galaxy could detect the Sun's wobbling motion, they could tell that there was a large planet (Jupiter) orbiting the Sun. They could even determine the planet's mass and the size of its orbit, even though the planet itself was unseen.

Detecting the wobble of other stars is not an easy task. One approach to the problem, called the **astrometric method,** involves making very precise measurements of a star's position in the sky relative to other stars. The goal is to find stars whose positions change in a cyclic way (Figure 8-16*b*). The measurements must be made with very high accuracy (0.001 arcsec or better) and, ideally, over a long enough time to span an entire orbital period of the star's motion. Because this technique is so challenging to put into practice, it has not yet led to any confirmed detections of extrasolar planets.

ANIMATION 8.5

A different approach to the problem is the **radial velocity method** (Figure 8-16*c*). This is based on the Doppler effect, which we described in Section 5-9. A wobbling star will alternately move away from and toward the Earth. This will cause the dark absorption lines in the star's spectrum (see Figure 5-13) to change their wavelengths in a periodic fashion. When the star is moving away from us, its spectrum will undergo a redshift to longer wavelengths. When the star is approaching, there will be a blueshift of the spectrum to shorter wavelengths. These wavelength shifts are very small because the star's motion around its orbit is quite slow. As an example, the Sun moves around its small orbit at only 12.5 m/s (45 km/h, or 28 mi/h). If the Sun were moving directly toward an observer at this speed, the hydrogen absorption line at a wavelength of 656 nm in the Sun's spectrum would be shifted by only 2.6×10^{-5} nm, or about 1 part in 25 million. Detecting these tiny shifts requires extraordinarily careful measurements and painstaking data analysis.

In 1995, Michel Mayor and Didier Queloz of the Geneva Observatory in Switzerland announced that by using the radial velocity method, they had discovered a planet orbiting the star 51 Pegasi, which is 47.9 light-years from the Sun in the constellation Pegasus (the Winged Horse). Their results were soon confirmed by the team of Geoff Marcy of San Francisco State University and Paul Butler of the University of California, Berkeley, using observations made at the University of California's Lick Observatory. For the first time, solid evidence had been found for a planet orbiting a star like our own Sun. Astronomers have since used the radial velocity method to discover planets orbiting more than 160 other stars at distances up to 600 light-years from the Sun. In at least 20 cases the star's "wobble" is too complex to have been caused by a single planet, so in these cases the star has a multiple-planet system. Figure 8-17 depicts a selection of these extrasolar planetary discoveries.

Extrasolar Planets: Surprising Masses and Orbits

Most of the extrasolar planets discovered by the radial velocity method have masses comparable with or larger than that of Saturn, and thus are presumably Jovian planets made primarily of hydrogen and helium. (This is difficult to confirm directly, because the spectra of the planets are very faint.) According to the picture we presented in Section 8-5, such Jovian planets would be expected to orbit relatively far from their stars, where temperatures were low enough to allow the buildup of a massive envelope of hydrogen and helium gas. But as Figure 8-17 shows, many extrasolar planets are in fact found orbiting very *close* to their stars. For example, the planet orbiting 51 Pegasi has a mass at least 0.46 times that of Jupiter but orbits only 0.052 AU from its star with an orbital period of just 4.23 days. In our own solar system, this orbit would lie well inside the orbit of Mercury!

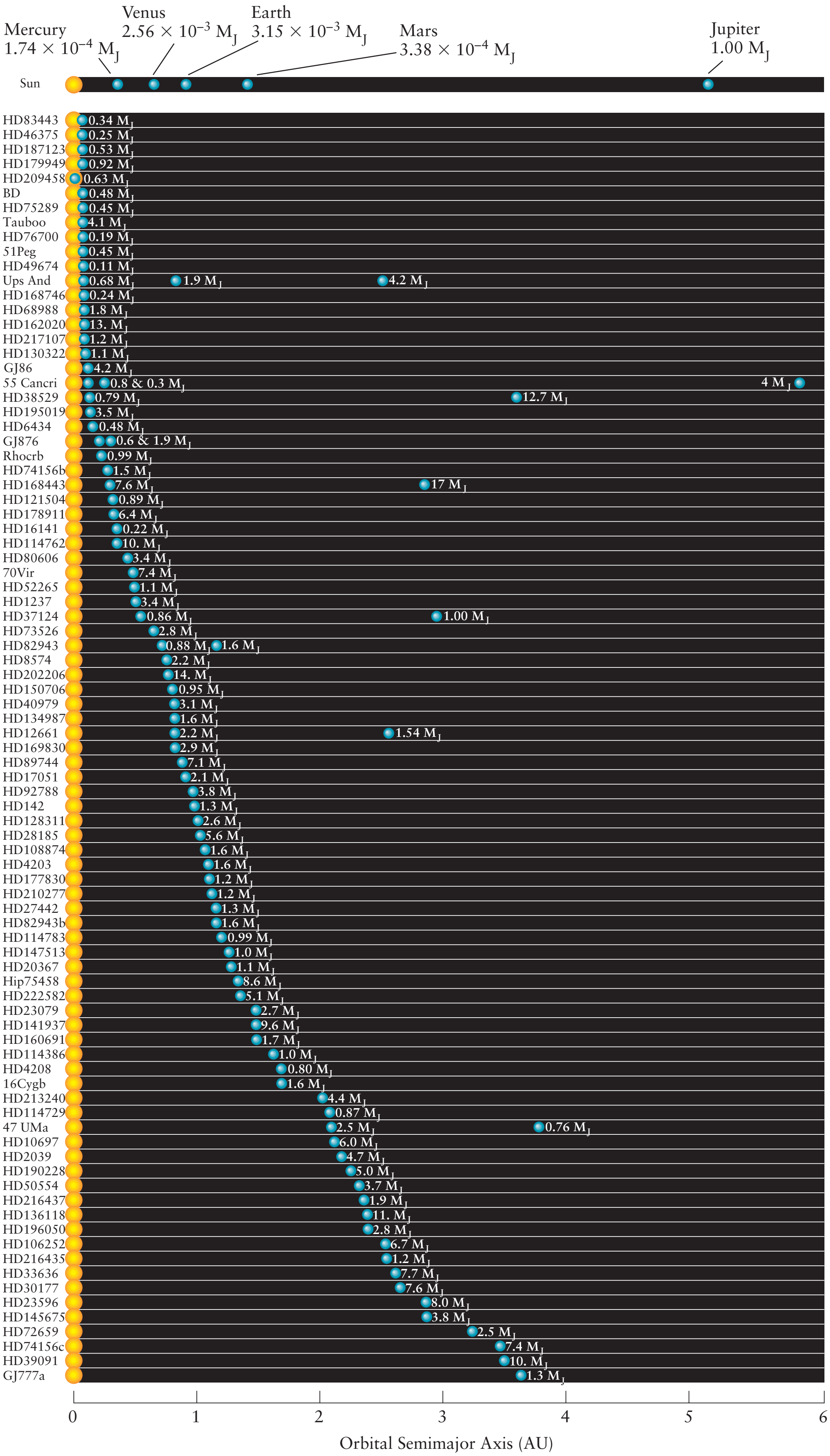
Another surprising result is that many of the extrasolar planets found so far have orbits with very large eccentricities (see Figure 4-10*b*). As an example, the planet around the star 16 Cygni B has an orbital eccentricity of 0.67; its distance from the star varies between 0.55 AU and 2.79 AU. This is quite unlike planetary orbits in our own solar system, where no planet has an orbital eccentricity greater than 0.25.

Do these observations mean that our picture of how planets form is incorrect? If Jupiterlike extrasolar planets such as that orbiting 51 Pegasi formed close to their stars, the mechanism of their formation must have been very different from that which operated in our solar system.

But another possibility is that extrasolar planets actually formed at large distances from their stars and have migrated inward since their formation. If enough gas and dust remain in a disk around a star after its planets form, interactions between the disk material and an orbiting planet will cause the planet to lose energy and to spiral inward toward the star around which it orbits. The planet's inward migration can eventually stop because of subtle gravitational effects from the disk or from the star. Gravitational interactions between the planet and the disk, or between planets in the same planetary system, could also have forced an extrasolar planet into a highly eccentric, noncircular orbit.

ANIMATION 8.6

One piece of evidence that young planets may spiral inward toward their parent stars is the spectrum of the star HD 82943, which has at least two planets orbiting it. The spectrum shows that this star's atmosphere contains a rare form of lithium that is found in planets, but which is destroyed in stars by nuclear reactions within 30 million years. The presence of this exotic form of lithium, known as ^{6}Li, means that in the past HD 82943 was orbited by at least one other planet.



WEB LINK 8.9

Figure 8-17

A Selection of Extrasolar Planets This figure summarizes what we know about planets orbiting a number of other stars. The star name is given at the left of each line. Each planet is shown at its average distance from its star (equal to the semimajor axis of its orbit). The mass of each planet—actually a lower limit—is given as a multiple of Jupiter's mass (M_J), equal to 318 Earth masses. Comparison with our own solar system (at the top of the figure) shows how closely many these extrasolar planets orbit their stars. (Adapted from the California and Carnegie Planet Search)

This planet vanished when it spiraled too close to the star, was vaporized, and was swallowed whole.

WEB LINK 8.10 Are all stars equally likely to have planets? The answer appears to be no: Only about 5% of the stars surveyed with the radial velocity method show evidence of planets. However, the percentage is 10% to 20% for stars in which heavy elements are at least as abundant as in the Sun. The conclusion is that heavy elements appear to play an important role in the evolution of planets from an interstellar cloud. This agrees with the idea discussed in Section 8-5 that planetesimals (which are composed of heavy elements) are the building blocks of planets.

Analyzing Extrasolar Planets with the Transit Method

The radial velocity method gives us only a partial picture of what extrasolar planets are like. It cannot give us precise values for a planet's mass, only a lower limit. (An exact determination of the mass would require knowing how the plane of the planet's orbit is inclined to our line of sight. Unfortunately, this angle is not known because the planet itself is unseen.) Furthermore, the radial velocity method by itself cannot tell us the diameter of a planet or what the planet is made of.

ANIMATION 8.7 A technique called the **transit method** makes it possible to fill in these blanks about the properties of certain extrasolar planets. This method looks for the rare situation in which a planet comes between us and its parent star, an event called a **transit** (Figure 8-18). As in a partial solar eclipse (Section 3-5), this causes a small but measurable dimming of the star's light. If a transit is seen, the orbit must be nearly edge-on to our line of sight. Knowing the orientation of the orbit, the information obtained by radial velocity measurements of the star tells us the true mass (not just a lower limit) of the orbiting planet. About 5% of all known extrasolar planets undergo transits of their parent

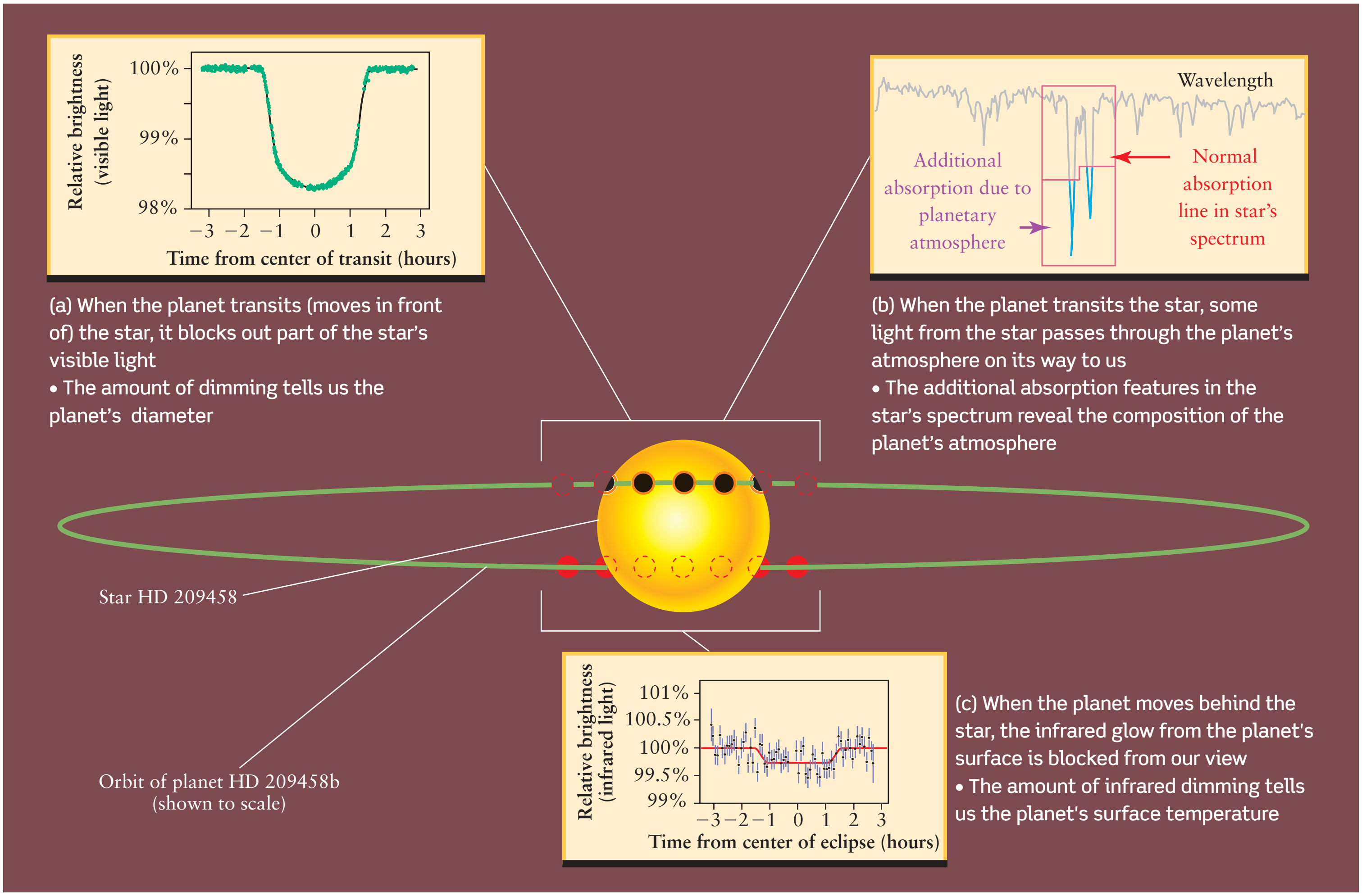
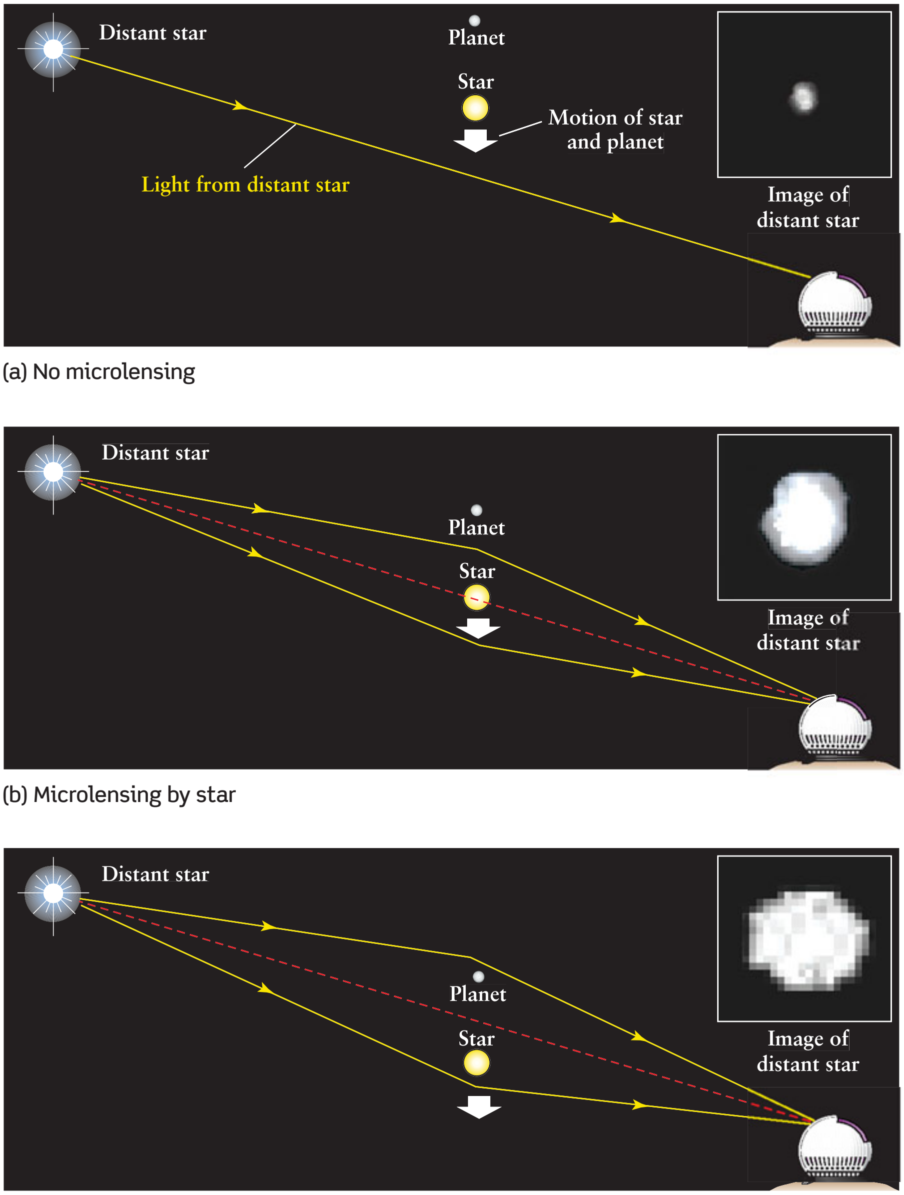


Figure 8-18

A Transiting Extrasolar Planet If the orbit of an extrasolar planet is nearly edge-on to our line of sight, like the planet that orbits the star HD 209458, we can learn about the planet's **(a)** diameter, **(b)** atmospheric composition, and **(c)** surface temperature. (S. Seager and C. Reed, *Sky and Telescope*; H. Knutson, D. Charbonneau, R. W. Noyes (Harvard-Smithsonian CfA), T. M. Brown (HAO/NCAR), and R. L. Gilliland (STScI); A. Feild (STScI); NASA/JPL-Caltech/D. Charbonneau, Harvard-Smithsonian CfA)



(a) No microlensing

(b) Microlensing by star

(c) Microlensing by star and planet

ANIMATION 8.8

Figure 8-19

Microlensing Reveals an Extrasolar Planet

(a) A star with a planet drifts across the line of sight between a more distant star and a telescope on Earth. **(b)** The gravity of the closer star bends the light rays from the distant star, focusing the distant star's light and making it appear brighter. **(c)** The gravity of the planet causes a second increase in the distant star's brightness.

star, and all of these planets turn out to have masses comparable to that of Jupiter. These results reinforce the idea that other stars can end up with planets much like those in our solar system.

ANIMATION 8.8

There are three other benefits of the transit method. One, the amount by which the star is dimmed during the transit depends on how large the planet is, and so tells us the planet's diameter (Figure 8-18*a*). Two, during the transit the star's light passes through the planet's atmosphere, where certain wavelengths are absorbed by the atmospheric gases. This absorption affects the spectrum of starlight that we measure and so allows us to determine the composition of the planet's atmosphere (Figure 8-18*b*). Three, with an infrared telescope it's possible to detect a slight dimming when the planet goes *behind* the star (Figure 8-18*c*). That is because the planet emits infrared radiation due to its own temperature, and this radiation is blocked when the planet is behind the star. Measuring the amount of dimming tells us the amount of radiation emitted by the planet, which in turn tells us the planet's surface temperature.

One example of what the transit method can tell us is about the planet that orbits the star HD 209458, which is 153 light-years from the Sun. The mass of this planet is 0.69 that of Jupiter, but its diameter is 1.32 times larger than that of Jupiter. This low-mass, large-volume planet thus has only one-quarter the density of Jupiter. It is also very hot: Because the planet orbits just 0.047 AU from the star, its surface temperature is a torrid 1130 K (860°C, or 1570°F). Observations of the spectrum during a transit reveal the presence of hydrogen, carbon, oxygen, and sodium in a planetary atmosphere that is literally evaporating away in the intense starlight. Discoveries such as these give insight into the exotic circumstances that can be found in other planetary systems.

Other Techniques for Discovering Extrasolar Planets

In 2004 astronomers began to use a property of space discovered by Albert Einstein as a tool for detecting extrasolar planets. Einstein's general theory of relativity makes the remarkable statement that a star's gravity can deflect the path of a light beam just as it deflects the path of a planet or spacecraft. If a star drifts through the line of sight between Earth and a more distant star, the closer star's gravity acts like a lens that focuses the more distant star's light. Such **microlensing** causes the distant star's image as seen in a telescope to become brighter. If the closer star has a planet, the planet's gravity will cause a secondary brightening whose magnitude depends on the planet's mass (Figure 8-19). Using this technique astronomers have detected a handful of extrasolar planets at distances up to 21,000 light-years, and expect to find many more.

Since 2004 astronomers have also been able to record images of a few extrasolar planets. At infrared wavelengths a star outshines a Jupiter-sized planet by only about 100 to 1, compared to 10^9 to 1 at visible wavelengths. Hence, by using an infrared telescope aided by adaptive optics (Section 6-3) it is possible to resolve both a star and its planet if the two are sufficiently far apart. Figure 8-20 shows an infrared image of the star 2M1207 and its planet. Unlike planets detected with the radial velocity or transit method, it is impractical to watch this planet go through a complete orbit: It is so far from its parent star that the orbital period is more than a thousand years. Instead, astronomers verify that it is a planet by confirming that the star and planet move together through space, as they must do if they are held together by their mutual gravitational attraction. While it is not possible to measure the planet's mass directly, the spectrum and brightness of the planet tell astronomers its surface temperature and diameter.

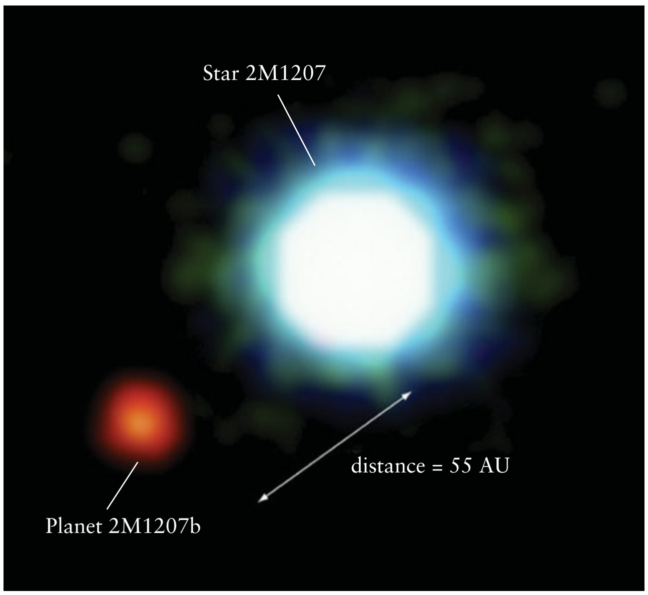


Figure 8-20 R **I** V U X G

Imaging an Extrasolar Planet This infrared image from the European Southern Observatory shows the star 2M1207 and a planet with about 1.5 times the diameter of Jupiter. First observed in 2004, this extrasolar planet was the first to be visible in a telescopic image. 2M1207 and its planet lie about 170 light-years from the Sun in the constellation Hydra (the Water Snake). (ESO/VLT/NACO)

The Search for Earthlike Planets

If there are planets orbiting other stars, are there any that resemble our own Earth? As of this writing we do not know the answer to this question. An Earth-sized planet has such weak gravity that it can produce only a tiny "wobble" in its parent star, making it very difficult to detect such planets using the radial velocity method. If an Earth-sized planet were to transit its parent star, its diameter is so small that it would cause only a miniscule dimming of the star's light. For these reasons, as of this writing, astronomers have been unable to detect extrasolar planets less massive than 7.5 Earth masses.

In the near future, however, orbiting telescopes being planned by both NASA and the European Space Agency (ESA) will search for terrestrial planets around other stars. One such orbiting telescope, scheduled for launch in 2008, is NASA's Kepler, which will use a one-meter telescope and sensitive detectors to look for transits of Earth-sized planets within a narrow patch of sky.

An even broader search for extrasolar planets will be carried out by ESA's Gaia mission, scheduled for launch in 2011. Gaia will survey a billion (10^9) stars—1% of all the stars in the Milky Way Galaxy—and will be able to detect star "wobbles" as small as 2×10^{-6} arcsec. With such high-precision data the astrometric method (Figure 8-16*b*) will finally come into its own. Astronomers estimate that Gaia will find from 10,000 to 50,000 Jupiter-sized planets. If our solar system is fairly typical, a substantial number of these planets should move around their parent stars in orbits like those of the Jovian planets around the Sun, with semimajor axes greater than 3 AU and low eccentricities. If Gaia finds such planetary systems that resemble our own, they will be natural places to look for Earth-sized planets. The next few decades may tell whether our own solar system is an exception or just one of a host of similar systems throughout the Galaxy.

Key Words

Term preceded by an asterisk (*) is discussed in Box 8-1.

accretion, p. 194
astrometric method (for detecting extrasolar planets), p. 200
atomic number, p. 188
center of mass, p. 200
chemical differentiation, p. 194
chondrule, p. 194
condensation temperature, p. 193
conservation of angular momentum, p. 191
core accretion model, p. 195
disk instability model, p. 196
extrasolar planet, p. 198
*half-life, p. 190
interstellar medium, p. 187
jets, p. 198
Kelvin-Helmholtz contraction, p. 191
meteorite, p. 189
microlensing, p. 204
nebulosity, p. 187
nebular hypothesis, p. 190
planetesimal, p. 194
protoplanet, p. 194

protoplanetary disk (proplyd), p. 192
protosun, p. 191
radial velocity method (for detecting extrasolar planets), p. 200
radioactive dating, p. 189
radioactive decay, p. 189
solar nebula, p. 190
solar wind, p. 198
T Tauri wind, p. 198
transit, p. 202
transit method (for detecting extrasolar planets), p. 202

Key Ideas

Models of Solar System Formation: The most successful model of the origin of the solar system is called the nebular hypothesis. According to this hypothesis, the solar system formed from a cloud of interstellar material called the solar nebula. This occurred 4.56 billion years ago (as determined by radioactive dating).

The Solar Nebula and Its Evolution: The chemical composition of the solar nebula, by mass, was 98% hydrogen and helium (elements that formed shortly after the beginning of the universe) and 2% heavier elements (produced much later in the centers of stars, and cast into space when the stars died). The heavier elements were in the form of ice and dust particles.

• The nebula flattened into a disk in which all the material orbited the center in the same direction, just as do the present-day planets.

Formation of the Planets and Sun: The terrestrial planets, the Jovian planets, and the Sun followed different pathways to formation.

• The four terrestrial planets formed through the accretion of dust particles into planetesimals, then into larger protoplanets.

• In the core accretion model, the four Jovian planets began as rocky protoplanetary cores, similar in character to the terrestrial planets. Gas then accreted onto these cores in a runaway fashion.

• In the alternative disk instability model, the Jovian planets formed directly from the gases of the solar nebula. In this model the cores formed from planetesimals falling into the planets.

• The Sun formed by gravitational contraction of the center of the nebula. After about 10^8 years, temperatures at the protosun's center became high enough to ignite nuclear reactions that convert hydrogen into helium, thus forming a true star.

Extrasolar Planets: Astronomers have discovered planets orbiting other stars.

• Most of these planets are detected by the "wobble" of the stars around which they orbit.

• A small but growing number of extrasolar planets have been discovered by the transit method, by microlensing, and direct imaging.

• Most of the extrasolar planets discovered to date are quite massive and have orbits that are very different from planets in our solar system.

Questions

Review Questions

1. Describe three properties of the solar system that are thought to be a result of how the solar system formed.
2. The graphite in your pencil is a form of carbon. Where were these carbon atoms formed?
3. What is the interstellar medium? How does it become enriched over time with heavy elements?
4. What is the evidence that other stars existed before our Sun was formed?
5. Why are terrestrial planets smaller than Jovian planets?
6. How do radioactive elements make it possible to determine the age of the solar system? What are the oldest objects that have been found in the solar system?
7. What is the tidal hypothesis? What aspect of the solar system was it designed to explain? Why was this hypothesis rejected?
8. What is the nebular hypothesis? Why is this hypothesis accepted?
9. What was the protosun? What caused it to shine? Into what did it evolve?
10. Why is it thought that a disk appeared in the solar nebula?
11. What are proplyds? What do they tell us about the plausibility of our model of the solar system's origin?
12. What is meant by a substance's condensation temperature? What role did condensation temperatures play in the formation of the planets?
13. What is a planetesimal? How did planetesimals give rise to the terrestrial planets?
14. (**a**) What is meant by accretion? (**b**) Why are the terrestrial planets denser at their centers than at their surfaces?
15. If hydrogen and helium account for 98% of the mass of all the atoms in the universe, why aren't the Earth and Moon composed primarily of these two gases?
16. What is a chondrule? How do we know they were not formed by the ambient heat of the solar nebula?
17. Why did the terrestrial planets form close to the Sun while the Jovian planets formed far from the Sun?
18. What are the competing models of how the Jovian planets formed?
19. Explain how our current understanding of the formation of the solar system can account for the following characteristics of the solar system: (**a**) All planetary orbits lie in nearly the same plane. (**b**) All planetary orbits are nearly circular. (**c**) The planets orbit the Sun in the same direction in which the Sun itself rotates.
20. Why is the combined mass of all the asteroids so small? Why is the combined mass of all trans-Neptunian objects so much greater than that for the asteroids?
21. Explain why most of the satellites of Jupiter orbit that planet in the same direction that Jupiter rotates.
22. What is the radial velocity method used to detect planets orbiting other stars? Why is it difficult to use this method to detect planets like Earth?
23. Summarize the differences between the planets of our solar system and those found orbiting other stars.

24. Is there evidence that planets have fallen into their parent stars? Explain.
25. What does it mean for a planet to transit a star? What can we learn from such events?
26. What is microlensing? How does it enable astronomers to discover extrasolar planets?
27. A 1999 news story about the discovery of three planets orbiting the star Upsilon Andromedae ("Ups And" in Figure 8-17) stated that "the newly discovered galaxy, with three large planets orbiting a star known as Upsilon Andromedae, is 44 light-years away from Earth." What is wrong with this statement?

Advanced Questions

Questions preceded by an asterisk (*) involve topics discussed in Box 4-4 or Box 8-1.

Problem-solving tips and tools

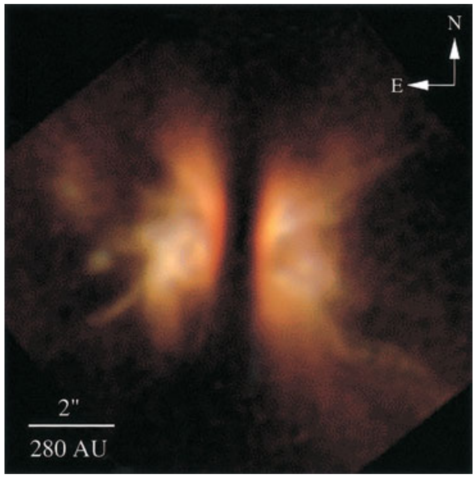
The volume of a disk of radius r and thickness t is $\pi r^2 t$. Box 1-1 explains the relationship between the angular size of an object and its actual size. An object moving at speed v for a time t travels a distance $d = vt$; Appendix 6 includes conversion factors between different units of length and time. To calculate the mass of 70 Virginis or the orbital period of the planet around 2M1207, review Box 4-4. Section 5-4 describes the properties of blackbody radiation.

28. Figure 8-4 shows that carbon, nitrogen, and oxygen are among the most abundant elements (after hydrogen and helium). In our solar system, the atoms of these elements are found primarily in the molecules CH_4 (methane), NH_3 (ammonia), and H_2O (water). Explain why you suppose this is.
29. (**a**) If the Earth had retained hydrogen and helium in the same proportion to the heavier elements that exist elsewhere in the universe, what would its mass be? Give your answer as a multiple of the Earth's actual mass. Explain your reasoning. (**b**) How does your answer to (a) compare with the mass of Jupiter, which is 318 Earth masses? (**c**) Based on your answer to (b), would you expect Jupiter's rocky core to be larger, smaller, or the same size as the Earth? Explain your reasoning.

*30. If you start with 0.80 kg of radioactive potassium (^{40}K), how much will remain after 1.3 billion years? After 2.6 billion years? After 3.9 billion years? How long would you have to wait until there was *no* ^{40}K remaining?

*31. Three-quarters of the radioactive potassium (^{40}K) originally contained in a certain volcanic rock has decayed into argon (^{40}Ar). How long ago did this rock form?

32. Suppose you were to use the Hubble Space Telescope to monitor one of the protoplanetary disks shown in Figure 8-8*b*. Over the course of 10 years, would you expect to see planets forming within the disk? Why or why not?
33. The protoplanetary disk at the upper right of Figure 8-8*b* is seen edge-on. The diameter of the disk is about 700 AU. (**a**) Make measurements on this image to determine the thickness of the disk in AU. (**b**) Explain why the disk will continue to flatten as time goes by.



R I V U X G

(Courtesy of D. Padgett and W. Brandner, IPAC/Caltech; K. Stapelfeldt, JPL; and NASA)

34. The accompanying infrared image shows IRAS 04302+2247, a young star that is still surrounded by a disk of gas and dust. The scale bar at the lower left of the image shows that at the distance of IRAS 04302+2247, an angular size of 2 arcseconds corresponds to a linear size of 280 AU. Use this information to find the distance to IRAS 04302+2247.
35. The image accompanying Question 34 shows a dark, opaque disk of material surrounding the young star IRAS 04302+2247. The disk is edge-on to our line of sight, so it appears as a dark band running vertically across this image. The material to the left and right of this band is still falling onto the disk. (**a**) Make measurements on this image to determine the diameter of the disk in AU. Use the scale bar at the lower left of this image. (**b**) If the thickness of the disk is 50 AU, find its volume in cubic meters. (**c**) The total mass of the disk is perhaps 2×10^{28} kg (0.01 of the mass of the Sun). How many atoms are in the disk? Assume that the disk is all hydrogen. A single hydrogen atom has a mass of 1.673×10^{-27} kg. (**d**) Find the number of atoms per cubic meter in the disk. Is the disk material thick or thin compared to the air that you breathe, which contains about 5.4×10^{25} atoms per cubic meter?
36. If the material in the jet shown in Figure 8-15*a* is moving at 200 km/s, how long ago was the material at the far right-hand end of the jet ejected from the star? Give your answer in years. (You will need to make measurements on the image.)

*37. The planet discovered orbiting the star 70 Virginis ("70Vir" in Figure 8-17), 59 light-years from Earth, moves in an orbit with semimajor axis 0.48 AU and eccentricity 0.40. The period of the orbit is 116.7 days. Find the mass of 70 Virginis. Compare your answer with the mass of the Sun. (*Hint:* The planet has far less mass than the star.)

*38. Because of the presence of Jupiter, the Sun moves in a small orbit of radius 742,000 km with a period of 11.86 years. (**a**) Calculate the Sun's orbital speed in meters per second. (**b**) An astronomer on a hypothetical planet orbiting the star

Vega, 25 light-years from the Sun, wants to use the astrometric method to search for planets orbiting the Sun. What would be the angular diameter of the Sun's orbit as seen by this alien astronomer? Would the Sun's motion be discernible if the alien astronomer could measure positions to an accuracy of 0.001 arcsec? (**c**) Repeat part (b), but now let the astronomer be located on a hypothetical planet in the Pleiades star cluster, 360 light-years from the Sun. Would the Sun's motion be discernible to this astronomer?

39. (**a**) Figure 8-18*c* shows how astronomers determine that the planet of HD 209458 has a surface temperature of 1130 K. Treating the planet as a blackbody, calculate the wavelength at which it emits most strongly. (**b**) The star HD 209458 itself has a surface temperature of 6030 K. Calculate its wavelength of maximum emission, assuming it to be a blackbody. (**c**) If a high-resolution telescope were to be used in an attempt to record an image of the planet orbiting HD 209458, would it be better for the telescope to use visible or infrared light? Explain your reasoning.

***40.** (**a**) The star 2M1207 shown in Figure 8-20 is 170 light-years from Earth. Find the angular distance between this star and its planet as seen from Earth. Express your answer in arcseconds. (**b**) The mass of 2M1207 is 0.025 that of the Sun; the mass of the planet is very much smaller. Calculate the orbital period of the planet, assuming that the distance between the star and planet shown in Figure 8-20 is the semimajor axis of the orbit. Is it possible that an astronomer could observe a complete orbit in one lifetime?

Discussion Questions

41. Propose an explanation why the Jovian planets are orbited by terrestrial-like satellites.

42. Suppose that a planetary system is now forming around some protostar in the sky. In what ways might this planetary system turn out to be similar to or different from our own solar system? Explain your reasoning.

43. Suppose astronomers discovered a planetary system in which the planets orbit a star along randomly inclined orbits. How might a theory for the formation of that planetary system differ from that for our own?

Web/eBook Questions

44. Search the World Wide Web for information about recent observations of protoplanetary disks. What insights have astronomers gained from these observations? Is there any evidence that planets have formed within these disks?

45. In 2000, extrasolar planets with masses comparable to that of Saturn were first detected around the stars HD 16141 (also called 79 Ceti) and HD 46375. Search the World Wide Web for information about these "lightweight" planets. Do these planets move around their stars in the same kind of orbit as Saturn follows around the Sun? Why do you suppose this is? How does the discovery of these planets reinforce the model of planet formation described in this chapter?

46. In 2006 a planet called XO-1b was discovered using the transit method. Search the World Wide Web for information about this planet and how it was discovered. What unusual kind of telescope was used to make this discovery? Have other extrasolar planets been discovered using the same kind of telescope?

Activities

Observing Projects

47. Use the *Starry Night Enthusiast™* program to investigate stars that have planets orbiting them. First display the entire celestial sphere (select **Guides > Atlas** in the **Favourites** menu). Then use the **Find** pane to find and center each of the stars listed below. To do this, click the magnifying glass icon on the left side of the edit box at the top of the Find pane and select **Star** from the drop-down menu; then type the name of the star in the edit box and press the Enter or Return key on the keyboard. Click on the **Info** tab on the left-hand side of the *Starry Night Enthusiast™* window for full information about the star. For each star, record the luminosity of the star (a measure of the star's total light output). How far from Earth is each star? Which stars are more luminous than the Sun? Which are less luminous? How do you think these differences would have affected temperatures in the nebula in which each star's planets formed (see Figure 8-10)? (i) 47 Ursae Majoris; (ii) 51 Pegasi; (iii) 70 Virginis; (iv) Rho Coronae Borealis.

48. Use the *Starry Night Enthusiast™* program to examine stars that have planets. Select **Stars > Extra-Solar Planets** in the **Favourites** menu. In the star map that appears, each circled star has one or more planets. (You can zoom in and zoom out using the buttons at the right side of the toolbar. Click the **Info** tab at the left of the main window to open the Info pane and open the **Other Data** panel. Then click on a circled star to learn more about its properties. Note that the information given for each star includes the *apparent magnitude*, which is a measure of how bright each star appears as seen from Earth. Apparent magnitude uses a "backwards" scale: The greater the value of the apparent magnitude, the *dimmer* the star. Most of the brighter stars you can see with the naked eye from the Earth have apparent magnitudes between 0 and 1, while the dimmest star you can see from a dark location has apparent magnitude 6. Are most of the circled stars visible to the naked eye? List at least two stars that are visible, and include their apparent magnitudes.

Alien Planets

by Geoff Marcy

Astronomers have now surveyed 2000 nearby stars in the search for orbiting planets. My team is using the 10-meter Keck telescope in Hawaii to measure the Doppler effect in stars that wobble because of planets orbiting around them. So far, we and other teams have found more than 200 planets, some more massive than Jupiter and some less massive than Neptune. We have now found 20 stars that have multiple planets orbiting them—full planetary systems. Often the planets orbit synchronously, with one planet orbiting the star two or three times for every orbit of another planet. This synchronization of the planets allows gravity to shepherd their motion, keeping them synchronized forever.

We hope to compare the architecture of these planetary systems to that of our own solar system. Is our solar system a common type? Do all planetary systems have giant planets orbiting far away from the host star, with small rocky planets orbiting close in?

Remarkably, the planetary systems observed so far seem very different from our own solar system. In some, a giant planet orbits very close to the star. More surprising is that almost every alien planet that orbits beyond 0.1 AU from its star resides in a highly elliptical orbit that resembles eccentric comet orbits. Why are these planets in such elliptical orbits so different from the nearly circular orbits of planets in our own solar system? Astronomers are baffled by this difference. One possibility is that planets usually form as close-knit families around a star. Over time, the planets may gravitationally pull on one another, yanking themselves out of their original circular orbits. These perturbed planets may then venture near other planets, yanking on them, too. Many of the planets may gravitationally slingshot each other completely out of the planetary system. These far flung planets are destined to roam the darkness of galactic space, cooling to frigid temperatures that are inhospitable to life.

The extrasolar planets cast a mystery back on the Earth. Why is our solar system immune to this chaotic episode that scatters planets into wacky orbits? Imagine the disaster if our Earth were suddenly thrust into a highly elliptical orbit. During half the year, we would be roasting too close to the Sun, with oceans vaporized into an enormous steam bath. The other half of the year our orbit would carry us too far from the Sun, causing all the oceans to freeze over. Life on Earth would be severely challenged to survive in such an elongated orbit.

Why are we humans so lucky as to live in a stable planetary system in which circular orbits ensure that we receive the same warming light intensity from our Sun, all year round? Perhaps the question to ask is: Would life have evolved here if the Earth suffered from wild temperature swings that would make liquid water rare? After all, intelligent life might not have evolved here if the Earth suffered from wild temperature swings that would make liquid water rare. We humans, and species in general, may flourish mostly on worlds that maintain nearly constant temperature. If so, our solar system and the Earth might be a rare galactic quirk that just happens to be suitable for life. We wouldn't be here otherwise. If this picture is correct, our Earth is indeed a precious oasis in our Milky Way Galaxy.

In the next few years, we plan to use the Doppler technique to discover planets having masses only 10 or 20 times that of our Earth. These would likely be rocky planets, allowing liquid water to puddle in ponds and lakes. Who knows what biology might emerge in such extraterrestrial chemistry labs! In the next decade, we will discover more planetary systems by using the Doppler method. We are working night and day to find Jovian planets that orbit 5 AU from their stars, similar to the orbital radius of our Jupiter. Their orbits, circular or elliptical, will shed light on a key question: How common are configurations like our solar system, and how common is advanced life in the universe?

When Geoff Marcy sat down to write this essay, more than 200 planets were known to orbit other stars. He leads the team that has found more than 120 of them. Dr. Marcy became interested in astronomy at the age of 14, when his parents bought him a small reflecting telescope. Since receiving his Ph.D. from the University of California, Santa Cruz, he has studied stars similar to our Sun. He helped show that magnetic regions on their surfaces cause "star spots" and stellar flares. He also showed that brown dwarfs—stars too small to burn hydrogen—rarely orbit other stars. His work may soon reveal whether a planetary system like ours is common or a quirk of the cosmos. Dr. Marcy is an astronomer at the University of California, Berkeley.

9

The Living Earth

RIVUXG

The two hemispheres of Earth. (NASA)

When astronauts made the first journeys from the Earth to the Moon between 1968 and 1972, they often reported that our planet is the most beautiful sight visible from space. Of all the worlds of the solar system, only Earth has the distinctive green color of vegetation, and only Earth has liquid water on its surface. Compared with the Moon, whose lifeless, dry surface has been ravaged by billions of years of impacts by interplanetary debris, the Earth seems an inviting and tranquil place.

Yet the appearance of tranquility is deceiving. The seemingly solid surface of the planet is in a state of slow but constant motion, driven by the flow of molten rock within the Earth's interior. Sunlight provides the Earth's atmosphere with the energy that drives our planet's sometimes violent weather, including all the cloud patterns visible in the images shown here.

Unseen in these images are immense clouds of subatomic particles that wander around the outside of the planet in two giant belts, held in thrall by the Earth's magnetic field. And equally unseen are trace gases in the Earth's atmosphere whose abundance may determine the future of our climate, and on which may depend the survival of entire species.

In this chapter our goal is to learn about the Earth's components—its dynamic oceans and atmosphere, its ever-changing surface, and its hot, active interior—and how they interact to make up our planetary home. In later chapters we will use this knowledge as a point of reference for studying the Moon and the other planets.

9-1 The Earth's atmosphere, oceans, and surface are extraordinarily active

The crew of an alien spacecraft exploring our solar system might overlook the Earth altogether. Although the largest of the terrestrial planets, with a mass greater than that of Mercury, Venus, and Mars put together, Earth is far smaller than any of the giant Jovian planets (see Table 7-1 and Table 9-1). But a more careful inspection would reveal the Earth to be unique among all the planets that orbit the Sun.

Dynamic Earth: Water, Air, and Land

Unlike the arid surfaces of Venus and Mars, the Earth's surface is very wet. Indeed, nearly 71% of the Earth's surface is covered with water (Figure 9-1). Water is also locked into the chemical structure of many Earth rocks, including those found in the driest deserts. Furthermore, the Earth's liquid water is in constant motion. The oceans ebb and flow with the tide, streams and rivers flow down to the sea, and storms whip lake waters into a frenzy.

To understand our dynamic planet, we must understand the energy sources that power its activity

The Earth's atmosphere is also in a state of perpetual activity. Winds blow at all altitudes, with speeds and directions that change from one hour to the next. The atmosphere is at its most

Learning Goals

By reading the sections of this chapter, you will learn

9-1 What powers the motions of the Earth's atmosphere, oceans, and land surfaces

9-2 How scientists have deduced the layered structure of our planet's interior

9-3 The evidence that the continents are being continuously moved and reshaped

9-4 How life on Earth is protected from subatomic particles emitted by the Sun

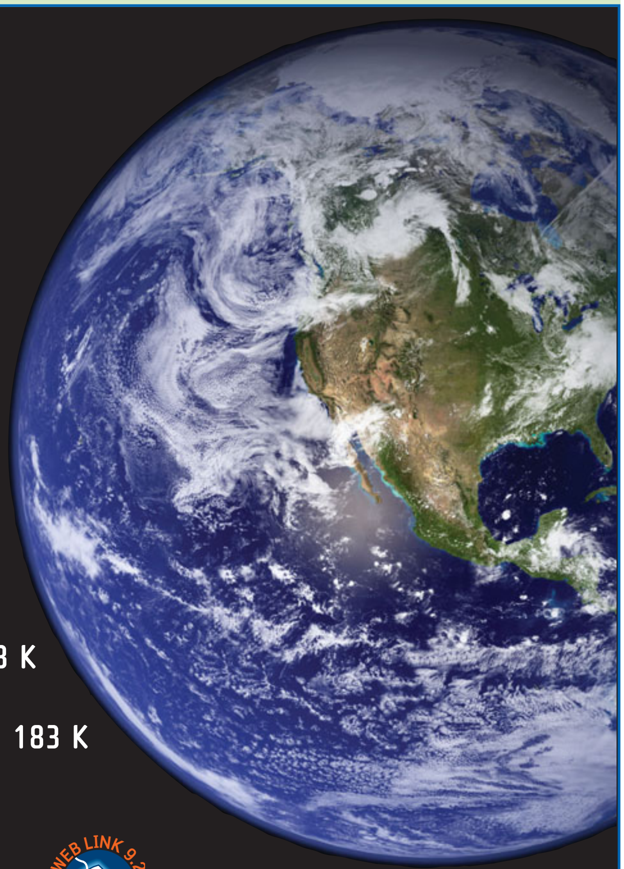
9-5 How the evolution of life has transformed the Earth's atmosphere

9-6 What causes the patterns of weather in our atmosphere

9-7 How human civilization is causing dramatic and adverse changes to our planetary habitat

Table 9-1 Earth Data

Average distance from Sun:	1.000 AU = 1.496×10^8 km
Maximum distance from Sun:	1.017 AU = 1.521×10^8 km
Minimum distance from Sun:	0.983 AU = 1.471×10^8 km
Eccentricity of orbit:	0.017
Average orbital speed:	29.79 km/s
Orbital period:	365.256 days
Rotation period:	23.9345 hours
Inclination of equator to orbit:	23.45°
Diameter (equatorial):	12,756 km
Mass:	5.974×10^{24} kg
Average density:	5515 kg/m^3
Escape speed:	11.2 km/s
Albedo:	0.31
Surface temperature range	Maximum: 60°C = 140°F = 333 K Mean: 14°C = 57°F = 287 K Minimum: −90°C = −130°F = 183 K
Atmospheric composition (by number of molecules):	78.08% nitrogen (N_2) 20.95% oxygen (O_2) 0.035% carbon dioxide (CO_2) about 1% water vapor



WEB LINK 9.2

(NASA)

dynamic when water evaporates to form clouds, then returns to the surface as rain or snow (Figure 9-2). While other worlds of the solar system have atmospheres, only the Earth's contains the oxygen that animals (including humans) need to sustain life.

The combined effects of water and wind cause erosion of mountains and beaches. But these are by no means the only forces reshaping the face of our planet. All across the Earth we find evidence that the surface has been twisted, deformed, and folded (Figure 9-3). What is more, new material is continually being added to the Earth's surface as lava pours forth from volcanoes and from immense cracks in the ocean floors. At the same time, other geologic activity slowly pushes old surface material back into our planet's interior. These processes and others work together to renew and refresh our planet's exterior. Thus, although the Earth is some 4.56 billion (4.56×10^9) years old, much of its surface is a few hundred million (a few times 10^8) years old (Figure 9-4). (We saw in Section 8-2 how scientists use radioactive dating to determine the ages of rocks and of the Earth as a whole.)

Earth's Energy Sources

What powers all of this activity in the Earth's oceans, atmosphere, and surface? There are three energy sources: radiation from the Sun, the tidal effects of the Moon, and the Earth's own internal heat (Table 9-2).

Figure 9-1 R I V U X G

The Earth's Dynamic Oceans Nearly three-quarters of the Earth's surface is covered with water, a substance that is essential to the existence of life. In contrast, there is no liquid water at all on Mercury, Venus, Mars, or the Moon. (Farley Lewis/Photo Researchers)

Figure 9-2 R I V U X G

The Earth's Dynamic Atmosphere This space shuttle image shows thunderstorm clouds over the African nation of Zaire. The tops of thunderstorm clouds frequently reach altitudes of 10,000 m (33,000 ft) or higher. At any given time, nearly 2000 thunderstorms are in progress over the Earth's surface. (JSC/NASA)

Figure 9-3 R I V U X G

The Earth's Dynamic Surface These tan-colored ridges, or hogbacks, in Colorado's Rocky Mountains were once layers of sediment at the bottom of an ancient body of water. Forces within the Earth folded this terrain and rotated the layers into a vertical orientation. The layers were revealed when wind and rain eroded away the surrounding material. (Tom Till/DRK)

Figure 9-4 R I V U X G

Old and Young Rocks in the Grand Canyon The ages of rocks in Arizona's Grand Canyon demonstrate that geologic processes take place over very long time scales. (John Wang/PhotoDisc/Getty Images)

Table 9-2 The Earth's Energy Sources

Activity	Energy Sources
Motion of water in oceans, lakes, rivers	Solar energy, tidal forces
Motion of the atmosphere	Solar energy
Reshaping of surface	Earth's internal heat
Life	Solar energy (a few species that live on the ocean floor make use of the Earth's internal heat)

The Sun is the principal source of energy for the atmosphere. The Earth's surface is warmed by sunlight, which in turn warms the air next to the surface. Hot air is less dense than cool air and so tends to rise (see the discussion of density in Box 7-1). As the air rises, it transfers heat to its surroundings. As a result, the rising air cools and becomes denser. It then sinks downward to be heated again, and the process starts over. This up-and-down motion is called **convection**, and the overall pattern of circulation is called a **convection current.** (You can see convection currents in action by heating water on a stove, as Figure 9-5 shows.) In Section 9-5 we will see how the Earth's rotation modifies the up-and-down motion of the atmosphere to produce a pattern of global circulation.

Solar energy also powers atmospheric activity by evaporating water from the surface. The energy in the water vapor is released when it condenses to form water droplets, like those that make up clouds. In a typical thunderstorm (see Figure 9-2), some 5×10^8 kg of water vapor is lifted to great heights. The amount of energy released when this water condenses is as much as a city of 100,000 people uses in a month!

Solar energy also helps to power the oceans. Warm water from near the equator moves toward the poles, while cold polar water returns toward the equator. As we saw in Section 4-8, however, there is back-and-forth motion of the oceans due to the tidal forces of the Moon and Sun. Sometimes these two influences can reinforce each other, as when a storm (caused by solar energy) reaches a coastline at high tide (caused by tidal forces), producing waves strong enough to seriously erode beaches and sea cliffs.

Neither solar energy nor tidal forces can explain the reshaping of the Earth's surface suggested by Figure 9-3. Rather, all geologic activity is powered by heat flowing from the interior of the Earth itself. The Earth formed by collisions among planetesimals (see Section 8-4), and these collisions heated the body of the Earth. The interior remains hot to this day. An additional source of heat is the decay of radioactive elements such as uranium and thorium deep inside the Earth.

The heat flow from the Earth's interior to its surface is minuscule—just 1/6000 as great as the flow of energy we receive from the Sun—but it has a profound effect on the face of our planet. In Sections 9-2 and 9-3 we will explore the interior structure of the Earth and discover the connection between geologic activity on the Earth's surface and heat coming from its interior.

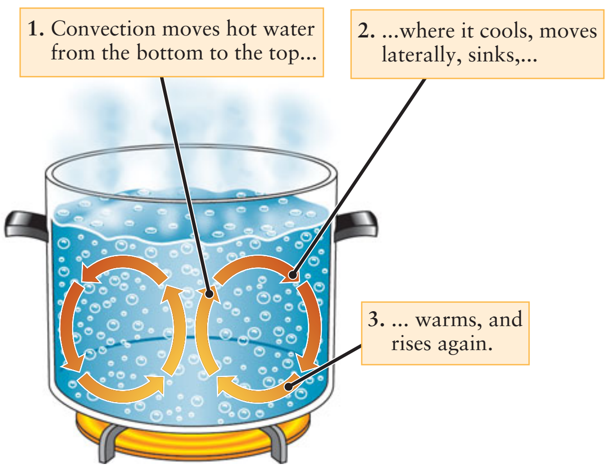


Figure 9-5

Convection in the Kitchen Heat supplied to the bottom of a pot warms the water there, making the water expand and lowering its average density. This low-density water rises and transfers heat to its cooler surroundings. The water that began at the bottom thus cools down, becomes denser, and sinks back to the bottom to repeat the process. (Adapted from F. Press, R. Siever, T. Grotzinger, and T. H. Jordan, *Understanding Earth*, 4th ed., W. H. Freeman, 2004)

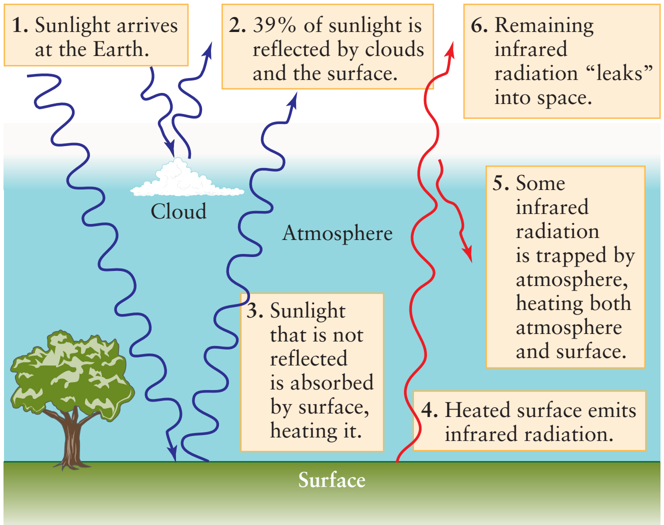
The Earth's Surface Temperature and the Greenhouse Effect

Since so little heat comes from inside our planet, the average surface temperature of the Earth depends almost entirely on the amount of energy that reaches us from the Sun in the form of electromagnetic radiation. (In an analogous way, whether you feel warm or cool outdoors on a summer day depends on whether you are in the sunlight and receiving lots of solar energy or in the shade and receiving little of this energy.)

If the Earth did nothing but *absorb* radiation from the Sun, it would get hotter and hotter until the surface temperature became high enough to melt rock. Happily, there are two reasons why this does not happen. One is that the clouds, snow, ice, and sand *reflect* about 31% of the incoming sunlight back into space. The fraction of incoming sunlight that a planet reflects is called its **albedo** (from the Latin for "whiteness"); thus the Earth's albedo is about 0.31. Thus, only 69% of the incoming solar energy is absorbed by the Earth. A second reason is that the Earth also *emits* radiation into space because of its temperature, in accordance with the laws that describe heated dense objects (see Section 5-3). The Earth's average surface temperature is nearly constant, which means that on the whole it is neither gaining nor losing energy. Thus, the rate at which the Earth emits energy into space must equal the rate at which it absorbs energy from the Sun.

To better understand this balance between absorbed and emitted radiation, remember that Wien's law tells us that the wavelength at which such an object emits most strongly (λ_{max}) is inversely proportional to its temperature (T) on the Kelvin scale (see Section 5-4 and Box 5-2). For example, the Sun's surface temperature is about 5800 K, and sunlight has its greatest intensity at a wavelength λ_{max} of 500 nm, in the middle of the visible spectrum. The Earth's average surface temperature of 287 K is far lower than the Sun's, so the Earth radiates most strongly at longer wavelengths in the infrared portion of the electromagnetic spectrum. The Stefan-Boltzmann law tells us that temperature also determines the *amount* of radiation that the Earth emits: The higher the temperature, the more energy it radiates.

Given the amount of energy reaching us from the Sun each second as well as the Earth's albedo, we can calculate the amount of solar energy that the Earth should *absorb* each second. Since this must equal the amount of electromagnetic energy that the Earth *emits* each second, which in turn depends on the Earth's average surface temperature, we can calculate what the Earth's average surface temperature should be. The result is a very chilly 254 K ($-19°C = -2°F$), so cold that oceans and lakes around the world should be frozen over. In fact, the Earth's actual average surface temperature is 287 K ($14°C = 57°F$). What is wrong with our model? Why is the Earth warmer than we would expect?



ANIMATION 9.1

Figure 9-6

The Greenhouse Effect Sunlight warms the Earth's surface, which due to its temperature emits infrared radiation. Much of this radiation is absorbed by atmospheric water vapor and carbon dioxide, helping to raise the average temperature of the surface. Some infrared radiation does penetrate the atmosphere and leaks into space. In a state of equilibrium, the rate at which the Earth loses energy to space in this way is equal to the rate at which it absorbs energy from the Sun.

The explanation for this discrepancy is called the **greenhouse effect:** Our atmosphere prevents some of the radiation emitted by the Earth's surface from escaping into space. Certain gases in our atmosphere called **greenhouse gases,** among them water vapor and carbon dioxide, are transparent to visible light but not to infrared radiation. Consequently, visible sunlight has no trouble entering our atmosphere and warming the surface. But the infrared radiation coming from the heated surface is partially trapped by the atmosphere, thus raising the temperatures of both the atmosphere and the surface. As the surface and atmosphere become hotter, they both emit more infrared radiation, part of which is able to escape into space. The temperature levels off when the amount of infrared energy that escapes just balances the amount of solar energy reaching the surface (Figure 9-6). The result is that our planet's surface is some 33°C (59°F) warmer than it would be without the greenhouse effect, and water remains unfrozen over most of the Earth.

The warming caused by the greenhouse effect gives our planet the moderate temperatures needed for the existence of life. For over a century, however, our technological civilization has been adding greenhouse gases to the atmosphere at an unprecedented rate. As we will see in Section 9-7, the likely consequences to our climate are extremely grave.

9-2 Studies of earthquakes reveal the Earth's layered interior structure

The kinds of rocks found on and near the Earth's surface provide an important clue about our planet's interior. The densities of typical surface rocks are around 3000 kg/m^3, but the average density of the Earth as a whole (that is, its mass divided by its volume) is 5515 kg/m^3. The interior of the Earth must therefore be composed of substances much denser than those found near the surface. But what is this substance? Why is the Earth's interior more dense than its crust? And is the Earth's interior solid like rock or molten like lava?

Like an exotic dessert, our planet's interior has layers of both solid and liquid material

An Iron-Rich Planet

Iron (chemical symbol Fe) is a good candidate for the substance that makes up most of the Earth's interior. This is so for two reasons. First, iron atoms are quite massive (a typical iron atom has 56 times the mass of a hydrogen atom), and second, iron is relatively abundant. (Figure 8-4 shows that it is the seventh most abundant element in our part of the Milky Way Galaxy.) Other elements such as lead and uranium have more massive atoms, but these elements are quite rare. Hence, the solar nebula could not have had enough of these massive atoms to create the Earth's dense interior. Furthermore, iron is common in meteoroids that strike the Earth, which suggests that it was abundant in the planetesimals from which the Earth formed.

The Earth was almost certainly molten throughout its volume soon after its formation, about 4.56×10^9 years ago. Energy released by the violent impacts of numerous meteoroids and asteroids and by the decay of radioactive isotopes likely melted the solid material collected from the earlier planetesimals. Gravity caused abundant, dense iron to sink toward the Earth's center, forcing less dense material to the surface. Figure 9-7*a* shows this process of *chemical differentiation.* (We discussed chemical differentiation in Section 8-4.) The result was a planet with the layered structure shown in Figure 9-7*b*—a central **core** composed of almost pure iron, surrounded by a **mantle** of dense, iron-rich minerals. The mantle, in turn, is surrounded by a thin **crust** of relatively light silicon-rich minerals. We live on the surface of this crust.

Seismic Waves as Earth Probes

How do we know that this layered structure is correct? The challenge in testing this model is that the Earth's interior is as inaccessible as the most distant galaxies in space. The deepest wells go down only a few kilometers, barely penetrating the surface of our planet. Despite these difficulties, geologists have learned basic properties of the Earth's interior by studying earthquakes and the seismic waves that they produce.

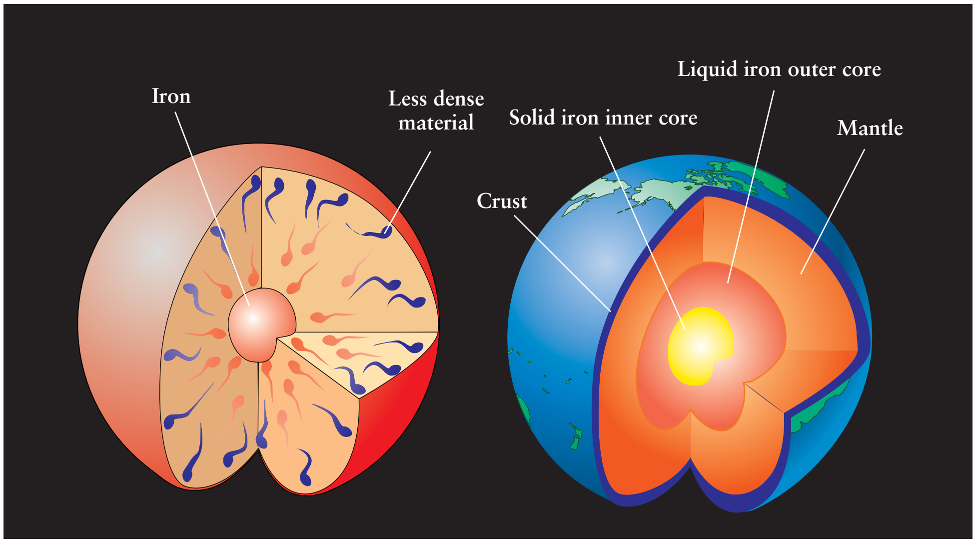
WEB LINK 9.3

Over the centuries, stresses build up in the Earth's crust. Occasionally, these stresses are relieved with a sudden motion called an **earthquake.** Most earthquakes occur deep within the Earth's crust. The point on the Earth's surface directly over an earthquake's location is called the **epicenter.**

Earthquakes produce three different kinds of **seismic waves,** which travel around or through the Earth in different ways and at different speeds. Geologists use sensitive instruments called **seismographs** to detect and record these vibratory motions. The first type of wave, which is analogous to water waves on the ocean, causes the rolling motion that people feel around an epicenter. These are called **surface waves** because they travel only

Figure 9-7

Chemical Differentiation and the Earth's Internal Structure **(a)** The newly formed Earth was molten throughout its volume. Dense materials such as iron (shown in orange) sank toward the center, while low-density materials (shown in blue) rose toward the surface. **(b)** The present-day Earth is no longer completely molten inside. A dense, solid iron core is surrounded by a less dense liquid core and an even less dense mantle. The crust, which includes the continents and ocean floors, is the least dense of all; it floats atop the mantle like the skin that forms on the surface of a cooling cup of cocoa.



(a) During differentiation, iron sank to the center and less dense material floated upward

(b) As a result of differentiation, the Earth has the layered structure that we see today

over the Earth's surface. The two other kinds of waves, called **P waves** (for "primary") and **S waves** (for "secondary"), travel through the interior of the Earth. P waves are called *longitudinal* waves because their oscillations are parallel to the direction of wave motion, like a spring that is alternately pushed and pulled. In contrast, S waves are called *transverse* waves because their vibrations are perpendicular to the direction in which the waves move. S waves are analogous to waves produced by a person shaking a rope up and down (Figure 9-8).

What makes seismic waves useful for learning about the Earth's interior is that they do not travel in straight lines. Instead, the paths that they follow through the body of the Earth are bent because of the varying density and composition of the Earth's interior. We saw in Section 6-1 that light waves behave in a very similar way. Just as light waves bend, or refract, when they pass from air into glass or vice versa (see Figure 6-2), seismic waves refract as they pass through different parts of the Earth's interior. By studying how the paths of these waves bend, geologists can map out the general interior structure of the Earth.

One key observation about seismic waves and how they bend has to do with the differences between S and P waves. When an earthquake occurs, seismographs relatively close to the epicenter record both S and P waves, but seismometers on the opposite side of Earth record only P waves. The absence of S waves was first explained in 1906 by British geologist Richard Dixon Oldham, who noted that transverse vibrations such as S waves cannot travel far through liquids. Oldham therefore concluded that our planet has a molten core. Furthermore, there is a region in which neither S waves nor P waves from an earthquake can be detected (Figure 9-9). This "shadow zone" results from the specific way in which P waves are refracted at the boundary between the solid mantle and the molten core. By measuring the size of the shadow zone, geologists have concluded that the radius of the molten core is about 3500 km (2200 mi), about 55% of our planet's overall radius but about double the radius of the Moon (1738 km = 1080 mi).

As the quality and sensitivity of seismographs improved, geologists discovered faint traces of P waves in an earthquake's shadow zone. In 1936, the Danish seismologist Inge Lehmann explained that some of the P waves passing through the Earth are deflected into the shadow zone by a small, solid **inner core** at the center of our planet. The radius of this inner core is about 1300 km (800 mi).

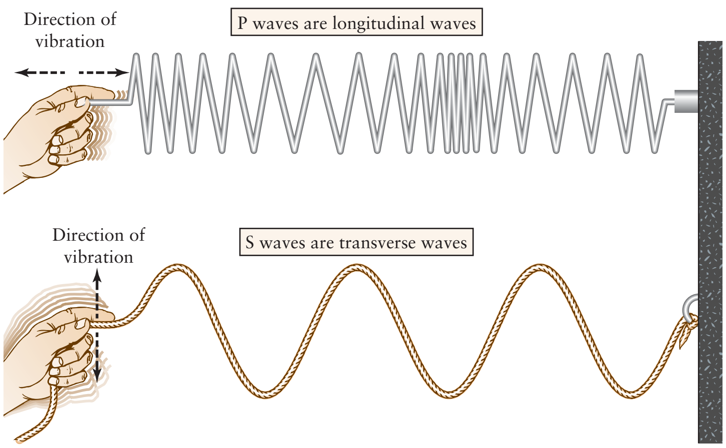


Figure 9-8

Seismic Waves Earthquakes produce two kinds of waves that travel through the body of our planet. One kind, called P waves, are longitudinal waves. They are analogous to those produced by pushing a spring in and out. The other kind, S waves, are transverse waves analogous to the waves produced by shaking a rope up and down.

Earth's Major Layers

The seismic evidence reveals that our planet has a curious internal structure—a liquid **outer core** sandwiched between a solid inner core and a solid mantle. Table 9-3 summarizes this structure. To understand

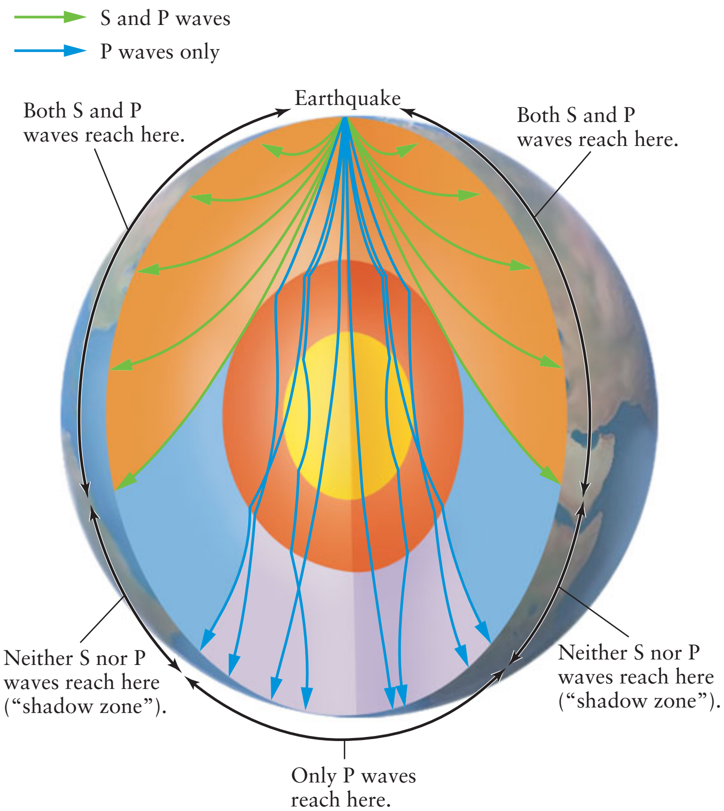


Figure 9-9

The Earth's Internal Structure and the Paths of Seismic Waves Seismic waves follow curved paths because of differences in the density and composition of the material in the Earth's interior. The paths curve gradually where there are gradual changes in density and composition. Sharp bends occur only where there is an abrupt change from one kind of material to another, such as at the boundary between the outer core and the mantle. Only P waves can pass through the Earth's liquid outer core.

this arrangement, we must look at how temperature and pressure inside the Earth affect the melting point of rock.

Both temperature and pressure increase with increasing depth below the Earth's surface. The temperature of the Earth's interior rises steadily from about 14°C on the surface to nearly 5000°C at our planet's center (Figure 9-10).

The Earth's outermost layer, the crust, is only about 5 to 35 km thick. It is composed of rocks for which the **melting point,** or temperature at which the rock changes from solid to liquid, is far higher than the temperatures actually found in the crust. Thus, the crust is solid.

The Earth's mantle, which extends to a depth of about 2900 km (1800 mi), is largely composed of substances rich in iron and magnesium. On the Earth's surface, specimens of these substances have melting points slightly over 1000°C. However, the melting point of a substance depends on the pressure to which it is subjected—the higher the pressure, the higher the melting point. As Figure 9-10 shows, the actual temperatures throughout most of the mantle are less than the melting point of all the substances of which the mantle is made. Hence, the mantle is primarily solid. However, the upper levels of the mantle—called the **asthenosphere** (from the Greek *asthenia,* meaning "weakness")—are able to flow slowly and are therefore referred to as being **plastic.**

CAUTION! It may seem strange to think of a plastic material as one that is able to flow. Normally we think of plastic objects as being hard and solid, like the plastic out of which compact discs and video cassettes are made. But to make these objects, the plastic material is heated so that it can flow into a mold, then cooled so that it solidifies. Strictly, the material is only "plastic" when it is able to flow. Maple syrup and tree sap are two other substances that flow at warm temperatures but become solid when cooled.

At the boundary between the mantle and the outer core, there is an abrupt change in chemical composition, from silicon-rich materials to almost-pure iron with a small admixture of nickel. Because this nearly pure iron has a lower melting point than the iron-rich materials, the melting curve in Figure 9-10 has a "jog" as it crosses from the mantle to the outer core and remains. As a result, the melting point is less than the temperature at depths of about 2900 to 5100 km (1800 to 3200 mi), and the outer core is liquid.

At depths greater than about 5100 km, the pressure is more than 10^{11} newtons per square meter. This is about 10^6 times ordinary atmospheric pressure, or about 10^4 tons per square inch. Because the melting point of the iron-nickel mixture under this pressure is higher than the actual temperature (see Figure 9-10), the Earth's inner core is solid.

Table 9-3 The Earth's Internal Structure

Region	Depth Below Surface (km)	Distance From Center (km)	Average Density (kg/m^3)
Crust (solid)	0–5 (under oceans) 0–35 (under continents)	6343–6378	3500
Mantle (plastic, solid)	from bottom of crust to 2900	3500–6343	3500–5500
Outer core (liquid)	2900–5100	1300–3500	10,000–12,000
Inner core (solid)	5100–6400	0–1300	13,000

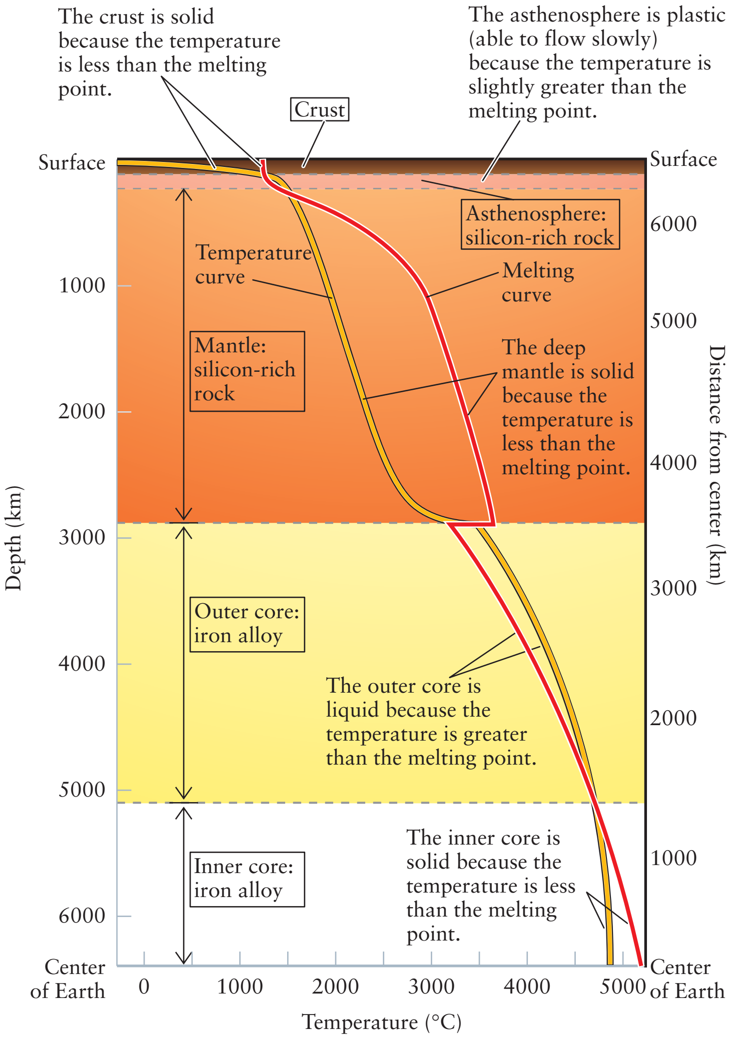


Figure 9-10

Temperature and Melting Point of Rock Inside the Earth The temperature (yellow curve) rises steadily from the Earth's surface to its center. The melting point of the Earth's material (red curve) is also shown on this graph. Where the temperature is below the melting point, as in the mantle and inner core, the material is solid; where the temperature is above the melting point, as in the outer core, the material is liquid. (Adapted from T. Grotzinger, T. H. Jordan, F. Press, and R. Siever, *Understanding Earth,* 5th ed., W. H. Freeman, 2007)

LOOKING DEEPER 9.2

Until the 1980s, geologists knew little more about the inner core than that it is solid and dense. Since then, evidence has accumulated that suggests the inner core is a single **crystal** of iron—that is, iron atoms arranged in orderly rows, like carbon atoms are arranged within a diamond. If so, the inner core is the largest crystalline object anywhere in the solar system. Furthermore, there are strong indications that the inner core is rotating at a slightly faster rate than the rest of the Earth! These remarkable discoveries suggest that even more surprises may lurk deep within the Earth's interior.

Heat naturally flows from where the temperature is high to where it is low. Figure 9-10 thus explains why there is a heat flow from the center of the Earth outward. We will see in the next section how this heat flow acts as the "engine" that powers our planet's geologic activity.

9-3 Plate movement produces earthquakes, mountain ranges, and volcanoes that shape the Earth's surface

WEB LINK 9.4

One of the most important geological discoveries of the twentieth century was the realization that the Earth's crust is constantly changing. We have learned that the crust is divided into huge **plates** whose motions produce earthquakes, volcanoes, mountain ranges, and oceanic trenches. This picture of the Earth's crust has come to be the central unifying theory of geology, much as the theory of evolution has become the centerpiece of modern biology.

Evidence from the bottom of the ocean confirmed the theory of moving continents

Continental Drift

Anyone who carefully examines a map of the Earth might come up with the idea of moving continents. South America, for example, would fit snugly against Africa were it not for the Atlantic Ocean. As Figure 9-11 shows, the fit between land masses on ei-

Figure 9-11

Fitting the Continents Together Africa, Europe, Greenland, North America, and South America fit together remarkably well. The fit is especially convincing if the edges of the continental shelves (shown in yellow) are used, rather than today's shorelines. This strongly suggests that these continents were in fact joined together at some point in the past. (Adapted from P. M. Hurley)

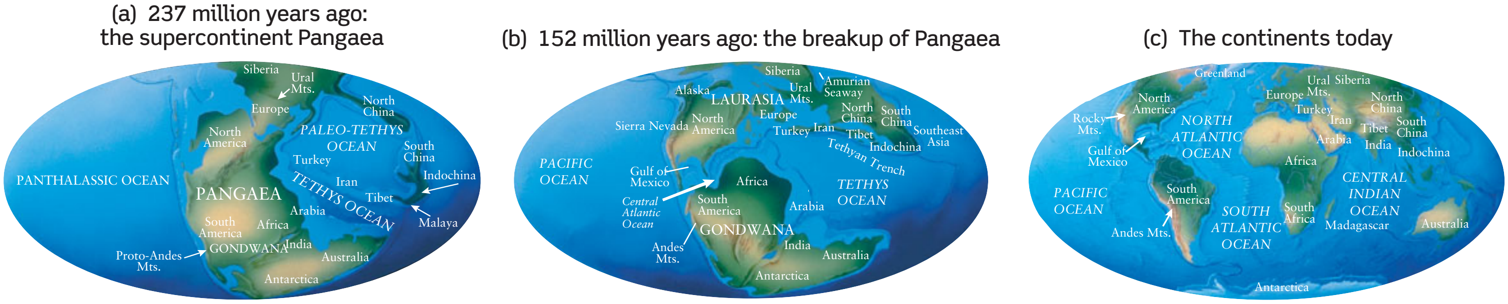


Figure 9-12

The Breakup of the Supercontinent Pangaea **(a)** The shapes of the continents led Alfred Wegener to conclude that more than 200 million (2×10^8) years ago, the continents were merged into a single supercontinent, which he called Pangaea. **(b)** Pangaea first split into two smaller land masses, Laurasia and Gondwana. **(c)** Over millions of years, the continents moved to their present-day locations. Among the evidence confirming this picture are nearly identical rock formations 200 million years in age that today are thousands of kilometers apart but would have been side by side on Pangaea. (Adapted from F. Press, R. Siever, T. Grotzinger, and T. H. Jordan, *Understanding Earth,* 4th ed., W. H. Freeman, 2004)

ther side of the Atlantic Ocean is quite remarkable. This observation inspired the German meteorologist Alfred Wegener to advocate "continental drift"—the idea that the continents on either side of the Atlantic Ocean have simply drifted apart. After much research, in 1915 Wegener published the theory that there had originally been a single gigantic supercontinent, which he called Pangaea (meaning "all lands"), that began to break up and drift apart roughly 200 million years ago. (No humans were present to witness this; the earliest humans did not appear on Earth until about 1.9 million years ago. At the time that Pangaea broke up, during what geologists refer to as the early Jurassic period, dinosaurs were the dominant land animals.)

Other geologists refined this theory, arguing that Pangaea must have first split into two smaller supercontinents, which they called Laurasia and Gondwana, separated by what they called the Tethys Ocean. Gondwana later split into Africa and South America, with Laurasia dividing to become North America and Eurasia. According to this theory, the Mediterranean Sea is a surviving remnant of the ancient Tethys Ocean (Figure 9-12).

Initially, most geologists ridiculed Wegener's ideas. Although it was generally accepted that the continents do "float" on the denser, somewhat plastic mantle beneath them, few geologists could accept the idea that entire continents could move around the Earth at speeds as great as several centimeters per year. The "continental drifters" could not explain what forces could be shoving the massive continents around.

Plate Tectonics

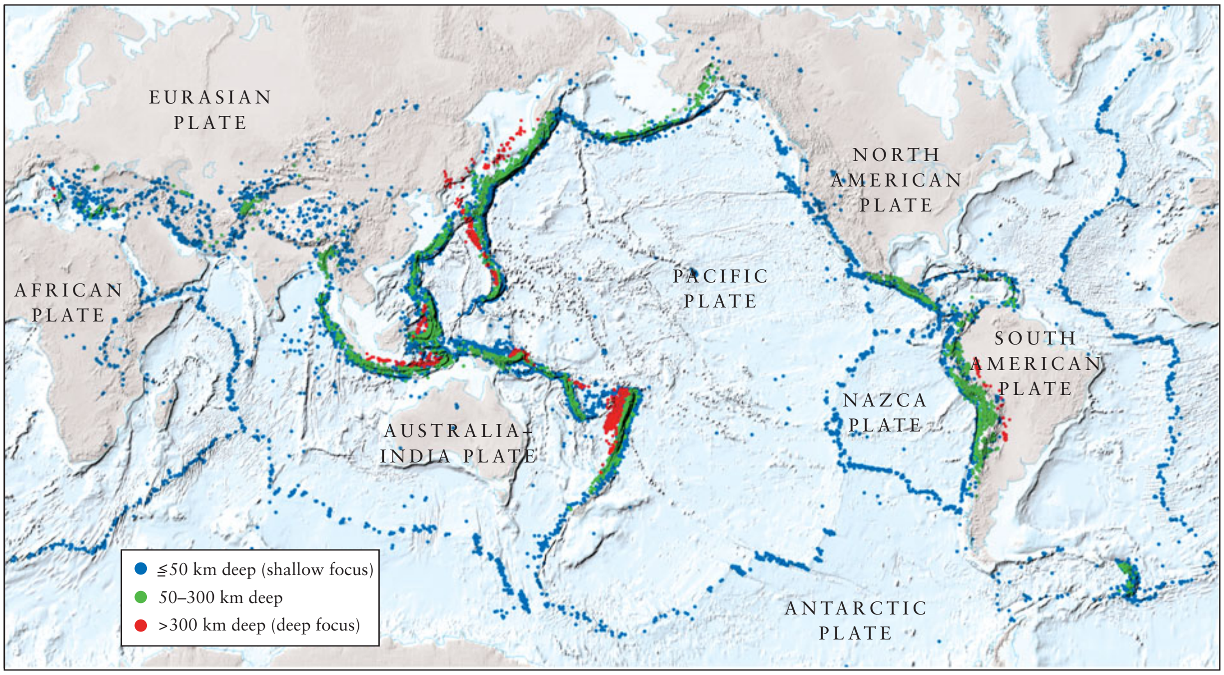
WEB LINK 9.5

Beginning in the mid-1950s, however, geologists found evidence that material is being forced upward to the crust from deep within the Earth. Bruce C. Heezen of Columbia University and his colleagues began discovering long mountain ranges on the ocean floors, such as the Mid-Atlantic Ridge, which stretches all the way from Iceland to Antarctica (Figure 9-13). During the 1960s, Harry Hess of Princeton University and Robert Dietz of the University of California again carefully examined the floor of the Atlantic Ocean. They concluded that rock from the Earth's mantle is being melted and then forced upward along the Mid-Atlantic Ridge, which is in essence a long chain of underwater volcanoes.

The upwelling of new material from the mantle to the crust forces the existing crusts apart, causing **seafloor spreading.** For example, the floor of the Atlantic Ocean to the east of the Mid-Atlantic Ridge is moving eastward and the floor to the west is moving westward. By explaining what fills in the gap between continents as they move apart, seafloor spreading helps to fill out the

Figure 9-13

The Mid-Atlantic Ridge This artist's rendition shows the Mid-Atlantic Ridge, an immense mountain ridge that rises up from the floor of the North Atlantic Ocean. It is caused by lava seeping up from the Earth's interior along a rift that extends from Iceland to Antarctica. (Courtesy of M. Tharp and B. C. Heezen)



ANIMATION 9.3

Figure 9-14

The Earth's Major Plates The boundaries of the Earth's major plates are the scenes of violent seismic and geologic activity. Most earthquakes occur where plates separate, collide, or rub together. Plate boundaries are therefore easily identified simply by plotting earthquake epicenters (shown here as dots) on a map. The colors of the dots indicate the depths at which the earthquakes originate. (Data from Harvard CMT catalog; plot by M. Boettcher and T. Jordan.)

theories of continental drift. Because of the seafloor spreading from the Mid-Atlantic Ridge, South America and Africa are moving apart at a speed of roughly 3 cm per year. Working backward, these two continents would have been next to each other some 200 million years ago—just as Wegener suggested (see Figure 9-11).

In the early 1960s, geologists began to find additional evidence supporting the existence of large, moving plates. Thus was born the modern theory of crustal motion, which came to be known as **plate tectonics** (from the Greek *tekton*, meaning "builder").

Geologists today realize that earthquakes tend to occur at the boundaries of the Earth's crustal plates, where the plates are colliding, separating, or rubbing against each other. The boundaries of the plates therefore stand out clearly when the epicenters of earthquakes are plotted on a map, as in Figure 9-14.

WEB LINK 9.6

The vast majority of volcanoes also occur at plate boundaries. Figure 9-15 shows a volcanic eruption at the boundary between the Pacific and Eurasian plates.

Convection and Plate Motion

ANIMATION 9.4

What makes the plates move? The answer is twofold. First, heat flows outward from the Earth's hot core to its cool crust, and second, this heat flows through the mantle by convection, the same process that takes place in the Earth's atmosphere or in a pot of boiling water.

Figure 9-5 shows that convection occurs when a fluid is heated from below. The heat that drives convection in the Earth's outer layers actually comes from very far below, at the boundary between the outer and inner cores. As material deep in the liquid core cools and solidifies to join the solid portion of the core, it releases the energy needed to heat the overlying mantle and cause

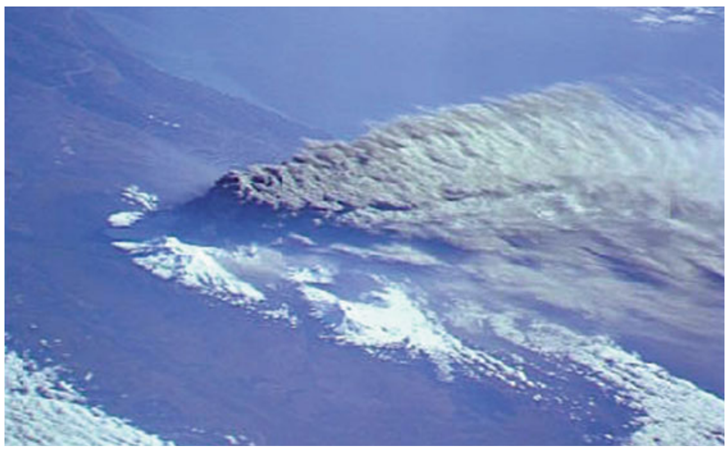
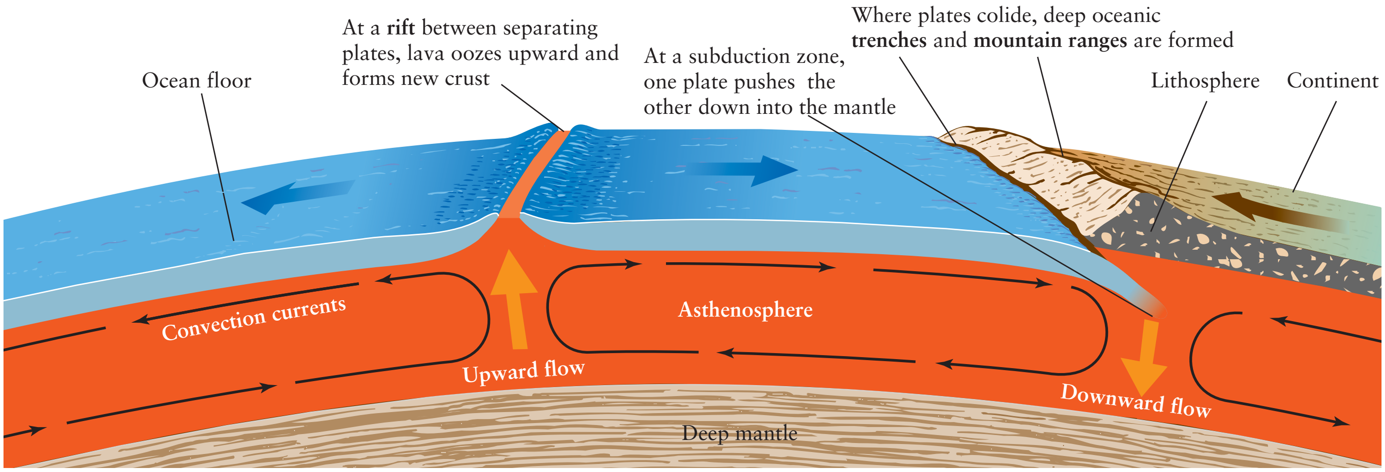


Figure 9-15 R I V U X G

An Erupting Volcano On September 30, 1994, a volcano erupted at the boundary of the Pacific and Eurasian plates on Russia's Kamchatka Peninsula. This space shuttle photograph shows an immense cloud of ash belching forth from this volcano. The cloud reached an altitude of 18 km (60,000 ft) above sea level and was carried by the winds for at least 1000 km from the volcano. (*STS-68*, NASA)



INTERACTIVE EXERCISE 9.1

Figure 9-16

The Mechanism of Plate Tectonics Convection currents in the asthenosphere, the soft upper layer of the mantle, are responsible for pushing around rigid, low-density crustal plates. New crust forms in oceanic rifts, where lava oozes upward between separating plates. Mountain ranges and deep oceanic trenches are formed where plates collide.

convection. (In Section 9-1 we described a similar process in Earth's atmosphere: When water vapor in the air cools and forms liquid drops, it releases the energy that powers thunderstorms.)

The asthenosphere, or upper level of the mantle, is hot and soft enough to permit an oozing, plastic flow. Atop the asthenosphere is a rigid layer, called the **lithosphere** (from the Greek word for "rock.") The lithosphere is divided into plates that ride along the convection currents of the asthenosphere. The crust is simply the uppermost layer of the lithosphere, with a somewhat different chemical composition than the lithosphere's lower regions.

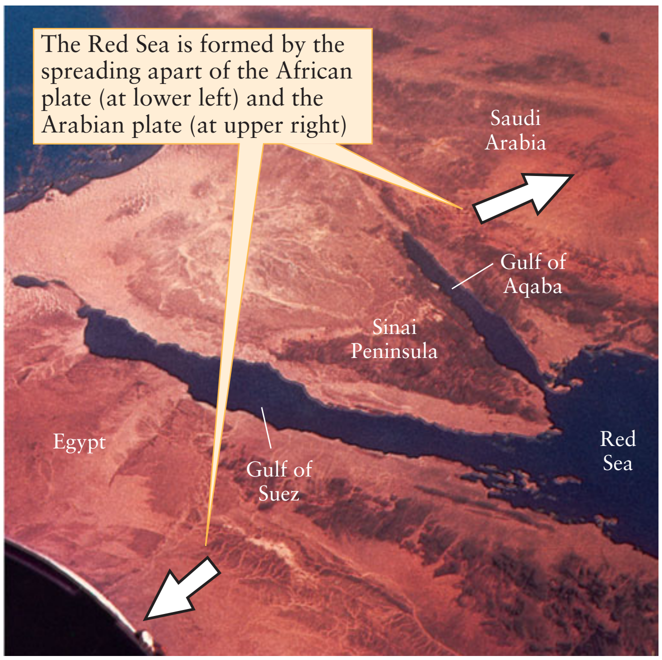
Figure 9-16 shows how convection causes plate movement. Molten subsurface rock seeps upward along **oceanic rifts,** where plates are separating. The Mid-Atlantic Ridge, shown in Figure 9-13, is an oceanic rift. Where plates collide, cool crustal material from one of the plates sinks back down into the mantle along a **subduction zone.** One such subduction zone is found along the west coast of South America, where the oceanic Nazca plate is being subducted into the mantle under the continental South American plate at a relatively speedy 10 centimeters per year. As the material from the subducted plate sinks, it pulls the rest of its plate along with it, thus helping to keep the plates in motion. New material is added to the crust from the mantle at the oceanic rifts and is "recycled" back into the mantle at the subduction zones. In this way the total amount of crust remains essentially the same.

ANIMATION 9.5 ANIMATION 9.6

The boundaries between plates are the sites of some of the most impressive geological activity on our planet. Great mountain ranges, such as the Sierras and Cascades along the western coast of North America and the Andes along South America's west coast, are thrust up by ongoing collisions between continental plates and the plates of the ocean floor. Subduction zones, where old crust is drawn back down into the mantle, are typically the locations of deep oceanic trenches, such as the Peru-Chile Trench off the west coast of South America. Figure 9-17 and Figure 9-18 show two well-known geographic features that resulted from tectonic activity at plate boundaries.

Plate Tectonics and the Varieties of Rocks

Plate tectonics also helps to explain geology on the scale of individual rocks and minerals. These are composed of chemical



ANIMATION 9.7

Figure 9-17 R I V U X G

The Separation of Two Plates The plates that carry Africa and Arabia are moving apart, leaving a great rift that has been flooded to form the Red Sea. This view from orbit shows the northern Red Sea, which splits into the Gulf of Suez and the Gulf of Aqaba. (*Gemini 12,* NASA)

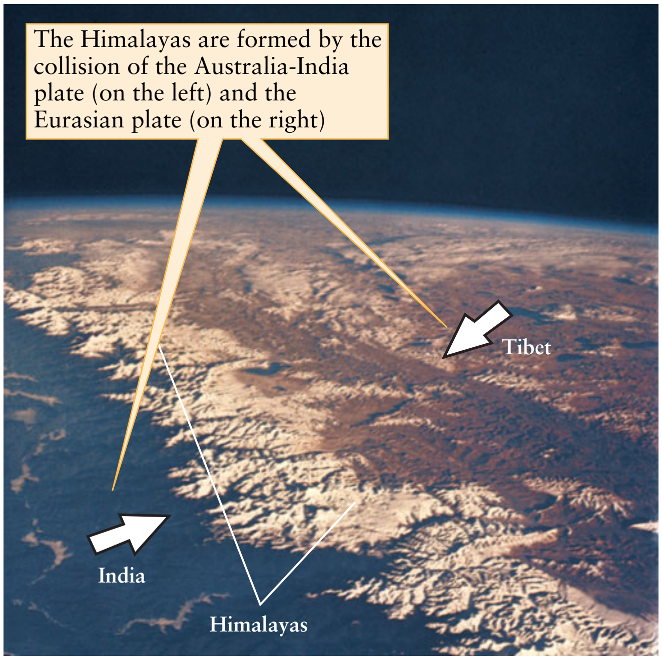


Figure 9-18 R I V U X G

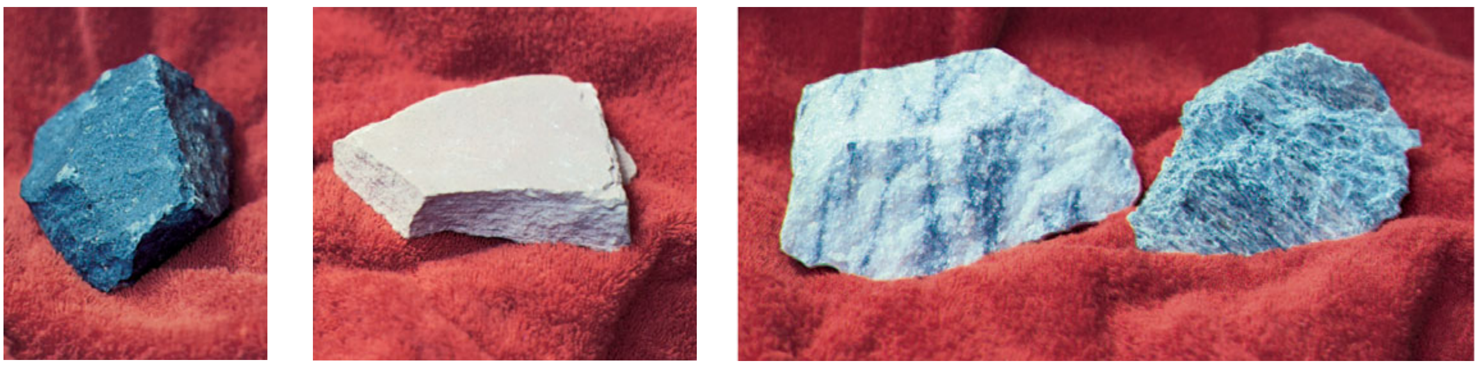
The Collision of Two Plates The plates that carry India and China are colliding. Instead of one plate being subducted beneath the other, both plates are pushed upward, forming the Himalayas. Mount Everest is one of the snow-covered peaks near the center of this photograph taken from orbit. (*Apollo 7*, NASA)

elements (see the periodic table in Box 5-5), but individual elements are rarely found in a pure state. The exceptions include diamonds, which are crystals of carbon, as well as nuggets of gold, silver, and copper. Somewhat more common are solids composed of a particular chemical combination of elements called a *compound*. An example is feldspar, a crystalline material made up of potassium, aluminum, silicon, and oxygen atoms. Diamond and feldspar are both **minerals—**naturally occurring solids composed of a single element or compound. Most common of all are **rocks,** which are solid parts of the Earth's crust that are composed of one or more minerals. For example, granite contains both feldspar and quartz (a mineral containing silicon and oxygen).

Geologic processes create three major categories of rocks (Figure 9-19). **Igneous rocks** result when minerals cool from a molten state. (Molten rock is called **magma** when it is buried below the surface and **lava** when it flows out upon the surface, as in a volcanic eruption.) The ocean floor is made predominantly of a type of igneous rock called basalt (Figure 9-19*a*). This is just what we would expect if the ocean floor is produced by material welling up from the mantle, as predicted by the theory of seafloor spreading.

Sedimentary rocks are produced by the action of wind, water, or ice. For example, winds can pile up layer upon layer of sand grains. Other minerals present amid the sand can gradually cement the grains together to produce sandstone (Figure 9-19*b*). Minerals that precipitate out of the oceans can cover the ocean floor with layers of a sedimentary rock called limestone. The motion of tectonic plates can move such rocks to places far from where they were formed. This explains why sedimentary rock from the floor of an ancient ocean can now be found in central Alaska and as hogback ridges in Colorado (see Figure 9-3).

Sometimes igneous or sedimentary rocks become buried far beneath the surface, where they are subjected to enormous pressure and high temperatures. These severe conditions change the structure of the rocks, producing **metamorphic rock** (Figure 9-19*c*). The presence of metamorphic rocks at the Earth's surface tells us that tectonic activity sometimes lifts up material from deep within the crust. This can happen when two plates collide, as shown in Figure 9-18. The boundaries of the colliding plates are thrust upward to form a new chain of mountains, and buried metamorphic rocks are brought to the surface.



(a) Igneous rock (basalt) (b) Sedimentary rock (sandstone) (c) Metamorphic rocks (marble, schist)

Figure 9-19 R I V U X G

Igneous, Sedimentary, and Metamorphic Rocks **(a)** Igneous rocks such as basalt are created when molten materials solidify. This example contains iron-rich minerals that give it its dark color. **(b)** Sedimentary rocks such as sandstone are typically formed when loose particles of soil or sand are fused into rock by the presence of other minerals, which act as a cement. **(c)** Metamorphic rocks are produced when igneous or sedimentary rocks are subjected to high temperatures and pressures deep within the Earth's crust. Marble (left) is formed from sedimentary limestone; schist (right) is formed from igneous rock. (W. J. Kaufmann III; specimens courtesy Mineral Museum, California Division of Mines)

The Cycle of Supercontinents

Plate tectonic theory offers insight into geology on the largest of scales, that of an entire supercontinent. In recent years, geologists have uncovered evidence that points to a whole succession of supercontinents that once broke apart and then reassembled. Pangaea is only the most recent supercontinent in this cycle, which repeats about every 500 million (5×10^8) years. As a result, intense episodes of mountain building have occurred at roughly 500-million-year intervals.

Apparently, a supercontinent sows the seeds of its own destruction because it blocks the flow of heat from the Earth's interior. As soon as a supercontinent forms, temperatures beneath it rise, much as they do under a book lying on an electric blanket. As heat accumulates, the lithosphere domes upward and cracks. Molten rock from the overheated asthenosphere wells up to fill the resulting fractures, which continue to widen as pieces of the fragmenting supercontinent move apart.

It can take a very long time for the heat trapped under a supercontinent to escape. Although Pangaea broke apart some 200 million years ago (see Figure 9-11), the mantle under its former location is still hot and is still trying to rise upward. As a result, Africa—which lies close to the center of this mass of rising material—sits several tens of meters higher than the other continents.

The changes wrought by plate tectonics are very slow on the scale of a human lifetime, but they are very rapid in comparison with the age of the Earth. For example, the period over which Pangaea broke into Laurasia and Gondwana was only about 0.4% of the Earth's age of 4.56×10^9 years. (To put this in perspective, 0.4% of a human lifetime is about 4 months.) The lesson of plate tectonics is that the seemingly permanent face of the Earth is in fact dynamic and ever-changing.

9-4 The Earth's magnetic field produces a magnetosphere that traps particles from the solar wind

We saw in Section 7-7 that Earth's magnetic field provides evidence that our planet's interior is partially molten. Our understanding is that the magnetic field is produced by the motion of iron-rich material in the liquid outer core. Because this material is a good conductor of electricity, its motions generate a magnetic field in a mechanism called a *dynamo*.

Like the motions of tectonic plates, the Earth's magnetic field results from our planet's internal heat

The Source of Earth's Magnetic Field

The same energy source that powers plate tectonics is also responsible for the Earth's dynamo. As we saw in Section 9-3, energy is released when material from our planet's liquid core cools and solidifies onto the solid core. This released energy stirs up the motions of the liquid core, and these motions generate a magnetic field. (While there is also fluid motion in the mantle, it does not produce an appreciable magnetic field: The silicon-rich rocks that comprise the mantle are poor conductors of electricity, and their motions are a million times slower than those in the outer core.)

LOOKING DEEPER 9.3

Studies of ancient rocks reinforce the idea that our planet's magnetism is due to fluid material in motion. When iron-bearing lava cools and solidifies to form igneous rock, it becomes magnetized in the direction of the Earth's magnetic field. By analyzing samples of igneous rock of different ages from around the world, geologists have found that the Earth's magnetic field actually flips over and reverses direction on an irregular schedule ranging from tens of thousands to hundreds of thousands of years. As an example, lava that solidified 30,000 years ago is magnetized in the opposite direction to lava that has solidified recently. Therefore, 30,000 years ago a compass needle would have pointed south, not north! If the Earth was a permanent magnet, like the small magnets used to attach notes to refrigerators, it would be hard to imagine how its magnetic field could spontaneously reverse direction. But computer simulations show that fields produced by moving fluids in the Earth's outer core can indeed change direction from time to time.

The Magnetosphere

The Earth's magnetic field has important effects far above the atmosphere, where it interacts dramatically with charged particles from the Sun. This *solar wind* is a flow of mostly protons and electrons that streams constantly outward from the Sun's upper atmosphere. Near the Earth, the particles in the solar wind move at speeds of roughly 450 km/s, or about a million miles per hour. Because this is considerably faster than sound waves can travel in the very thin gas between the planets, the solar wind is said to be *supersonic.* (Because the gas between the planets is so thin, interplanetary sound waves carry too little energy to be heard by astronauts.)

If the Earth had no magnetic field, we would be continually bombarded by the solar wind. But our planet does have a magnetic field, and the forces that this field can exert on charged particles are strong enough to deflect them away from us. The region of space around a planet in which the motion of charged particles is dominated by the planet's magnetic field is called the planet's **magnetosphere.** Figure 9-20 is a scale drawing of the Earth's magnetosphere, which was discovered in the late 1950s by the first satellites placed in orbit.

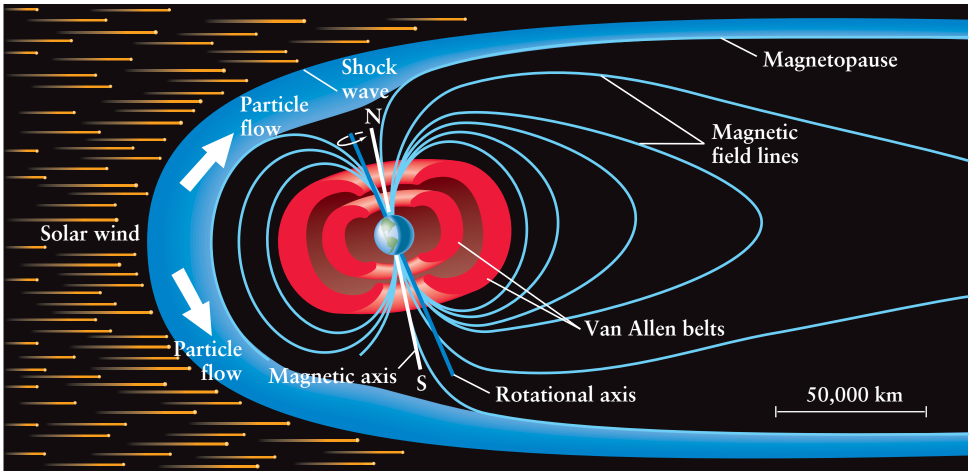
When the supersonic particles in the solar wind first encounter the Earth's magnetic field, they abruptly slow to subsonic speeds. The boundary where this sudden decrease in velocity occurs is called a **shock wave.** Still closer to the Earth lies another boundary, called the **magnetopause,** where the outward magnetic pressure of the Earth's field is exactly counterbalanced by the impinging pressure of the solar wind. Most of the particles of the solar wind are deflected around the magnetopause, just as water is deflected to either side of the bow of a ship.

Some charged particles of the solar wind manage to leak through the magnetopause. When they do, they are trapped by the Earth's magnetic field in two huge, doughnut-shaped rings around Earth called the **Van Allen belts.** These belts were discovered in 1958 during the flight of the first successful U.S. Earth-orbiting satellite. They are named after the physicist James Van Allen, who

INTERACTIVE EXERCISE 9.2

Figure 9-20

The Earth's Magnetosphere The Earth's magnetic field carves out a cavity in the solar wind, shown here in cross section. A shock wave marks the boundary where the supersonic solar wind is abruptly slowed to subsonic speeds. Most of the particles of the solar wind are deflected around the Earth in a turbulent region (colored blue in this drawing). The Earth's magnetic field also traps some charged particles in two huge, doughnut-shaped rings called the Van Allen belts (shown in red). This figure shows only a slice through the Van Allen belts.



insisted that the satellite carry a Geiger counter to detect charged particles. The inner Van Allen belt, which extends over altitudes of about 2000 to 5000 km, contains mostly protons. The outer Van Allen belt, about 6000 km thick, is centered at an altitude of about 16,000 km above the Earth's surface and contains mostly electrons.

Aurorae

Sometimes the magnetosphere becomes overloaded with particles. The particles then leak through the magnetic fields at their weakest points and cascade down into the Earth's upper atmosphere, usually in a ring-shaped pattern (Figure 9-21*a*). As these high-speed charged particles collide with atoms in the upper atmosphere, they excite the atoms to high energy levels. The atoms then emit visible light as they drop down to their ground states, like the excited gas atoms in a neon light (see Section 5-8). The result is a beautiful, shimmering display called an **aurora** (*plural* **aurorae**). These are also called the **northern lights** (**aurora borealis**) or **southern lights** (**aurora australis**), depending on the hemisphere in which the phenomenon is observed. Figures 9-21*b* and 9-21*c* show the aurorae as seen from orbit and from the Earth's surface.

Occasionally, a violent event on the Sun's surface sends a particularly intense burst of protons and electrons toward Earth. The resulting auroral display can be exceptionally bright and can often be seen over a wide range of latitudes. Such events also disturb radio transmissions and can damage communication satellites and transmission lines.

It is remarkable that the Earth's magnetosphere, including its vast belts of charged particles, was entirely unknown until a few decades ago. Such discoveries remind us of how little we truly understand and how much remains to be learned even about our own planet.

(a) R I V **U** X G (b) R I **V** U X G (c) R I **V** U X G

VIDEO 9.2

Figure 9-21

The Aurora An increased flow of charged particles from the Sun can overload the Van Allen belts and cascade toward the Earth, producing aurorae. **(a)** This false-color ultraviolet image from the *Dynamics Explorer 1* spacecraft shows a glowing oval of auroral emission about 4500 km in diameter centered on the north magnetic pole. **(b)** This photograph shows the aurora australis over Antarctica as seen from an orbiting space shuttle. **(c)** This view from Alaska shows aurorae at their typical altitudes of 100 to 400 km. The green color shows that the light is emitted by excited oxygen atoms in the upper atmosphere. (a: Courtesy of L. A. Frank and J. D. Craven, University of Iowa; b: MTU/Geological & Mining Engineering & Sciences; c: J. Finch/Photo Researchers, Inc.)

9-5 The Earth's atmosphere has changed substantially over our planet's history

Both plate tectonics and the Earth's magnetic field paint a picture of a planet with a dynamic, evolving surface and interior. Our atmosphere, too, has changed and evolved substantially over the Earth's 4.56-billion-year history. As we will see, this evolution explains why we have an atmosphere totally unlike that of any other world in the solar system.

The composition of our atmosphere has been dramatically altered by the evolution of life

Earth's Early Atmosphere

When the Earth first formed by accretion of planetesimals (see Section 8-4), gases were probably trapped within the Earth's interior in the same proportions that they were present in the solar nebula. But since the early Earth was hot enough to be molten throughout its volume, most of these trapped gases were released. As we discussed in Section 7-4 and Box 7-2, the Earth's gravity was too weak to prevent hydrogen and helium—the two most common kinds of atoms in the universe, but also the least massive—from leaking away into space. The atmosphere that remained still contained substantial amounts of hydrogen, but in the form of relatively massive molecules of water vapor (H_2O) made by combining two atoms of hydrogen with one atom of oxygen, the third most common element in our part of the Milky Way Galaxy (see Figure 8-4). In fact, water vapor was probably the dominant constituent of the early atmosphere, which is thought to have been about 100 times denser than our present-day atmosphere.

Water vapor is one of the greenhouse gases that we discussed in Section 9-1. It traps infrared radiation from the Earth's surface, and its presence in the early atmosphere helped to sustain the high temperature of the surface. But if water vapor had been the *only* constituent of the atmosphere, you would not be reading these words! The reason is that as the molten Earth inevitably cooled, water vapor in the atmosphere condensed into raindrops and fell to Earth to form the oceans. As water vapor was lost from the atmosphere, its contribution to the greenhouse effect weakened, which would have made the surface temperature drop even lower. A further cooling factor is that the young Sun was only about 70% as bright as it is today. The net result is that the entire Earth should have been frozen over! Ice is so reflective that the Earth would have remained frozen even as the Sun aged and became more luminous. Liquid water is absolutely essential to all living creatures, so life as we know it would probably never have evolved on such an icy Earth.

In fact, the first living organisms appeared on Earth within 400 million years after the planet first formed. Hence, the Earth could not have been frozen over for very long, if at all. What saved our planet from a perpetual deep freeze was the presence of carbon, the fourth most common of the elements. When combined with oxygen, carbon forms carbon dioxide (CO_2), a greenhouse gas that remains gaseous at low temperatures. Carbon dioxide would have been released into the atmosphere by volcanic activity, a process called **outgassing** (see Figure 9-15). It would also have been added to the atmosphere by carbon-rich meteors striking the planet's surface. Once CO_2 was in the atmosphere, its greenhouse effect raised the planet's temperature and melted the ice. Some of the water evaporated into the atmosphere, further enhancing the Earth's greenhouse effect.

Fewer than one in 2500 of the molecules in today's atmosphere is carbon dioxide. But CO_2 must have been thousands of times more abundant in the early Earth's atmosphere in order to melt the global ice sheath. Unlike hydrogen or helium, this excess CO_2 was not lost into space; instead, it has been trapped in rocks. Carbon dioxide dissolves in rainwater and falls into the oceans, where it combines with other substances to form a class of minerals called *carbonates*. (Limestone and marble are examples of carbonate-bearing rock.) These form sediments on the ocean floor, which are eventually recycled into the crust by subduction. As an example, marble (Figure 9-19*c*) is a metamorphic rock formed deep within the crust from limestone, a carbonate-rich sedimentary rock.

This process removed most of the CO_2 from the atmosphere within the first billion (10^9) years after the formation of the Earth. Although this weakened the greenhouse effect, temperatures remained warm as the Sun's brightness increased. The small amounts of atmospheric CO_2 that remain today are the result of a balance between volcanic activity (which releases CO_2 into the atmosphere) and the formation of carbonates (which removes CO_2). (As we will see in Section 9-7, human activity is upsetting this balance.)

Life's Impact on Earth's Atmosphere

The appearance of life on Earth set into motion a radical transformation of the atmosphere. Early single-cell organisms converted energy from sunlight into chemical energy using **photosynthesis,** a chemical process that consumes CO_2 and water and releases oxygen (O_2). Oxygen molecules are very reactive, so originally most of the O_2 produced by photosynthesis combined with other substances to form minerals called oxides. (Evidence for this can be found in rock formations of various ages. The oldest rocks have very low oxide content, while oxides are prevalent in rocks that formed after the appearance of organisms that used photosynthesis.) But as life proliferated, the amount of photosynthesis increased dramatically. Eventually so much oxygen was being produced that it could not all be absorbed to form oxides, and O_2 began to accumulate in the atmosphere. Figure 9-22 shows how the amount of O_2 in the atmosphere has increased over the history of the Earth.

About 2 billion (2×10^9) years ago, a new type of life evolved to take advantage of the newly abundant oxygen. These new organisms produce energy by consuming oxygen and releasing carbon dioxide—a process called **respiration** that is used by all modern animals, including humans. Such organisms thrived because photosynthetic plants continued to add even more oxygen to the atmosphere.

Several hundred million years ago, the number of oxygen molecules in the atmosphere stabilized at 21% of the total, the same as the present-day value. This value represents a balance between the release of oxygen from plants by photosynthesis and the intake of oxygen by respiration. Thus, the abundance of oxygen is regulated almost exclusively by the presence of life—a situation that has no parallel anywhere else in the solar system.

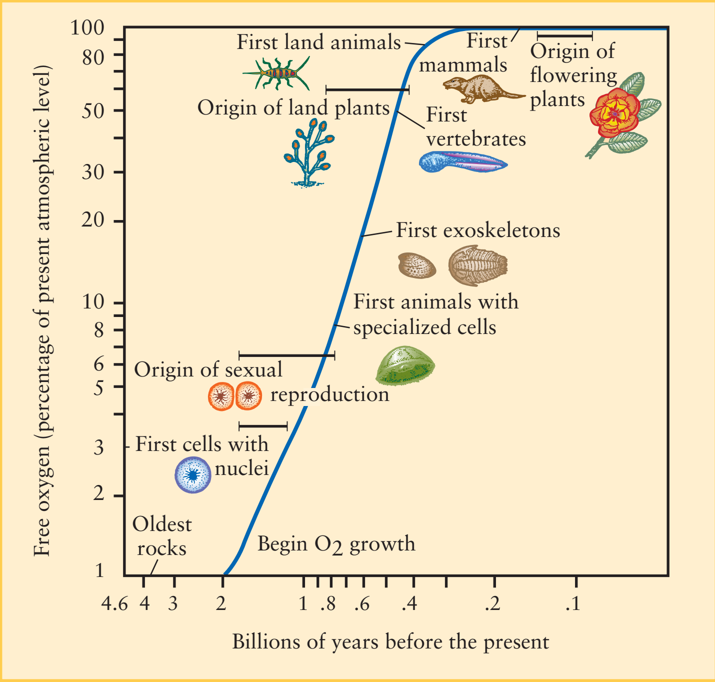


Figure 9-22

The Increase in Atmospheric Oxygen This graph shows how the amount of oxygen in the atmosphere (expressed as a percentage of its present-day value) has evolved with time. Note that the atmosphere contained essentially no oxygen until about 2 billion years ago. (Adapted from Preston Cloud, "The Biosphere," *Scientific American*, September 1983, p. 176)

The most numerous molecules in our atmosphere are nitrogen (N_2), which make up 78% of the total. These, too, are a consequence of the presence of life on Earth. Certain bacteria extract oxygen from minerals called nitrates, and in the process liberate nitrogen into the atmosphere. The amount of atmospheric nitrogen is kept in check by lightning. The energy in a lightning flash causes atmospheric nitrogen and oxygen to combine into nitrogen oxides, which dissolve in rainwater, fall into the oceans, and form nitrates.

Comparing Atmospheres: Earth, Venus, and Mars

WEB LINK 9.7

Table 9-4 shows the dramatic differences between the Earth's atmosphere and those of Venus and Mars. (Mercury, the other terrestrial planet, is too small and has too little gravity to hold an appreciable atmosphere.) The greater intensity of sunlight on Venus caused higher temperatures, which boiled any liquid water and made it impossible for CO_2 to be taken out of the atmosphere and put back into rocks. The atmosphere thus became far denser than our own and rich in greenhouse gases. The result was a very strong greenhouse effect that raised temperatures on Venus to their present value of about 460°C (733 K = 855°F).

Just the opposite happened on Mars, where sunlight is less than half as intense as on Earth. The lower temperatures drove CO_2 from the atmosphere into Martian rocks, and froze all of the water beneath the planet's surface. The atmosphere that remains on Mars has a similar composition to that of Venus but is less than 1/10,000 as dense. On neither Venus nor Mars was life able to blossom and transform the atmosphere as it did here on Earth.

We have thus uncovered a general rule about the terrestrial planets:

The closer a terrestrial planet is to the Sun, the more important the greenhouse effect in that planet's atmosphere. The stronger the greenhouse effect, the higher the planet's surface temperature.

This rule suggests that if the Earth had formed a bit closer to or farther from the Sun, temperatures on our planet might have been too high or too low for life ever to evolve. Thus, our very existence is a result of the Earth's special position in the solar system.

Table 9-4 Chemical Compositions of Three Planetary Atmospheres

	Venus	Earth	Mars
Nitrogen (N_2)	3.5%	78.08%	2.7%
Oxygen (O_2)	almost zero	20.95%	almost zero
Carbon dioxide (CO_2)	96.5%	0.035%	95.3%
Water vapor (H_2O)	0.003%	about 1%	0.03%
Other gases	almost zero	almost zero	2%

9-6 Like Earth's interior, our atmosphere has a layered structure

While life has shaped our atmosphere's chemical composition, the structure of the atmosphere is controlled by the influence of sunlight. Scientists describe the structure of any atmosphere in terms of two properties: temperature and atmospheric pressure, which vary with altitude.

Circulation in our atmosphere results from convection and the Earth's rotation

Pressure , Temperature, and Convection in the Atmosphere

LOOKING DEEPER 9.1

Atmospheric pressure at any height in the atmosphere is caused by the weight of all the air above that height. The average atmospheric pressure at sea level is defined to be one **atmosphere** (1 atm), equal to 1.01×10^5 N/m^2 or 14.7 pounds per square inch. As you go up in the atmosphere, there is less air above you to weigh down on you. Hence, atmospheric pressure decreases smoothly with increasing altitude.

Unlike atmospheric pressure, temperature varies with altitude in a complex way. Figure 9-23 shows that temperature decreases with increasing altitude in some layers of the atmosphere, but in other layers actually *increases* with increasing altitude. These differences result from the individual ways in which each layer is heated.

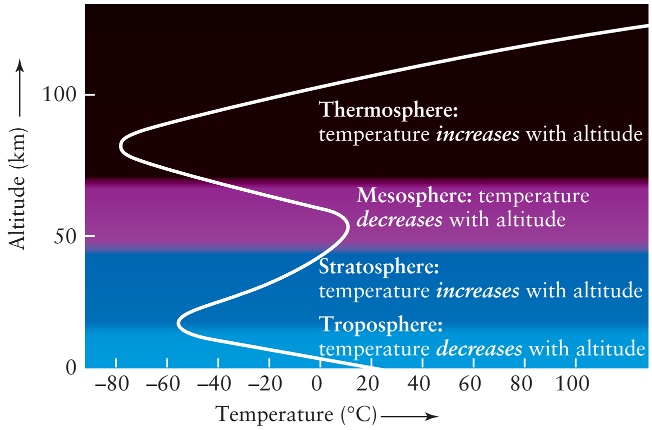


Figure 9-23

Temperature Profile of the Earth's Atmosphere This graph shows how the temperature in the Earth's atmosphere varies with altitude. In the troposphere and mesosphere, temperature decreases with increasing altitude; in the stratosphere and thermosphere, temperature actually increases with increasing altitude.

ANIMATION 9.10

The lowest layer, called the **troposphere,** extends from the surface to an average altitude of 12 km (roughly 7.5 miles, or 39,000 ft). It is heated only indirectly by the Sun. Sunlight warms the Earth's surface, which heats the lower part of the troposphere. By contrast, the upper part of the troposphere remains at cooler temperatures. This vertical temperature variation causes convection currents that move up and down through the troposphere (see Section 8-1). All of the Earth's weather is a consequence of this convection.

Convection on a grand scale is caused by the temperature difference between the Earth's equator and its poles. If the Earth did not rotate, heated air near the equator would rise upward and flow at high altitude toward the poles. There it would cool and sink to lower altitudes, at which it would flow back to the equator. However, the Earth's rotation breaks up this simple convection pattern into a series of **convection cells.** In these cells, air flows east and west as well as vertically and in a north-south direction. The structure of these cells explains why the prevailing winds blow in different directions at different latitudes (Figure 9-24).

Upper Layers of the Atmosphere

Almost all the oxygen in the troposphere is in the form of O_2, a molecule made of two oxygen atoms. But in the **stratosphere,** which extends from about 12 to 50 km (about 7.5 to 31 mi) above the surface, an appreciable amount of oxygen is in the form of **ozone,** a molecule made of *three* oxygen atoms (O_3). Unlike O_2, ozone is very efficient at absorbing ultraviolet radiation from the Sun, which means that the stratosphere can directly absorb solar energy. The result is that the temperature actually increases as you move upward in the stratosphere. Convection requires that the temperature must decrease, not increase, with increasing altitude, so there are essentially no convection currents in the stratosphere.

Above the stratosphere lies the **mesosphere.** Very little ozone is found here, so solar ultraviolet radiation is not absorbed within the mesosphere, and atmospheric temperature again declines with increasing altitude.

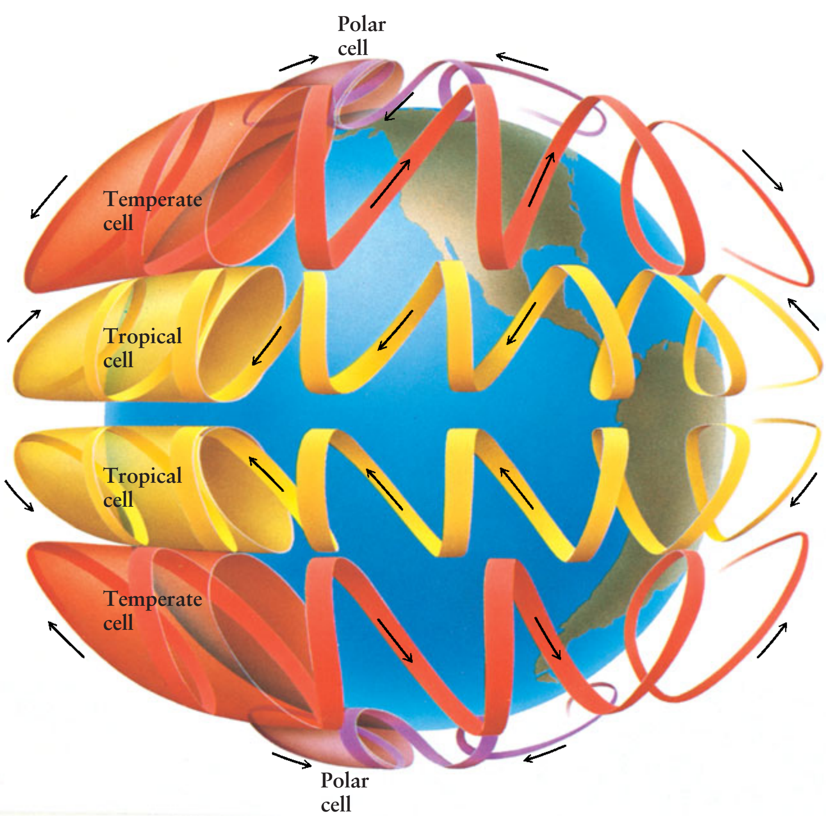


Figure 9-24

Circulation Patterns in the Earth's Atmosphere The dominant circulation in our atmosphere consists of six convection cells, three in the northern hemisphere and three in the southern hemisphere. In the northern temperate region (including the continental United States), the prevailing winds at the surface are from the southwest toward the northeast. Farther south, within the northern tropical region (for example, Hawaii), the prevailing surface winds are from northeast to southwest.

LOOKING DEEPER 9.4

The temperature of the mesosphere reaches a minimum of about −75°C (= −103°F = 198 K) at an altitude of about 80 km (50 mi). This minimum marks the bottom of the atmosphere's thinnest and uppermost layer, the **thermosphere,** in which temperature once again rises with increasing altitude. This is not due to the presence of ozone, because in this very low-density region oxygen and nitrogen are found as individual atoms rather than in molecules. Instead, the thermosphere is heated because these isolated atoms absorb very-short-wavelength solar ultraviolet radiation (which oxygen and nitrogen molecules cannot absorb).

CAUTION! At altitudes near 300 km the temperature of the thermosphere is about 1000°C (1800°F). This is near the altitude at which the space shuttle and satellites orbit the Earth. Nonetheless, a satellite in orbit does *not* risk being burned up as it moves through the thermosphere. The reason is that the thermosphere is far less dense than the atmosphere at sea level. The high temperature simply means that an average atom in the thermosphere is moving very fast (see Box 7-2). But because the thermosphere is so thin (only about 10^{-11} as dense as the air at sea level), these fast-moving atoms are few and far between. Hence, the thermosphere contains very little energy. Nearly all the heat that an orbiting satellite receives is from sunlight, not the thermosphere.

The *Cosmic Connections* figure compares the layered structure of our atmosphere with that of the Earth's interior.

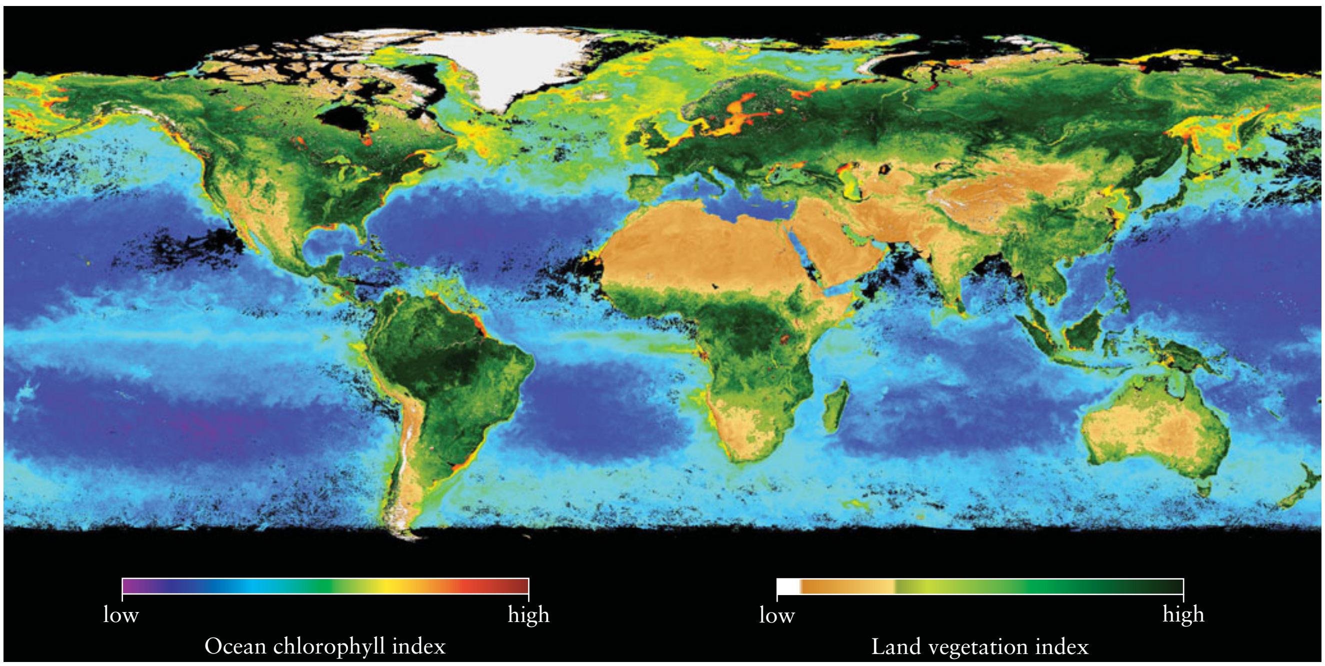
9-7 A burgeoning human population is profoundly altering the Earth's biosphere

One of the extraordinary characteristics of the Earth is that it is covered with life, from the floors of the oceans to the tops of mountains and from frigid polar caps to blistering deserts. So far in this chapter we have hinted at how our planet and living organisms interact: the greenhouse effect has given the Earth a suitable temperature for the evolution of life (Section 9-1), and over billions of years that evolution has transformed the chemical composition of the atmosphere (Section 9-5). Let's explore in greater depth how Earth and the organisms that live on it, especially humans, affect each other.

Global warming and its consequences pose a major challenge to our civilization

The Biosphere and Natural Climate Variation

All life on Earth subsists in a relatively thin layer called the **biosphere,** which includes the oceans, the lowest few kilometers of the troposphere, and the crust to a depth of almost 3 kilometers. Figure 9-25 is a portrait of the Earth's biosphere based on NASA satellite data. The biosphere, which has taken billions of years to evolve to its present state, is a delicate, highly complex system in which plants and animals depend on each other for their mutual survival.



WEB LINK 9.8

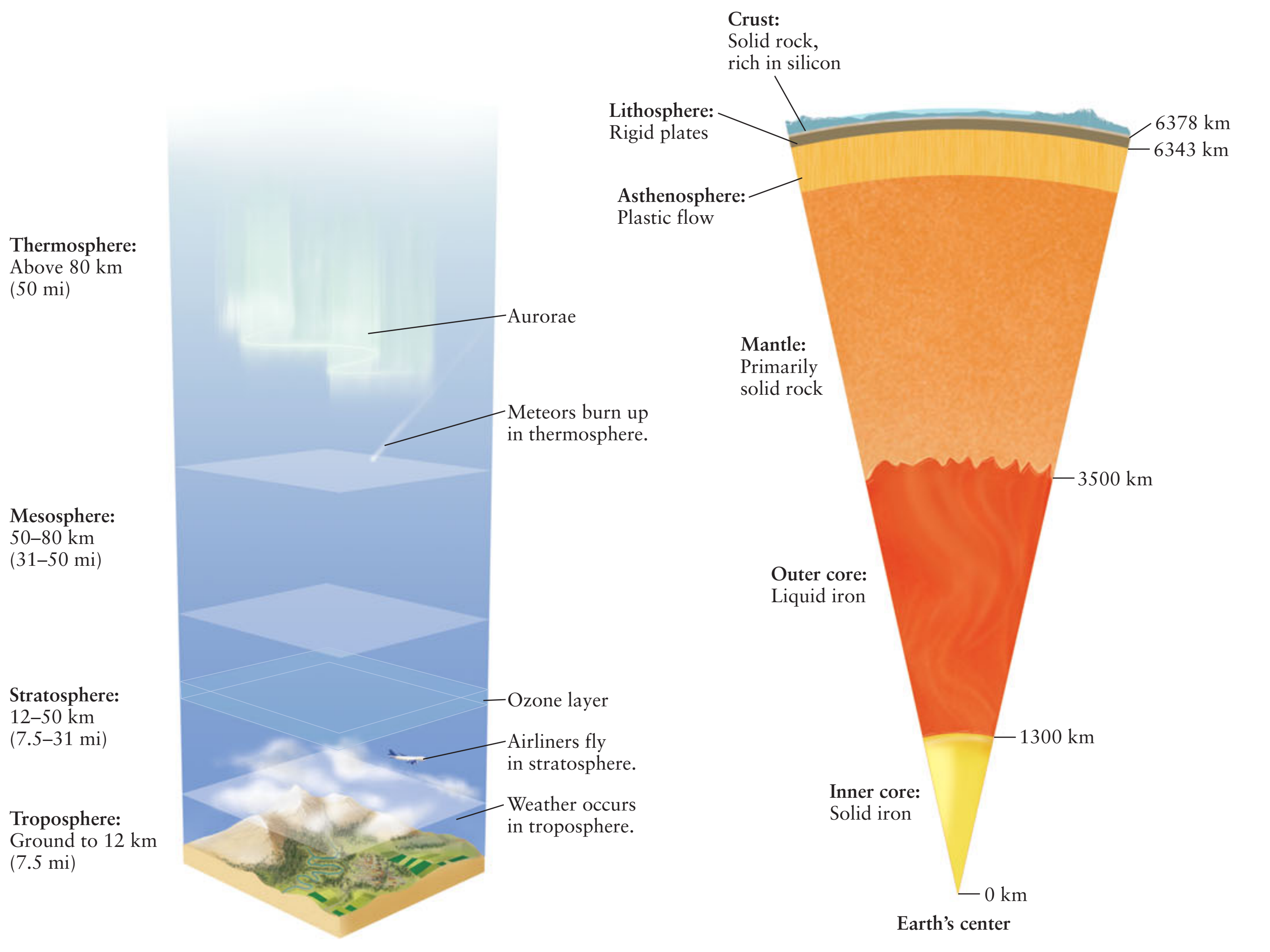
Figure 9-25

The Earth's Biosphere This image, based on data from the *SeaWIFS* spacecraft, shows the distribution of plant life over the Earth's surface. The ocean colors show where free-floating microscopic plants called phytoplankton are found. (NASA Visible Earth)

COSMIC CONNECTIONS

Comparing Earth's Atmosphere and Interior

Earth's atmosphere (which is a gas) and Earth's interior (which is partly solid, partly liquid) both decrease in density and pressure as you go farther away from the Earth's center.



Structure of Earth's Atmosphere

Structure of Earth's interior

The state of the biosphere depends crucially on the temperature of the oceans and atmosphere. Even small temperature changes can have dramatic consequences. An example that recurs every three to seven years is the El Niño phenomenon, in which temperatures at the surface of the equatorial Pacific Ocean rise by 2 to 3°C. Ordinarily, water from the cold depths of the ocean is able to well upward, bringing with it nutrients that are used by microscopic marine organisms called phytoplankton that live near the surface (see Figure 9-25). But during an El Niño, the warm surface water suppresses this upwelling, and the phytoplankton starve. This wreaks havoc on organisms such as mollusks that feed on phytoplankton, on the fish that feed on the mollusks, and on the birds and mammals that eat the fish. During the 1982–1983 El Niño, a quarter of the adult sea lions off the Peruvian coast starved, along with all of their pups.

Many different factors can change the surface temperature of our planet. One is that the amount of energy radiated by the Sun can vary up or down by a few tenths of a percent. Reduced solar brightness may explain the period from 1450 to 1850 when European winters were substantially colder than they are today.

Other factors are the gravitational influences of the Moon and the other planets. Thanks to these influences, the eccentricity of the Earth's orbit varies with a period of 90,000 to 100,000 years, the tilt of its rotation axis varies between 22.1° and 24.5° with a 40,000-year period, and the orientation of its rotation axis changes due to precession (see Section 2-6) with a 26,000-year period. These variations can affect climate by altering the amount of solar energy that heats the Earth during different parts of the year. They help explain why the Earth periodically undergoes an extended period of low temperatures called an *ice age,* the last of which ended about 11,000 years ago.

As we saw in Sections 9-1 and 9-5, one of the most important factors affecting global temperatures is the abundance of greenhouse gases such as CO_2. Geologic processes can alter this abundance, either by removing CO_2 from the atmosphere (as happens when fresh rock is uplifted and exposed to the air, where it can absorb atmospheric CO_2 to form carbonates) or by supplying new CO_2 (as in volcanic eruptions like that shown in Figure 9-15). From time to time in our planet's history, natural events have caused dramatic increases in the amount of greenhouse gases in the atmosphere. One such event may have taken place 251 million (2.51×10^8) years ago, when Siberia went through a period of intense volcanic activity. (The evidence for this is a layer of igneous rock in Siberia that covers an area about the size of Europe. Like the rock shown in Figure 9-19*a*, this layer—which radioactive dating reveals to be 2.51×10^8 years old—is solidified lava.) The tremendous amounts of CO_2 released by this activity would have elevated the global temperature by several degrees. Remarkably, the fossil record reveals that 95% of all species on Earth became extinct at this same time. The coincidence of these two events suggests that greenhouse-induced warming can have catastrophic effects on life.

Human Effects on the Biosphere: Deforestation

Our species is having an increasing effect on the biosphere because our population is skyrocketing. Figure 9-26 shows the sharp rise in the human population that began in the late 1700s with the Industrial Revolution and the spread of modern ideas about hygiene. This rise accelerated in the twentieth century thanks to medical and technological advances ranging from antibiotics to high-yield grains. In 1960 there were 3 billion people on Earth; in 1975, 4 billion; and in 1999, 6 billion. Projections by the United Nations Population Division show that there will be more than 8 billion people on Earth by the year 2030 and more than 9 billion by 2050.

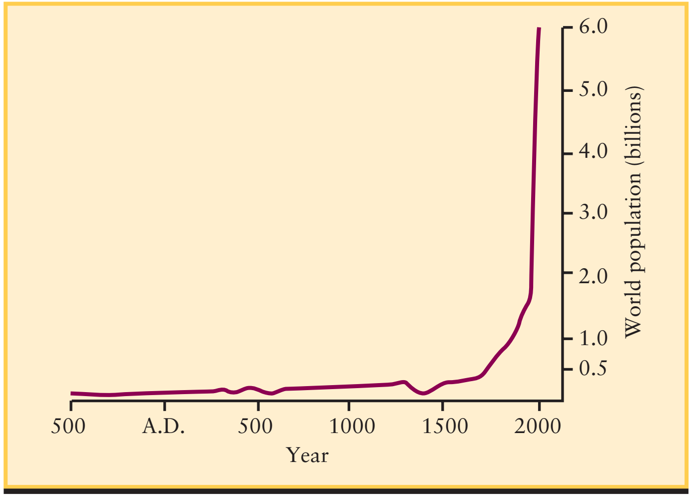


Figure 9-26

The Human Population Data and estimates from the U.S. Bureau of the Census, the Population Reference Bureau, and the United Nations Population Fund were combined to produce this graph showing the human population from 500 B.C. to 2000 A.D. The population began to rise in the eighteenth century and has been increasing at an astonishing rate since 1900.

Every human being has basic requirements: food, clothing, and housing. We all need fuel for cooking and heating. To meet these demands, we cut down forests, cultivate grasslands, and build sprawling cities. A striking example of this activity is occurring in the Amazon rain forest of Brazil. Tropical rain forests are vital to our planet's ecology because they absorb significant amounts of CO_2 and release O_2 through photosynthesis. Although rain forests occupy only 7% of the world's land areas, they are home to at least 50% of all plant and animal species on Earth. Nevertheless, to make way for farms and grazing land, people simply cut down the trees and set them on fire—a process called slash-and-burn. Such deforestation, along with extensive lumbering operations, is occurring in Malaysia, Indonesia, and Papua New Guinea. The rain forests that once thrived in Central America, India, and the western coast of Africa are almost gone (Figure 9-27).

Human Effects on the Biosphere: The Ozone Layer

Human activity is also having potentially disastrous effects on the upper atmosphere. Certain chemicals released into the air—in particular chlorofluorocarbons (CFCs), which have been used in refrigeration and electronics, and methyl bromide, which is used in fumigation—are destroying the ozone in the stratosphere. We saw in Section 9-6 that ozone molecules absorb ultraviolet

Figure 9-27 R I V U X G

The Deforestation of Amazonia The Amazon, the world's largest rain forest, is being destroyed at a rate of 20,000 square kilometers per year in order to provide land for grazing and farming and as a source for lumber. About 80% of the logging is being carried out illegally. (Martin Wendler/Okapia/Photo Researchers)

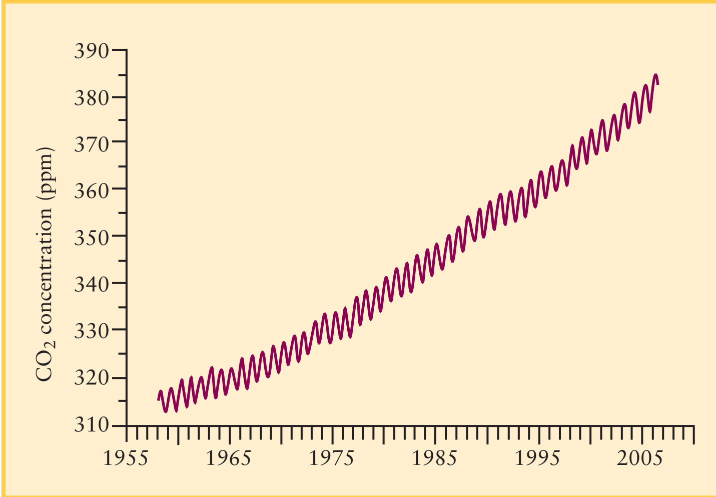


Figure 9-29

Atmospheric Carbon Dioxide Is Increasing This graph shows measurements of atmospheric carbon dioxide in parts per million (ppm). The sawtooth pattern results from plants absorbing more carbon dioxide during the spring and summer. The CO_2 concentration in the atmosphere has increased by 21% since continuous observations started in 1958. (NOAA/Scripps Institution of Oceanography)

radiation from the Sun. Without this high-altitude **ozone layer,** solar ultraviolet radiation would beat down on the Earth's surface with greatly increased intensity. Such radiation breaks apart most of the delicate molecules that form living tissue. Hence, a complete loss of the ozone layer would lead to a catastrophic ecological disaster.

In 1985 scientists discovered an **ozone hole,** a region with an abnormally low concentration of ozone, over Antarctica. Since then this hole has generally expanded from one year to the next (Figure 9-28). Smaller but still serious effects have been observed in the stratosphere above other parts of the Earth. As a result, there has been a worldwide increase in the number of deaths due to skin cancer caused by solar ultraviolet radiation. By international agreement, CFCs are being replaced by compounds that do not deplete stratospheric ozone, and sunlight naturally produces more ozone in the stratosphere. But even in the best of circumstances, the damage to the ozone layer is not expected to heal for many decades.

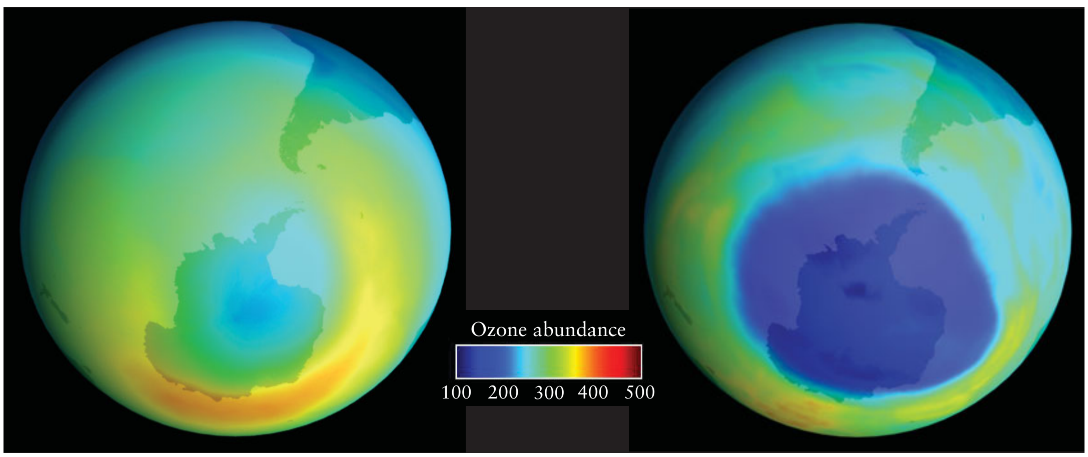
Human Effects on the Biosphere: Global Warming and Climate Change

The most troubling influence of human affairs on the biosphere is a consequence of burning fossil fuels (petroleum and coal) in automobiles, airplanes, and power plants as well as burning forests and brushland for agriculture and cooking (Figure 9-27). This burning releases carbon dioxide into the Earth's atmosphere—and we are adding CO_2 to the atmosphere faster than plants and geological processes can extract it. Figure 9-29 shows how the

WEB LINK 9.10

Figure 9-28

The Antarctic Ozone Hole These two false-color images show that there was a net decrease of 50% in stratospheric ozone over Antarctica between October 1979 and September 2003. The amount of ozone at midlatitudes, where most of the human population lives, decreased by 10 to 20% over the same period. (GSFC/NASA)



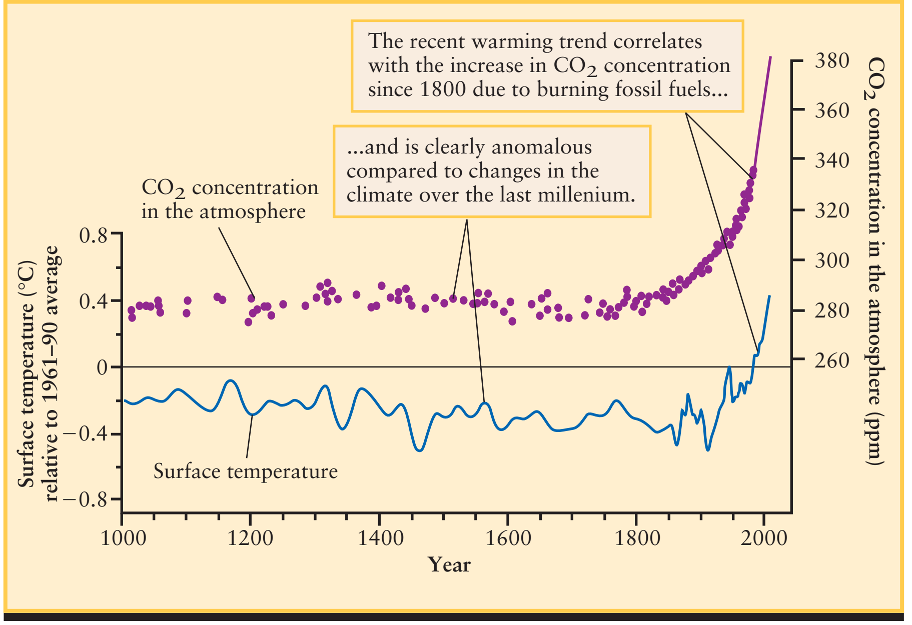
October 1979

September 2003

WEB LINK 9.11

Figure 9-30

Atmospheric CO_2 and Changes in Global Temperature This figure shows how the carbon dioxide concentration in our atmosphere (upper curve) and the Earth's average surface temperature (lower curve) have changed since 1000 A.D. The increase in CO_2 since 1800 due to burning fossil fuels has strengthened the greenhouse effect and caused a dramatic temperature increase. (Intergovernmental Panel on Climate Change and Hadley Centre for Climate Prediction and Research, U.K. Meteorological Office)

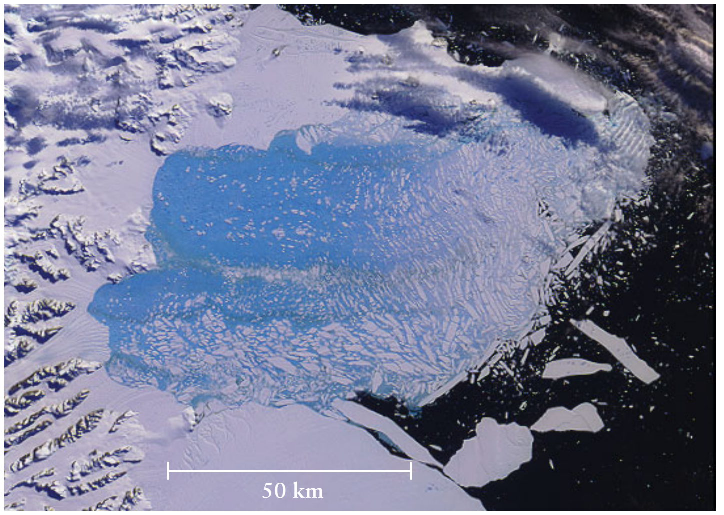


carbon dioxide content of the atmosphere has increased since 1958, when scientists began to measure this quantity on an ongoing basis.

To put the values shown in Figure 9-29 into perspective, we need to know the atmospheric CO_2 concentration in earlier eras. Scientists have learned this by analyzing air bubbles trapped at various depths in the ice that blankets the Antarctic and Greenland. Each winter a new ice layer is deposited, so the depth of a bubble indicates the year in which it was trapped. Figure 9-30 uses data obtained in this way to show how the atmospheric CO_2 concentration has varied since 1000 A.D. While there has been some natural variation in the concentration, its value has skyrocketed since the beginning of the Industrial Revolution around 1800. Data from older, deeper bubbles of trapped air show that in the 650,000 years before the Industrial Revolution, the CO_2 concentration was never greater than 300 parts per million. The present-day CO_2 concentration is greater than this by 25%, and has grown to its present elevated level in just over half a century. If there are no changes in our energy consumption habits, by 2050 the atmospheric CO_2 concentration will be greater than 600 parts per million.

Increasing atmospheric CO_2 is of concern because this strengthens the greenhouse effect and raises the Earth's average surface temperature. Figure 9-30 also shows how this average temperature has varied since 1000 A.D. (Like the CO_2 data, the temperature data from past centuries comes from analyzing trapped air bubbles. Scientists measure the relative amounts of two different types of atmospheric oxygen called ^{16}O and ^{18}O, described in Box 5-5, in a bubble. The ratio of these is a sensitive measure of the temperature at that time the air was trapped inside the ice.) The recent dramatic increase in atmospheric CO_2 concentration has produced an equally dramatic increase in the average surface temperature. This temperature increase is called **global warming.** Other explanations for global warming have been proposed, such as changes in the Sun's brightness, but only greenhouse gases produced by human activity can explain the steep temperature increase shown in Figure 9-30. These gases include methane (CH_4) and nitrous oxide (N_2O), which are released in relatively small amounts by agriculture and industry but which are far more effective greenhouse gases than CO_2.

The effects of global warming can be seen around the world. Nine of the 10 warmest years on record have occurred since 1995, and the years since 2000 have seen increasing numbers of droughts, water shortages, and unprecedented heat waves. Glaciers worldwide are receding, the size of the ice cap around the North Pole has decreased by 20% since 1979, and a portion of the Antarctic ice shelf has broken off (Figure 9-31).



WEB LINK 9.12

Figure 9-31 R I V U X G

A Melting Antarctic Ice Shelf Global warming caused the Larsen B ice shelf to break up in early 2002. This ice shelf, which was about the size of Rhode Island, is thought to have been part of the Antarctic coast for the past 12,000 years. (NASA/GSFC/LaRC/JPL, MIST Team)

Unfortunately, global warming is predicted to intensify in the decades to come. The UN Intergovernmental Panel on Climate Change predicts that if nothing is done to decrease the rate at which we add greenhouse gases to our atmosphere, the average surface temperature will continue to rise by an additional 1.4 to 5.8°C during the twenty-first century. What is worse, the temperature increase is predicted to be greater at the poles than at the equator. The global pattern of atmospheric circulation (Figure 9-24) depends on the temperature difference between the warm equator and cold poles, so this entire pattern will be affected. The same is true for the circulation patterns in the oceans. As a result, temperatures will rise in some regions and decline in others and the patterns of rainfall will be substantially altered. Agriculture depends on rainfall, so these changes in rainfall patterns can cause major disruptions in the world food supply. Studies suggest that the climate changes caused by a 3°C increase in the average surface temperature would cause a worldwide drop in cereal crops of 20 to 400 million tons, putting 400 million more people at risk of hunger.

The melting of polar ice due to global warming poses an additional risk to our civilization. When floating ice like that found near the North Pole melts, the ocean level remains the same. (You can see this by examining a glass of water with an ice cube floating in it. The water level doesn't change when the ice melts.) But the ocean level rises when ice on land melts and runs off into the sea. The Greenland ice cap has been melting at an accelerating rate since 2000 and has the potential to raise sea levels by half a meter or more. Low-lying coastal communities such as Boston and New Orleans, as well as river cities such as London, will have a greater risk of catastrophic flooding. Some island nations of the Pacific will disappear completely beneath the waves.

While global warming is an unintended consequence of human activity, the solution to global warming will require concerted and thoughtful action. Global warming cannot be stopped completely: Even if we were to immediately halt all production of greenhouse gases, the average surface temperature would increase an additional 2°C by 2100 thanks to the natural inertia of the Earth's climate system. Instead, our goal is to minimize the effects of global warming by changing the ways in which we produce energy, making choices about how to decrease our requirements for energy, and finding ways to remove CO_2 from the atmosphere and trap it in the oceans or beneath our planet's surface. Confronting global warming is perhaps the greatest challenge to face our civilization in the twenty-first century.

Key Words

albedo, p. 212
asthenosphere, p. 215
atmosphere (atm), p. 224
atmospheric pressure, p. 224
aurora (*plural* aurorae), p. 222
aurora australis, p. 222
aurora borealis, p. 222
biosphere, p. 226
convection, p. 210
convection cell, p. 225
convection current, p. 210
core, p. 213
crust (of Earth), p. 213
crystal, p. 216
earthquake, p. 213
epicenter, p. 213
global warming, p. 230
greenhouse effect, p. 213
greenhouse gas, p. 213
igneous rock, p. 220
inner core (of Earth), p. 214
lava, p. 220
lithosphere, p. 219
magma, p. 220
magnetopause, p. 221
magnetosphere, p. 221
mantle, p. 213
melting point, p. 215
mesosphere, p. 225
metamorphic rock, p. 220
mineral, p. 220
northern lights, p. 222
oceanic rift, p. 219
outer core (of Earth), p. 214
outgassing, p. 223
ozone, p. 225
ozone layer, p. 229
ozone hole, p. 229
P wave, p. 214
photosynthesis, p. 223
plastic, p. 215
plate (lithospheric), p. 216
plate tectonics, p. 218
respiration, p. 223
rock, p. 220
S wave, p. 214
seafloor spreading, p. 217
sedimentary rock, p. 220
seismic wave, p. 213
seismograph, p. 213
shock wave, p. 221
southern lights, p. 222
stratosphere, p. 225
subduction zone, p. 219
surface wave, p. 214
thermosphere, p. 226
troposphere, p. 225
Van Allen belts, p. 221

Key Ideas

The Earth's Energy Sources: All activity in the Earth's atmosphere, oceans, and surface is powered by three sources of energy.

• Solar energy is the energy source for the atmosphere. In the greenhouse effect, some of this energy is trapped by infrared-absorbing gases in the atmosphere, raising the Earth's surface temperature.

• Tidal forces from the Moon and Sun help to power the motion of the oceans.

• The internal heat of the Earth is the energy source for geologic activity.

The Earth's Interior: Studies of seismic waves (vibrations produced by earthquakes) show that the Earth has a small, solid inner core surrounded by a liquid outer core. The outer core is surrounded by the dense mantle, which in turn is surrounded by the thin low-density crust.

• Seismologists deduce the Earth's interior structure by studying how longitudinal P waves and transverse S waves travel through the Earth's interior.

• The Earth's inner and outer cores are composed of almost pure iron with some nickel mixed in. The mantle is composed of iron-rich minerals.

• Both temperature and pressure steadily increase with depth inside the Earth.

Plate Tectonics: The Earth's crust and a small part of its upper mantle form a rigid layer called the lithosphere. The lithosphere is divided into huge plates that move about over the plastic layer called the asthenosphere in the upper mantle.

• Plate tectonics, or movement of the plates, is driven by convection within the asthenosphere. Molten material wells up at oceanic rifts, producing seafloor spreading, and is returned to the asthenosphere in subduction zones. As one end of a plate is subducted back into the asthenosphere, it helps to pull the rest of the plate along.

• Plate tectonics is responsible for most of the major features of the Earth's surface, including mountain ranges, volcanoes, and the shapes of the continents and oceans.

• Plate tectonics is involved in the formation of the three major categories of rocks: igneous rocks (cooled from molten material), sedimentary rocks (formed by the action of wind, water, and ice), and metamorphic rocks (altered in the solid state by extreme heat and pressure).

The Earth's Magnetic Field and Magnetosphere: Electric currents in the liquid outer core generate a magnetic field. This magnetic field produces a magnetosphere that surrounds the Earth and blocks the solar wind from hitting the atmosphere.

• A bow-shaped shock wave, where the supersonic solar wind is abruptly slowed to subsonic speeds, marks the outer boundary of the magnetosphere.

• Most of the particles of the solar wind are deflected around the Earth by the magnetosphere.

• Some charged particles from the solar wind are trapped in two huge, doughnut-shaped rings called the Van Allen belts. An excess of these particles can initiate an auroral display.

The Earth's Atmosphere: The Earth's atmosphere differs from those of the other terrestrial planets in its chemical composition, circulation pattern, and temperature profile.

• The Earth's atmosphere evolved from being mostly water vapor to being rich in carbon dioxide. A strong greenhouse effect kept the Earth warm enough for water to remain liquid and to permit the evolution of life.

• The appearance of photosynthetic living organisms led to our present atmospheric composition, about four-fifths nitrogen and one-fifth oxygen.

• The Earth's atmosphere is divided into layers called the troposphere, stratosphere, mesosphere, and thermosphere. Ozone molecules in the stratosphere absorb ultraviolet light.

• Because of the Earth's rapid rotation, the circulation in its atmosphere is complex, with three circulation cells in each hemisphere.

The Biosphere: Human activity is changing the Earth's biosphere, on which all living organisms depend.

• Industrial chemicals released into the atmosphere have damaged the ozone layer in the stratosphere.

• Deforestation and the burning of fossil fuels are increasing the greenhouse effect in our atmosphere and warming the planet. This can lead to destructive changes in the climate.

Questions

Review Questions

1. Describe the various ways in which the Earth is unique among the planets of our solar system.
2. Describe the various ways in which the Earth's surface is reshaped over time.
3. Why are typical rocks found on the Earth's surface much younger than the Earth itself?
4. What is convection? What causes convection in the Earth's atmosphere?
5. Describe how energy is transferred from the Earth's surface to the atmosphere by both convection and radiation.
6. If heat flows to the Earth's surface from both the Sun and the Earth's interior, why do we say that the motions of the atmosphere are powered by the Sun?
7. How does solar energy help power the motion of water in the Earth's oceans?
8. How does the greenhouse effect influence the temperature of the atmosphere? Which properties of greenhouse gases in the atmosphere cause this effect?
9. How do we know that the Earth was once entirely molten?
10. What are the different types of seismic waves? Why are seismic waves useful for probing the Earth's interior structure?
11. Describe the interior structure of the Earth.
12. What is a plastic material? Which parts of the Earth's interior are described as being plastic?
13. The deepest wells and mines go down only a few kilometers. What, then, is the evidence that iron is abundant in the Earth's core? That the Earth's outer core is molten but the inner core is solid?
14. The inner core of the Earth is at a higher temperature than the outer core. Why, then, is the inner core solid and the outer core molten instead of the other way around?
15. Describe the process of plate tectonics. Give specific examples of geographic features created by plate tectonics.
16. Explain how convection in the Earth's interior drives the process of plate tectonics.
17. Why do you suppose that active volcanoes, such as Mount St. Helens in Washington State, are usually located in mountain ranges that border on subduction zones?
18. What is the difference between a rock and a mineral?
19. What are the differences among igneous, sedimentary, and metamorphic rocks? What do these rocks tell us about the sites at which they are found?
20. Why do geologists suspect that Pangaea was the most recent in a succession of supercontinents?
21. Why do geologists think that the Earth's magnetic field is produced in the liquid outer core rather than in the mantle?
22. Describe the Earth's magnetosphere. If the Earth did not have a magnetic field, do you think aurorae would be more common or less common than they are today?
23. What are the Van Allen belts?
24. What phenomena tended to make the young Earth freeze over? What other phenomena prevented this from happening?
25. Summarize the history of the Earth's atmosphere. What role has biological activity played in this evolution?
26. Ozone and carbon dioxide and ozone each make up only a fraction of a percent of our atmosphere. Why, then, should we be concerned about small increases or decreases in the atmospheric abundance of these gases?
27. How are scientists able to measure what the atmospheric CO_2 concentration and average surface temperature were in the distant past?
28. Does global warming increase the surface temperature of all parts of the Earth by equal amounts or by different amounts? What consequences does this have?

Advanced Questions

Problem-solving tips and tools

You can find most of the Earth data that you need in Tables 9-1 and 9-3. You will need to know that a sphere has surface area $4\pi r^2$ and volume $4\pi r^3/3$, where r is the sphere's radius. You may have to consult an atlas to examine the geography of the South Atlantic. Also, remember that the average density of an object is its mass divided by its volume. Sections 5-3 and 5-4 and Box 5-2 describe how to solve problems involving blackbody radiation, Section 2-6 discusses precession, and Section 4-4 describes the properties of elliptical orbits.

29. The total power in sunlight that reaches the top of our atmosphere is 1.75×10^{17} W. (**a**) How many watts of power are reflected back into space due to the Earth's albedo? (**b**) If the Earth had no atmosphere, all of the solar power that was not reflected would be absorbed by the Earth's surface. In equilibrium, the heated surface would act as a blackbody that radiates as much power as it absorbs from the Sun. How much power would the entire Earth radiate? (**c**) How much power would one square meter of the surface radiate? (**d**) What would be the average temperature of the surface? Give your answer in both the Kelvin and Celsius scales. (**e**) Why is the Earth's actual average temperature higher than the value you calculated in (d)?

30. On average, the temperature beneath the Earth's crust increases at a rate of 20°C per kilometer. At what depth would water boil? (Assume the surface temperature is 20°C and ignore the effect of the pressure of overlying rock on the boiling point of water.)

31. What fractions of Earth's total volume are occupied by the core, the mantle, and the crust?

32. What fraction of the total mass of the Earth lies within the inner core?

33. (**a**) Using the mass and diameter of the Earth listed in Table 9-1, verify that the average density of the Earth is 5500 kg/m^3. (**b**) Assuming that the average density of material in the Earth's mantle is about 3500 kg/m^3, what must the average density of the core be? Is your answer consistent with the values given in Table 9-3?

34. Identical fossils of the reptile *Mesosaurus,* which lived 300 million years ago, are found in eastern South America and western Africa and nowhere else in the world. Explain how these fossils provide evidence for the theory of plate tectonics.

35. Measurements of the sea floor show that the Eurasian and North American plates have moved 60 km apart in the past 3.3 million years. How far apart (in millimeters) do they move in one year? (By comparison, your fingernails grow at a rate of about 50 mm/year.)

36. The oldest rocks found on the continents are about 4 billion years old. By contrast, the oldest rocks found on the ocean floor are only about 200 million years old. Explain why there is such a large difference in ages.

37. It was stated in Section 7-7 that iron loses its magnetism at temperatures above 770°C. Use this fact and Figure 9-10 to explain why the Earth's magnetic field cannot be due to a magnetized solid core, but must instead be caused by the motion of electrically conducting material in the liquid core.

38. Most auroral displays (like those shown in Figure 9-21*c*) have a green color dominated by emission from oxygen atoms at a wavelength of 557.7 nm. (**a**) What minimum energy (in electron volts) must be imparted to an oxygen atom to make it emit this wavelength? (**b**) Why is your answer in (a) a *minimum* value?

39. Describe how the present-day atmosphere and surface temperature of the Earth might be different (**a**) if carbon dioxide had never been released into the atmosphere; (**b**) if carbon dioxide had been released, but life had never evolved on Earth.

40. The photograph below shows the soil at Daspoort Tunnel near Pretoria, South Africa. The whitish layer that extends from lower left to upper right is 2.2 billion years old. Its color is due to a lack of iron oxide. More recent soils typically contain iron oxide and have a darker color. Explain what this tells us about the history of the Earth's atmosphere.

R I V U X G

(Courtesy of H. D. Holland)

41. Earth's atmospheric pressure decreases by a factor of one-half for every 5.5-km increase in altitude above sea level. Construct a plot of pressure versus altitude, assuming the pressure at sea level is one atmosphere (1 atm). Discuss the characteristics of your graph. At what altitude is the atmospheric pressure equal to 0.001 atm?

42. The Earth is at perihelion on January 3 and at aphelion on July 4. Because of precession, in 15,000 A.D. the amount of sunlight in summer will be more than at present in the northern hemisphere but less than at present in the southern hemisphere. Explain why.

43. Antarctica has an area of 13 million square kilometers and is covered by an icecap that varies in thickness from 300 meters near the coast to 1800 meters in the interior. Estimate the volume of this icecap. Assuming that water and ice have roughly the same density, estimate the amount by which the water level of the world's oceans would rise if Antarctica's ice were to melt completely (see Figure 9-31). What portions of the Earth's surface would be inundated by such a deluge?

Discussion Questions

44. The human population on Earth is currently doubling about every 30 years. Describe the various pressures placed on the Earth by uncontrolled human population growth. Can such growth continue indefinitely? If not, what natural and human controls might arise to curb this growth? It has been suggested that overpopulation problems could be solved by colonizing the Moon or Mars. Do you think this is a reasonable solution? Explain your answer.
45. In order to alleviate global warming, it will be necessary to dramatically reduce the amount of carbon dioxide that we release into the atmosphere by burning petroleum. What changes in technology and society do you think will be needed to bring this about?

Web/eBook Questions

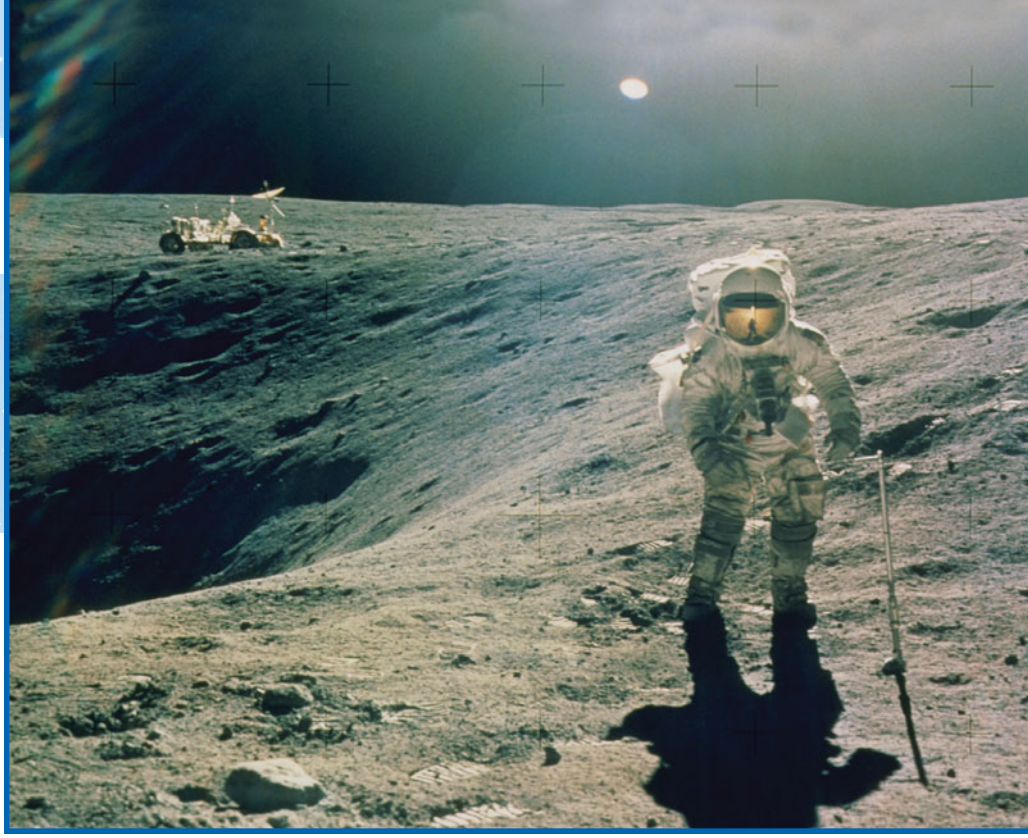
46. Search the World Wide Web for information about Rodinia, the supercontinent that predated Pangaea. When did this supercontinent form? When did it break apart? Do we have any evidence of supercontinents that predated Rodinia? Why or why not?
47. Because of plate tectonics, the arrangement of continents in the future will be different from today. Search the World Wide Web for information about "Pangaea Ultima," a supercontinent that may form in the distant future. When is it predicted to form? How will it compare to the supercontinent that existed 200 million years ago (see Figure 9-12*a*)?
48. Use the World Wide Web to investigate the current status of the Antarctic ozone hole. Is the situation getting better or worse? Is there a comparable hole over the North Pole? Why do most scientists blame the chemicals called CFCs for the existence of the ozone hole?
49. Use the World Wide Web to research predictions of the Earth's future surface temperature. What are some predictions for the surface temperature in 2050? In 2100? What effects may the increased temperature have on human health?
50. The Kyoto Protocol is an agreement made by a number of nations around the world to reduce their production of greenhouse gases. Use the World Wide Web to investigate the status of the Kyoto Protocol. How many nations have signed the protocol? What fraction of the world's greenhouse gas production comes from these nations? Have any developed nations failed to sign? How effective has the protocol been?
51. **Observing Mountain Range Formation.** Access the two animations "The Collision of Two Plates: South America" and "The Collision of Two Plates: The Himalayas" in Chapter 9 of the *Universe* Web site or eBook. (**a**) In which case are the mountains formed by tectonic uplift? In which case are the mountains formed by volcanoes from rising lava? (**b**) For each animation, describe which plate is moving in which direction.

Activities

Observing Project

52. Use the *Starry Night Enthusiast*™ program to view the Earth from space. In the **Favourites** menu, select **Solar System > Earth** to place yourself in the position of an astronaut flying outside his spaceship at about 5800 km above the Earth's surface on September 26, 2002. [You may need to click once on a **Zoom** button to show the Earth against the background stars. You may also see the astronaut's spacesuit and feet in the foreground. This foreground can be removed by clicking off **Feet** in the **View** menu.] Click and hold down and move the mouse to use the **Location Scroller** to rotate the cloud-enshrouded Earth beneath you, allowing you to view different parts of the Earth. You can change the **Time** to view different parts of this surface in daylight. (**a**) Is there any evidence for the presence of an atmosphere on Earth? Explain. Remove the cloud cover by opening **Options > Solar System,** clicking on **Planets-Moons** to display the Planets-Moons Options panel and turning off **Show atmosphere.** It is also helpful to remove all the Earth-orbiting satellites by clicking on **View > Solar System > Satellites.** (**b**) Can you see any evidence of plate tectonics as you rotate the Earth again? Locate the position of your home and zoom in on it, using the Zoom tool on the right of the toolbar to set the Field of View to about 16° × 11°. Again, use the location scroller to move around on the Earth. (**c**) Can you see any evidence of the presence of life or of man-made objects? Right-click on the Earth and click on Google Map to examine regions of the Earth in great detail on these images from an orbiting satellite. You can attempt to locate your own home on these maps. As an exercise, find the country of Panama, zoom in progressively upon the Panama Canal and search for ships traversing this incredible waterway. (**d**) What do you conclude about the importance of sending spacecraft to planets to explore their surfaces at close range? Close the internet connection to Google Map. In *Starry Night Enthusiast*™ open the **Favourites** menu, select **Solar System,** and click on **Earth** to return to the initial time and position above the Earth. Rotate the Earth to place eastern Brazil, on the eastern tip of South America, near to the center of the window. At the time of this observation this area is near the terminator (the dividing line between the day and night sides of the Earth). (**e**) As seen from eastern Brazil, is the sun rising or setting? Explain.

10 Our Barren Moon



RIVUXG

Walking on the lunar surface, April 1972. (John Young, *Apollo 16,* NASA/Science Photo Library)

WEB LINK 10.1

Other than the Earth itself, the most familiar world in the solar system is the Moon. It is so near to us that some of its surface features are visible to the naked eye. But the Moon is also a strange and alien place, with dramatic differences from our own Earth. It has no substantial atmosphere, no global magnetic field, and no liquid water of any kind. On the airless Moon, the sky is black even at midday. And unlike the geologically active Earth, the Moon has a surface that changes very little with time. When *Apollo 16* astronauts Charlie Duke (shown in the photograph) and John Young explored the region of the lunar highlands known as the Descartes Formation, the youngest rocks that they found were virtually the same age as the oldest rocks found on Earth.

Because the Moon has changed so little over the eons, it has preserved the early history of the inner solar system and the terrestrial planets. In this chapter we will see evidence that the Moon's formation and early evolution was violent and chaotic. The *Apollo* missions revealed that the Moon may have formed some 4.5 billion years ago as the result of a titanic collision between the young Earth and a rogue protoplanet the size of Mars. The young Moon was then pelted incessantly for hundreds of millions of years by large chunks of interplanetary debris, producing a cratered landscape. We will discover that the largest of these impacts formed immense circular basins that then flooded with molten lava. You can see the solidified lava as dark patches that cover much of the face of the Moon. In later chapters we will find other evidence that catastrophic collisions have played an important role in shaping the solar system.

10-1 The Moon's airless, dry surface is covered with plains and craters

Compared with the distances between planets, which are measured in tens or hundreds of millions of kilometers, the average distance from the Earth to the Moon is just 384,400 km (238,900 mi). Despite being so close, the Moon has an angular diameter of just $\frac{1}{2}°$. This tells us that it is a rather small world. The diameter of the Moon is 3476 km (2160 mi), just 27% of the Earth's diameter and about the same as the distance from Las Vegas to Philadelphia or from London to Cairo (**Figure 10-1**). **Table 10-1** lists some basic data about the Moon.

Motions of the Earth-Moon System

Although the Moon has a small mass (just 1.23% of the Earth's mass), Newton's third law tells us that the Moon exerts just as much gravitational force on the Earth as the Earth does on the Moon (see Section 4-6). Hence, it is not strictly correct to say that the Moon orbits the Earth; rather, they both orbit around a point between their centers called the **center of mass** of the Earth-Moon

Learning Goals

By reading the sections of this chapter, you will learn

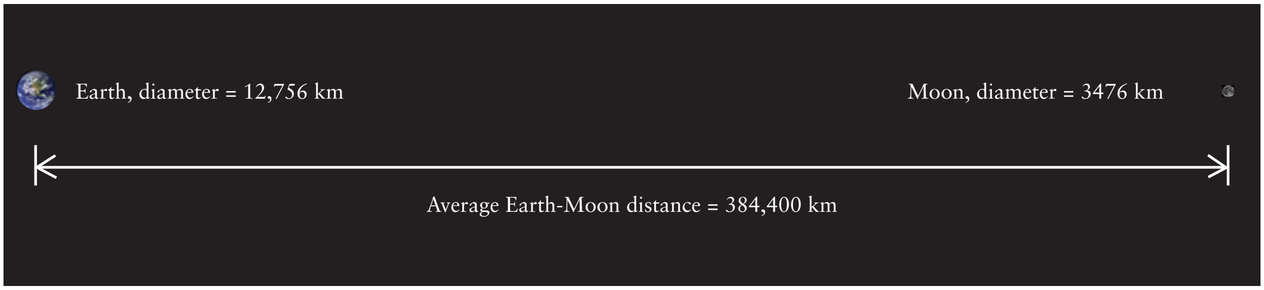
10-1 The nature of the Moon's surface

10-2 The story of human exploration of the Moon

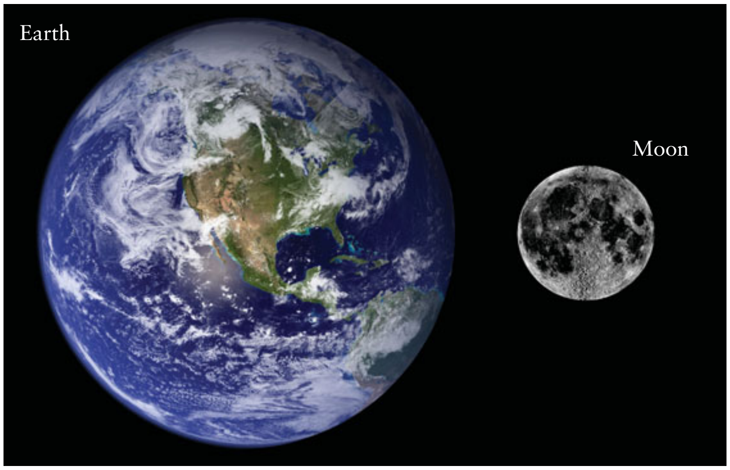
10-3 How we have learned about the Moon's interior

10-4 How Moon rocks differ from rocks on Earth

10-5 Why scientists think the Moon formed as the result of a violent collision between worlds



(a) The Earth-Moon system



(b) The Earth and Moon to scale, shown 10 times larger than in part (a)

Figure 10-1 R I V U X G

Comparing the Earth and Moon **(a)** The Moon is a bit more than one-quarter the diameter of the Earth. The average Earth-Moon distance is about 30 times the Earth's diameter. **(b)** The Earth has blue oceans, an atmosphere streaked with white clouds, and continents continually being reshaped by plate tectonics. By contrast, the Moon has no oceans, no atmosphere, and no evidence of plate tectonics. (a: NASA; b: John Sanford, Science Photo Library)

system. (Because the Earth is so much more massive than the Moon, the center of mass is close to the Earth's center: Indeed, it actually lies within the Earth's interior.) The center of mass then follows an elliptical orbit around the Sun (Figure 10-2*a*). In a similar way, a spinning wrench sliding along a table actually rotates around its center of mass (Figure 10-2*b*).

The Moon's Rotation and Libration

Even without binoculars or a telescope, you can easily see that dark gray and light gray areas cover vast expanses of the Moon's rocky surface. If you observe the Moon over many nights, you will see the Moon go through its phases as the dividing line between the illuminated and darkened portion of the Moon (the **terminator**) shifts. But you will always see the same pattern of dark and light areas, because the Moon keeps the same side turned toward the Earth; you never see the **far side** (or back side) of the Moon. We saw in Section 3-2 that this is the result of the Moon's **synchronous rotation:** It takes precisely the same amount of time for the Moon to rotate on its axis (one lunar "day") as it does to complete one orbit around the Earth.

ANIMATION 10.1

With patience, however, you can see slightly more than half the lunar surface. This is because the Moon appears to wobble slightly over the course of an orbit: It seems to rock back and forth around its north-south axis and to nod up and down in a north-south direction. This apparent periodic wobbling, called **libration,** permits us to view 59% of our satellite's surface.

LOOKING DEEPER 10.1

We stress that the Moon only *appears* to be wobbling. In fact, its rotation axis keeps nearly the same orientation in space as the Moon goes around its orbit. The reason why the Moon seems to rock back and forth is that its orbit around the Earth is slightly elliptical. As a result, the Moon's orbital motion does not keep pace with its rotation at all points around the orbit. Furthermore, because the Moon's rotation axis is not exactly perpendicular to the plane of its orbit, it appears to us to nod up and down.

An Airless World

Clouds always cover some portion of the Earth's surface, but clouds are never seen on the Moon (see Figure 10-1). This is because the Moon is too small a world to have an atmosphere. Its surface gravity is low, only about one-sixth as great as that of the Earth, and thus any gas molecules can easily escape into space (see Box 7-2). Because there is no atmosphere to scatter sunlight, the daytime sky on the Moon appears as black as the nighttime sky on the Earth (see the photograph that opens this chapter).

The absence of an atmosphere means that the Moon can have no liquid water on its surface. Here on Earth, water molecules are kept in the liquid state by the pressure of the atmosphere pushing down on them. To see what happens to liquid water on the

Table 10-1 Moon Data

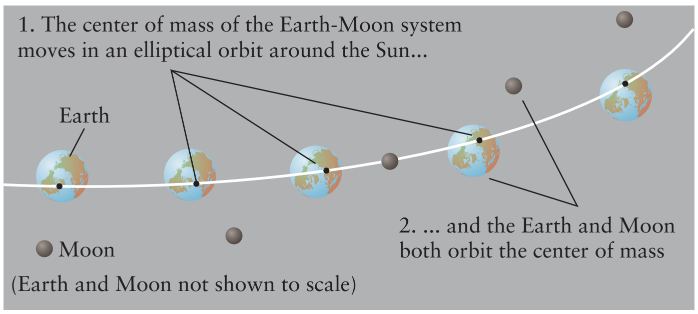
Distance from Earth (center to center):	Average: 384,400 km = 238,900 mi Maximum (apogee): 405,500 km Minimum (perigee): 363,300 km
Eccentricity of orbit:	0.0549
Average orbital speed:	3680 km/h
Sidereal period (relative to fixed stars):	27.322 days
Synodic period (new moon to new moon):	29.531 days
Inclination of lunar equator to orbit:	6.68°
Inclination of orbit to ecliptic:	5.15°
Diameter (equatorial):	3476 km = 2160 mi = 0.272 Earth diameter
Mass:	7.349×10^{22} kg = 0.0123 Earth mass
Average density:	3344 kg/m^3
Escape speed:	2.4 km/s
Surface gravity (Earth = 1):	0.17
Albedo:	0.11
Average surface temperatures:	Day: 130°C = 266°F = 403 K Night: −180°C = −292°F = 93 K
Atmosphere:	Essentially none

WEB LINK 10.2

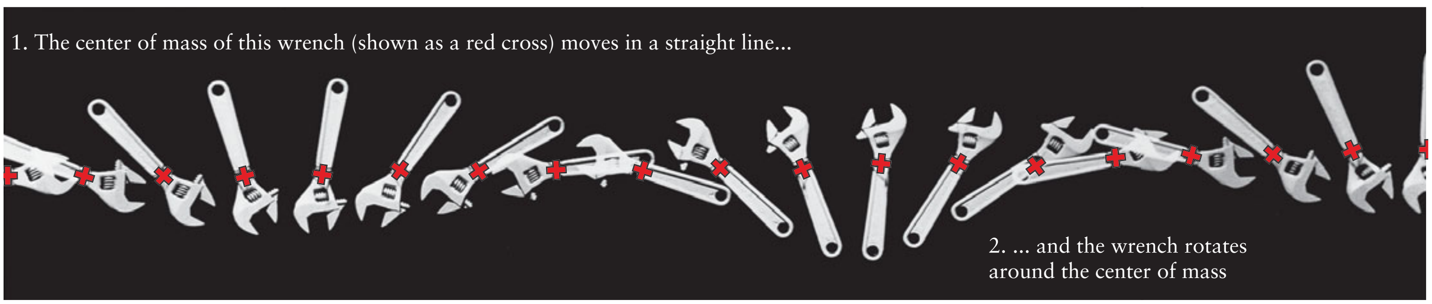
R I V U X G

(Larry Landolfi, Science Photo Library)

airless Moon, consider what happens when the pressure of the atmosphere is reduced. The air pressure in Denver, Colorado (elevation 1650 m, or 5400 ft), is only 83% as great as at sea level. Therefore, in Denver, less energy has to be added to the molecules in a pot of water to make them evaporate, and water boils at only 95°C (= 368 K = 203°F), as compared with 100°C (= 373 K = 212°F) at sea level. (This is why some foods require longer cooking times at high elevations, where the boiling water used for cooking is not as hot as at sea level.) On the Moon, the atmospheric pressure is essentially zero and the boiling temperature is



(a)



(b)

Figure 10-2 R I V U X G

Motion of the Earth-Moon System (a) The Earth and Moon both orbit around their center of mass, which in turn follows an elliptical orbit around the Sun. **(b)** The illustration in part (a) is analogous to this time-lapse image of a spinning wrench sliding across a table.
(b: Berenice Abbott/Photo Researchers)

lower than the temperature of the lunar surface. Under these conditions, water can exist as a solid (ice) or a vapor but not as a liquid.

CAUTION! If astronauts were to venture out onto the lunar surface without wearing spacesuits, the lack of atmosphere would *not* cause their blood to boil. That's because our skin is strong enough to contain bodily fluids. In the same way, if we place an orange in a sealed container and remove all the air, the orange retains all of its fluid and does not explode. It even tastes the same afterward! The reasons why astronauts wore pressurized spacesuits on the Moon (see the photograph that opens this chapter) were to provide oxygen for breathing, to regulate body temperature, and to protect against ultraviolet radiation from the Sun. Since the Moon has no atmosphere, and thus no ozone layer like that of the Earth to screen out ultraviolet wavelengths (Section 9-7), an unprotected astronaut would suffer a sunburn after just 10 seconds of exposure!

Lunar Craters

Since the Moon has no atmosphere to obscure its surface, you can get a clear view of several different types of lunar features with a small telescope or binoculars. These include *craters,* the dark-colored *maria,* and the light-colored *lunar highlands* or *terrae* (Figure 10-3). Taken together, these different features show the striking differences between the surfaces of the Earth and the Moon.

With an Earth-based telescope, some 30,000 **craters** are visible, with diameters ranging from 1 km to several hundred km. Close-up photographs from lunar orbit have revealed millions of craters too small to be seen from Earth. Following a tradition established in the seventeenth century, the most prominent craters are named after famous philosophers, mathematicians, and scientists, such as Plato, Aristotle, Pythagoras, Copernicus, and Kepler. Virtually all lunar craters, both large and small, are the result of the Moon's having been bombarded by meteoritic material. For this reason, they are also called **impact craters** (see Section 7-6). One piece of evidence that lunar craters are caused by impacts is that many large craters have a central peak, with a shape that could only result from high-speed impacts (see Figure 7-10*a*).

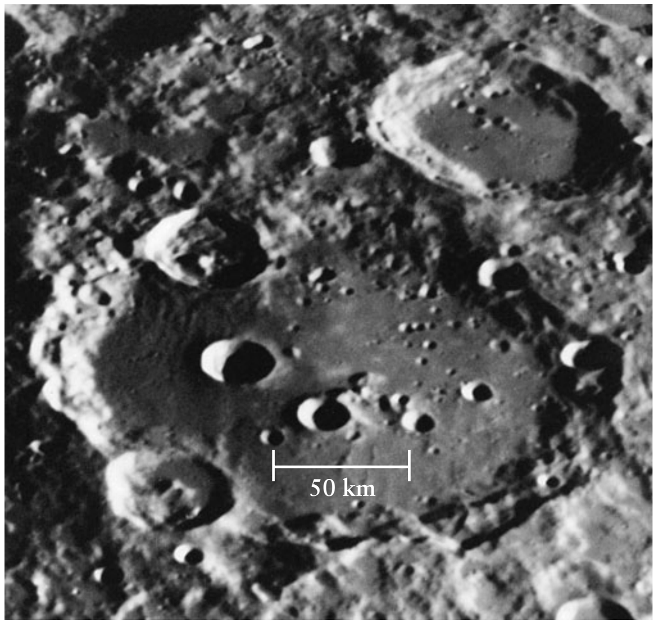


Figure 10-4 R I V U X G

The Crater Clavius This photograph from the 5-meter (200-in.) Palomar telescope shows one of the largest craters on the Moon. Clavius has a diameter of 232 km (144 mi) and a depth of 4.9 km (16,000 ft), measured from the crater's floor to the top of the surrounding rim. Later impacts formed the smaller craters inside Clavius. (Palomar Observatory)

WEB LINK 10.3

A meteoroid striking the lunar surface generates a shock wave over the surface outward from the point of impact. Such shock waves can spread over an area much larger than the size of the meteoroid that generated the wave. Very large craters more than 100 km across, such as the crater Clavius shown in Figure 10-4, were probably created by the impact of a fast-moving piece of rock only a few kilometers in radius.

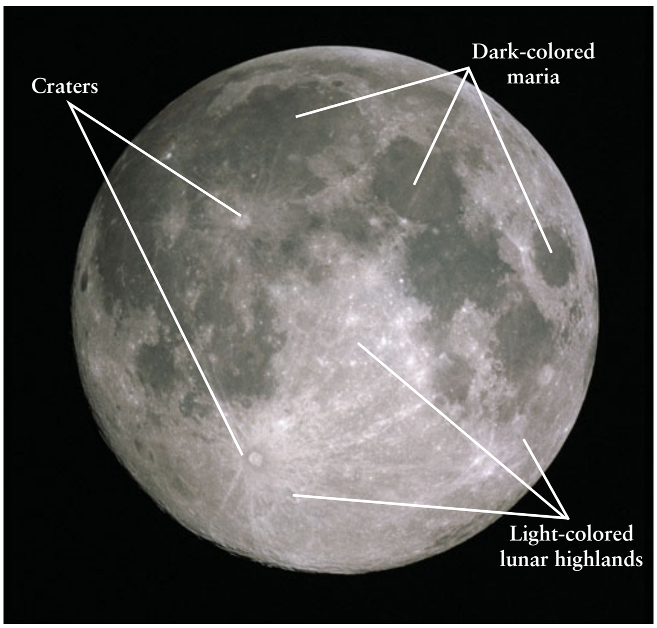


Figure 10-3 R I V U X G

The Moon as Seen from Earth The key features of the lunar surface can be seen with binoculars, a small telescope, or even the naked eye. (Larry Landolfi, Science Photo Library)

Maria: Dark and Relatively Young

The large dark areas on the lunar surface shown in Figure 10-3 are called **maria** (pronounced "MAR-ee-uh"). They form a pattern that looks crudely like a human face, sometimes called "the man in the Moon." The singular form of maria is **mare** (pronounced "MAR-ay"), which means "sea" in Latin. These terms date from the seventeenth century, when observers using early telescopes thought these dark features were large bodies of water.

They gave the maria fanciful and romantic names such as Mare Tranquillitatis (Sea of Tranquillity), Mare Nubium (Sea of Clouds), Mare Nectaris (Sea of Nectar), Mare Serenitatis (Sea of Serenity), and Mare Imbrium (Sea of Showers). While modern astronomers still use these names, they now understand that the maria are not bodies of water (which, as we have seen, could not exist on the airless Moon) but rather the remains of huge lava flows. The maria get their distinctive appearance from the dark color of the solidified lava.

On the whole, the maria have far fewer craters than the surrounding terrain. Since craters are caused by meteoritic bombardment, this means that the maria have not been exposed to that bombardment for as long as the surrounding terrain. Hence, the maria must be relatively young, and the lava flows that formed them must have occurred at a later stage in the Moon's geologic history (Figure 10-5). The craters that are found in the maria were caused by the relatively few impacts that have occurred since the maria solidified (Figure 10-6).

Although they are much larger than craters, maria also tend to be circular in shape (see Figure 10-5). This suggests that, like craters, these depressions in the lunar surface were also created by impacts. It is thought that very large meteoroids or asteroids some tens of kilometers across struck the Moon, forming basins. These depressions subsequently flooded with lava that flowed out from the Moon's interior through cracks in the lunar crust. The solidified lava formed the maria that we see today. The *Cosmic Connections* figure depicts our understanding of how lunar craters and maria formed.

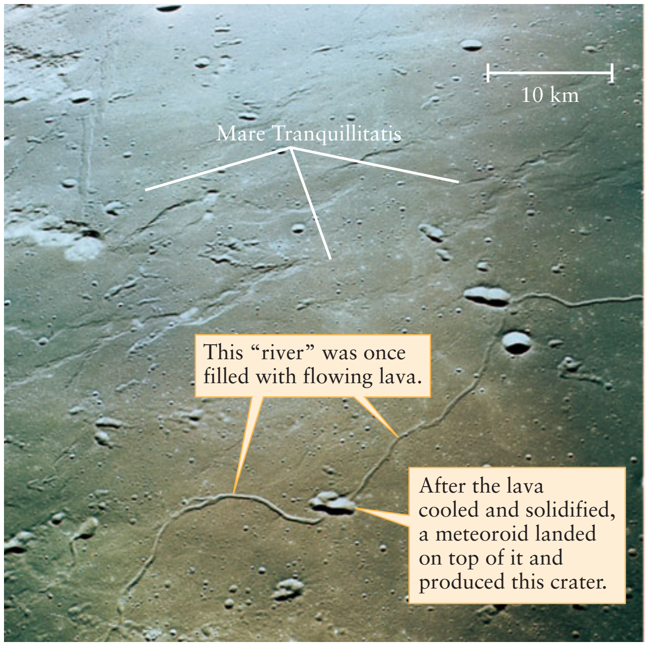


Figure 10-6 R I V U X G

Details of Mare Tranquillitatis This color photograph from lunar orbit reveals numerous tiny craters in the surface of a typical mare. The curving "river," or rille, was carved out by flowing lava that later solidified; similar features are found in volcanic areas on Earth. The *Apollo 11* landing site is near the center of the top edge of this image. (*Apollo 10*, NASA)

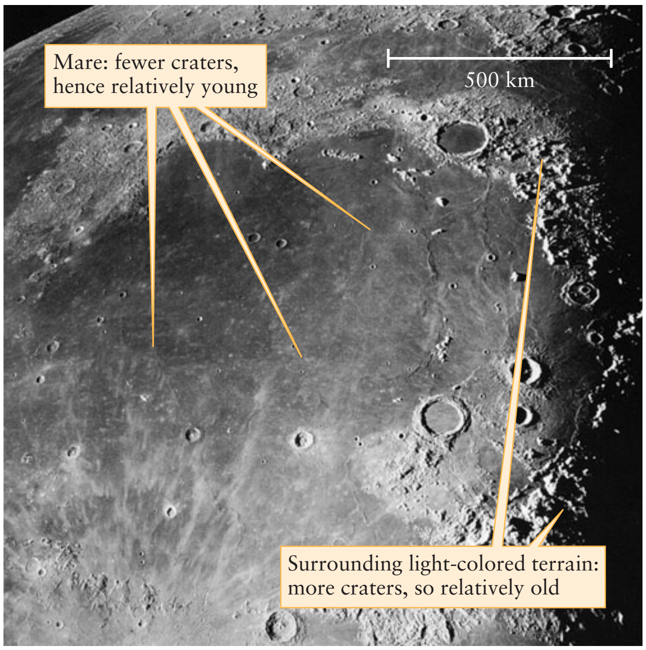


Figure 10-5 R I V U X G

Mare Imbrium from Earth Mare Imbrium is the largest of 14 dark plains that dominate the Earth-facing side of the Moon. Its diameter of 1100 km (700 mi) is about the same as the distance from Chicago to Philadelphia or from London to Rome. The maria formed after the surrounding light-colored terrain, so they have not been exposed to meteoritic bombardment for as long and hence have fewer craters. (Carnegie Observatories)

An impact large enough to create a mare basin must have thrust upward tremendous amounts of material around the impact site. This explains the mountain ranges that curve in circular arcs around mare basins. Analysis of lunar rocks as well as observations made from lunar orbit have validated this picture of the origin of lunar mountains.

Lunar Highlands: Light-Colored and Ancient

The light-colored terrain that surrounds the maria is called **terrae,** from the Latin for "lands." (Seventeenth-century astronomers thought that this terrain was the dry land that surrounded lunar oceans.) Detailed measurements by astronauts in lunar orbit demonstrated that the maria on the Moon's Earth-facing side are 2 to 5 km below the average lunar elevation, while the terrae extend to several kilometers above the average elevation. For this reason terrae are often called **lunar highlands.** The flat, low-lying, dark gray maria cover only 15% of the lunar surface; the remaining 85% is light gray lunar highlands. Since the lunar highlands are more heavily cratered than the maria, we can conclude that the highlands are older.

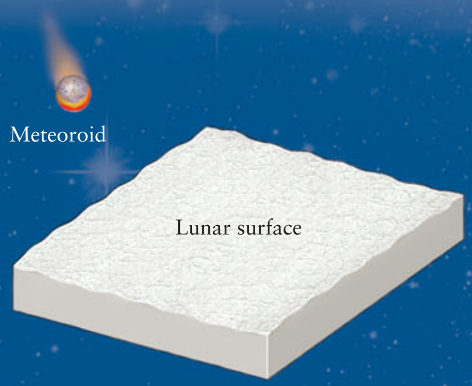
WEB LINK 10.4

Remarkably, when the Moon's far side was photographed for the first time by the Soviet *Luna 3* spacecraft in 1959, scientists were surprised to find almost

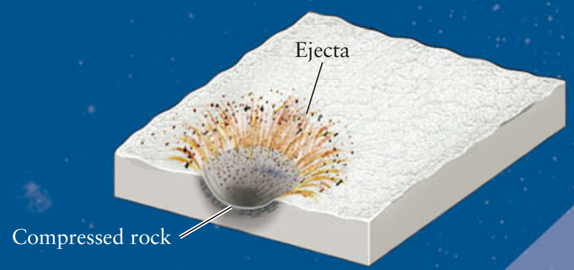
COSMIC CONNECTIONS

The Formation of Craters and Maria on the Moon

The physical features of lunar craters and maria show that they were formed by meteoroids impacting the Moon's surface at high speed. The crater labeled in the photograph, called Aristillus after a Greek astronomer who lived around 300 B.C., is 55 km (34 mi) across and 3600 m (12,000 ft) deep. (Photograph: Lunar and Planetary Institute/Universities Space Research Association)

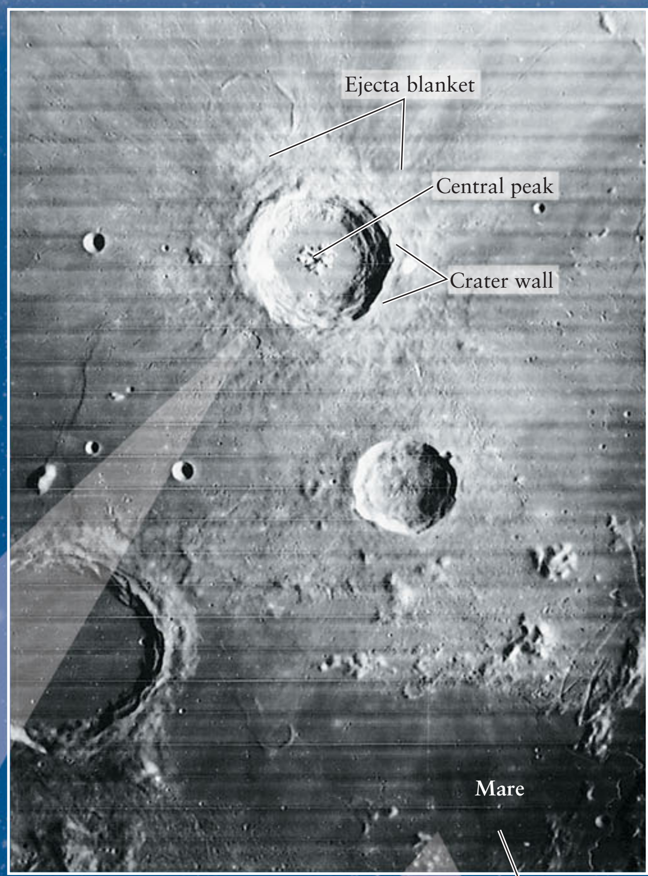


1. A meteoroid approaches the lunar surface.



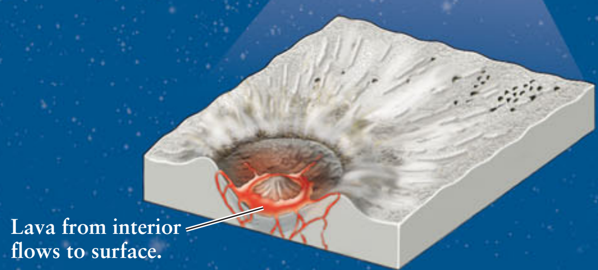
2. When the meteoroid strikes, it ejects rocks and boulders and produces a shock wave in the lunar surface.

3. What remains is a crater with a central peak. The ejected material forms a blanket around the crater and can cause secondary craters.



R I V U X G

Lava fills crater and solidifies to form the dark mare floor.



4. A very large meteoroid can crack the lunar crust, forming a mare.

no maria there. Thus, lunar highlands predominate on the side of the Moon that faces away from the Earth (Figure 10-7). Presumably, the crust is thicker on the far side, so even the most massive impacts there were unable to crack through the crust and let lava flood onto the surface. The Moon is not unique in having two hemispheres with different crustal thicknesses: The Earth's northern hemisphere has much more continental crust than its southern hemisphere, and the southern hemisphere of Mars has a thicker crust than the northern hemisphere.

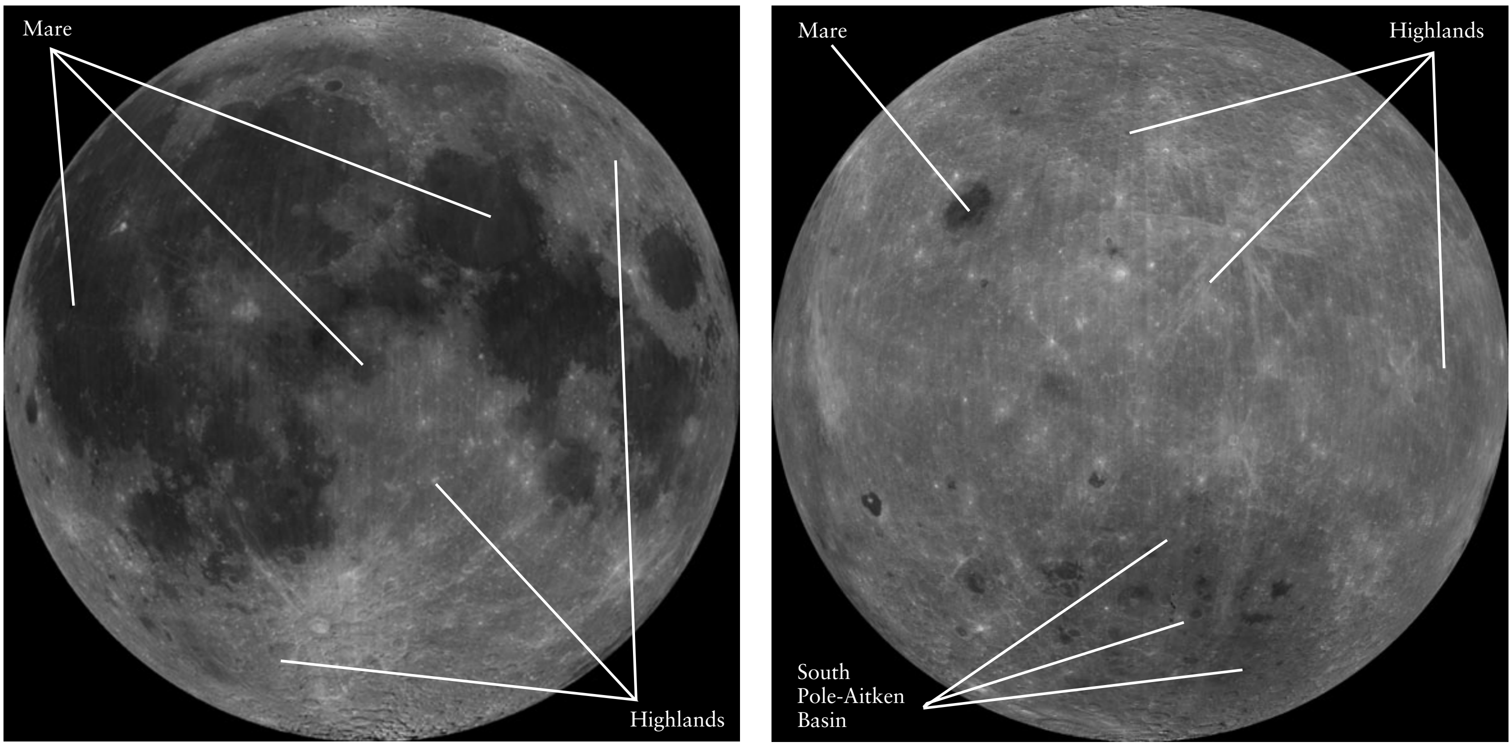
Although the Moon's far side is deficient in maria compared to the near side, the highlands on the far side are as heavily pockmarked by impacts as those on the near side. The most prominent feature on the far side is the South Pole–Aitken Basin, the largest known impact crater in the solar system. This basin is about 2500 km (1600 mi) across—about the same size as the continent of Europe—and 12 km (7 mi) deep.

In contrast to the Earth and its active geology, the Moon's surface is geologically dead

A World Without Plate Tectonics

Something is entirely missing from our description of the Moon's surface—any mention of plate tectonics. Indeed, no evidence for plate tectonics can be found on the Moon. Recall from Section 9-3 that the Earth's major mountain ranges were created by collisions between lithospheric plates. In contrast, it appears that the Moon is a *one-plate world:* Its entire lithosphere is a single, solid plate. There are no rifts where plates are moving apart, no mountain ranges of the sort formed by collisions between plates, and no subduction zones. Thus, while lunar mountain ranges bear the names of terrestrial ranges, such as the Alps, Carpathians, and Apennines, they are entirely different in character: they were formed by material ejected from impact sites, not by plate tectonics. Geologically, the Moon is a dead world.

In Section 7-6 we discussed the general rule that a world with abundant craters has an old, geologically inactive surface. The Moon is a prime example of this rule. Without an atmosphere to cause erosion and without plate tectonics, the surface of the Moon changes only very slowly. That is why the Moon's craters, many of which are now known to be billions of years old, remain visible today. On the Earth, by contrast, the continents and seafloor are continually being reshaped by seafloor spreading, mountain building, and subduction. Thus, any craters that were formed by impacts on the ancient Earth's surface have long since been erased. There are fewer than 200 impact craters on the Earth today; these were formed within the last few hundred million years and have not yet been erased.



Near side: highlands and maria

Far side: highlands but almost no maria

VIDEO 10.1

Figure 10-7 R I V U X G

The Near and Far Sides of the Moon About 50,000 individual infrared images from the *Clementine* spacecraft were combined to create these views of the near (Earth-facing) side and far side of the Moon. (NASA)

10-2 Human exploration of the Moon in the 1960s and 1970s has been continued by robotic spacecraft

WEB LINK 10.5

For thousands of years, storytellers have invented fabulous tales of voyages to the Moon. The seventeenth-century French satirist Cyrano de Bergerac wrote of a spacecraft whose motive power was provided by spheres of morning dew. (After all, reasoned Cyrano, dew rises with the morning sun, so a spacecraft would rise along with it.) In his imaginative tale *Somnium,* Cyrano's contemporary Johannes Kepler (the same Kepler who deduced the laws of planetary motion) used the astronomical knowledge of his time to envision what it would be like to walk on the Moon's surface. In 1865 the French author Jules Verne published *From the Earth to the Moon,* a story of a spacecraft sent to the Moon from a launching site in Florida.

Almost exactly a hundred years later, Florida was indeed the starting point of the first voyages made by humans to other worlds. Between 1969 and 1972, 12 astronauts walked on the Moon, and fantasy became magnificent reality.

The Moon is the only world other than Earth to be visited by humans

The First Spacecraft to the Moon

As in Verne's story, politics had much to do with the motivation for going to the Moon. But in fact, there were excellent scientific reasons to do so. Because the Earth is a geologically active planet, typical terrestrial surface rocks are only a few hundred million years old, which is only a small fraction of the Earth's age. Thus, all traces of the Earth's origins have been erased. By contrast, rocks on the geologically inactive surface of the Moon have been essentially undisturbed for billions of years. Samples of lunar rocks have helped answer many questions about the Moon and have shed light on the origin of the Earth and the birth of the entire solar system.

WEB LINK 10.6 VIDEO 10.2

Lunar missions began in 1959, when the Soviet Union sent three small spacecraft—*Lunas 1, 2,* and *3*—toward the Moon. American attempts to reach the Moon began in the early 1960s with Project Ranger. Equipped with six television cameras, the *Ranger* spacecraft transmitted close-up views of the lunar surface taken in the final few minutes before they crashed onto the Moon. These images showed far more detail than even the best Earth-based telescope.

In 1966 and 1967, five *Lunar Orbiter* spacecraft were placed in orbit around the Moon and made a high-resolution photographic survey of 99.5% of the lunar surface. Some of these photographs show features as small as 1 meter across and were essential in helping NASA scientists choose suitable landing sites for the astronauts.

Even after the *Ranger* missions, it was unclear whether the lunar surface was a safe place to land. One leading theory was that billions of years of impacts by meteoroids had ground the Moon's surface to a fine powder, much like that used by dental hygienists to polish teeth. Perhaps a spacecraft attempting to land would simply sink into a quicksandlike sea of dust! Thus, before a manned landing on the Moon could be attempted, it was necessary to try a soft landing of an unmanned spacecraft. This was the purpose of the *Surveyor* program. Between June 1966 and January 1968, five *Surveyors* successfully touched down on the Moon, sending back pictures and data directly from the lunar surface. These missions demonstrated convincingly that the Moon's surface was as solid as that of the Earth. Figure 10-8 shows an astronaut visiting *Surveyor 3,* two and a half years after it had landed on the Moon.

The *Apollo* and *Luna* Missions

WEB LINK 10.7

The first of six manned lunar landings took place on July 20, 1969, when the *Apollo 11* lunar module *Eagle* set down in Mare Tranquillitatis (see Figure 10-6). Astronauts Neil Armstrong and Edwin "Buzz" Aldrin were the first humans to set foot on the Moon. *Apollo 12* also landed in a mare, Oceanus Procellarum (Ocean of Storms). The *Apollo 13* mission experienced a nearly catastrophic inflight explosion that made it impossible for it to land on the Moon. Fortunately, titanic efforts by the astronauts and ground personnel brought it safely home. The remaining four missions, *Apollo 14* through *Apollo 17,* were made in progressively more challenging terrain, chosen to permit the exploration of a wide variety of geologically interesting features. The first era of human exploration of the Moon culminated in December 1972, when *Apollo 17* landed in

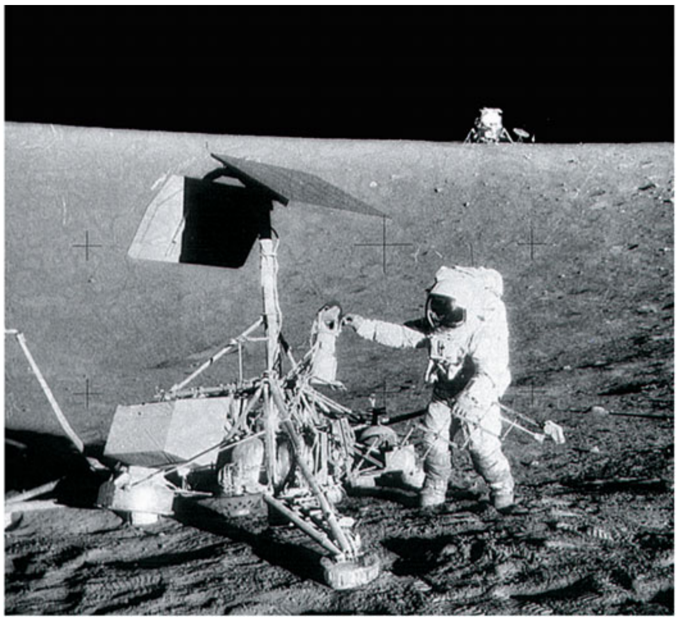


Figure 10-8 R I V U X G

Visiting an Unmanned Pioneer *Surveyor 3* landed on the Moon in April 1967. It was visited in November 1969 by *Apollo 12* astronaut Alan Bean, who took pieces of the spacecraft back to the Earth for analysis. (The *Apollo 12* lunar module is visible in the distance.) The retrieved pieces showed evidence of damage by micrometeoroid impacts, demonstrating that small bits of space debris are still colliding with the Moon. (Pete Conrad, *Apollo 12,* NASA) a rugged region of the lunar highlands. Figure 10-9 shows one of the *Apollo* bases.

In a curious postscript to the *Apollo* missions, in the 1990s an "urban legend" arose that the Moon landings had never taken place and were merely an elaborate hoax by NASA. While amusing, this legend does not hold up under even the slightest scientific scrutiny. For example, believers in the "Moon hoax" cannot explain why the rocks brought back from the Moon are substantially different in their chemistry from Earth rocks, as we will see later in this chapter. It makes as much sense to ask "Do you believe that humans actually went to the Moon?" as it does to ask "Do you believe there was a First World War?" or "Do you believe there is such a place as Antarctica?"

Between 1966 and 1976, a series of unmanned Soviet spacecraft also orbited the Moon and soft-landed on its surface. The first soft landing, by *Luna 9,* came four months before the U.S. *Surveyor 1* arrived. The first lunar satellite, *Luna 10,* orbited the Moon four months before *Lunar Orbiter 1*. In the 1970s, robotic spacecraft named *Luna 17* and *Luna 21* landed vehicles that roamed the lunar surface, and *Lunas 16, 20,* and *24* brought samples of rock back to the Earth. The *Luna* samples complement those returned by the *Apollo* astronauts because they were taken from different parts of the Moon's surface.

Recent Lunar Exploration

Unmanned spacecraft continued the exploration of the Moon in the 1990s and 2000s. In 1994 a small spacecraft named *Clementine* spent more than two months observing the Moon from lunar orbit. Although originally intended to test lightweight imaging systems for future defense satellites, *Clementine* proved to be a remarkable tool for lunar exploration. It carried an array of very high-resolution cameras sensitive to ultraviolet and infrared light as well as the visible spectrum (see Figure 10-7). Different types of materials on the lunar surface reflect different wavelengths, so analysis of *Clementine* images made in different parts of the electromagnetic spectrum has revealed the composition of large areas of the Moon's surface (Figure 10-10). The task of analyzing the Moon's surface composition was carried out in even greater depth by the European Space Agency's *SMART-1* spacecraft, which orbited the Moon from 2004 to 2006 and carried even more sensitive instruments than *Clementine*.

One remarkable result of the *Clementine* mission was evidence for a patch of water ice tens or hundreds of kilometers across at the Moon's south pole, in low-lying locations where sunlight never reaches and where temperatures are low enough to prevent ice from evaporating. Radio waves beamed from *Clementine* toward these areas were detected by radio telescopes on the Earth and showed the characteristic signature of reflection from ice.

Data from the *Lunar Prospector* spacecraft, which went into orbit around the Moon in January 1998, reinforced the *Clementine* findings and indicated that even more ice might lie in deep craters at the Moon's north pole. The ice may have been deposited by comets (see Section 7-5) that crashed into the lunar surface.

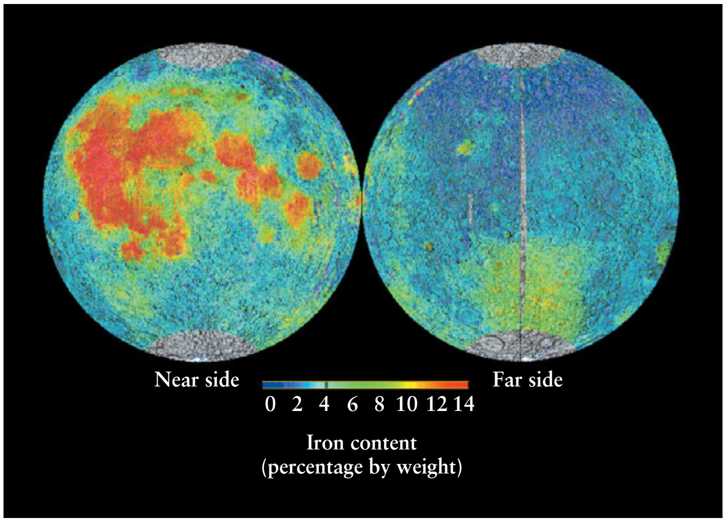


Figure 10-10

Iron on the Moon Images at different wavelengths from the *Clementine* spacecraft were used to make this map of the concentration of iron on the lunar surface. The areas of highest concentration (red) coincide closely with the maria on the near side (compare Figure 10-7), confirming that the maria formed from iron-rich lavas. The lowest iron concentration (blue) is found in the lunar highlands. (No data were collected in the gray areas.) The large green region of intermediate iron concentration on the far side is the South Pole–Aitken Basin (see Figure 10-7). The impact that created this basin may have excavated all the way to the Moon's mantle, in which iron is more abundant than in the crust. (JSC/NASA)

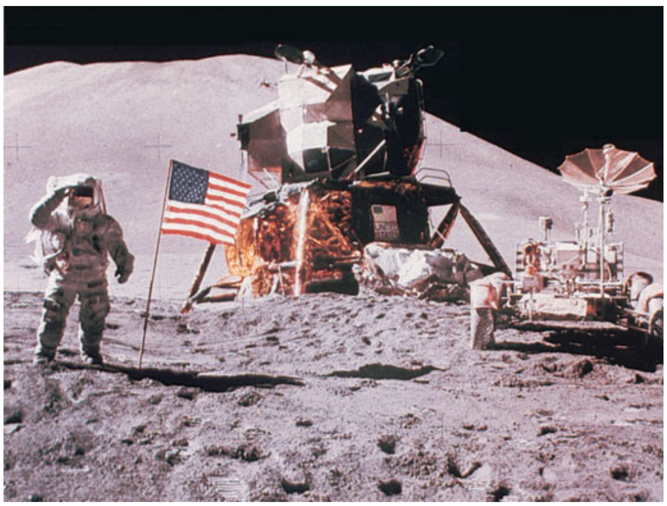


Figure 10-9 R I V U X G

The *Apollo 15* Base This photograph shows astronaut James Irwin and the *Apollo 15* landing site at the foot of the Apennine Mountains near the eastern edge of Mare Imbrium. The hill in the background is about 5 km away and rises about 3 km high. At the right is a Lunar Rover, an electric-powered vehicle used by astronauts to explore a greater radius around the landing site. The last three *Apollo* missions carried Lunar Rovers. (Dave Scott, *Apollo 15,* NASA)

One complication is that the *Lunar Prospector* observations show only that there is an excess of hydrogen atoms at the lunar poles. These could be trapped within water molecules (H_2O) or within other, more exotic minerals. At the end of the *Lunar Prospector* mission in July 1999, the spacecraft was crashed into a crater at the lunar south pole in the hope that a plume of water vapor might rise from the impact site. Although more than a dozen large Earth-based telescopes watched the Moon during the impact, no such plume was observed, nor was any debris of any kind. Radar observations made from Earth in 2003 suggest that if there is ice at the lunar poles, it is in sheets no more than a few centimeters thick. A new generation of European, Japanese, Indian, Chinese, and U.S. unmanned spacecraft may help provide a definitive answer about ice at the Moon's poles.

10-3 The Moon has no global magnetic field but has a small core beneath a thick mantle

We saw in Section 7-6 and Section 7-7 that a small planet or satellite will have little internal heat, and hence is likely to have a mostly solid interior. Lacking substantial amounts of moving molten material in its interior, a small world is unlikely to generate a global magnetic field. As we will see, these general rules describe the Moon very well.

Compared to earthquakes, moonquakes are few and feeble—but they reveal key aspects of the Moon's interior

The Moon's Interior: The Core

The Moon landings gave scientists an unprecedented opportunity to explore an alien world. The *Apollo* spacecraft were therefore packed with an assortment of apparatus that the astronauts deployed around the landing sites (see Figure 10-9). For example, all the missions carried magnetometers, which confirmed that the present-day Moon has no global magnetic field. However, careful magnetic measurements of lunar rocks returned by the *Apollo* astronauts indicated that the Moon did have a weak magnetic field when the rocks solidified billions of years ago. Hence, the Moon must originally have had a small, molten, iron-rich core. (We saw in Section 7-7 that the Earth's magnetic field is generated by fluid motions in its interior.) The core presumably solidified at least partially as the Moon cooled, so that the lunar magnetic field disappeared.

WEB LINK 10.11

More recently, scientists used the *Lunar Prospector* to probe the character of the Moon's core. The spacecraft made extensive measurements of lunar gravity and of how the Moon responds when it passes through the Earth's magnetosphere (Section 9-4). When combined with detailed observations of how the Earth's tidal forces affect the motions of the Moon, the data indicate that the present-day Moon has a partially liquid, iron-rich core about 700 km (435 mi) in diameter. While 32% of the Earth's mass is in its core, the core of the Moon contains only 2% to 3% of the lunar mass.

The Moon's Interior: The Mantle

The *Apollo* astronauts also set up seismometers on the Moon's surface, which made it possible for scientists to investigate the Moon's interior using seismic waves just as is done for the Earth (Section 9-2). It was found that the Moon exhibits far less seismic activity than the Earth. Roughly 3000 **moonquakes** were detected per year, whereas a similar seismometer on the Earth would record hundreds of thousands of earthquakes per year. Furthermore, typical moonquakes are very weak. A major terrestrial earthquake is in the range from 6 to 8 on the Richter scale, while a major moonquake measures 0.5 to 1.5 on that scale and would go unnoticed by a person standing near the epicenter.

Analysis of the feeble moonquakes reveals that most originate 600 to 800 km below the surface, deeper than most earthquakes. On Earth, the deepest earthquakes mark the boundary between the solid lithosphere and the plastic asthenosphere. This is because the lithosphere is brittle enough to fracture and produce seismic waves, whereas the deeper rock of the asthenosphere oozes and flows rather than cracks. We may conclude that the Moon's lithosphere is about 800 km thick (Figure 10-11). By contrast, the Earth's lithosphere is only 50 to 100 km thick.

The lunar asthenosphere extends down to the Moon's relatively small iron-rich core, which is more than 1400 km below the lunar surface. The asthenosphere and the lower part of the lithosphere are presumably composed of relatively dense iron-rich rocks. The uppermost part of the lithosphere is a lower-density crust, with an average thickness of about 60 km on the Earth-facing side and up to 100 km on the far side. For comparison, the thickness of the Earth's crust ranges from 5 km under the oceans to about 30 km under major mountain ranges on the con-

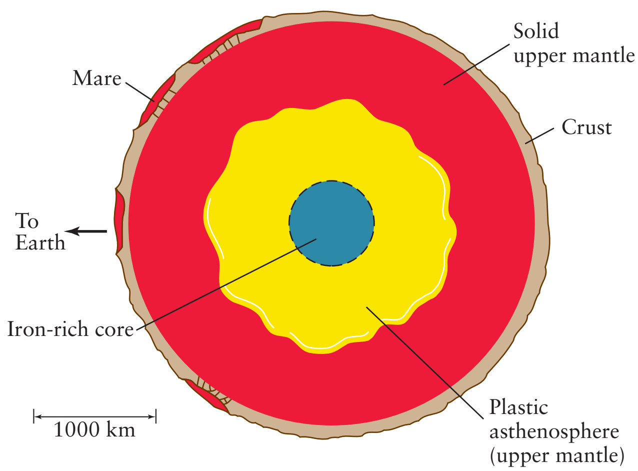


Figure 10-11

The Internal Structure of the Moon Like the Earth, the Moon has a crust, a mantle, and a core. The lunar crust has an average thickness of about 60 km on the Earth-facing side but about 100 km on the far side. The crust and solid upper mantle form a lithosphere about 800 km thick. The plastic (nonrigid) asthenosphere extends all the way to the base of the mantle. The iron-rich core is roughly 700 km in diameter. (Compare Figure 9-9.)

tinents (see Table 9-3). This slightly lopsided distribution of mass between the near and far sides of the Moon helps to keep the Moon in synchronous rotation, so that we always see the same side of the Moon (see Section 4-8).

On the whole, the Moon's interior is much more rigid and less fluid than the interior of the Earth. Plate tectonics requires that there be fluid motion just below a planet's surface, so it is not surprising that there is no evidence for plate tectonics on the lunar surface.

The Origin of Moonquakes

Earthquakes tend to occur at the boundaries between tectonic plates, where plates move past each other, collide, or undergo subduction (see Figure 9-14). But there are no plate motions on the Moon. What, then, causes moonquakes? The answer turns out to be the Earth's tidal forces. Just as the tidal forces of the Sun and Moon deform the Earth's oceans and give rise to ocean tides (see Figure 4-26), the Earth's tidal forces deform the solid body of the Moon. The amount of the deformation changes as the Moon moves around its elliptical orbit and the Earth-Moon distance varies. As a result, the body of the Moon flexes slightly, triggering moonquakes. The tidal stresses are greatest when the Moon is nearest the Earth—that is, at perigee (see Section 3-5)—which is just when the *Apollo* seismometers reported the most moonquakes. **Box 10-1** has more information about how the tidal stresses on the Moon depend on its distance from Earth.

Without tectonics, and without the erosion caused by an atmosphere or oceans, the only changes occurring today on the lunar surface are those due to meteoroid impacts. These impacts were also monitored by the seismometers left on the Moon by the *Apollo* astronauts. These devices, which remained in operation for several years, were sensitive enough to detect a hit by a grapefruit-sized meteoroid anywhere on the lunar surface. The data show that every year the Moon is struck by 80 to 150 meteoroids having masses between 0.1 and 1000 kg (roughly $\frac{1}{4}$ lb to 1 ton).

10-4 Lunar rocks reveal a geologic history quite unlike that of Earth

WEB LINK 10.12

One of the most important scientific goals of the *Apollo* missions was to learn as much as possible about the lunar surface. Although only one of the 12 astronauts who visited the Moon was a professional geologist, all of the astronauts received intensive training in field geology, and they were in constant communication with planetary scientists on Earth as they explored the lunar surface.

Weathering by Meteoroids

Although no wind or rain disturbs the lunar surface, it is "gardened" over the ages by the impact of tiny meteoroids

The Moon has no atmosphere or oceans to cause "weathering" of the surface. But the *Apollo* astronauts found that the lunar surface has undergone a kind of erosion due to billions of years of relentless meteoritic bombardment. This bombardment has pulverized the surface rocks into a layer of fine powder and rock fragments called the **regolith**, from the Greek for "blanket of stone" (**Figure 10-12**). This layer varies in depth from about 2 to 20 m. Just as the rough-surfaced acoustic tile used in ceilings absorbs sound waves, the regolith absorbs most of the sunlight that falls on it. This helps to account for the Moon's very low albedo (see Table 10-1).

Moon Rocks

In addition to their observations of six different landing sites, the *Apollo* astronauts brought back 2415 individual samples of lunar material totaling 382 kg (842 lb). In addition, the unmanned Soviet spacecraft *Luna 16, 20,* and *24* returned 300 g ($\frac{2}{3}$ lb) from three other sites on the Moon. This collection of lunar material has provided important information about the early history of the Moon that could have been obtained in no other way.

All of the lunar samples are igneous rocks; there are no metamorphic or sedimentary rocks (see Section 9-3, especially Figure 9-19). This suggests that most or all of the Moon's surface was once molten. Indeed, Moon rocks are composed mostly of the same minerals that are found in volcanic rocks on Earth.

Astronauts who visited the maria discovered that these dark regions of the Moon are covered with basaltic rock quite similar to the dark-colored rocks formed by lava from volcanoes on

Figure 10-12 R I V U X G

The Regolith Billions of years of bombardment by space debris have pulverized the uppermost layer of the Moon's surface into powdered rock. This layer, called the regolith, is utterly bone-dry. It nonetheless sticks together like wet sand, as shown by the sharp outline of an astronaut's bootprint. (*Apollo 11,* NASA)

BOX 10-1 Tools of the Astronomer's Trade

Calculating Tidal Forces

The gravitational force between any two objects decreases with increasing distance between the objects. This principle leads to a simple formula for estimating the tidal force that the Earth exerts on parts of the Moon.

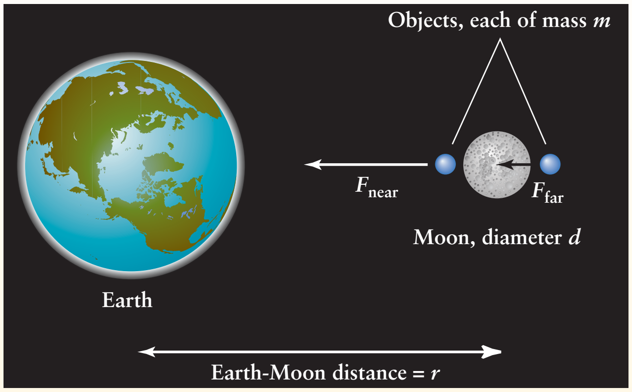
Consider two small objects, each of mass *m*, on opposite sides of the Moon. Because the two objects are at different distances from the Earth's center, the Earth exerts different forces F_{near} and F_{far} on them (see the accompanying illustration). The consequence of this difference is that the two objects tend to pull away from each other and away from the center of the Moon (see Section 4-8, especially Figure 4-23). The *tidal force* on these two objects, which is the force that tends to pull them apart, is the difference between the forces on the individual objects:

$$F_{tidal} = F_{near} - F_{far}$$

Both F_{near} and F_{far} are inversely proportional to the square of the distance from the Earth (see Section 4-7). If this distance were doubled, both forces would decrease to $(1/2)^2 = 1/4$ of their original values. But the tidal force F_{tidal}, which is the *difference* between these two forces, decreases even more rapidly with distance: It is inversely proportional to the *cube* of the distance from the Earth to the Moon. That is, doubling the Earth-Moon distance decreases the tidal force to $(1/2)^3 = 1/8$ of its original value. If we use the symbols M_{Earth} for the Earth's mass (5.974×10^{24} kg), *d* for the Moon's diameter, *r* for the center-to-center distance from the Earth to the Moon, and *G* for the universal constant of gravitation (6.67×10^{-11} newton m^2/kg^2), the tidal force is given approximately by the formula

$$F_{tidal} = \frac{2GM_{Earth}md}{r^3}$$

EXAMPLE: Calculate the tidal force for two 1-kg lunar rocks at the locations shown in the figure.



Situation: We are asked to calculate a tidal force. We know the masses of the Earth (M_{Earth}) and of each of the two rocks ($m = 1$ kg). The Earth-Moon distance (*r*) and the diameter of the Moon (*d*, equal to the separation between the two rocks) are given in Table 10-1.

Tools: We use the equation given above for the tidal force F_{tidal}.

Answer: To use the given values in the equation, we must first convert the values for the average Earth-Moon distance *r* and the Moon's diameter *d* from kilometers to meters:

$$d = 3476 \text{ km} \times \frac{10^3 \text{ m}}{1 \text{ km}} = 3.476 \times 10^6 \text{ m}$$

$$r = 384{,}400 \text{ km} \times \frac{10^3 \text{ m}}{1 \text{ km}} = 3.844 \times 10^8 \text{ m}$$

The tidal force is then

$$F_{tidal} = \frac{2(6.67 \times 10^{-11})(5.974 \times 10^{24})(1)(3.476 \times 10^6)}{(3.844 \times 10^8)^3}$$
$$= 4.88 \times 10^{-5} \text{ newton}$$

Hawaii and Iceland. The rock of these low-lying lunar plains is called **mare basalt** (Figure 10-13).

In contrast to the dark maria, the lunar highlands are composed of a light-colored rock called **anorthosite** (Figure 10-14). On the Earth, anorthositic rock is found only in such very old mountain ranges as the Adirondacks in the eastern United States. In comparison to the mare basalts, which have more of the heavier elements like iron, manganese, and titanium, anorthosite is rich in silicon, calcium, and aluminum. Anorthosite is therefore less dense than basalt. During the period when the Moon's surface was molten, the less dense anorthosite rose to the top, forming the terrae that make up the majority of the present-day lunar surface.

Although anorthosite is the dominant rock type in the lunar highlands, most of the rock samples collected there were not pure anorthosite but rather **impact breccias.** These are composites of different rock types that were broken apart, mixed, and fused together by a series of meteoritic impacts (Figure 10-15). The

Review: To put our result into perspective, let's compare it to the *weight* of a 1-kg rock on the Moon. The weight of an object is equal to its mass multiplied by the acceleration due to gravity (see Section 4-6). This acceleration is equal to 9.8 m/s^2 on Earth, but is only 0.17 as great on the Moon. So, the weight of a 1-kg rock on the Moon is

$$0.17 \times 1 \text{ kg} \times 9.8 \text{ m/s}^2 = 1.7 \text{ newtons}$$

Thus, the tidal force on lunar rocks is *much* less than their weight. This is a good thing: If the tidal force (which tries to pull a rock away from the Moon's center) were greater than the weight (which pulls it toward the Moon's center), loose objects would levitate off the Moon's surface and fly into space!

The tidal force of the Earth on the Moon deforms the solid body of the Moon, so that it acquires *tidal bulges* on its near and far sides. The mass of each bulge must be proportional to the tidal force that lifts lunar material away from the Moon's center. So, the above formula tells us that the mass of each bulge is inversely proportional to the cube of the Earth-Moon distance *r:*

$$m_{\text{bulge}} = \frac{A}{r^3}$$

(Determining the value of the constant A requires knowing how easily the Moon deforms, which is a complicated problem beyond our scope.) We can then use our formula for the tidal force F_{tidal} to tell us the *net* tidal force on the Moon. To do this, we think of the objects of mass m on opposite sides of the Moon as being the tidal bulges. So, we substitute m_{bulge} for m in the tidal force formula:

$$F_{\text{tidal-net}} = \frac{2GM_{\text{Earth}}m_{\text{bulge}}d}{r^3} = \frac{2GM_{\text{Earth}}}{r^3}\frac{A}{r^3}d$$
$$= \frac{2GM_{\text{Earth}}Ad}{r^6}$$

Thus, the net tidal force on the Moon is inversely proportional to the *sixth* power of the Earth-Moon distance. Even a small decrease in this distance can cause a substantial increase in the net tidal force.

EXAMPLE: Compare the net tidal force on the Moon at perigee (when it is closest to the Earth) and at apogee (when it is farthest away).

Situation: We are asked to *compare* the tidal forces on the Moon at two different distances from the Earth. To do this, we will find the *ratio* of the tidal force at perigee to the tidal force at apogee.

Tools: We use the equation given above for the net tidal force on the Moon.

Answer: The Earth-Moon distances at perigee and apogee are given in Table 10-1. If we take the ratio of the tidal forces at these two distances, the constants (including the unknown quantity A) cancel out:

$$\frac{F_{\text{tidal-net-perigee}}}{F_{\text{tidal-net-apogee}}} = \frac{2GM_{\text{Earth}}Ad/r^6{}_{\text{perigee}}}{2GM_{\text{Earth}}Ad/r^6{}_{\text{apogee}}} = \left(\frac{r_{\text{apogee}}}{r_{\text{perigee}}}\right)^6$$
$$= \left(\frac{405{,}500 \text{ km}}{363{,}000 \text{ km}}\right)^6 = (1.116)^6 = 1.93$$

Review: Our result tells us that the net tidal force at perigee is 1.93 times as great (that is, almost double) as at apogee. Tidal forces on the Moon help create the stresses that generate moonquakes, so it is not surprising that these quakes are more frequent at perigee than at apogee.

prevalence of breccias is evidence that the lunar highlands have undergone eons of bombardment from space.

Every rock found on Earth, even those from the driest desert, has some water locked into its mineral structure. But lunar rocks are totally dry. With the exception of ice at the lunar poles (see Section 10-2), there is no evidence that water has ever existed on the Moon. Because the Moon lacks both an atmosphere and liquid water, it is not surprising that no traces of life have ever been found there.

By carefully measuring the abundances of trace amounts of radioactive elements in lunar samples and applying the principles of radioactive dating (see Section 8-2), geologists have determined that lunar rocks formed more than 3 billion years ago. Of these ancient rocks, however, anorthosite is much older than the mare basalts. Typical anorthositic specimens from the highlands are between 4.0 and 4.3 billion years old. All these extremely ancient specimens are probably samples of the Moon's original crust. In sharp contrast, all the mare basalts are between 3.1 and 3.8 bil-

Figure 10-13 R I V U X G

Mare Basalt This 1.53-kg (3.38-lb) specimen of mare basalt was brought back by the crew of *Apollo 15*. Gas must have dissolved under pressure in the lava from which this rock solidified. When the lava reached the airless lunar surface, the pressure on the lava dropped and the gas formed bubbles. Some of the bubbles were frozen in place as the rock cooled, forming the holes on its surface. (Figure 9-19*a* shows a sample of basalt from Earth.) (NASA)

lion years old. With no plate tectonics to bring fresh material to the surface, no new anorthosites or basalts have formed on the Moon for more than 3 billion years.

The History of Lunar Cratering

By correlating the ages of Moon rocks with the density of craters at the sites where the rocks were collected, geologists have found that the rate of impacts on the Moon has changed over the ages. The ancient, heavily cratered lunar highlands are evidence of an intense bombardment that dominated the Moon's early history. For nearly a billion years, rocky debris left over from the formation of the planets rained down upon the Moon's young surface. As Figure 10-16 shows, this barrage extended from 4.56 billion years ago, when the Moon's surface solidified, until about 3.8 billion years ago. At its peak, this bombardment from space would have produced a new crater of about 1 km radius somewhere on the Moon about once per century. (If this seems like a long time interval, remember that we are talking about a bombardment that lasted hundreds of millions of years and produced millions of craters over that time.)

The rate of impacts should have tapered off as meteoroids and planetesimals were swept up by the newly formed planets. In fact, radioactive dating shows that the impact rate spiked upward between 4.0 and 3.8 billion years ago (see Figure 10-16). One proposed explanation is that the orbits of Jupiter and Saturn changed slightly but suddenly about 4.0 billion years ago during the process of settling into their present-day orbits. This would have changed the gravitational forces that these planets exerted on the asteroid belt and could have disturbed the orbits of many asteroids, sending them careening toward the inner solar system.

Whatever the explanation for the final epoch of heavy bombardment, major impacts during this period gouged out the mare basins. Between 3.8 and 3.1 billion years ago iron-rich magma oozed up from the Moon's still-molten mantle, flooding the mare basins with lava that solidified to form basalt (see the *Cosmic Connections* figure).

The relative absence of craters in the maria (see Figure 10-5) tells us that the impact rate has been quite low since the lava solidified. During these past 3.1 billion years the Moon's surface has changed very little.

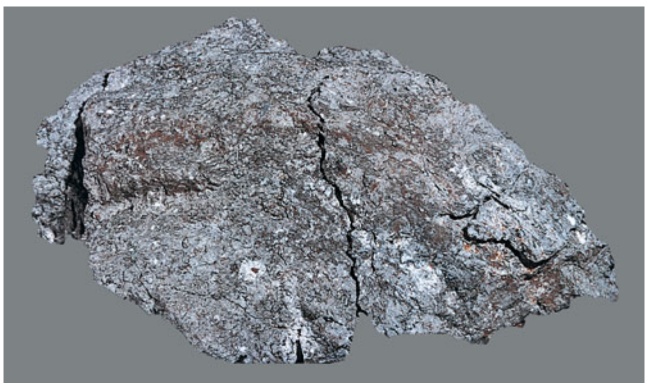


Figure 10-14 R I V U X G

Anorthosite The light-colored lunar terrae (highlands) are composed of this ancient type of rock, which is thought to be the material of the original lunar crust. Lunar anorthosites vary in color from dark gray to white; this sample from the *Apollo 16* mission is a medium gray. It measures 18 × 16 × 7 cm. (NASA)

Figure 10-15 R I V U X G

Impact Breccias These rocks are evidence of the Moon's long history of bombardment from space. Parts of the Moon's original crust were shattered and strewn across the surface by meteoritic impacts. Later impacts compressed and heated this debris, welding it into the type of rock shown here. Such impact breccias are rare on Earth but abundant on the Moon. (NASA)

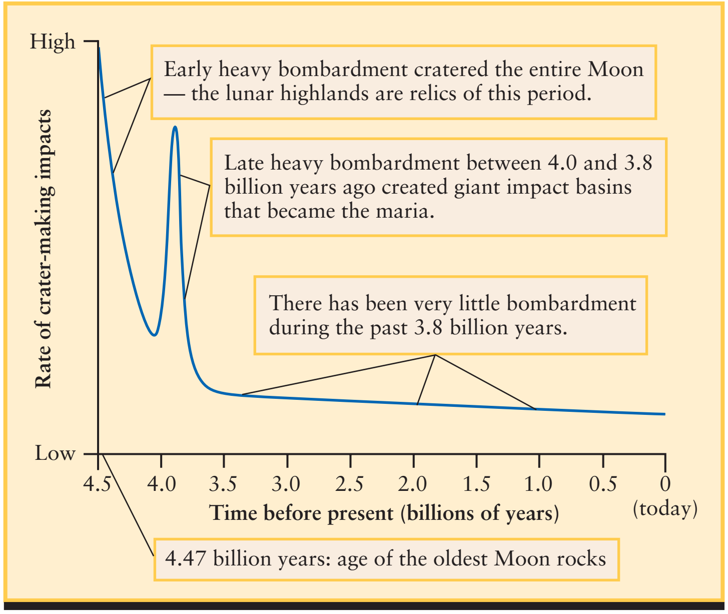


Figure 10-16 INTERACTIVE EXERCISE 10.1

The Rate of Crater Formation on the Moon This graph shows the rate at which impact craters formed over the Moon's history. The impact rate today is only about 1/10,000 as great as during the most intense bombardment. (Adapted from T. Grotzinger, T. H. Jordan, F. Press, and R. Siever, *Understanding Earth*, 5th ed., W. H. Freeman, 2007)

10-5 The Moon probably formed from debris cast into space when a huge protoplanet struck the young Earth

The lunar rocks collected by the *Apollo* and *Luna* missions have provided essential information about the history of the Moon. In particular, they have helped astronomers come to a consensus about one of the most important questions in lunar science: Where did the Moon come from?

The Receding Moon

Seventy years before the first spacecraft landed on the Moon, the British astronomer George Darwin (second son of the famous evolutionist Charles Darwin) deduced that the Moon must be slowly moving away from the Earth. He began with the notion that the Moon's tidal forces elongate the oceans into a football shape (see Section 4-8, especially Figure 4-26). However, the long axis of this "football" does not point precisely at the Moon. The Earth spins on its axis more rapidly than the Moon revolves around the Earth, and this rapid rotation carries the tidal bulge about 10° ahead of a line connecting the Earth and Moon (Figure 10-17). This misaligned bulge produces a small but steady gravitational force that tugs the Moon forward and lifts it into an ever larger orbit around the Earth. In other words, Darwin concluded that the Moon must be spiraling away from the Earth.

It became possible to test Darwin's conclusions with the aid of a simple device that the *Apollo 11*, *14*, and *15* and *Luna 21* missions left on the Moon—a set of reflectors, similar to the orange and red ones found in automobile taillights. Since 1969, scientists on Earth have been firing pulses of laser light at these reflectors and measuring very accurately the length of time it takes each pulse to return to Earth. Knowing the speed of light, they can use this data to calculate the distance to the Moon to an accuracy of just 3 centimeters. They have found that the Moon is moving away from the Earth at a very gradual rate of 3.8 cm per year—which is just what Darwin predicted.

As the Moon moves away from the Earth, its sidereal period is getting longer in accordance with Kepler's third law (see Section 4-7). At the same time, friction between the oceans and the body of the Earth is gradually slowing the Earth's rotation. The length of the Earth's day is therefore increasing, by approximately 0.002 second per century.

Theories of the Moon's Origins

These observations mean that in the distant past, the Earth was spinning faster than it is now and the Moon was much closer. Darwin theorized that the early Earth may have been spinning so fast that a large fraction of its mass tore away, and that this fraction coalesced to form the Moon. This is called the **fission theory** of the Moon's origin. Prior to the *Apollo* program, two other theories were in competition with the fission theory. The **capture theory** posits that the Moon was formed elsewhere in the solar system and then drawn into orbit about the Earth by gravitational forces. By contrast, the **co-creation theory** proposes that the Earth and the Moon were formed at the same time but separately.

One fact used to support the fission theory was that the Moon's average density (3344 kg/m^3) is comparable to that of the Earth's outer layers, as would be expected if the Moon had been

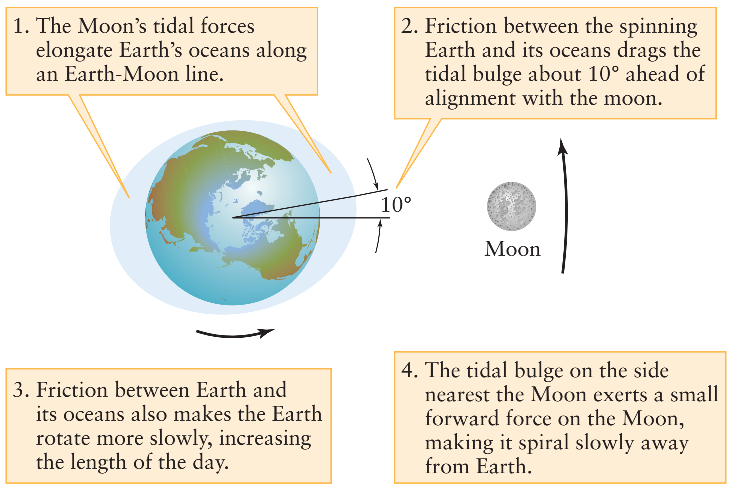


Figure 10-17 INTERACTIVE EXERCISE 10.2

The Moon's Tidal Recession The Earth's rapid rotation drags the tidal bulge of the oceans about 10° ahead of a direct alignment with the Moon. The bulge on the side nearest the Moon exerts more gravitational force than the other, more distant bulge. The net effect is a small forward force on the Moon that makes it spiral slowly away from the Earth.

flung out of a rapidly rotating proto-Earth. However, the fission theory predicts that lunar and terrestrial rocks should be similar in composition. In fact, samples returned from the Moon by the *Apollo* and *Luna* missions show that they are significantly different.

Volatile elements (such as potassium and sodium) boil at relatively low temperatures under 900°C, whereas **refractory elements** (such as titanium, calcium, and aluminum) boil at 1400°C or higher. Compared with terrestrial rocks, the lunar rocks have slightly greater proportions of the refractory elements and slightly lesser proportions of the volatile elements. This suggests that the Moon formed from material that was heated to a higher temperature than that from which the Earth formed. Some of the volatile elements boiled away, leaving the young moon relatively enriched in the refractory elements.

LOOKING DEEPER 10.2

Proponents of the capture theory used these differences to argue that the Moon formed elsewhere and was later captured by the Earth. They also noted that the plane of the Moon's orbit is close to the plane of the ecliptic, as would be expected if the Moon had originally been in orbit about the Sun but was later captured by the Earth.

There are difficulties with the capture theory, however. If the Earth did capture the Moon intact, then a host of conditions must have been satisfied entirely by chance. The Moon must have coasted to within 50,000 km of the Earth at exactly the right speed to leave a solar orbit and must have gone into orbit around the Earth without actually hitting our planet.

Proponents of the co-creation theory argued that it is easier for a planet to capture swarms of tiny rocks. In this theory the Moon formed from just such rocky debris. Great numbers of rock fragments orbited the newborn Sun in the plane of the ecliptic along with the protoplanets. Heat generated in collisions could have baked the volatile elements out of these smaller rock fragments. Then, just as planetesimals accreted to form the proto-Earth in orbit about the Sun, the fragments in orbit about the Earth accreted to form the Moon.

The Collisional Ejection Theory

The present scientific consensus is that *none* of these three theories—fission, capture, and co-creation—is correct. Instead, the evidence points toward an idea proposed in 1975 by William Hartmann and Donald Davis and independently by Alastair Cameron and William Ward. In this **collisional ejection theory,** the proto-Earth was struck off-center by a Mars-sized object, and this collision ejected debris from which the Moon formed.

The collisional ejection theory agrees with what we know about the early history of the solar system. We saw in Section 8-4 that smaller objects collided and fused together to form the inner planets. Some of these collisions must have been quite spectacular, especially near the end of planet formation, when most of the mass of the inner solar system was contained in a few dozen large protoplanets. The collisional ejection theory proposes that one such protoplanet struck the proto-Earth about 4.51 billion years ago, about halfway between the age of the solar system (4.56 billion years) and the age of the oldest known Moon rocks (4.47 billion years). Figure 10-18 shows the results of a supercomputer simulation of this cataclysm. In the simulation, energy released during the collision produces a huge plume of vaporized rock that squirts out from the point of impact. As this ejected material cools, it coalesces to form the Moon. The tidal effects depicted in Figure 10-17 then cause the size of the Moon's orbit to gradually increase.

The difference in chemical composition between lunar rocks and Earth rocks helps to constrain theories of the Moon's origin

The collisional ejection theory also agrees with many properties of lunar rocks and of the Moon as a whole. For example, rock vaporized by the impact would have been depleted of volatile elements and water, leaving the moon rocks we now know. If the off-center collision took place after chemical differentiation had occurred on the Earth, so that our planet's iron had sunk to its center, then relatively little iron would have been ejected to become part of the Moon. This explains the Moon's low density and the small size of its iron core. It also explains a curious property of the South Pole–Aitken Basin (see Figure 10-7), where an ancient impact excavated the surface down to a depth of 12 km. Data from the *Clementine* spacecraft show that iron concentration in this basin is only 10% (see Figure 10-10), far less than the 20–30% concentration at a corresponding depth below the Earth's surface.

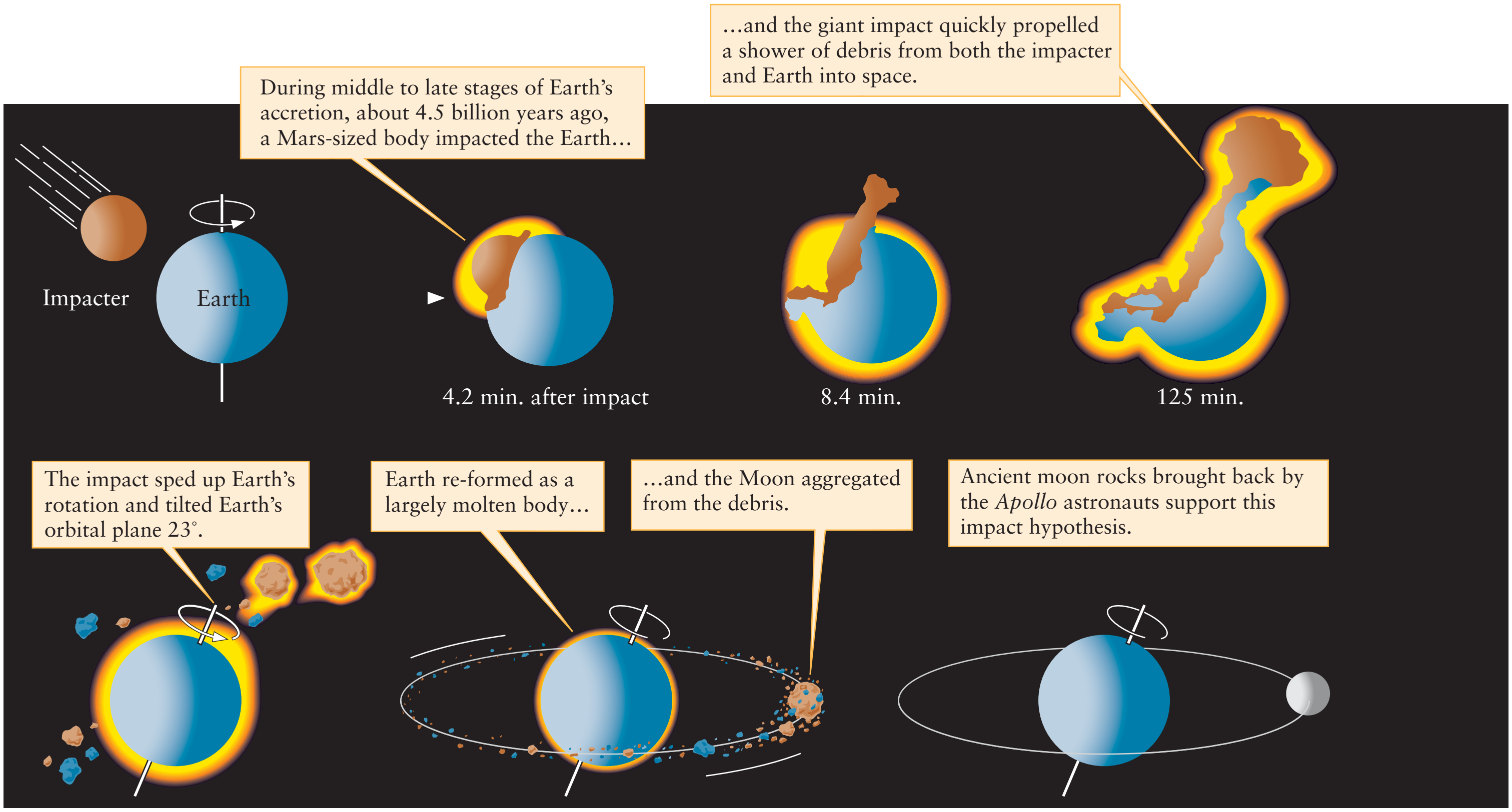
An Overview of the Moon's History

We can now summarize the entire geologic history of the Moon. The surface of the newborn Moon was probably molten for many years, both from heat released during the impact of rock fragments falling into the young satellite and from the decay of short-lived radioactive isotopes. As the Moon gradually cooled, low-density lava floating on the Moon's surface began to solidify into the anorthositic crust that exists today. The barrage of rock fragments that ended about 3.8 billion years ago produced the craters that cover the lunar highlands.

During the relatively brief period of heavy bombardment between 4.0 and 3.8 billion years ago (see Figure 10-16), more than a dozen asteroid-size objects, each measuring at least 100 km across, struck the Moon and blasted out the vast mare basins. Meanwhile, heat from the decay of long-lived radioactive elements like uranium and thorium began to melt the inside of the Moon. From 3.8 to 3.1 billion years ago, great floods of molten rock gushed up from the lunar interior, filling the impact basins and creating the basaltic maria we see today.

Very little has happened on the Moon since those ancient times. A few relatively fresh craters have been formed, but the astronauts visited a world that has remained largely unchanged for more than 3 billion years. During that same period on the Earth, by contrast, the continents have been totally transformed time and time again (see Section 9-3).

Many questions and mysteries still remain. The six American and three Soviet lunar landings have brought back samples from only nine locations, barely scratching the lunar surface. We still know very little about the Moon's far side and poles. Are there really vast ice deposits at the poles? How much of the Moon's interior is molten? Just how large is its iron core? How old are the youngest lunar rocks? Did lava flows occur over western Oceanus Procellarum only 2 billion years ago, as crater densities there sug-



ANIMATION 10.2

Figure 10-18

The Formation of the Moon This figure shows how the Moon could have formed in the aftermath of a collision between a Mars-sized protoplanet and the proto-Earth. (Adapted from T. Grotzinger, T. H. Jordan, F. Press, and R. Siever, *Understanding Earth,* 5th ed., W. H. Freeman, 2007)

gest? Could there still be active volcanoes on the Moon? There is still much to be learned by exploring the Moon.

Key Words

anorthosite, p. 246
capture theory (of Moon's formation), p. 249
center of mass, p. 235
co-creation theory (of Moon's formation), p. 249
collisional ejection theory (of Moon's formation), p. 250
crater, p. 238
far side (of the Moon), p. 236
fission theory (of Moon's formation), p. 249
impact breccia, p. 246
impact crater, p. 238
libration, p. 236
lunar highlands, p. 239
mare (*plural* maria), p. 238
mare basalt, p. 246
moonquake, p. 244
refractory element, p. 250
regolith, p. 245
synchronous rotation, p. 238
terminator, p. 236
terrae, p. 239
volatile element, p. 250

Key Ideas

Appearance of the Moon: The Earth-facing side of the Moon displays light-colored, heavily cratered highlands and dark-colored, smooth-surfaced maria. The Moon's far side has almost no maria.

• Virtually all lunar craters were caused by space debris striking the surface. There is no evidence of plate tectonic activity on the Moon.

Internal Structure of the Moon: Much of our knowledge about the Moon has come from human exploration in the 1960s and early 1970s and from more recent observations by unmanned spacecraft.

• Analysis of seismic waves and other data indicates that the Moon has a crust thicker than that of the Earth (and thickest on the far side of the Moon), a mantle with a thickness equal to about 80% of the Moon's radius, and a small iron core.

• The Moon's lithosphere is far thicker than that of the Earth. The lunar asthenosphere probably extends from the base of the lithosphere to the core.

• The Moon has no global magnetic field today, although it had a weak magnetic field billions of years ago.

Geologic History of the Moon: The anorthositic crust exposed in the highlands was formed between 4.3 and 4.0 billion years ago. An era of heavy bombardment formed the maria basins between 4.0 and 3.8 billion years ago, and the mare basalts solidified between 3.8 and 3.1 billion years ago.

• The Moon's surface has undergone very little change over the past 3 billion years.

• Meteoroid impacts have been the only significant "weathering" agent on the Moon. The Moon's regolith, or surface layer of powdered and fractured rock, was formed by meteoritic action.

• All of the lunar rock samples are igneous rocks formed largely of minerals found in terrestrial rocks. The lunar rocks contain no water and also differ from terrestrial rocks in being relatively enriched in the refractory elements and depleted in the volatile elements.

Origin of the Moon: The collisional ejection theory of the Moon's origin holds that the proto-Earth was struck by a Mars-sized protoplanet and that debris from this collision coalesced to form the Moon. This theory successfully explains most properties of the Moon.

• The Moon was molten in its early stages, and the anorthositic crust solidified from low-density magma that floated to the lunar surface. The mare basins were created later by the impact of planetesimals and filled with lava from the lunar interior.

• Tidal interactions between the Earth and Moon are slowing the Earth's rotation and pushing the Moon away from the Earth.

Questions

Review Questions

1. Is it correct to say that the Moon orbits the Earth? If not, what is a more correct description?
2. If the Moon always keeps the same face toward the Earth, how is it possible for Earth observers to see more than half of the Moon's surface?
3. Why does the sky look black on the Moon even during daytime?
4. Why is it impossible for liquid water to exist on the surface of the Moon?
5. Describe two reasons why astronauts needed to wear spacesuits on the lunar surface.
6. Describe the kinds of features that can be seen on the Moon with a small telescope.
7. Are impact craters on the Moon the same size as the meteoroids that made the impact? Explain your answer.
8. Describe the differences between the maria and the lunar highlands. Which kind of terrain covers more of the Moon's surface? Which kind of terrain is more heavily cratered? Which kind of terrain was formed later in the Moon's history? How do we know?
9. Describe the differences between the near and far sides of the Moon. What is thought to be the likely explanation for these differences?
10. What does it mean to say the Moon is a "one-plate world"? What is the evidence for this statement?
11. Why was it necessary to send unmanned spacecraft to land on the Moon before sending humans there?
12. What is the evidence that ice exists at the lunar poles? Is this evidence definitive?
13. Why was it useful for the *Apollo* astronauts to bring magnetometers and seismometers to the Moon?
14. Could you use a magnetic compass to navigate on the Moon? Why or why not?
15. Describe the evidence that (**a**) the Moon has a more solid interior than the Earth and (**b**) the Moon's interior is not completely solid.
16. Explain why moonquakes occur more frequently when the Moon is at perigee than at other locations along its orbit.
17. Why is the Earth geologically active while the Moon is not?
18. What is the regolith? What causes its powdery character?
19. Why are there no sedimentary rocks on the Moon?
20. On the basis of moon rocks brought back by the astronauts, explain why the maria are dark-colored but the lunar highlands are light-colored.
21. Briefly describe the main differences and similarities between Moon rocks and Earth rocks.
22. Rocks found on the Moon are between 3.1 and 4.47 billion years old. By contrast, the majority of the Earth's surface is made of oceanic crust that is less than 200 million years old, and the very oldest Earth rocks are about 4 billion years old. If the Earth and Moon are essentially the same age, why is there such a disparity in the ages of rocks on the two worlds?
23. If the Earth's tidal bulge pointed directly toward the Moon, would the Moon still be receding from the Earth? Explain.
24. Why do most scientists favor the collisional ejection theory of the Moon's formation?
25. Some people who supported the fission theory proposed that the Pacific Ocean basin is the scar left when the Moon pulled away from the Earth. Explain why this idea is probably wrong.

Advanced Questions

Questions preceded by an asterisk (*) involve topics discussed in Box 10-1.

Problem-solving tips and tools

Recall that the average density of an object is its mass divided by its volume. The volume of a sphere is $4\pi r^3/3$, where r is the sphere's radius. The surface area of a sphere of radius r is $4\pi r^2$, while the surface area of a circle of radius r is πr^2. Recall also that the acceleration of gravity on the Earth's surface is 9.8 m/s^2. You may find it useful to know that a 1-pound (1-lb) weight presses down on the Earth's surface with a force of 4.448 newtons. You might want to review Newton's universal law of gravitation in Section 4-7. The time to travel a certain distance is equal to the distance traveled divided by the speed of motion. Consult Table 10-1 and the Appendices for any additional data.

26. Suppose two worlds (say, a planet and its satellite) have masses m_1 and m_2, and the center-to-center distance between the worlds is r. The distance d_{cm} from the center of world 1 to the center of mass of the system of two worlds is given by the formula

$$d_c = \frac{m_2 r}{m_1 + m_2}$$

(**a**) Suppose world 1 is the Earth and world 2 is the Moon. If the Earth and Moon are at their average center-to-center distance, find the distance from the center of the Earth to the center of mass of the Earth-Moon system. (**b**) Is the Earth-

Moon system's center of mass within the Earth? How far below the Earth's surface is it located? (**c**) Find the distance from the center of the Sun (mass 1.989×10^{30} kg) to the center of mass of the Sun-Earth system. How does this compare to the diameter of the Sun? Is it a good approximation to say that the Earth orbits around the center of the Sun?

27. If you view the Moon through a telescope, you will find that details of its craters and mountains are more visible when the Moon is near first quarter phase or third quarter phase than when it is at full phase. Explain why.

28. In a whimsical moment during the *Apollo 14* mission, astronaut Alan Shepard hit two golf balls over the lunar surface. Give two reasons why they traveled much farther than golf balls do on Earth.

29. Temperature variations between day and night are much more severe on the Moon than on Earth. Explain why.

30. How much would an 80-kg person weigh on the Moon? How much does that person weigh on the Earth?

31. Using the diameter and mass of the Moon given in Table 10-1, verify that the Moon's average density is about 3344 kg/m^3. Explain why this average density implies that the Moon's interior contains much less iron than the interior of the Earth.

***32.** In Box 10-1 we calculated the tidal force that the Earth exerts on two 1-kg rocks located on the near and far sides of the Moon. We assumed that the Earth-Moon distance was equal to its average value. Repeat this calculation (**a**) for the Moon at perigee and (**b**) for the Moon at apogee. (**c**) What is the ratio of the tidal force on the rocks at perigee to the tidal force at apogee?

33. The youngest lunar anorthosites are 4.0 billion years old, and the youngest mare basalts are 3.1 billion years old. Would you expect to find any impact breccias on the Moon that formed less than 3.1 billion years ago? Explain your answer.

34. In the maria, the lunar regolith is about 2 to 8 meters deep. In the lunar highlands, by contrast, it may be more than 15 meters deep. Explain how the different ages of the maria and highlands can account for these differences.

35. The mare basalts are volcanic rock. Is it likely that active volcanoes exist anywhere on the Moon today? Explain.

36. Calculate the round-trip travel time for a pulse of laser light that is fired from a point on the Earth nearest the Moon, hits a reflector at the point on the Moon nearest the Earth, and returns to its point of origin. Assume that the Earth and Moon are at their average separation from each other.

37. Before the *Apollo* missions to the Moon, there were two diametrically opposite schools of thought about the history of lunar geology. The "cold moon" theory held that all lunar surface features were the result of impacts. The most violent impacts melted the surface rock, which then solidified to form the maria. The opposite "hot moon" theory held that all lunar features, including maria, mountains, and craters, were the result of volcanic activity. Explain how lunar rock samples show that neither of these theories is entirely correct.

***38.** When the Moon originally coalesced, it may have been only one-tenth as far from the Earth as it is now. (**a**) When the Moon first coalesced, was the Earth's tidal force strong enough to lift rocks off the lunar surface? Explain. (**b**) Compared with the net tidal force that the Earth exerts on the Moon today, how many times larger was the net tidal force on the newly coalesced Moon? (This strong tidal force kept the one axis of the Moon oriented toward the Earth, and the Moon kept that orientation after it solidified.)

Discussion Questions

39. Comment on the idea that without the presence of the Moon in our sky, astronomy would have developed far more slowly.

40. No *Apollo* mission landed on the far side of the Moon. Why do you suppose this was? What would have been the scientific benefits of a mission to the far side?

41. NASA is planning a new series of manned missions to the Moon. Compare the advantages and disadvantages of exploring the Moon with astronauts as opposed to using mobile, unmanned instrument packages.

42. Describe how you would empirically test the idea that human behavior is related to the phases of the Moon. What problems are inherent in such testing?

43. How would our theories of the Moon's history have been affected if astronauts had discovered sedimentary rock on the Moon?

44. Imagine that you are planning a lunar landing mission. What type of landing site would you select? Where might you land to search for evidence of recent volcanic activity?

Web/eBook Questions

45. In 2005 the *SMART-1* spacecraft detected calcium on the lunar surface. Search the World Wide Web for information about the *SMART-1* mission and this discovery. How was the presence of calcium detected? What does this tell astronomers about the origin of the Moon?

46. **Determining the Size of the Planetesimal That Formed the Moon.** Access the animation "The Formation of the Moon" in Chapter 10 of the *Universe* Web site or eBook. By making measurements on the screen with a ruler, determine how many times larger the proto-Earth is than the impacting planetesimal. If Mars is about 50% the size of Earth, how does the planetesimal compare in size with present-day Mars?

Activities

Observing Projects

WEB LINK 10.13

Observing tips and tools

If you do not have access to a telescope, you can learn a lot by observing the Moon through binoculars. Note that the Moon will appear right-side-up through binoculars but inverted through a telescope; if you are using a map of the Moon to aid your observations, you will need to take this into account. Inexpensive maps of the Moon can be purchased from most good bookstores or educational supply stores. You can determine the phase of the Moon either by looking at a calendar (most of which tell you the dates of new moon, first quarter, full moon, and third quarter), by checking the weather page of your newspaper, by consulting the current issue of *Sky & Telescope* or *Astronomy* magazine, by using the ***Starry Night Enthusiast™*** program, or by using the World Wide Web.

47. Observe the Moon through a telescope every few nights over a period of two weeks between new moon and full moon. Make sketches of various surface features, such as craters, mountain ranges, and maria. How does the appearance of these features change with the Moon's phase? Which features are most easily seen at a low angle of illumination? Which features show up best with the Sun nearly overhead?

48. Use the *Starry Night Enthusiast*™ program to observe the changing appearance of the Moon. Display the entire celestial sphere by selecting **Guides > Atlas** in the **Favourites** menu. Open the **Find** pane by clicking the **Find** tab at the top of the left border of the view window. Click the menu button (the blue colored button with a downward- pointing arrowhead) at the left of the entry in the list for the **Moon** and select the **Magnify** option. This will center a magnified image of the Moon in the view as seen from the center of a transparent Earth. Close the **Find** pane by clicking its tab. Click on the down arrow to the right of the **Time Flow Rate** control and select **hours** from the drop-down menu. Then click on the **Run Time Forward** button (a triangle that points to the right like a Play button). (**a**) Describe how the phase of the Moon changes over time. (**b**) Look carefully at features near the left-hand and right-hand limbs (edges) of the Moon. Are these features always at the same position relative to the limb? Explain in terms of libration.

49. Use the *Starry Night Enthusiast*™ program to observe the apparent change in size of the Moon as seen from the surface of the Earth. Click the **Home** button in the toolbar. Stop the time flow by clicking the **Stop** time button (the button with a square icon in the **Time Flow Rate** section of the toolbar). Click each field of the **Time** and **Date** display pane in the toolbar and use the keyboard to set the time to 12:00:00 A.M. and the date to October 16, 2006. You can now set up the view of the Moon as if you were observing from a transparent Earth in continuous darkness. Open the **Options** pane by clicking its tab on the left border of the view window. In the **Local View** layer of the Options pane, uncheck the boxes beside the **Daylight** and **Local Horizon** options. Open the **Find** pane and click the menu button at the left of the entry for the Moon and select **Magnify** from the menu to display a stationary image of the magnified Moon in the center of the view. Notice the Moon's phase. (**a**) Select **Options > Solar System > Planets-Moons. . .** from the menu. In the Planets-Moons dialog box, click the slide control next to the **Show dark side** label near the top of the window and adjust the control all the way to the right (**Brighter**) side of the scale. Then click the **OK** button to close the dialog box. Note that the image of the Moon now appears full because *Starry Night Enthusiast*™ has artificially brightened the dark side of the image of the Moon, effectively removing the appearance of the Moon's phases. (**b**) Use the + button in the Zoom section of the toolbar to adjust the field of view to about **55′ × 45′**. *Starry Night Enthusiast*™ can display a reference field of view (FOV) upon this sky. Open the **FOV** pane by clicking its tab. Select the **30 Arcminutes** option. Then click the FOV tab to close the pane. (**c**) The final view is of the Moon, its dark side artificially brightened, as it would be seen from your home location if the Earth were airless and transparent, surrounded by a yellow FOV circle 30 arcminutes in diameter. Note the size of the Moon relative to this reference circle. Set the **Time Flow Rate** in the toolbar to 1 minute. **Run Time Forward** for least 24 hours and observe the apparent size of the Moon relative to the reference circle. (**c**) Note that the apparent size of the Moon changes somewhat over the course of a day (of simulated time). Explain in terms of the Earth's rotation. (*Hint:* In this view, *Starry Night Enthusiast*™ has made the Earth transparent, so you can see objects that would normally be below the horizon. As the Earth rotates, your observing location on the surface is carried along and your distance from the Moon changes.) (**d**) Change the **Time Flow Rate** to **1 day** and again click the **Run Time Forward** button. Does the apparent size of the Moon always stay the same, or does it vary? Explain what this tells you about the shape of the Moon's orbit.

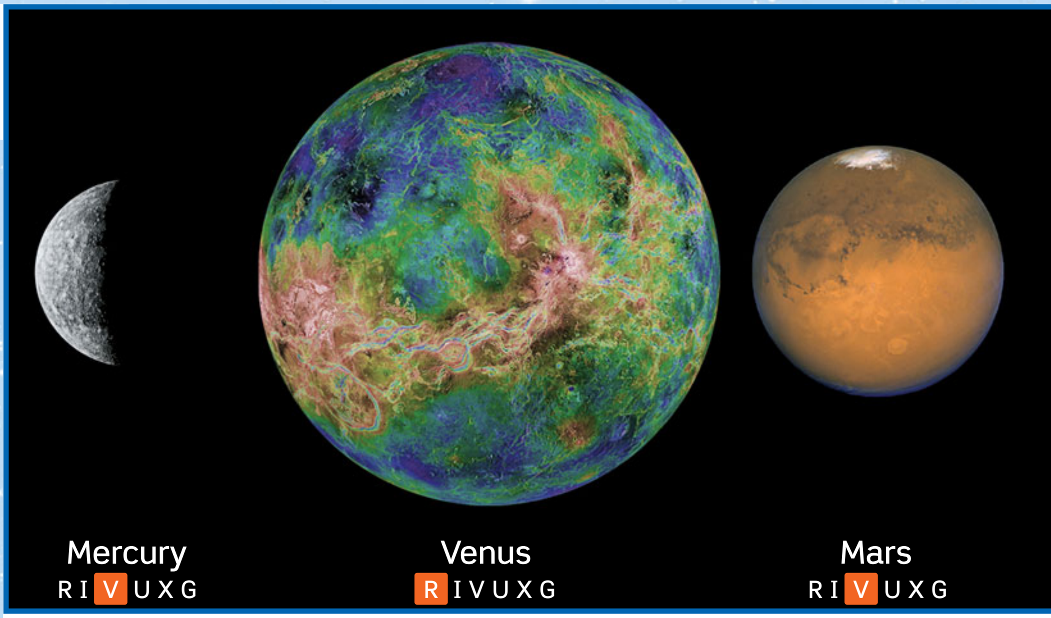
50. Use the *Starry Night Enthusiast*™ program to examine the Moon. Select **Solar System > Moon** from the **Favourites** menu. (If desired, remove the image of the astronaut by clicking on **Feet** in the **View** menu) You can rotate the image of the Moon by placing the mouse cursor over the image, holding down the mouse button, and moving the mouse. (On a two-button mouse, hold down the left mouse button.) (**a**) From what you can see in the image, what evidence can you find that the Moon is geologically inactive? Explain. (**b**) Spreading outward from some of the largest craters on the Moon are straight lines of light-colored material called rays that were caused by material ejected outward by the impact that caused the crater. Rotate the Moon around to see the entire illuminated surface. Can you find any rays on the Moon? Zoom in on the Moon to examine various surface features such as craters and mountain ranges. Estimate the length of several rays extending from craters by measuring their length on the screen with a ruler and comparing them to the diameter of the Moon, which is about 30 minutes of arc when seen from Earth.

Collaborative Exercise

51. The image of Crater Clavius in Figure 10-4 reveals numerous craters. Using the idea that the Moon's landscape can only be changed by impacts, make a rough sketch showing ten of the largest craters and label them from oldest (those that showed up first) to youngest (the most recent ones). Explain your reasoning and any uncertainties.

11

Mercury, Venus, and Mars: Earthlike yet Unique



WEB LINK 11.1 VIDEO 11.1

(Mercury: NASA; Venus: NASA/JPL, MIT, and USGS; Mars: NASA, J. Bell/ Cornell University, and M. Wolff/SSI)

These images above show the three planets that share the inner solar system with our Earth. All three have solid surfaces, and, in principle, a properly protected astronaut could stand on any of them. The differences between these three worlds, however, are pronounced.

Mercury is small, airless, and extensively cratered. It is also mysterious: Half of its surface has never been viewed at close range, and it has a perplexing and unexpected magnetic field. It also rotates in a manner unique in the solar system, spinning three times on its axis for every two orbits around the Sun.

Venus is nearly the same size as Earth, but it is shrouded by a perpetual cloud cover that hides its surface from view. To penetrate the clouds and learn what lies beneath, two advanced technologies were needed: radar, which allowed astronomers to "see" through the clouds, and unmanned spacecraft, which orbited Venus at close range and even landed on its surface. The false-color topographic map shown here reveals that Venus has no true continents but merely highlands (shown in red) that rise gently above the planet's lower-lying areas (shown in blue). We have also learned that Venus's atmosphere is thick and searing hot, and that its clouds contain droplets of corrosive sulfuric acid.

Mars has captivated the popular imagination like no other planet. But rather than being the abode of warlike aliens, Mars proves to be an enigmatic world. Some parts of its surface are drier than any desert on Earth, while other locations show evidence of having been underwater for extended periods. Our challenge is to understand how these three nominally Earthlike worlds evolved to be so unique and so different than our own Earth.

Learning Goals

By reading the sections of this chapter, you will learn

11-1 What astronomers have learned by observing the terrestrial planets from Earth

11-2 The radically different ways in which Mercury, Venus, and Mars rotate on their axes

11-3 The outstanding features of Mercury, and why its magnetic field came as a surprise

11-4 How the advent of the space age transformed our understanding of Venus and Mars

11-5 How geologic activity took a very different form on Venus than on Earth, and why it essentially stopped on Mars

11-6 The key differences among the atmospheres of Earth, Venus, and Mars

11-7 How the atmospheres of Earth, Venus, and Mars evolved to their present states

11-8 The evidence that there was once liquid water on Mars

11-9 What we know about the two small satellites of Mars

11-1 Mercury, Venus, and Mars can all be seen with the naked eye

At various times Mercury, Venus, and Mars are among the brightest objects in the sky. At their greatest brilliance, each of these planets appears brighter than any star, which is why they have been known since ancient times and why their motions played a role in the religious beliefs of many ancient cultures.

Naked-Eye Observations of Mercury and Venus

Viewing Mercury is difficult because it is so close to the Sun; Venus is easier to see but covered with clouds; Mars is best seen at opposition

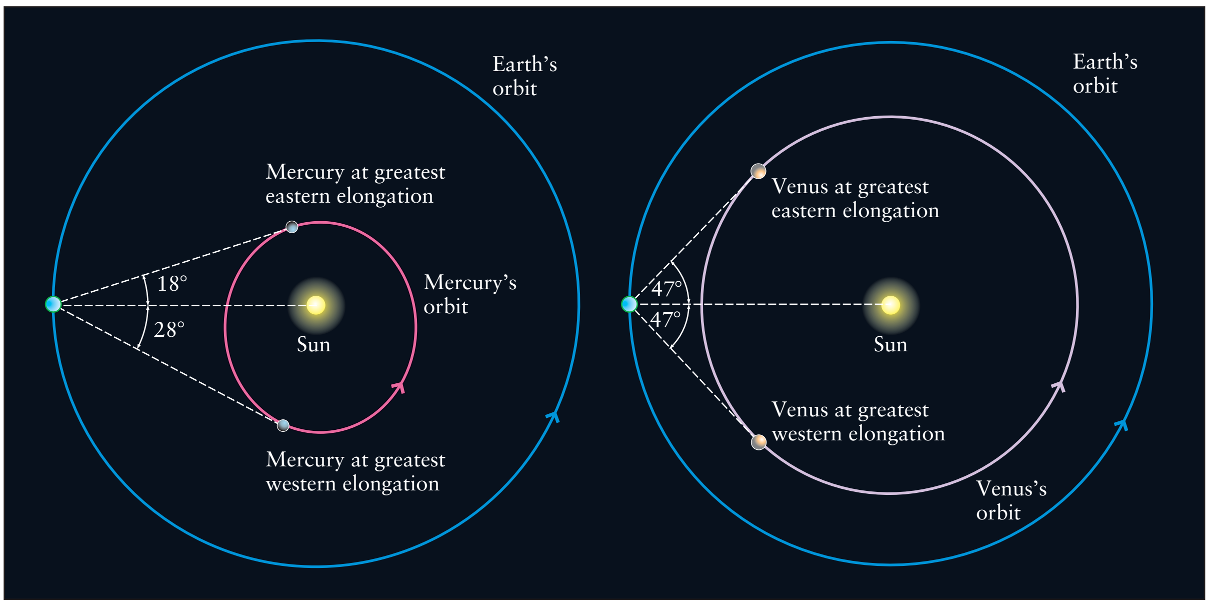
Mercury and Venus are *inferior* planets whose orbits around the Sun are smaller than the Earth's,: that is, each moves in an orbit with a semimajor axis *a* less than 1 astronomical unit (AU). For Mercury, a = 0.387 AU (57.9 million kilometers, or 36.0 million miles), and for Venus, a = 0.723 AU (108 million kilometers, or 67.2 million miles). As a result, Mercury and Venus never appear very far from the Sun in our sky (Figure 11-1). Table 11-1 and Table 11-2 summarize some basic information about these planets and their orbits.

We get the best view of either Mercury or Venus when it appears as far from the Sun in the sky as it can be, at its greatest eastern or western elongation (Section 4-2). On dates near its **greatest eastern elongation,** Mercury or Venus appears after sunset over the western horizon as an "evening star." On dates near its **greatest western elongation,** Mercury or Venus appears as a "morning star" that rises before the Sun in the eastern sky.

CAUTION! Remember that "greatest *western* elongation" and "greatest *eastern* elongation" refer to a planet's position in the sky relative to the Sun. When Mercury or Venus is at greatest western elongation, it is west of the Sun in the sky and has already risen at dawn when the Sun is rising in the east. When Mercury or Venus is at greatest eastern elongation, it is east of the Sun in the sky and is still above the horizon when the Sun sets in the west.

WEB LINK 11.5

Because Mercury's orbit is so close to the Sun, its maximum elongation is only 28° and it is quite difficult to observe. (It is said that Copernicus never saw it.) The celestial sphere appears to rotate at 15° per hour (360° divided by 24 hours), so Mercury never rises more than 2 hours before sunrise or sets more than 2 hours after sunset. Unfortunately, Mercury's orbit is very elliptical (its eccentricity of 0.206 is greater than that of any other planet) and is inclined to the ecliptic—the plane of the Earth's orbit around the Sun—by about 7°. As a result, at greatest elongation Mercury is often much less than 28° from the horizon at sunset or sunrise. Hence, some elongations are more favorable for viewing Mercury than others, as Figure 11-2 shows. A total of six or seven greatest elongations (both eastern and western) occur each year, but usually only two of these will be favorable for viewing the planet.



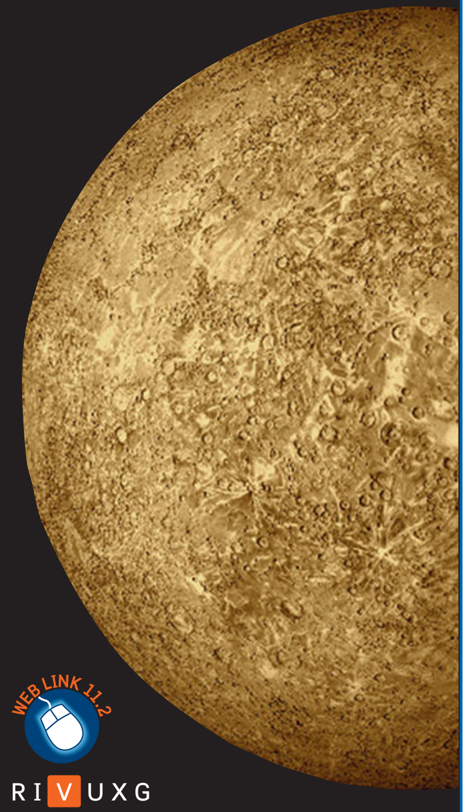
ANIMATION 11.1

Figure 11-1

The Orbits of Mercury and Venus Mercury moves around the Sun every 88 days in a rather eccentric orbit. As seen from the Earth, the angle between Mercury and the Sun at greatest eastern or western elongation can be as large as 28° (when Mercury is near aphelion) or as small as 18° (near perihelion). By contrast, Venus follows a larger, nearly circular orbit with a 224.7-day period. The angle between Venus and the Sun at eastern or western elongation is 47°.

Table 11-1 Mercury Data

Average distance from Sun:	0.387 AU = 5.79×10^7 km
Maximum distance from Sun:	0.467 AU = 6.98×10^7 km
Minimum distance from Sun:	0.307 AU = 4.60×10^7 km
Eccentricity of orbit:	0.206
Average orbital speed:	47.9 km/s
Orbital period:	87.969 days
Rotation period:	58.646 days
Inclination of equator to orbit:	0.5°
Inclination of orbit to ecliptic:	7° 00′ 16″
Diameter (equatorial):	4880 km = 0.383 Earth diameter
Mass:	3.302×10^{23} kg = 0.0553 Earth mass
Average density:	5430 kg/m^3
Escape speed:	4.3 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.12
Average surface temperatures:	Day: 350°C = 662°F = 623 K Night: −170°C = 2274°F = 103 K
Atmosphere:	Essentially none



(Astrogeology Team, U. S. Geological Survey)

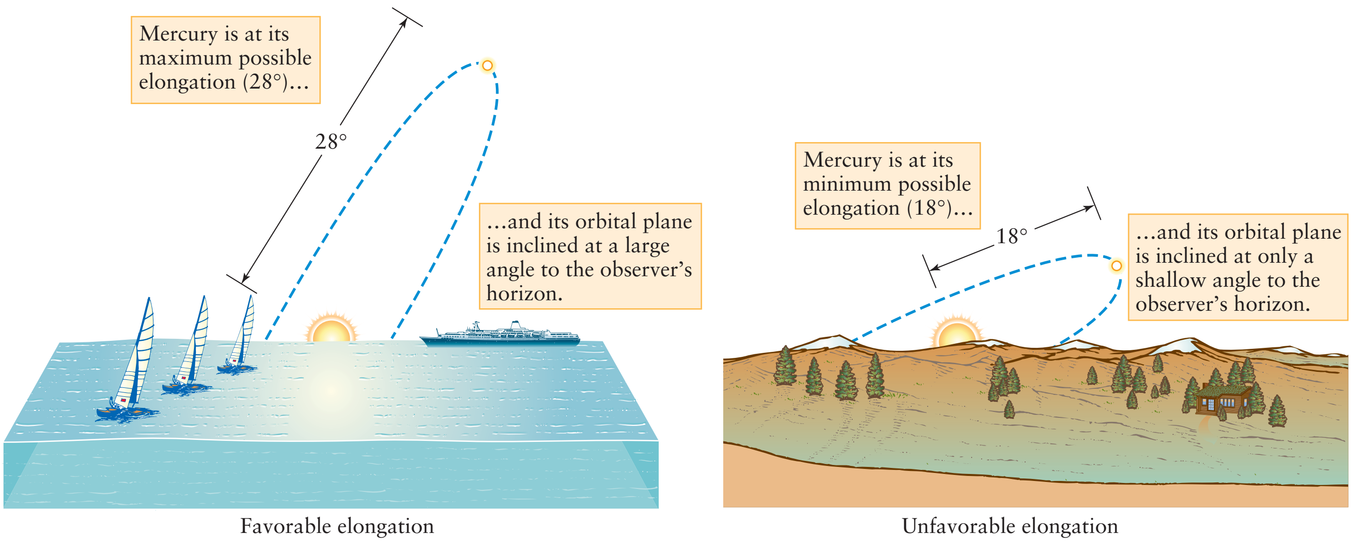
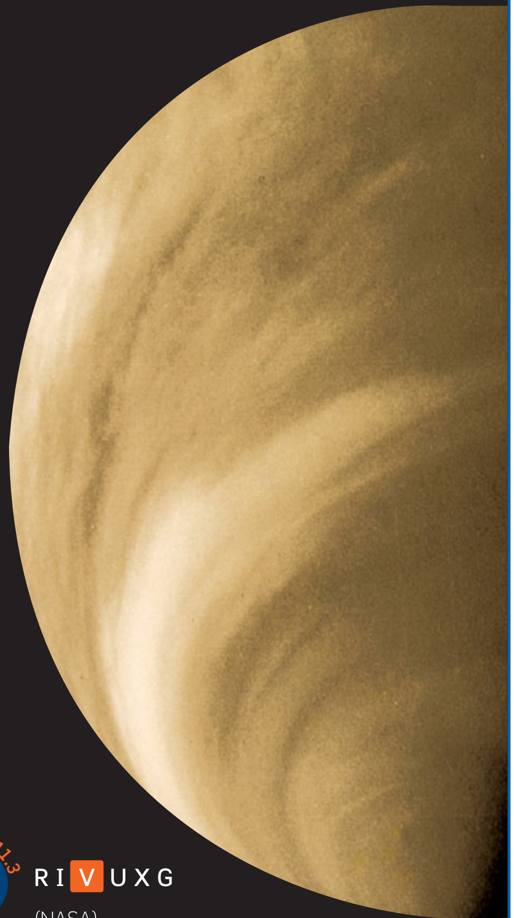


Figure 11-2

Favorable Versus Unfavorable Elongations The tilt of the Earth's axis, the inclination and eccentricity of Mercury's orbit, and the latitude of the observer combine to make an elongation either favorable (left illustration) or unfavorable (right illustration) for viewing Mercury.

Table 11-2 Venus Data

Average distance from Sun:	0.723 AU = 1.082×10^8 km
Maximum distance from Sun:	0.728 AU = 1.089×10^8 km
Minimum distance from Sun:	0.718 AU = 1.075×10^8 km
Eccentricity of orbit:	0.0068
Average orbital speed:	35.0 km/s
Orbital period:	224.70 days
Rotation period:	243.01 days (retrograde)
Inclination of equator to orbit:	177.4°
Inclination of orbit to ecliptic:	3.39°
Diameter (equatorial):	12,104 km = 0.949 Earth diameter
Mass:	4.868×10^{24} kg = 0.815 Earth mass
Average density:	5243 kg/m^3
Escape speed:	10.4 km/s
Surface gravity (Earth = 1):	0.91
Albedo:	0.59
Average surface temperature:	460°C = 860°F = 733 K
Atmospheric composition (by number of molecules):	96.5% carbon dioxide (CO_2) 3.5% nitrogen (N_2) 0.003% water vapor (H_2O)



WEB LINK 11.3

R I V U X G

(NASA)

Like all the planets, Mercury shines by reflected sunlight. Because it orbits so close to the Sun, it is exposed to sunlight that on average is about 7 times as intense as on the Earth. Furthermore, Mercury is never more than 1.5 AU from Earth. These factors explain why Mercury can have up to twice the brightness of Sirius, the brightest star in the nighttime sky. Mercury would be even brighter if its surface did not have a rather low albedo of 0.12 (that is, it reflects only about 12% of the sunlight that falls on it—about the same as weathered asphalt).

WEB LINK 11.6

The orbit of Venus is about twice the size of Mercury's orbit, nearly circular, and inclined to the ecliptic by only 3.39°. As a result, Venus can be seen about 47° away from the Sun and all elongations are nearly equally favorable. At greatest eastern elongation, which occurs at intervals of about 19 months, Venus sets in the west about 3 hours after sunset. About 5 months later Venus is at greatest western elongation and rises in the east about 3 hours before sunrise.

At its greatest brilliance, Venus is 16 times brighter than Sirius and is outshone only by the Sun and the Moon. Venus is more brilliant than Mercury because it is relatively large (more than double the diameter of Mercury and almost the same size as the Earth) and has a much higher albedo of 0.59 (it reflects 59% of the sunlight that falls on it).

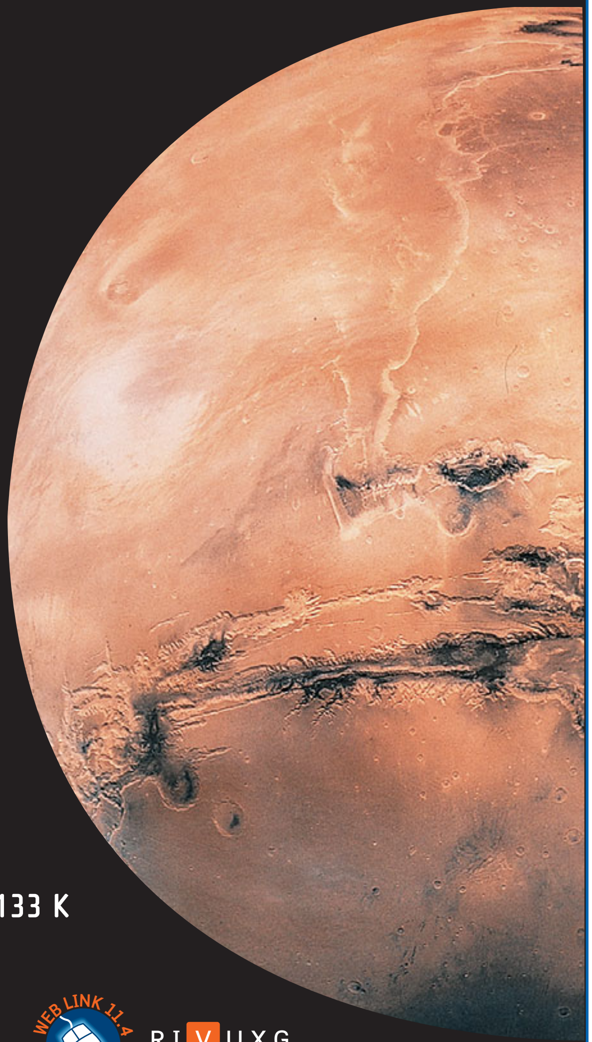
Naked-Eye Observations of Mars

WEB LINK 11.7

Unlike Mercury and Venus, Mars is a *superior* planet with an orbit larger than the Earth's orbit. As Table 11-3 shows, its orbital semimajor axis is a = 1.524 AU (227.9 million kilometers, or 141.6 million miles). Hence, Mars and the Sun are sometimes on opposite sides of the sky as seen from Earth—that is, Mars is at opposition (see Figure 4-6)—and appears high in our night sky. Such oppositions occur at intervals of about 780 days. However, some oppositions provide better views of Mars than others because Mars has a noticeably elongated orbit (Figure 11-3). As a result, we get the best view of Mars when it is simultaneously at opposition and near the perihelion of its elliptical orbit, a configuration called a **favorable opposition.** The Earth-Mars distance can then be as small as 0.37 AU, or 56 million kilometers (35 million miles), and the angular diameter of Mars can be as large as 25.1 arcsec—about the same as a person's head seen at a distance of 1.6 km (1 mile). Under these conditions, Mars appears in the nighttime sky as a brilliant red object $3\frac{1}{2}$ times brighter than Sirius.

Table 11-3 Mars Data

Average distance from Sun:	1.524 AU = 2.279×10^8 km
Maximum distance from Sun:	1.666 AU = 2.492×10^8 km
Minimum distance from Sun:	1.381 AU = 2.067×10^8 km
Eccentricity of orbit:	0.093
Average orbital speed:	24.1 km/s
Orbital period:	686.98 days = 1.88 years
Rotation period:	$24^h\ 37^m\ 22^s$
Inclination of equator to orbit:	25.19°
Inclination of orbit to ecliptic:	1.85°
Diameter (equatorial):	6794 km = 0.533 Earth diameter
Mass:	6.418×10^{23} kg = 0.107 Earth mass
Average density:	3934 kg/m^3
Escape speed:	5.0 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.15
Surface temperatures:	Maximum: 20°C = 70°F = 293 K Mean: −23°C = −10°F = 250 K Minimum: −140°C = −220°F = 133 K
Atmospheric composition (by number of molecules):	95.3% carbon dioxide (CO_2) 2.7% nitrogen (N_2) 0.03% water vapor (H_2O) 2% other gases



WEB LINK 11.4

R I V U X G

(NASA, USGS)

Unfortunately, the time from one favorable opposition to the next is about 15 years. Hence, astronomers take advantage of all oppositions, even the not-so-favorable ones, to observe Mars. When Mars is at opposition but near aphelion the Earth-Mars distance can be as large as 0.68 AU, or 101 million kilometers (63 million miles).

Telescopic Views of Mercury, Venus, and Mars

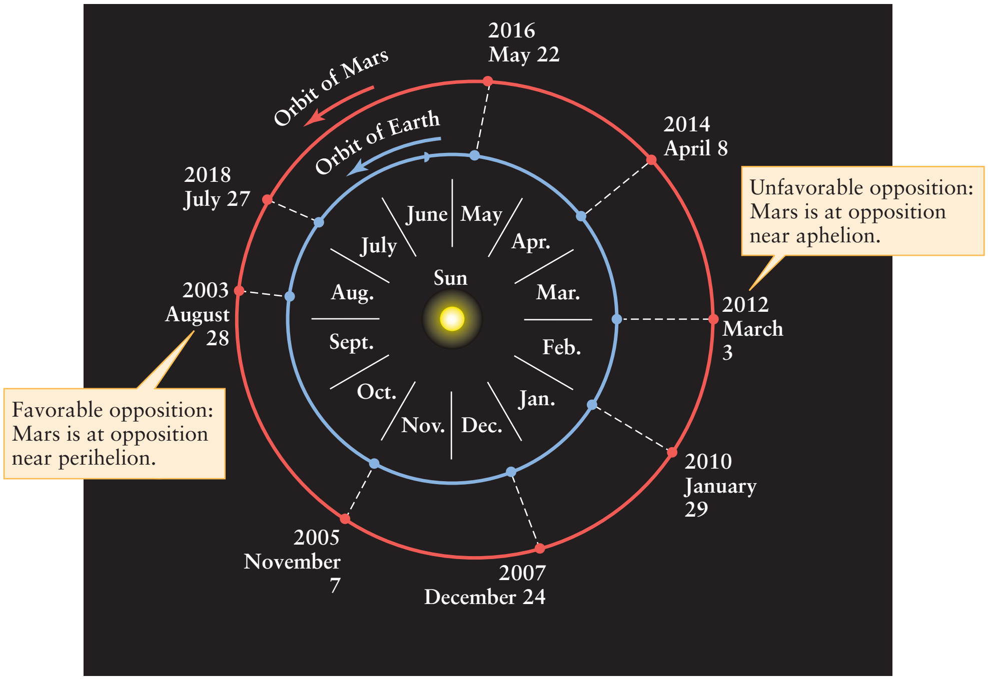
Naked-eye observations of Mercury are best made at dusk or dawn, but the best telescopic views are obtained in the daytime when the planet is high in the sky, far above the degrading atmospheric effects near the horizon. A yellow filter can eliminate much of the blue light from our sky. The photograph in Figure 11-4*a*, which is among the finest Earth-based views of Mercury, was taken during daytime.

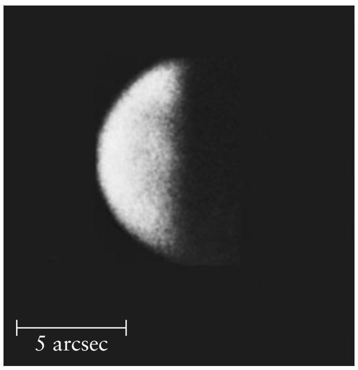
While an Earth-based telescope reveals some surface details on Mercury, Venus appears almost completely featureless, with neither continents nor mountains (see Figure 4-13). Astronomers soon realized that they were not seeing the true surface of the planet. Rather, Venus must be covered by a thick, unbroken layer of clouds. A cloud layer would also explain why Venus reflects such a large fraction of the sunlight that falls on it. Direct evidence that Venus has a thick atmosphere came when nineteenth-century astronomers observed Venus near the time of inferior conjunction. This is when Venus lies most nearly between the Earth and the Sun, so that we see the planet lit from behind. As Figure 11-4*b* shows, sunlight is scattered by Venus's atmosphere, producing a luminescent ring around the planet that would not otherwise be present. No such ring is seen around Mercury at inferior conjunction, which indicates that Mercury has no appreciable atmosphere.

ANIMATION 11.2

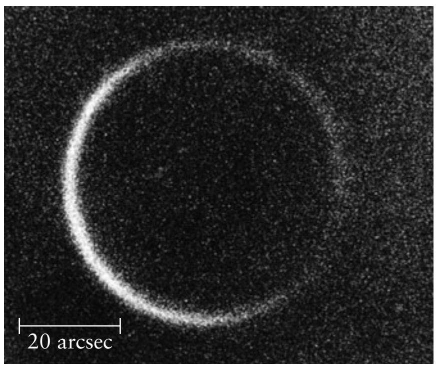
Figure 11-3

The Orbits of Earth and Mars The best times to observe Mars are at opposition, when Mars is on the side of Earth opposite the Sun. The red and blue dots connected by dashed lines show the positions of Mars and Earth at various oppositions. The months shown around the Sun refer to the time of year when the Earth is at each position around its orbit.





(a) Mercury at greatest elongation

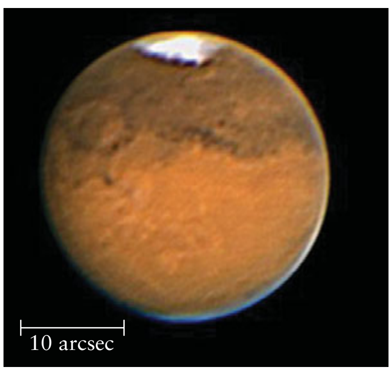


(b) Venus at inferior conjunction

WEB LINK 11.8

Figure 11-4 R I V U X G

Earth-Based Views of Mercury, Venus, and Mars
(a) Hazy markings are faintly visible in this photograph of Mercury, one of the best ever produced with an Earth-based telescope. Note that Mercury goes through phases like Venus (see Figure 4-13). **(b)** Venus at inferior conjunction shows its atmosphere as a faint ring surrounding the planet. This photograph was processed to reveal the ring, which is too faint to show in Figure 4-13. **(c)** A 25-cm (10-in.) telescope with a CCD detector (see Section 6-4) was used to make this image of Mars. Compare this with the Hubble Space Telescope image that opens this chapter, which was taken during the same month in 2003 and which shows the same face of Mars. (a: New Mexico State University Observatory; b: Lowell Observatory; c: Courtesy of Sheldon Faworski and Donald Parker)



(c) Mars at opposition

Unlike airless Venus or cloud-shrouded Venus, Mars has a thin, almost cloudless atmosphere that permits a clear view of the surface. Under the right conditions, a relatively small telescope can reveal substantial detail on the Martian surface. Figure 11-4*c* shows an image of Mars during the very favorable 2003 opposition, when Mars was closer to Earth than it had been in several thousand years. The thin strip of blue and orange around the right-hand edge of Mars in this image is caused by the Martian atmosphere. This image also shows that different parts of the Martian surface have different colors. Most striking are the whitish ice caps at the Martian poles, which bear a striking superficial resemblance to the Arctic and Antarctic regions on Earth.

CAUTION! Although Mars appears bright red to Earth observers, its surface is actually reddish-brown. A sunlit brown surface, if surrounded by the blackness of space, is perceived by the human eye as having a red color.

11-2 While Mars rotates much like the Earth, Mercury's rotation is coupled to its orbital motion and Venus's rotation is slow and retrograde

We have seen that the surface of Mars is relatively easy to observe with visible-light telescopes. By contrast, only a few faint, hazy markings can be seen on Mercury's surface, and the surface of Venus is perpetually hidden by clouds. These differences explain why the rotation of Mars has been well understood since the mid-seventeenth century, while it was not until the 1960s that astronomers accurately measured the rotation of Mercury and Venus. As we will see, Mars rotates in a very Earthlike way, while Mercury and Venus rotate like no other objects in the solar system.

Radar technology revealed the curious rotation of Mercury and Venus

The Rotation of Mars

WEB LINK 11.9

The first reliable record of surface features on Mars was made by the Dutch scientist Christiaan Huygens, who observed the planet during the opposition of 1659. He identified a prominent dark feature that we now call Syrtis Major. After observing this feature for several weeks, Huygens concluded that the rotation period of Mars is approximately 24 hours, the same as the Earth.

In 1666, the Italian astronomer Gian Domenico Cassini made more-refined observations which showed that a Martian day is 37.5 minutes longer than on Earth. More than a century later, the German-born English astronomer William Herschel found that Mars's axis of rotation is not perpendicular to the plane of the planet's orbit, but is tilted by about 25° away from the perpendicular. This is very close to the Earth's $23\frac{1}{2}°$ tilt (see Figure 2-12). This striking coincidence means that Mars experiences Earthlike seasons, with opposite seasons in the northern and southern Martian hemispheres (see Section 2-5). Because Mars takes nearly 2 (Earth) years to orbit the Sun, the Martian seasons last nearly twice as long as on Earth.

The Challenge of Observing Mercury's Rotation

During the 1880s, the Italian astronomer Giovanni Schiaparelli attempted to make the first map of Mercury. Unfortunately, Schiaparelli's telescopic views of Mercury were so vague and indistinct that he made an understandable but major error, which went uncorrected for more than half a century. He erroneously concluded that Mercury always keeps the same side facing the Sun.

Many objects in our solar system are in synchronous rotation, so that their rotation period equals their period of revolution—a situation also called **1-to-1 spin-orbit coupling.** We saw in Section 4-8 how the Earth's tidal forces keep the Moon in synchronous rotation, so that it always keeps the same side toward the Earth. Tidal forces also keep the two moons of Mars with the same side facing their parent planet, and likewise many of the satellites of Jupiter and Saturn.

It had been suggested as early as 1865 that the Sun's tidal forces would keep Mercury in synchronous rotation. But this is not how Mercury rotates. The first clue about Mercury's true rotation period came in 1962, when astronomers detected radio radiation coming from the innermost planet.

As we learned in Sections 5-3 and 5-4, every dense object (such as a planet) emits electromagnetic radiation with a continuous spectrum. The dominant wavelength of this radiation depends on the object's temperature. Only at absolute zero does a dense object emit no radiation at all.

If Mercury exhibited synchronous rotation, one side of the planet would remain in perpetual, frigid darkness, quite near absolute zero. To test this idea, in 1962 the radio astronomer W. E. Howard and his colleagues at the University of Michigan began monitoring radiation from Mercury. (If the planet had one side that was very cold, most of the emission from that side should be at quite long wavelengths. Hence, a radio telescope was used for these observations.) They were surprised to discover that the temperature on the planet's nighttime side is about 100 K (= −173°C = −280°F), not nearly as cold as expected. These observations were in direct contradiction to the idea of synchronous rotation.

One idea offered to explain Howard's observations was that Mercury rotates synchronously, but that winds in the planet's atmosphere carried warmth from the daytime side of the planet around to the nighttime side. But, in fact, there are no winds on Mercury. Its daytime temperature is too high and its gravity too weak to retain any substantial atmosphere (see Box 7-2).

The definitive observation was made in 1965, when Rolf B. Dyce and Gordon H. Pettengill used the giant 1000-ft radio telescope at the Arecibo Observatory in Puerto Rico to bounce powerful radar pulses off Mercury. The outgoing radiation consisted of microwaves of a very specific wavelength. In the reflected signal echoed back from the planet, the wavelength had shifted as a result of the Doppler effect (see Section 5-9, especially Figure 5-26). As Mercury rotates, one side of the planet approaches the Earth, while the other side recedes from the Earth. Microwaves reflected from the planet's approaching side were shortened in wavelength, whereas those from its receding side were lengthened (Figure 11-5). Thus, the radar pulse went out at one specific wavelength, but it came back spread over a small wavelength

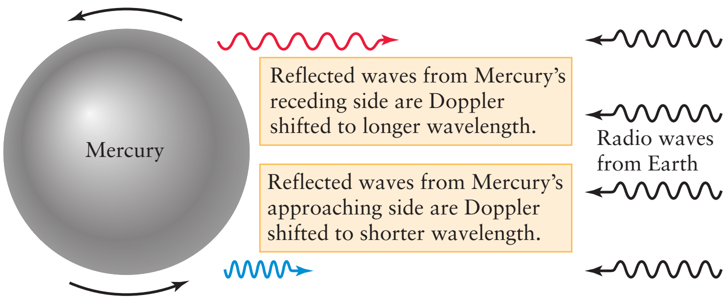


Figure 11-5

Measuring Mercury's Rotation Period As Mercury rotates, one side of the planet moves away from the Earth and the other side toward the Earth. If radio waves of a single wavelength are beamed toward Mercury, waves reflected from these two sides will be Doppler shifted to longer and shorter wavelengths, respectively. By measuring the wavelength shift of the reflected radiation, astronomers deduced how rapidly Mercury rotates and thus determined its rotation period.

range. From the width of this wavelength range, Dyce and Pettengill deduced that Mercury's rotation period is approximately 58.6 days.

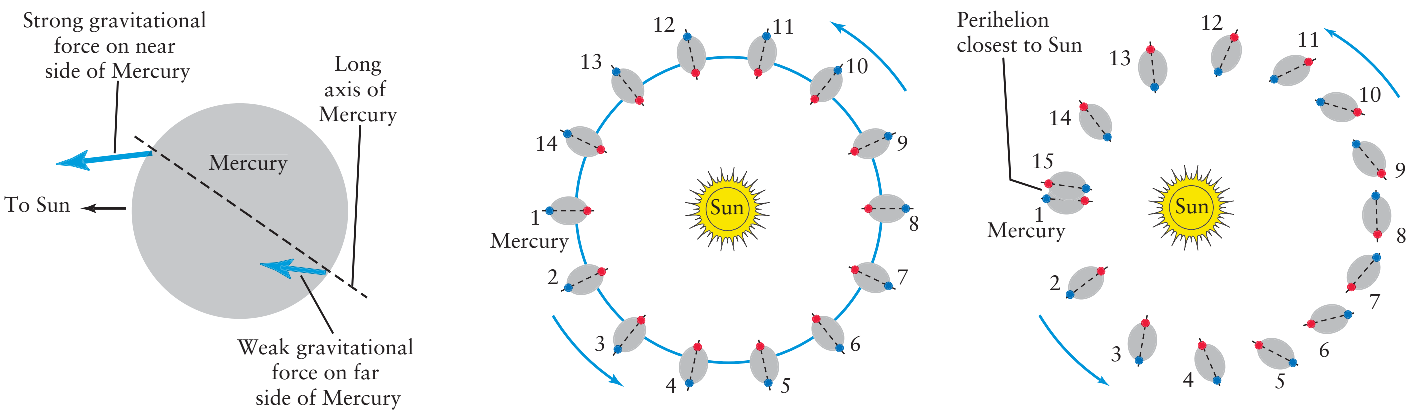
Spin-Orbit Coupling and the Curious Rotation of Mercury

Giuseppe Colombo, an Italian physicist with a long-standing interest in Mercury, was intrigued by Dyce and Pettingill's results. Colombo noted that their result for the rotation period is very close to two-thirds of Mercury's sidereal period of 87.969 days:

$$2/3 \ (87.969 \text{ days}) = 58.646 \text{ days}$$

Colombo therefore boldly speculated that Mercury's true rotation period is exactly 58.646 days, or 58 days and 15½ hours. He realized that this figure would mean that Mercury is locked into a **3-to-2 spin-orbit coupling:** The planet makes *three* complete rotations on its axis for every *two* complete orbits around the Sun. No other planet or satellite in the solar system has this curious relationship between its rotation and its orbital motion.

Figure 11-6 shows how gravitational forces from the Sun cause Mercury's 3-to-2 spin-orbit coupling. The force of gravity decreases with increasing distance, which explains how the Moon is able to raise a tidal bulge in the Earth's oceans (see Section 4-8). Mercury has no oceans, but it has a natural bulge of its own; thanks to the Sun's tidal forces, the planet is slightly elongated along one axis. The stronger gravitational force that the Sun exerts on the near side of the planet tends to twist the long axis to point toward the Sun, as Figure 11-6*a* shows. Indeed, Mercury's long axis would always point toward the Sun if its orbit were circular or nearly so. In this case the same side of Mercury would always face the Sun, and there would be synchronous rotation (Figure 11-6*b*). But Mercury's orbit has a rather high eccentricity, and the twisting effect on Mercury decreases rapidly as the planet moves away from the Sun. As a result, Mercury's long axis points toward the Sun only at perihelion (Figure 11-6*c*). From one perihelion to the next, alternate sides of Mercury face the Sun.



(a) Mercury is slightly elongated: The different gravitational forces on Mercury's two ends tend to twist the long axis to point toward the Sun.

(b) If Mercury were in a circular orbit, its long axis would always point toward the Sun: Mercury would be in synchronous rotation (1-to-1 spin-orbit coupling).

(c) In fact Mercury is in an elliptical orbit, and its long axis only points toward the Sun at perihelion: Mercury spins on its axis 1½ times during each complete orbit (3-to-2 spin-orbit coupling).

Figure 11-6

Mercury's Spin-Orbit Coupling **(a)** The Sun's gravitational force on the near side of Mercury's long axis is greater than the force on the far side. This tends to twist the long axis to point toward the Sun. **(b)** If Mercury were in a circular orbit, the twisting effect shown in (a) would always keep the same side of Mercury (shown by a red dot) facing the Sun. **(c)** Because Mercury's orbit is rather elongated, its rotation is more complex: The end of Mercury's long axis marked by a red dot faces the Sun at one perihelion (point 1), but at the next perihelion (point 15) the opposite end—marked by a blue dot—faces the Sun.

Because of the 3-to-2 spin-orbit coupling, the average time from sunrise to sunset on Mercury is just equal to its orbital period, or just under 88 days. This helps explain the tremendous difference between daytime and nighttime temperatures on Mercury. Not only is sunlight about 7 times more intense on Mercury than on the Earth (because of the smaller size of Mercury's orbit), but that sunlight has almost 3 Earth months to heat up the surface. As a result, daytime temperatures at the equator are high enough—about 430°C (roughly 700 K, or 800°F)—to melt lead. (In comparison, a typical kitchen oven reaches only about 300°C or 550°F.)

The time from sunset to the next sunrise is also 88 days, and the surface thus has almost 3 Earth months of darkness during which to cool down. Therefore, nighttime temperatures reach to below −170°C (about 100 K, or −270°F). This is cold enough to freeze carbon dioxide and methane. The surface of Mercury is truly inhospitable!

While the Sun moves slowly across Mercury's sky, it does not always move from east to west as it does as seen from Earth. The reason is that Mercury's speed along its elliptical orbit varies substantially, in accordance with Kepler's second law (see Section 4-4, especially Figure 4-11). It moves fastest (59 km/s) at perihelion and slowest (39 km/s) at aphelion.

As seen from Mercury's surface, the Sun rises in the east and sets in the west, just as it does on the Earth. When Mercury is near perihelion, however, the planet's rapid motion along its orbit outpaces its leisurely rotation about its axis (one rotation in 58.646 days). Hence, the usual east-west movement of the Sun across Mercury's sky is interrupted, and the Sun actually stops and moves backward (from west to east) for a few Earth days. If you were standing on Mercury watching a sunset occurring at perihelion, the Sun would not simply set. It would dip below the western horizon and then come back up, only to set a second time a day or two later.

Observing Venus's Rotation: Penetrating the Clouds with Radio

Venus's perpetual cloud cover makes it impossible to measure the planet's rotation using visible-light telescopes. (It is possible to use visible-light telescopes to track features in the planet's cloud cover. But winds in the atmosphere cause such features to move relative to Venus's surface, so this approach does not give a direct measurement of how the planet itself rotates.) To penetrate the planet's perpetual cloud cover, astronomers applied to Venus the same technique of using radio waves and the Doppler effect that revealed the rotation of Mercury.

Clouds may contain gas, dust, haze, water droplets, or other small particles. In general, electromagnetic radiation can pass easily through such a cloud only if the wavelength is large compared to the size of the particles. We then say that the cloud is *transparent* to the radiation. For example, clouds in the Earth's atmosphere are made of water droplets with an average diameter of about 20 μm (2×10^{-5} m, or 20,000 nm). Visible light has wavelengths between 400 to 700 nm, which is less than the droplet size. Hence, visible light cannot easily pass through such clouds, which is why cloudy days are darker than sunny days. But radio waves, with wavelengths of 0.1 m or more, and microwaves, with wavelengths from 10^{-3} m to 0.1 m, can pass through such a cloud with ease. That is why your mobile phone, radio, or television works just as well on a cloudy or foggy day as on a clear one.

Like clouds in the Earth's atmosphere, the clouds of Venus are transparent to radio waves and microwaves. Beginning in the early 1960s, advances in radio telescope technology made it possible to send microwave radiation to Venus and detect the waves reflected from its surface. Just as for Mercury (see Figure 11-5), the Doppler shift of waves reflected from the two sides of Venus reveal the speed and direction of the planet's rotation.

Venus: Where the Sun Rises in the West

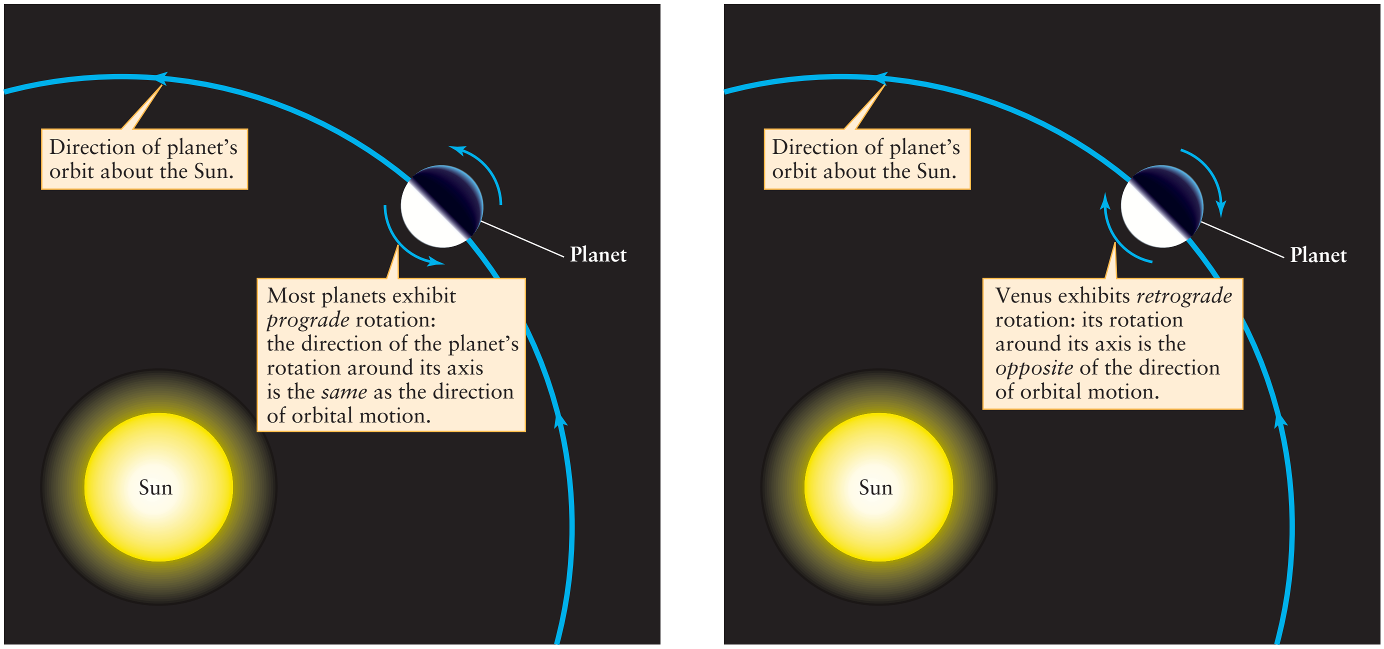
These measurements show that Venus rotates very slowly; the sidereal rotation period of the planet is 243.01 days, even longer than the planet's 224.7-day orbital period. To an imaginary inhabitant of Venus who could somehow see through the cloud cover, stars would move across the sky at a rate of only $1\frac{1}{2}°$ per Earth day. As seen from the Earth, by contrast, stars move $1\frac{1}{2}°$ across the sky in just 6 minutes.

Not only does Venus rotate slowly, it also rotates in an unusual direction. Most of the planets in the solar system spin on their axes in **prograde rotation.** Prograde means "forward," and planets with prograde rotation spin on their axes in the same direction in which they orbit the Sun (**Figure 11-7*a***). As seen from the surface of a planet with prograde rotation, such as the Earth, the Sun and stars rise in the east and set in the west.

Venus is an exception to the rule: It spins in **retrograde rotation.** That is, the direction in which it spins on its axis is backward compared to the direction in which it orbits the Sun, as Figure 11-7*b* shows. (Recall that "retrograde" means "backward.") If an observer on the surface of Venus could see through the thick layer of clouds, the Sun and stars would rise in the west and set in the east!

CAUTION! Be careful not to confuse retrograde *rotation* with retrograde *motion*. When Venus is near inferior conjunction, so that it is passing the Earth on its smaller, faster orbit around the Sun, it appears to us to move from east to west on the celestial sphere from one night to the next. This apparent motion is called retrograde motion, because it is backward to the apparent west-to-east motion that Venus displays most of the time. (You may want to review the discussion of retrograde motion in Sections 4-1 and 4-2.) By contrast, the retrograde rotation of Venus means that it spins on its axis from east to west, rather than west to east like the Earth.

Venus's retrograde rotation adds to the puzzle of our solar system's origins. If you could view our solar system from a great distance above the Earth's north pole, you would see all the planets orbiting the Sun counterclockwise. Closer examination would reveal that the Sun and most of the planets also *rotate* counterclockwise on their axes; the exceptions are Venus and Uranus. Most of the satellites of the planets also move counterclockwise along their orbits and rotate in the same direction. Thus, the rotation of Venus is not just opposite to its orbital motion; it is opposite to most of the orbital and rotational motions in the solar system!



(a) Prograde rotation

(b) Retrograde rotation

ANIMATION 11.3

Figure 11-7

Prograde and Retrograde Rotation **(a)** If you could view the solar system from a point several astronomical units above the Earth's north pole, you would see all of the planets orbiting the Sun in a counterclockwise direction. Most of the planets also rotate counterclockwise on their axes in prograde (forward) rotation. **(b)** Venus is an exception; from your perspective high above the plane of the solar system, you would see Venus rotating clockwise in retrograde (backward) rotation.

As we saw in Section 8-4, the Sun and planets formed from a solar nebula that was initially rotating. (Had it not been rotating, all of the material in the nebula would have fallen inward toward the protosun, leaving nothing to form the planets.) Because the planets formed from the material of this rotating cloud, they tend to rotate on their axes in that same direction. It is difficult to imagine how Venus and Uranus could have bucked this trend. One theory suggests that the tidal forces exerted by the Sun tended to elongate Venus's atmosphere toward the Sun, much as the Moon's tidal forces elongate the Earth's oceans toward the Moon (see Section 4-8, especially Figure 4-25). Friction between the atmosphere and Venus's surface then acted to slow the planet's rotation. By themselves, these tidal effects would put Venus into synchronous prograde rotation. But in addition, the Sun's heat on the illuminated side of Venus generates strong winds in the planet's atmosphere, and the frictional forces of these winds drive Venus into slow retrograde rotation.

Venus's rotation has other puzzling aspects. The length of an apparent solar day on Venus—that is, from when the Sun is highest in the sky to when it is again highest in the sky (see Section 2-7)—is 116.8 Earth days. Remarkably, this is almost exactly one-fifth as long as the planet's 584-day synodic period. (We saw in Section 4-2 that this is the time between successive inferior conjunctions, when Venus and the Earth are closest together.) Is this curious ratio the result of gravitational interactions between Venus and the Earth? Or is it sheer coincidence? No one knows the answer.

11-3 Mercury is cratered like the Moon but has a surprising magnetic field

Imagine an alien astronomer observing Earth from Mercury, from above the clouds of Venus, or from Mars with the same telescope technology available to our own astronomers. Such an astronomer would be unable to resolve any features on Earth less than a few hundred kilometers across. It would be impossible for her to learn about the Earth's mountain ranges, its volcanoes, or even its cities. Earth astronomers face the same limitations in studying the other terrestrial planets. To truly understand these other worlds, it is essential to study them at close range using spacecraft. In this section we will see what a single spacecraft has been able to teach us about Mercury's surface and interior. Later in this chapter we will see how a small fleet of spacecraft sent to Venus and Mars has revolutionized our knowledge of those planets.

Spacecraft observations at close range were necessary to reveal Mercury's unusual properties

Mariner 10 to Mercury

LOOKING DEEPER 11.1

The first spacecraft to provide detailed knowledge about Mercury was *Mariner 10*. Launched in 1973, this spacecraft went into an orbit around the Sun that brought it close to Mercury on three occasions in 1974 and 1975. The images transmitted back to Earth showed features as small as 1 km, hundreds of times smaller than the finest details made using Earth-based telescopes. Figure 11-8 shows a mosaic made by combining a number of *Mariner 10* images.

The *Mariner 10* images show only one hemisphere of Mercury's surface, since the time interval between flybys was equal to twice the planet's orbital period and 3 times its rotation period. Hence, the same side of Mercury was illuminated by the Sun during each flyby. The other side of Mercury has yet to be explored at close range.

Mercury's Cratered Surface

As *Mariner 10* closed in on Mercury, scientists were struck by the Moonlike pictures appearing on their television monitors. It was obvious that Mercury, like the Moon, is a barren, heavily cratered world, with no evidence for plate tectonics. This is what we would expect based on Mercury's small size (see Table 7-1 and the figure that opens this chapter). As we saw in Section 7-6, a small world is expected to have little internal heat, and, hence, little or no geologic activity and an ancient, cratered surface (see Figure 7-11). But craters are not the only features of Mercury's surface; there are also gently rolling plains, long, meandering cliffs, and an unusual sort of jumbled terrain. As we will see, Mercury's distinctive surface shows that this planet is *not* merely a somewhat larger version of the Moon.

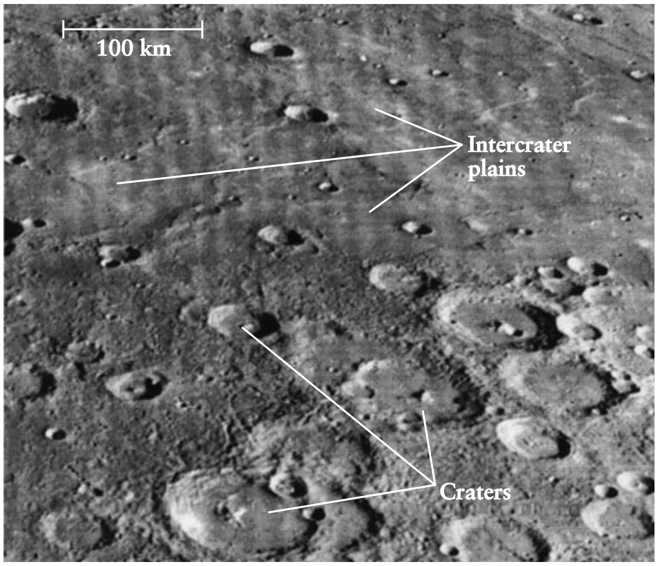
Figure 11-9 shows a typical close-up view sent back from *Mariner 10*. The consensus among astronomers is that most of the craters on both Mercury and the Moon were produced during the first 700 million years after the planets formed. Debris remaining after planet formation rained down on these young worlds, gouging out most of the craters we see today. We saw in Section 10-4 that the strongest evidence for this chronology comes from analysis and dating of Moon rocks. *Mariner 10* did not land on Mercury, so we are not able to make the same kind of direct analysis of rocks from the planet's surface.

Unlike the Moon, Mercury's surface has extensive low-lying plains (examine the upper half of Figure 11-9). These large, smooth areas are about 2 km lower than the cratered terrain. These probably have a similar origin to the lunar maria, which were produced by extensive lava flows between 3.1 and 3.8 billion years ago (see Section 10-4). Primordial lava flows probably also explain the plains of Mercury. As large meteoroids punctured the planet's thin, newly formed crust, lava welled up from the molten interior to flood low-lying areas.

From the number of craters that pit them, Mercury's plains appear to have been formed near the end of the era of heavy bombardment, a little more than 3.8 billion years ago. Mercury's plains are therefore older than most of the lunar maria. Analysis of *Mariner 10* images made at different wavelengths also shows that the material in Mercury's plains has a lower iron content than the lunar maria. This is presumably why the plains of Mercury do not have the dark color of the Moon's maria.

Scarps: Evidence of a Wrinkled Planet

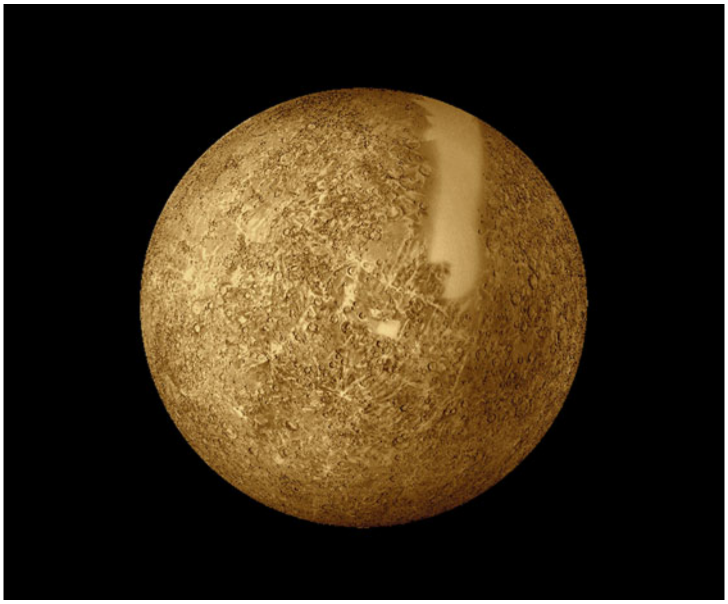
Mariner 10 also revealed numerous long cliffs, called **scarps**, meandering across Mercury's surface (Figure 11-10). Some scarps rise as much as 3 km (2 mi) above the surrounding plains and are 20 to 500 km long. These cliffs probably formed as the planet cooled and contracted.



VIDEO 11.2

Figure 11-9 R I V U X G

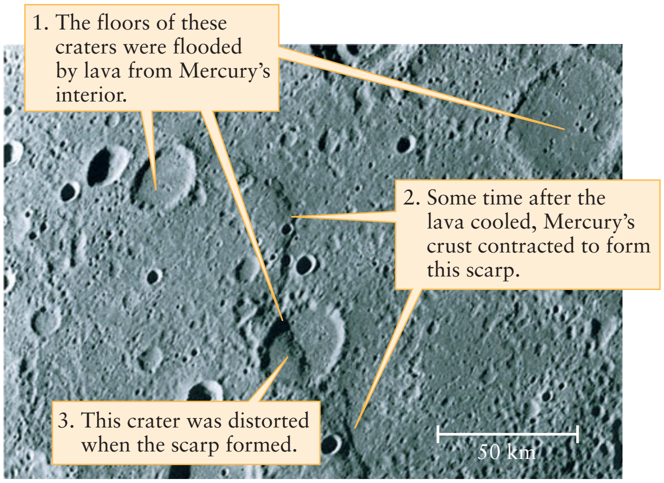
Mercurian Craters and Plains This view of Mercury's northern hemisphere was taken by *Mariner 10* at a range of 55,000 km (34,000 mi) from the planet's surface. Numerous craters and extensive intercrater plains appear in this photograph, which covers an area 480 km (300 mi) wide. (NASA)



WEBLINK 11.10

Figure 11-8 R I V U X G

***Mariner 10* Mosaic of Mercury** To make this mosaic of the side of Mercury viewed by *Mariner 10,* scientists combined dozens of images recorded by the spacecraft as it flew toward and away from the planet. The blank swatch running down from Mercury's north pole is a region that was not imaged. (Astrogeology Team, U.S. Geological Survey)



ANIMATION 11.4

Figure 11-10 R I V U X G

A Scarp A long cliff, or scarp, called Santa Maria Rupes runs across this *Mariner 10* image. This scarp is more than a kilometer high and extends for several hundred kilometers across a region near Mercury's equator. The area shown is approximately 200 km (120 mi) across. (NASA)

ANALOGY The shrinkage of Mercury's crust is probably a result of a general property of most materials: They shrink when cooled and expand when heated. The lid on a jar of jam makes a useful analogy. When the jar is kept cold in the refrigerator, the metal lid contracts more than the glass jar. This makes a tight seal, but also makes the lid hard to unscrew. You can loosen the lid by running hot water over it; this makes the metal lid expand more than the glass jar, helping to break the seal.

If there had still been molten material beneath Mercury's surface when this contraction took place, lava would have leaked onto the surface around the scarps. This does not appear to have happened. Hence, the scarps must have formed relatively late in Mercury's history, after the lava flows had ended and after the planet had solidified to a substantial depth beneath the surface. With the exception of the scarps, there are no features on Mercury that resemble the boundaries of tectonic plates. Thus, we can regard Mercury's crust, like that of the Moon, as a single plate.

Fire and Ice: The Caloris Basin and Mercury's Poles

The most impressive feature discovered by *Mariner 10* was a huge impact scar called the Caloris Basin (*calor* is the Latin word for "heat"). The Sun is directly over the Caloris Basin during alternating perihelion passages, and thus it is the hottest place on the planet once every 176 days. During each of the *Mariner 10* flybys, the Caloris Basin happened to lie on the terminator (the line dividing day from night; see Section 10-1). Hence, in Figure 11-11 slightly more than half of this basin is hidden on the night side of the planet.

The Caloris Basin, which measures 1300 km (810 mi) in diameter, is both filled with and surrounded by smooth lava plains. The basin was probably gouged out by the impact of a large meteoroid that penetrated the planet's crust, allowing lava to flood out onto the surface and fill the basin. Because relatively few craters pockmark these lava flows, the Caloris impact must be relatively young. It must have occurred toward the end of the cratermaking period that dominated the first 700 million years of our solar system's history.

The impact that created the huge Caloris Basin must have been so violent that it shook the entire planet. On the side of Mercury opposite the Caloris Basin, *Mariner 10* discovered a consequence of this impact—a jumbled, hilly region covering about 500,000 square kilometers, about twice the size of the state of Wyoming. Geologists theorize that seismic waves from the Caloris impact became focused as they passed through Mercury. As this concentrated seismic energy reached the far surface of the planet, it deformed the surface and created jumbled terrain. (This same process may also have taken place on the Moon: There is a region of chaotic hills on the side of the Moon directly opposite from the large impact basin called Mare Orientale.)

WEB LINK 11.11

In the decades since the *Mariner 10* mission, astronomers have continued to study Mercury with both visible-light and radio telescopes. Radar observations have detected patches at Mercury's north and south poles that are unusually effective at reflecting radio waves. It has been suggested that these patches may be regions of water ice deep within craters where the Sun's rays never reach. (We saw in Section 10-2 that ice may also exist in shadowed regions at the Moon's poles.) If this is correct, then Mercury is truly a world of extremes, with perpetual ice caps at one or both poles but with midday temperatures at the equator that are high enough to melt lead.

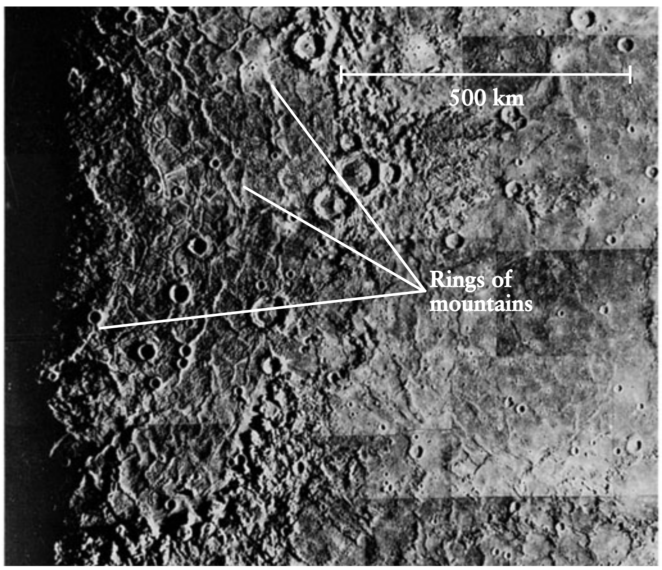
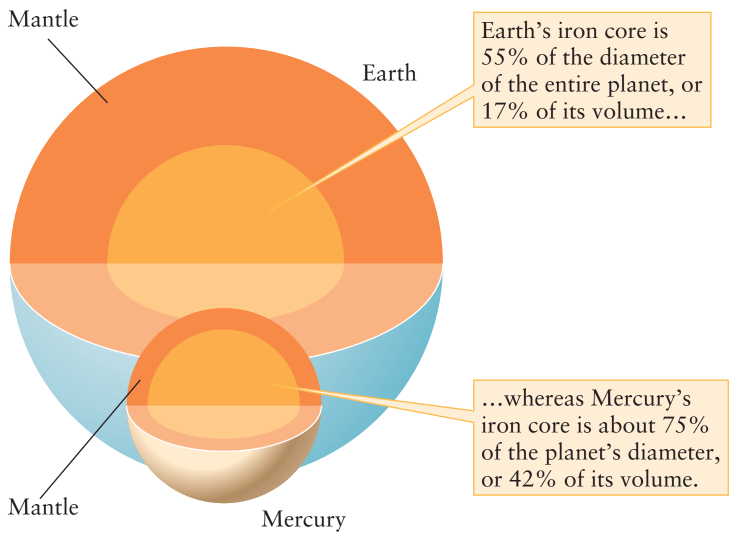


Figure 11-11 R I V U X G

The Caloris Basin An impact created this 1300-km (810-mi) diameter basin on Mercury about 4 billion years ago. Its center is hidden in the shadows just beyond the left side of the image. The impact fractured the surface extensively, forming several concentric chains of mountains. The mountains in the outermost ring are up to 2 km (6500 ft) high. (NASA)



INTERACTIVE EXERCISE 11.1

Figure 11-12

The Internal Structures of Mercury and the Earth Compared to the Earth's core, Mercury's iron-rich core takes up a much larger fraction of the planet's volume. Indeed, Mercury is the most iron-rich planet in the solar system. Surrounding Mercury's core is a 600-km-thick rocky mantle.

Mercury's Interior and Iron Core

By measuring how much *Mariner 10* was deflected by Mercury's gravity, scientists were able to make a precise determination of Mercury's mass. Given the mass and the diameter of Mercury, they could then calculate that the planet has an average density of 5430 kg/m^3. This is quite similar to the Earth's average density of 5515 kg/m^3. We saw in Section 9-2 that typical rocks from the Earth's surface have a density of only about 3000 kg/m^3 because they are composed primarily of lightweight, mineral-forming elements. The higher average density of our planet is caused by the Earth's iron core. By studying how the Earth vibrates during earthquakes, geologists have deduced that our planet's iron core occupies about 17% of the Earth's volume.

Pressures inside a planet increase the density of rock by squeezing its atoms closer together. Because the Earth is 18 times more massive than Mercury, the weight of this larger mass compresses the Earth's core much more than Mercury's core. If the Earth were uncompressed, its density would be 4400 kg/m^3, whereas Mercury's uncompressed density would still be a hefty 5300 kg/m^3. This higher uncompressed density means that Mercury has a *larger* proportion of iron than the Earth: An iron core must occupy about 42% of Mercury's volume. Mercury is therefore the most iron-rich planet in the solar system. Figure 11-12 is a scale drawing of the interior structures of Mercury and the Earth.

Several theories have been proposed to account for Mercury's high iron content. According to one theory, the inner regions of the primordial solar nebula were so warm that only those substances with high condensation temperatures—like iron-rich minerals—could have condensed into solids. Another theory suggests that a brief episode of very powerful solar winds could have stripped Mercury of its low-density mantle shortly after the Sun formed. A third possibility is that during the final stages of planet formation, Mercury was struck by a large planetesimal. Supercomputer simulations show that this cataclysmic collision would have ejected much of the lighter mantle, leaving a disproportionate amount of iron to reaccumulate to form the planet we see today (Figure 11-13).

Clues About the Core: Mercury's Magnetic Field

An important clue to the structure of Mercury's iron core came from the *Mariner 10* magnetometers, which discovered that Mercury has a magnetic field similar to that of the Earth but only about 1% as strong. We saw in Section 7-7 that for a planet to have a global magnetic field, it must have moving liquid material in its interior that conducts electricity. This moving material acts

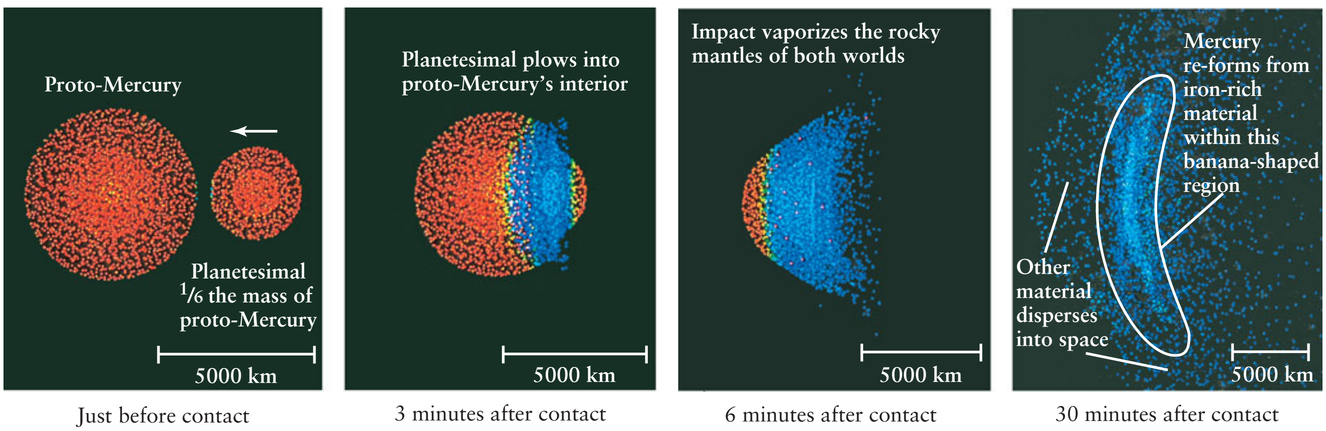
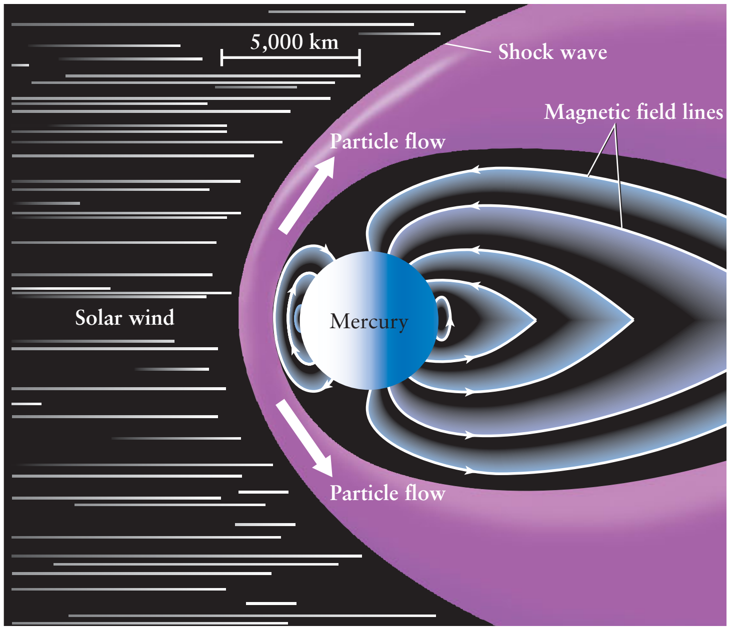


Figure 11-13

Stripping Mercury's Mantle by a Collision To account for Mercury's high iron content, one theory proposes that a collision with a planet-sized object stripped Mercury of most of its rocky mantle. These four images show a supercomputer simulation of a head-on collision between proto-Mercury and a planetesimal one-sixth its mass. (Courtesy of W. Benz, A. G. W. Cameron, and W. Slattery) as a dynamo and generates the magnetic field. Hence, we conclude that (1) at least part of Mercury's core must be in a liquid state, and (2) there must be a source of energy to make material flow within this liquid region in order to produce electric currents. The second requirement is evidence that Mercury, like the Earth, also has a *solid* part of its core: As material deep in the liquid core cools and solidifies to join the solid portion of the core, it releases the energy needed to stir up the motions of the remaining liquid material. Mercury's magnetic field therefore suggests that its core has the same general structure as the Earth's core (recall Figure 9-9).

Mercury's magnetic field comes as something of a surprise. The ancient, cratered surface of Mercury is evidence of a lack of geologic activity, which in turn shows that Mercury must have lost the internal heat that powers such activity. This is as we would expect for such a small planet (see Section 7-6). But the existence of a global magnetic field shows that Mercury is still partially molten inside, which is evidence that the planet has some internal heat. The evidence from cratering and from the global magnetic field are thus in contradiction with each other.

Two other observations further complicate our understanding of Mercury's interior. One is that the amount of electrically conducting molten material that remains within Mercury is thought to be too little to account for even the relatively weak global magnetic field. Another is that a planet must rotate fairly rapidly in order to stir its molten interior into the kind of motion that generates a magnetic field. But as we saw in Section 11-2, Mercury rotates very *slowly:* It takes 58.646 days to spin on its axis. We are forced to conclude that we still have much to learn about the interior of Mercury.



ANIMATION 11.5

Figure 11-14

Mercury's Magnetosphere Mercury's weak magnetic field has only 1% the strength of the Earth's field. This is just strong enough to carve out a cavity in the solar wind, preventing the impinging particles from striking the planet's surface directly. Most of the particles of the solar wind are deflected around the planet in a turbulent region colored purple in this scale drawing. (Compare this with the Earth's much larger magnetosphere, shown in Figure 9-20.)

Mercury's Magnetosphere

Whatever the origin of Mercury's magnetic field, we know that it interacts with the solar wind much as does the Earth's field, although on a much smaller scale (Figure 11-14). The solar wind is a constant flow of charged particles (mostly protons and electrons) away from the outer layers of the Sun's upper atmosphere. A planet's magnetic field can repel and deflect the impinging particles, thereby forming an elongated "cavity" in the solar wind called a magnetosphere. (We discussed the Earth's magnetosphere in Section 9-4.)

Charged-particle detectors aboard *Mariner 10* mapped the structure of Mercury's magnetosphere. When the particles in the solar wind first encounter Mercury's magnetic field, they are abruptly slowed, producing a shock wave that marks the boundary where this sudden decrease in velocity occurs. Most of the particles from the solar wind are deflected around the planet, just as water is deflected to either side of the bow of a ship. Mercury's magnetosphere thus prevents the solar wind from reaching the planet's surface. Because Mercury's magnetic field is much weaker than that of the Earth, it is not able to capture particles from the solar wind. Hence, it has no structures like the Van Allen belts that surround the Earth (recall Figure 9-20).

Future Exploration of Mercury

Much about Mercury still remains unknown. What is the character of the side of the planet that *Mariner 10* did not see? What is the chemical composition of the surface rocks? Was the surface of Mercury once completely molten? What caused Mercury to have such a high iron content? What portion of the planet's core is liquid, and what portion is solid? Is there indeed ice perpetually frozen at the poles? Learning the answers will require extensive observations of Mercury by a spacecraft at close range.

WEB LINK 11.12

One such spacecraft, *MESSENGER* (*ME*rcury *S*urface, *S*pace *EN*vironment, *GE*ochemistry, and *R*anging), was launched in 2004 and is scheduled to go into orbit around Mercury in 2011. Its sophisticated instruments will image the side of the planet that *Mariner 10* did not observe, make detailed measurements of surface composition, and help reveal the nature of Mercury's core. Another Mercury mission, *BepiColombo,* is being planned by the European Space Agency in collaboration with the Japanese Institute of Space and Astronautical Science. Named for the physicist who first proposed Mercury's 3-to-2 spin-orbit coupling, *BepiColombo* is actually two spacecraft: an orbiter that will study the planet itself and a smaller orbiter that will explore Mercury's magnetosphere. If launched as scheduled in 2013, *BepiColombo* will reach Mercury in 2019. Until this new generation of spacecraft begins returning new data, Mercury will remain one of the most enigmatic worlds of the solar system.

11-4 The first missions to Venus and Mars demolished decades of speculations about those planets

Prior to the 1960s, scientists developed a number of intriguing ideas about Venus and Mars. While these ideas were consistent with observations made using Earth-based telescopes, they needed to be radically revised with the advent of spacecraft data.

Speculations About Venus: A Lush Tropical Paradise?

Venus was once thought to be steamy and tropical, and Mars was thought to have vegetation that varied with the seasons

Venus is bathed in more intense sunlight than Earth because it is closer to the Sun. If Venus had no atmosphere, and if its surface had an albedo like that of Mercury or the Moon, heating by the Sun would bring its surface temperature to around 45°C (113°F)—comparable to that found in the hottest regions on Earth. What was unclear until the 1960s was how much effect Venus's atmosphere has on the planet's surface temperature.

We saw in Section 9-1 that gases such as water vapor (H_2O) and carbon dioxide (CO_2) in the Earth's atmosphere trap some of the infrared radiation that is emitted from our planet's surface. This elevates the temperatures of both the atmosphere and its surface, a phenomenon called the greenhouse effect. In 1932, Walter S. Adams and Theodore Dunham Jr. at the Mount Wilson Observatory found absorption lines of CO_2 in the spectrum of sunlight reflected from Venus, indicating that carbon dioxide is also present in the Venusian atmosphere. (Section 7-3 describes how astronomers use spectroscopy to determine the chemical compositions of atmospheres.) Thus, Venus's surface, like the Earth's, should be warmed by the greenhouse effect.

However, Venus's perpetual cloud cover reflects back into space a substantial amount of the solar energy reaching the planet. This effect by itself acts to cool Venus's surface, just as clouds in our atmosphere can make overcast days cooler than sunny days. Some scientists suspected that this cooling kept the greenhouse effect in check, leaving Venus with surface temperatures below the boiling point of water. Venus might then have warm oceans and possibly even life in the form of tropical vegetation. But if the greenhouse effect were strong enough, surface temperatures could be so high that any liquid water would boil away. Then Venus would have a dry, desertlike surface with no oceans, lakes, or rivers.

Close-Up Observations of Venus: Revealing a Broiled Planet

This scientific controversy was resolved in 1962 when the unmanned U.S. spacecraft *Mariner 2* (Figure 11-15) made the first close flyby of Venus. As we learned in Sections 5-3 and 5-4, a dense object (like a planet's surface) emits radiation whose intensity and spectrum depend on the temperature of the object. *Mariner 2* carried instruments that measured radiation coming from the planet at two microwave wavelengths, 1.35 cm and 1.9 cm. Venus's atmosphere is transparent to both these wavelengths, so *Mariner 2* saw radiation that had been emitted by the planet's surface and then passed through the atmosphere like visible light through glass.

WEB LINK 11.13

Figure 11-15

The *Mariner 2* Spacecraft *Mariner 2* was the first of all spacecraft from Earth to make a successful flyby of another planet. After coming within 34,773 km of Venus on December 14, 1962, it went into a permanent orbit around the Sun. (GSFC/NASA)

From the amount of radiation that *Mariner 2* detected at these two wavelengths, astronomers concluded that the surface temperature of Venus was more than 400°C—well above the boiling point of water and higher than even daytime temperatures on Mercury. Thus, there cannot be any liquid water on the planet's surface. Water vapor absorbs microwaves at 1.35 cm, so if there were substantial amounts of water vapor in Venus's atmosphere, it would have blocked this wavelength from reaching the detectors on board *Mariner 2*. In fact, the spacecraft did detect strong 1.35-cm emissions from Venus. Thus, the atmosphere, too, must be all but devoid of water.

This picture of Venus as a dry, hellishly hot world was confirmed in 1970 by the Soviet spacecraft *Venera 7*, which survived a descent through the Venusian atmosphere and managed to transmit data for a few seconds directly from the planet's surface. *Venera 7* and other successful Soviet landers during the early 1970s finally determined the surface temperature to be a nearly constant 460°C (860°F). Thus, Venus has an extraordinarily strong greenhouse effect, and the planet's surface is no one's idea of a tropical paradise.

Speculations About Mars: A World With Plant Life and Canals?

As we saw in Section 11-2, Mars's axis of rotation is tilted by almost the same angle as the Earth's axis, and so Mars goes through seasons much like those on Earth. Observations with Earth-based telescopes show that the colors of Mars (see Figure 11-4*c*) vary with the seasons: During spring and summer in a Martian hemisphere, the polar cap in that hemisphere shrinks and the dark markings (which sometimes look greenish) become very distinct. Half a Martian year later, with the approach of fall and winter, the dark markings fade and the polar cap grows. Could these seasonal variations mean that there is vegetation on Mars that changes seasonally, just as on the Earth? And if there is plant life on Mars, might there not also be intelligent beings?

Such speculations were fueled by the Italian astronomer Giovanni Schiaparelli, who observed Mars during the favorable opposition of 1877. He reported that during moments of "good seeing," when the air is exceptionally calm and clear, he was able to see 40 straight-line features crisscrossing the Martian surface (Figure 11-16). He called these dark linear features *canali*, an Italian word for "channels," which was soon mistranslated into English as "canals." The alleged discovery of canals implied that there were intelligent creatures on Mars capable of substantial engineering feats. This speculation helped motivate the American millionaire Percival Lowell to finance a major new observatory near Flagstaff, Arizona, primarily to study Mars. By the end of the nineteenth century, Lowell had reported observations of 160 Martian canals.

Although many astronomers observed Mars, not all saw the canals. In 1894, the American astronomer Edward Barnard, working at Lick Observatory in California, complained that "to save my soul I can't believe in the canals as Schiaparelli draws them." But objections by Barnard and others did little to sway the proponents of the canals.

As the nineteenth century drew to a close, speculation about Mars grew more and more fanciful. Perhaps the reddish-brown color of the planet meant that Mars was a desert world, and perhaps the Martian canals were an enormous planetwide irrigation network. From these ideas, it was a small leap to envision Mars as a dying world with canals carrying scarce water from melting polar caps to farmlands near the equator. The terrible plight of the Martian race formed the basis of inventive science fiction by Edgar Rice Burroughs, Ray Bradbury, and many others. It also led to the notion that the Martians might be a warlike race who schemed to invade the Earth for its abundant resources. (In Roman mythology, Mars was the god of war.) Stories of alien invasions, from H. G. Wells's 1898 novel *The War of the Worlds* down to the present day, all owe their existence to the *canali* of Schiaparelli.

Figure 11-16

The Mirage of the Martian Canals Giovanni Schiaparelli studied the Martian surface using a 20-cm (8-in.) telescope, the same size used by many amateur astronomers today. He recorded his observations in drawings like this one, which shows a network of linear features that Percival Lowell and others interpreted as irrigation canals. Later observations with larger telescopes revealed that the "canals" were mere illusions. (Michael Hoskin, ed., *The Cambridge Illustrated History of Astronomy*, Cambridge University Press, 1997, p. 286. Illustration by G. V. Schiaparelli. Courtesy Institute of Astronomy, University of Cambridge, UK)

Observations of Mars: Revealing a Windblown, Cratered World

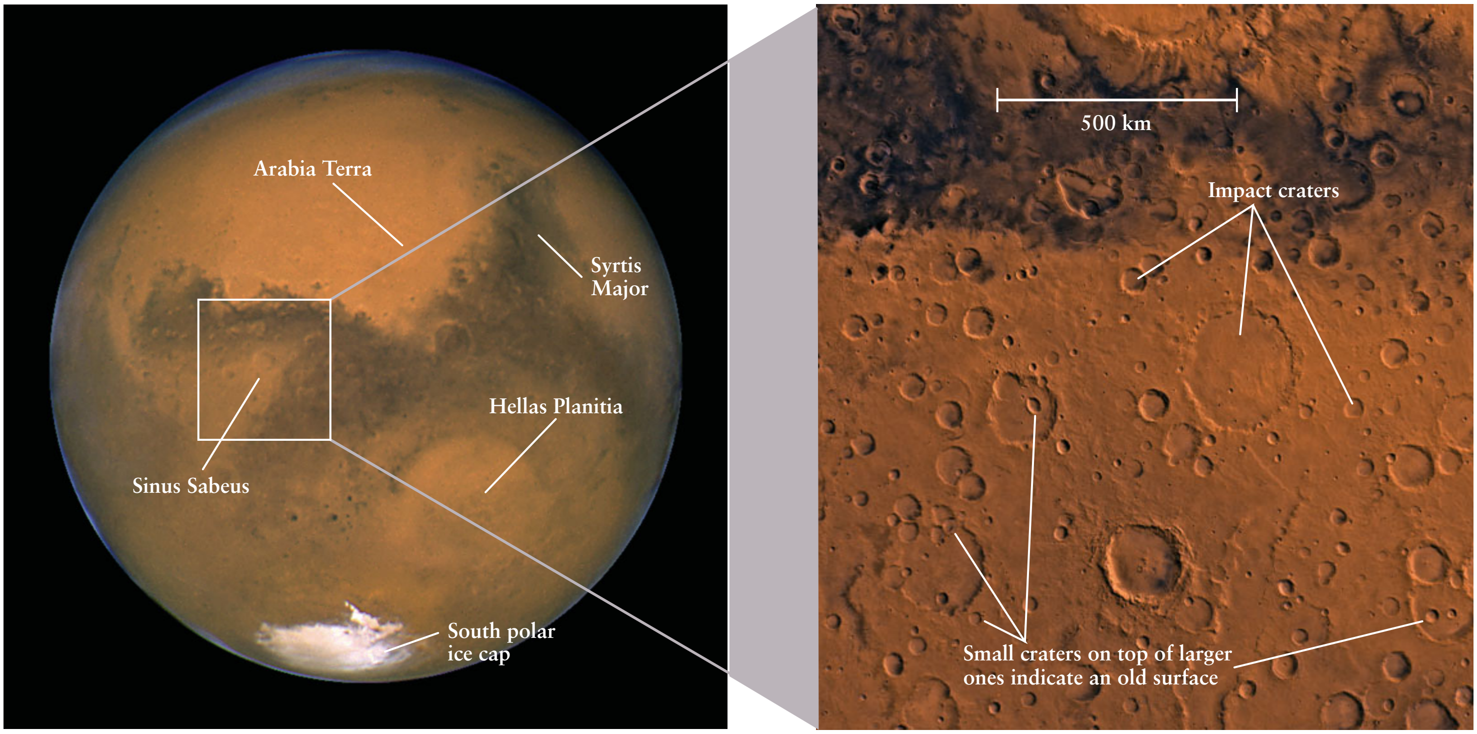
However, during the first decades of the twentieth century the Greek astronomer Eugène Antoniadi observed Mars with a state-of-the-art telescope and found that the "canals" were actually unconnected dark spots. There was no evidence whatsoever of linear canals. Why, then, were Schiaparelli, Lowell, and others so certain that the canals were there? One reason is that their observations were made from the Earth's surface, at the bottom of an often turbulent atmosphere that blurs images seen through a telescope. A second reason is that the human eye and brain can readily be deceived. The brain can connect together two dark streaks on the Martian surface to give the perception of a single "canal." In this way did astronomers such as Schiaparelli and Lowell delude themselves.

WEB LINK 11.14

The other speculation, that Mars was covered with vegetation, was conclusively ruled out several decades later. In the 1960s, three American spacecraft flew past Mars and sent back the first close-up pictures of the planet's surface. (Figure 11-17 shows even better images from a subsequent mission to Mars.) These images showed that the dark surface markings are just different-colored terrain.

Why did many Earth-based observers report that dark areas on Mars had the greenish hue of vegetation? The probable explanation is a quirk of human color vision. When a neutral gray area is viewed next to a bright red or brown area, the eye perceives the gray to have a blue-green color.

The seasonal variations in color can be explained by winds in the Martian atmosphere that blow in different directions in different seasons. These seasonal winds blow fine dust across the Martian surface, producing planetwide dust storms that can be seen from Earth (Figure 11-18). The motion of dust covers some parts of the Martian terrain and exposes others. Thus, Earth observers see large areas of the planet vary from dark to light with



(a) Mars from the Hubble Space Telescope

(b) Closeup of Sinus Sabeus region

Figure 11-17 R I V U X G

Martian Craters **(a)** This image, made during the favorable opposition of 2003, shows cratered regions on the side of Mars opposite to that in the image that opens this chapter. Arabia Terra is dotted with numerous flat-bottom craters. Syrtis Major was first identified by Christiaan Huygens in 1659. A single titanic impact carved out Hellas Planitia, which is 5 times the size of Texas. **(b)** This mosaic of images from the *Viking Orbiter 1* and *2* spacecraft shows an extensively cratered region located south of the Martian equator. (a: NASA; J. Bell, Cornell University; and M. Wolff, SSI; b: USGS)

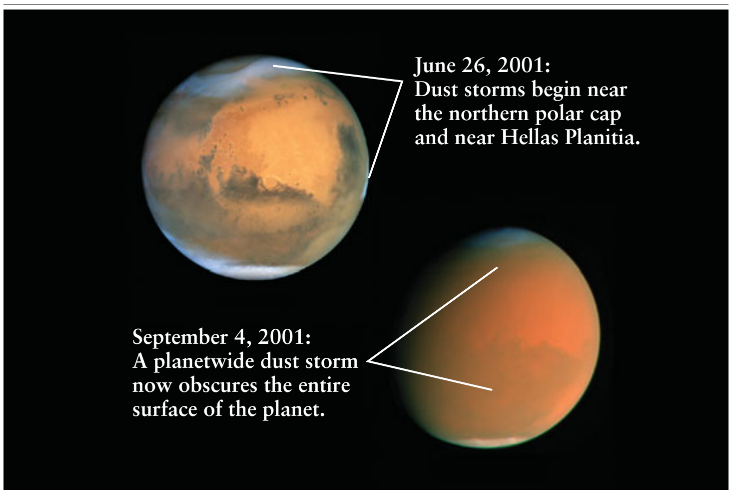


Figure 11-18 R I V U X G

A Martian Dust Storm Dust storms on Mars can expand to cover the entire planet. These Hubble Space Telescope images show a particularly intense storm that took place in 2001, when it was spring in the Martian northern hemisphere and autumn in the southern hemisphere. (NASA; J. Bell, Cornell University; M. Wolff, SSI; and the Hubble Heritage Team, STScI/AURA)

the passage of the seasons, mimicking the color changes that would be expected from vegetation.

The most remarkable discovery of the missions to Mars in the 1960s was that the planet's surface is pockmarked with craters, as Figure 11-17*b* and Figure 7-10*c* show. (Although many of the Martian craters are quite large, they had escaped detection from Earth because the thin Martian atmosphere obscures the planet's surface somewhat. That is why even Hubble Space Telescope images like Figure 11-17*a* do not show Martian craters distinctly, and why it took close-up images made by spacecraft near Mars to reveal these craters.) During that same decade of the 1960s scientists were learning that most of the craters on the Moon were formed by interplanetary debris that struck the lunar surface more than 3 billion years ago. The Martian craters, too, are the result of long-ago impacts from space. Since so many craters survive to the present day, at least part of the Martian surface must be extremely ancient (see Section 7-6).

The episode of the Martian canals and Martian vegetation was not the first time that a number of scientists came to very wrong conclusions. Like any human activity, science will always involve human error and human frailties. But scientific investigation is fundamentally self-correcting, because new observations and experiments can always call into question the scientific theories of the past.

11-5 Both Venus and Mars have volcanoes and craters—but no Earthlike plate tectonics

From a distance, Venus and Mars appear radically different: Venus is nearly the size of Earth and has a thick atmosphere, while Mars is much smaller and has only a thin atmosphere. Yet spacecraft observations reveal that these two worlds have many surface features in common, including volcanoes and impact craters. By comparing the surfaces of these two worlds to the Earth we can gain insight into the similarities and differences between the three largest terrestrial planets.

Venus has no plate tectonics because its crust is too thin, while on Mars the crust is too thick

Observing Venus and Mars from Orbit

WEB LINK 11.15

To make a detailed study of a planet's surface, a spacecraft that simply flies by the planet will not suffice. Instead, it is necessary to place a spacecraft in orbit around the planet. Since the 1970s a number of spacecraft have been placed in Venus orbit and Mars orbit.

In order to map the surface of Venus through the perpetual cloud layer, several of the Venus orbiters carried radar devices. A beam of microwave radiation from the orbiter easily penetrates Venus's clouds and reflects off the planet's surface; a receiver on the orbiter then detects the reflected beam. Different types of terrain reflect microwaves more or less efficiently, so astronomers are able to construct a map of the Venusian surface by analyzing the reflected radiation.

ANIMATION 11.6

Magellan, the most recent spacecraft to orbit Venus, also carried a radar altimeter that bounced microwaves directly off the ground directly below the spacecraft. By measuring the time delay of the reflected waves, astronomers can determine the height and depth of Venus's terrain.

By contrast, a Mars orbiter can use more conventional telescopes to view the Martian surface through that planet's thin atmosphere. Instead of using a radar altimeter to map surface elevations, the *Mars Global Surveyor* spacecraft (which entered Mars's orbit in 1997) used a laser beam for the same purpose.

The Topography of Venus and Mars

Figure 11-19 and Figure 11-20 show topographic maps of Venus and Mars derived using radar and laser altimeters respectively. (Note that the scale of these two maps is different: The diameter of Mars is only 56% as large as the diameter of Mars.) The topographies of both worlds differ in important ways from that of our Earth. Our planet has two broad classes of terrain: About 71% of the surface is oceanic crust and about 27% is continental crust that rises above the ocean floors by about 4–6 km on average. On Venus, by contrast, about 60% of the terrain lies within

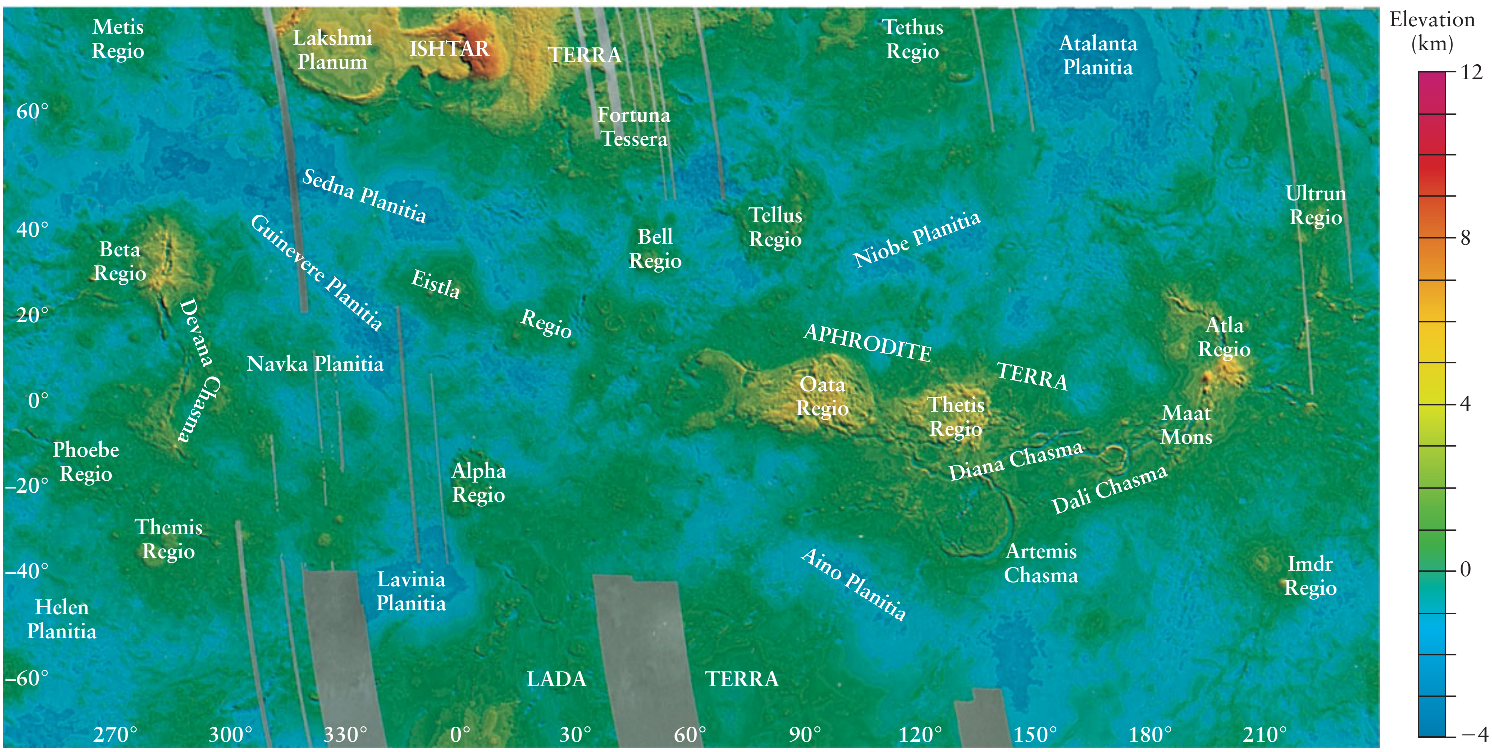
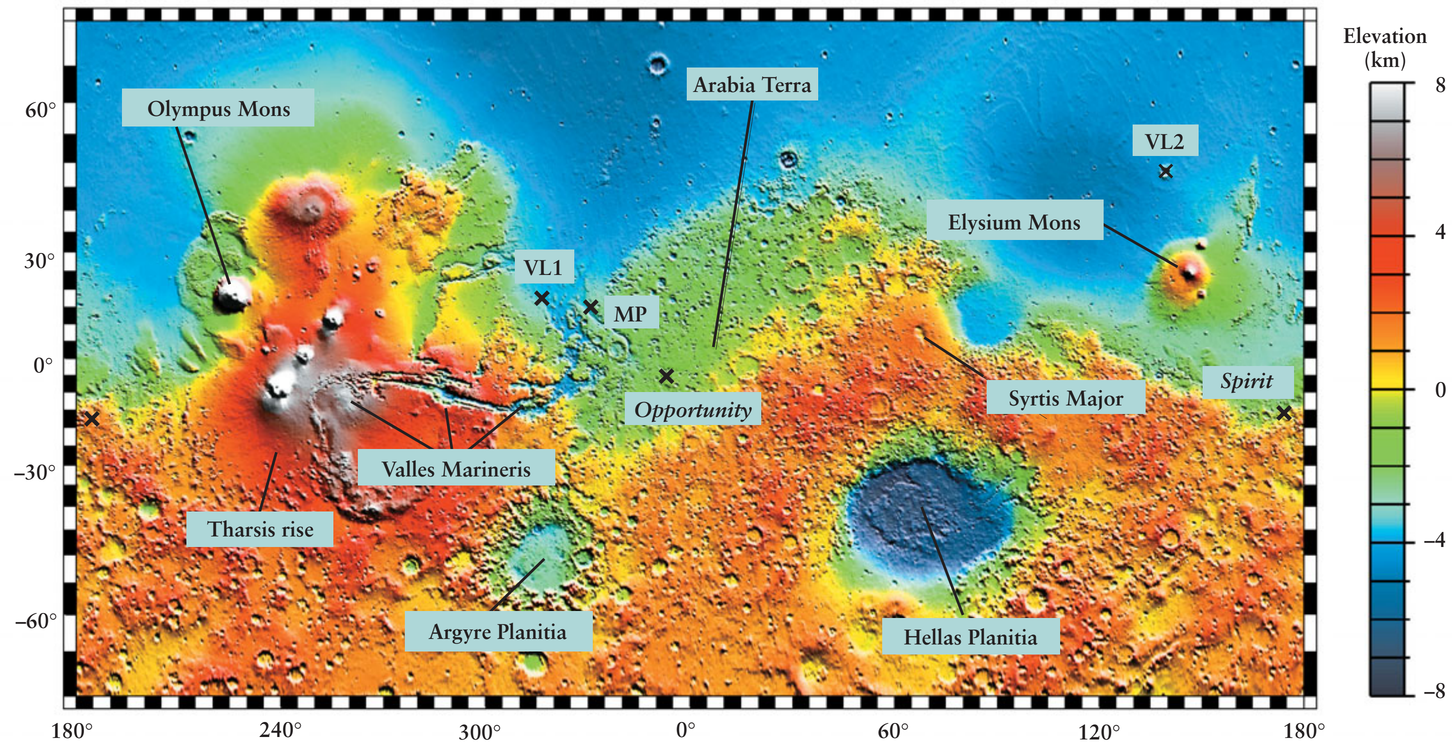


Figure 11-19 R I V U X G

A Topographic Map of Venus Radar altimeter measurements by *Magellan* were used to produce this topographic map of Venus. Color indicates elevations above (positive numbers) or below (negative numbers) the planet's average radius. (The blue areas are *not* oceans!). Gray areas were not mapped by *Magellan*. Flat plains of volcanic origin cover most of the planet's surface, with only a few continentlike highlands. (Peter Ford, MIT; NASA/JPL)



ANIMATION 11.7

Figure 11-20 R I V U X G

A Topographic Map of Mars This map was generated from measurements made by the laser altimeter on board the *Mars Global Surveyor* spacecraft. As in Figure 11-19, color indicates elevations above or below the planet's average radius. Most of the southern hemisphere lies several kilometers above the northern hemisphere, with the exception of the immense impact feature called Hellas Planitia. The landing sites for *Viking Landers 1* and *2* (VL1 and VL2), *Mars Pathfinder* (MP), and the *Mars Exploration Rovers* (*Spirit* and *Opportunity*) are each marked with an X. (MOLA Science Team, NASA/GSFC)

500 m of the average elevation, with only a few localized highlands (shown in yellow and red in Figure 11-19). Mars is different from both Earth and Venus: Rather than having continents scattered among low-lying ocean floors, all of the high terrain on Mars (shown in red and orange in Figure 11-20) is in the southern hemisphere. Hence, planetary scientists refer to Mars as having **northern lowlands** and **southern highlands.** The implication is that the Martian crust is about 5 km thicker in the southern hemisphere than in the northern hemisphere, a situation called the **crustal dichotomy.** In this sense Mars resembles the Moon, which has a thicker crust on the far side than on the side that faces the Earth (see Section 10-1).

Tectonics on Venus: A Light, Flaky Crust

Before radar maps like Figure 11-19 were available, scientists wondered whether Venus had plate tectonics like those that have remolded the face of the Earth. Venus is only slightly smaller than the Earth, and should have retained enough heat to sustain a molten interior and the convection currents that drive tectonic activity on Earth (see Section 9-3, especially Figure 9-16). If this were the case, then the same tectonic effects might also have shaped the surface of Venus. As we saw in Section 9-3, the Earth's hard outer shell, or lithosphere, is broken into about a dozen large plates that slowly shuffle across the globe. Long mountain ranges, like the Mid-Atlantic Ridge (see Figure 9-13), are created where fresh magma wells up from the Earth's interior to push the plates apart.

Radar images from *Magellan* show *no* evidence of Earthlike tectonics on Venus. On Earth, long chains of volcanic mountains (like the Cascades in North America or the Andes in South America) form along plate boundaries where subduction is taking place. Mountainous features on Venus, by contrast, do not appear in chains. There are also no structures like the Earth's Mid-Atlantic Ridge, which suggests that there is no seafloor spreading on Venus. With no subduction or seafloor spreading, there have been only limited horizontal displacement of Venus's lithosphere. Thus, like the Moon (see Section 10-1) and Mercury (see Section 11-3), Venus is a one-plate planet.

Unlike the Moon, however, Venus has had local, small-scale deformations and reshaping of the surface. One piece of evidence for this is that roughly a fifth of Venus's surface is covered by folded and faulted ridges. Further evidence comes from close-up *Magellan* images that show that Venus has about a thousand craters larger than a few kilometers in diameter, many more than have been found on Earth but only a small fraction of the number on the Moon or Mercury. We saw in Section 7-6 that the number of impact craters is a clue to the age of a planet's surface. Such craters formed at a rapid rate during the early history of the solar system, when considerable interplanetary debris still orbited

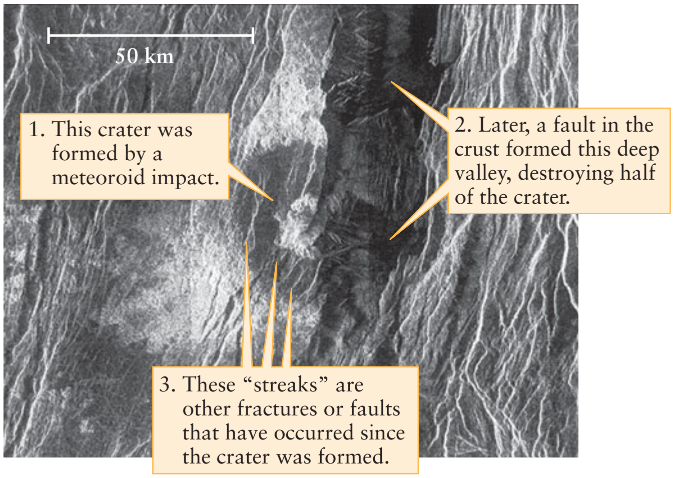


Figure 11-21 R I V U X G

A Partially Obliterated Crater on Venus This *Magellan* image shows how the right half of an old impact crater 37 km (20 mi) in diameter was erased by a fault in the crust. This crater lies in Beta Regio (see the left side of Figure 11-19). Most features on Venus are named for women in history and legend; this crater commemorates Emily Greene Balch, an American economist and sociologist who won the 1946 Nobel Peace Prize. (NASA/JPL)

the Sun, and have formed at a much slower rate since then. Consequently, the more craters a planet has, the older its surface. The number of craters on Venus indicates that the Venusian surface is roughly 500 million years old. This is about twice the age of the Earth's surface but much younger than the surfaces of the Moon or Mercury, each of which is billions of years old. No doubt Venus was more heavily cratered in its youth, but localized activity in its crust has erased the older craters (Figure 11-21).

Surprisingly, Venus's craters are uniformly scattered across the planet's surface. We would expect that older regions on the surface—which have been exposed to bombardment for a longer time—would be more heavily cratered, while younger regions would be relatively free of craters. For example, the ancient highlands on the Moon are much more heavily cratered than the younger maria (see Section 10-4). Because such variations are not found on Venus, scientists conclude that the entire surface of the planet has essentially the *same* age. This is very different from the Earth, where geological formations of widely different ages can be found.

One model that can explain these features suggests that the convection currents in Venus's interior are actually more vigorous than inside the Earth, but that the Venusian crust is much thinner than the continental crust on Earth. Rather than sliding around like the plates of the Earth's crust, the thin Venusian crust stays in roughly the same place but undergoes wrinkling and flaking (Figure 11-22). Hence, this model is called **flake tectonics.** The Earth, too, may have displayed flake tectonics billions of years ago when its interior was hotter.

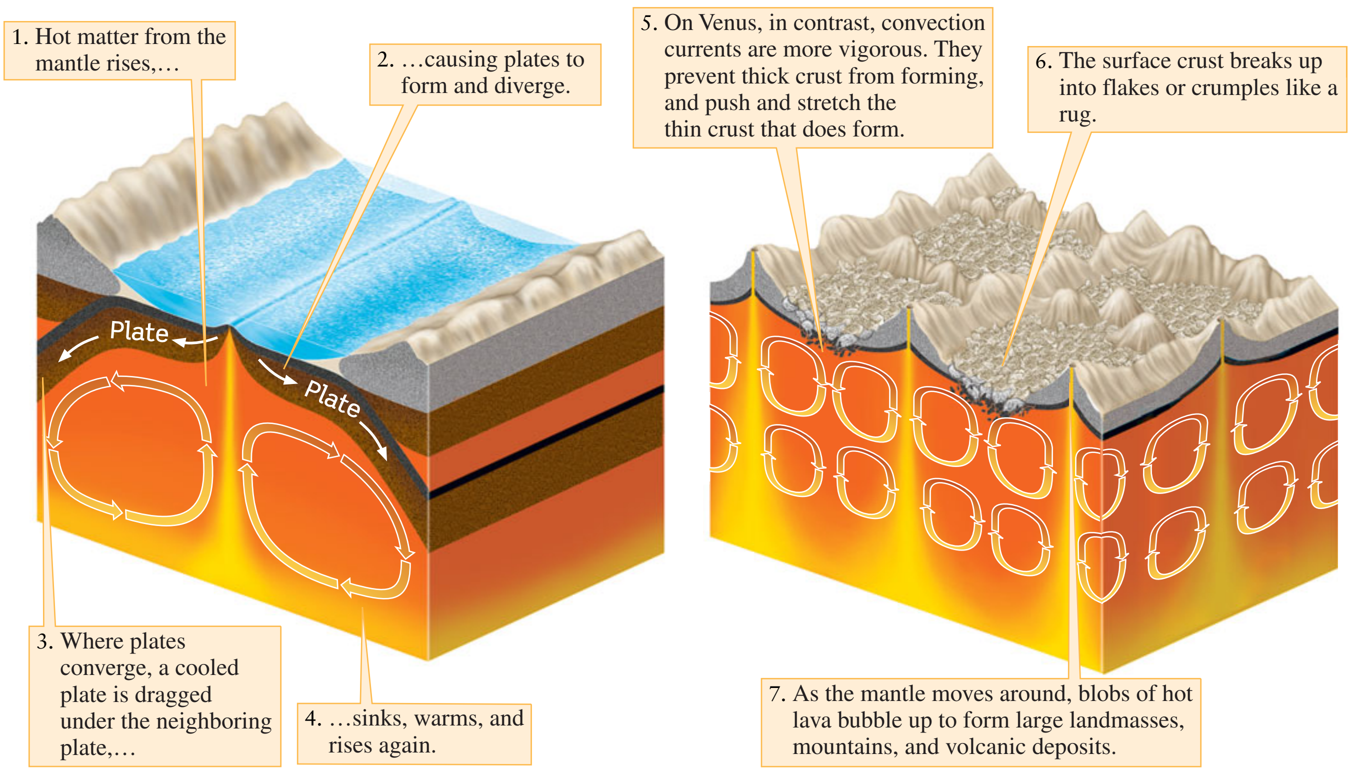


Figure 11-22

Plate Tectonics Versus Flake Tectonics This illustration shows the difference between plate tectonics on Earth and the model of flake tectonics on Venus. (Adapted from T. Grotzinger, T. H. Jordan, F. Press, and R. Siever, *Understanding Earth*, 5th ed., W. H. Freeman, 2007)

Although Venus almost certainly has molten material in its interior, it has no planetwide magnetic field. As we discussed in Section 7-7, this may be because Venus rotates too slowly to generate the kind of internal motions that would produce a magnetic field. With no magnetic field, Venus has no magnetosphere. The planet is nonetheless shielded from the solar wind by ions in its upper atmosphere.

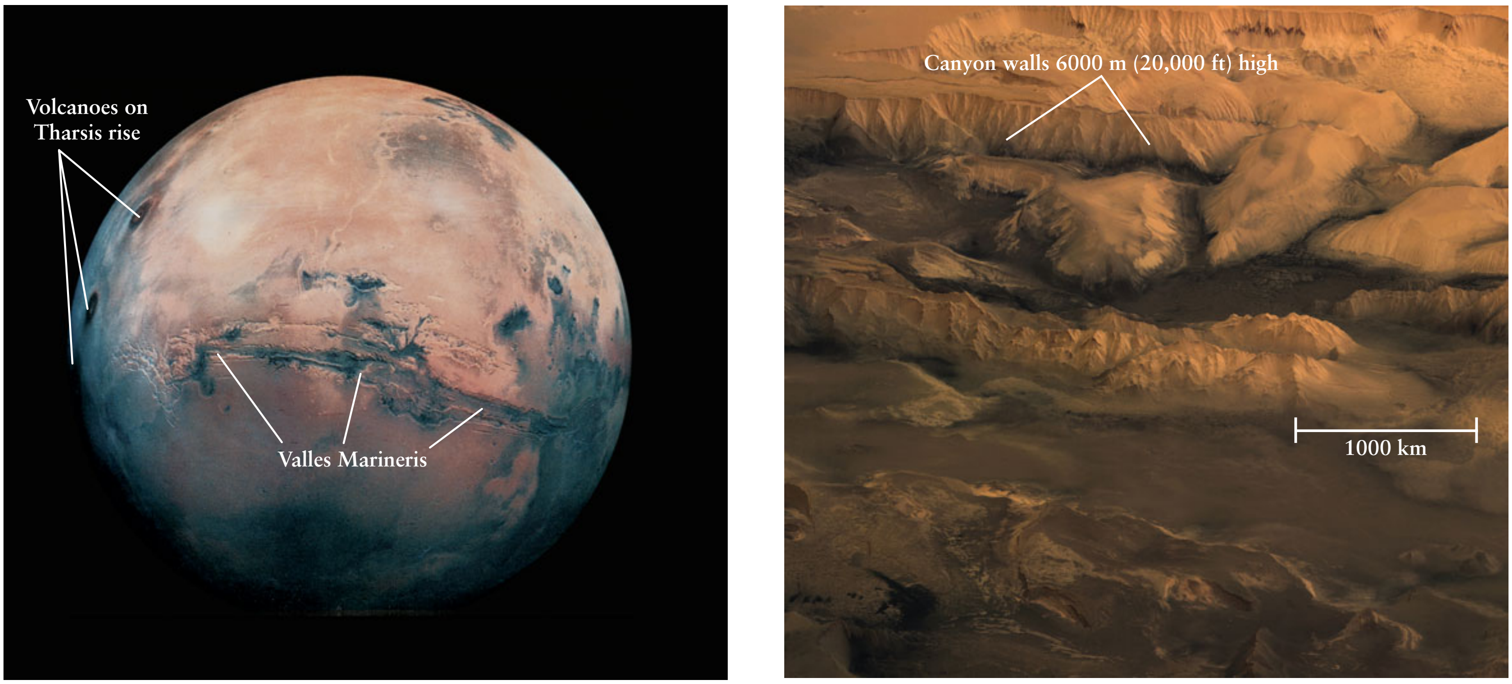
Tectonics on Mars: A Thick, Rigid Crust

Like Venus, Mars lacks the global network of ridges and subduction zones that plate tectonics has produced on the Earth. Hence, the entire crust of Mars makes up a single tectonic plate, as is the case on the Moon, Mercury, and Venus. The explanation is quite different from that for Venus, however: Because Mars is a much smaller world than Earth or Venus, the outer layers of the red planet have cooled more extensively. Thus, Mars lacks plate tectonics because its crust is too thick for one part of the crust to be subducted beneath another. We see that for a terrestrial planet to have plate tectonics, the crust must not be too thin (like Venus) or too thick (like Mars), but just right (like Earth).

This idea has been verified by carefully monitoring the motion of a spacecraft orbiting Mars. If there is a concentration of mass (such as a thicker crust) at one location on the planet, gravitational attraction will make the spacecraft speed up as it approaches the concentration and slow down as it moves away. A team of scientists headed by David Smith of NASA's Goddard Space Flight Center and Maria Zuber of MIT analyzed the orbit of *Mars Global Surveyor* in just this way. They found that unlike the Earth's crust, which varies in thickness from 5 to 35 km, the Martian crust is about 40 km thick under the northern lowlands but about 70 km thick under the southern highlands. Both regions of the Martian crust are too thick to undergo subduction, making plate tectonics impossible.

Although there is no plate motion on Mars, there are features on the planet's surface that indicate there has been substantial motion of material in the Martian mantle. The Tharsis rise, visible on the left-hand side of Figure 11-20, is a dome-shaped bulge that has been lifted 5 to 6 km above the planet's average elevation. Apparently, a massive plume of magma once welled upward from a hot spot under this region. East of the Tharsis rise, a vast chasm runs roughly parallel to the Martian equator (Figure 11-23). If this canyon were located on Earth, it would stretch from Los Angeles to New York. In honor of the *Mariner 9* spacecraft that first revealed its presence in 1971, this chasm has been named Valles Marineris.

Valles Marineris has heavily fractured terrain at its western end near the Tharsis rise. At its eastern end, by contrast, it is dominated by ancient cratered terrain. Many geologists suspect that Valles Marineris was caused by the same upwelling of material



(a) Mars and Valles Marineris

(b) The central region of Valles Marineris

Figure 11-23 R I **V** U X G

Valles Marineris (a) This mosaic of *Viking Orbiter* images shows the huge rift valley of Valles Marineris, which extends from west to east for more than 4000 km (2500 mi) and is 600 km (400 mi) wide at its center. Its deepest part is 8 km (5 mi) beneath the surrounding plateau. At its western end is the Tharsis rise. Compare this image with Figure 11-20. **(b)** This perspective image from the *Mars Express* spacecraft shows what you would see from a point high above the central part of Valles Marineris. (a: USGS/NASA; b: ESA/DLR/FU Berlin, G. Neukum) that formed the Tharsis rise. As the Martian surface bulged upward at Tharsis, there would have been tremendous stresses on the crust, which would have caused extensive fracturing. Thus, Valles Marineris may be a **rift valley,** a feature created when a planet's crust breaks apart along a fault line. Rift valleys are found on Earth; two examples are the Red Sea (see Figure 9-17) and the Rhine River valley in Europe. Other, smaller rifts in the Martian crust are found all around the Tharsis rise. All of these features are very old, however, and it is thought that there has been little geologic activity on Mars for billions of years.

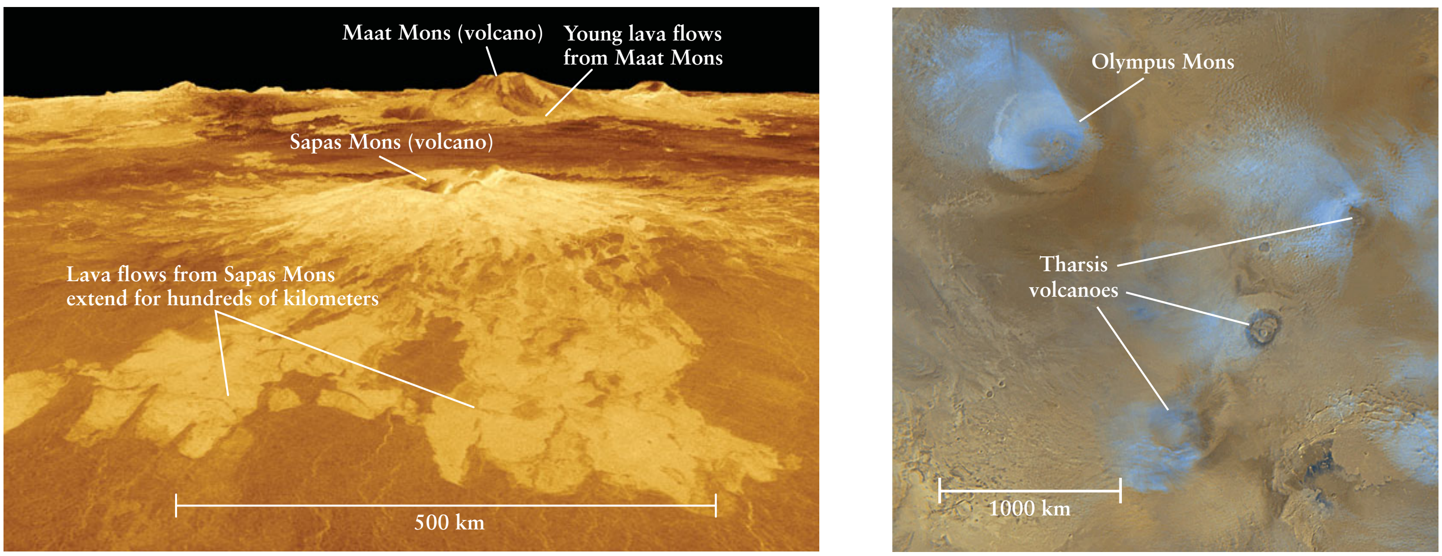
Additional evidence that may point to ancient geologic activity on Mars is the crustal dichotomy between the northern lowlands and the southern highlands. The southern highlands are much more heavily cratered than either Earth or Venus, though less so than the Moon, while the northern lowlands are remarkably smooth and free of craters. (You can see this difference in Figure 11-20.) Since most cratering occurred early in the history of the solar system, this implies that the northern lowlands are relatively young, while the more heavily cratered southern highlands are relatively old. One proposed explanation is that older craters in the northern lowlands were erased by tectonic activity that took place long ago when the Martian crust had not yet cooled to its present thickness. Other hypotheses are that older craters could have been erased by a giant asteroid impact or by lava flows.

A final piece of evidence about ancient Mars is the existence of locally magnetized areas in the old southern highlands. These areas presumably solidified during an era in which the interior of Mars was much hotter, and moving, molten material in the interior developed a magnetic field. Today, by contrast, Mars has no planetwide magnetic field. There is probably still molten material in the core, but the Martian core is thought to contain substantial amounts of sulfur in addition to iron. While temperatures in the core should be high enough to melt sulfur and sulfur compounds, the electrical properties of these substances are such that their motions do not generate the electric currents needed to produce a magnetic field.

Volcanoes on Venus and Mars

Radar images of Venus and visible-light images of Mars show that both planets have a number of large volcanoes (Figure 11-24). *Magellan* observed more than 1600 major volcanoes and volcanic features on Venus, two of which are shown in Figure 11-24*a*. Both of these volcanoes have gently sloping sides. A volcano with this characteristic is called a **shield volcano,** because in profile it resembles an ancient Greek warrior's shield lying on the ground. Martian volcanoes are less numerous than those on Venus, but they are also shield volcanoes; the largest of these, Olympus Mons, is the largest volcano in the solar system (Figure 11-24*b*). Olympus Mons rises 24 km (15 mi) above the surrounding plains. By comparison, the highest volcano on Earth, Mauna Loa in the Hawaiian Islands, has a summit only 8 km (5 mi) above the ocean floor.

Most volcanoes on Earth are found near the boundaries of tectonic plates, where subducted material becomes molten magma and rises upward to erupt from the surface. This cannot explain the volcanoes of Venus and Mars, since there are no subduction



(a) Volcanoes and lava flows on Venus R I V U X G

(b) Cloud-topped volcanoes on Mars R I V U X G

Figure 11-24

Volcanoes on Venus and Mars **(a)** The false color in this computer-generated perspective view suggests the actual color of sunlight that penetrates Venus's thick clouds. The brighter color of the extensive lava flows indicates that they reflect radio waves more strongly. To emphasize the gently sloping volcanoes, the vertical scale has been exaggerated 10 times. **(b)** The volcanoes of Mars also have gently sloping sides. In this view looking down from Mars orbit you can see bluish clouds topping the summits of the volcanoes. These clouds, made of water ice crystals, form on most Martian afternoons. (a: NASA, JPL Multimission Image Processing Laboratory; b: NASA/JPL/Malin Space Science Systems)

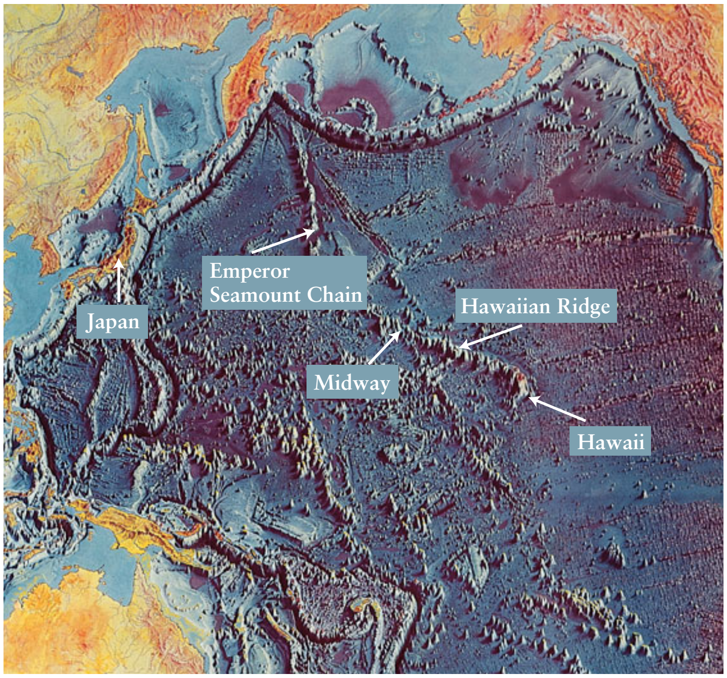


Figure 11-25

Hot-Spot Volcanoes on Earth A hot spot under the Pacific plate has remained essentially stationary for 70 million years while the plate has moved some 6000 km to the northwest. The upwelling magma has thus produced a long chain of volcanoes. The Hawaiian Islands are the newest of these; the oldest, the Emperor Seamount Chain, have eroded so much that they no longer protrude above the ocean surface.

zones on those planets. Instead, Venusian and Martian volcanoes probably formed by **hot-spot volcanism.** In this process, magma wells upward from a hot spot in a planet's mantle, elevating the overlying surface and producing a shield volcano.

On Earth, hot-spot volcanism is the origin of the Hawaiian Islands. These islands are part of a long chain of shield volcanoes that formed in the middle of the Pacific tectonic plate as that plate moved over a long-lived hot spot (Figure 11-25). On Venus and Mars, by contrast, the absence of plate tectonics means that the crust remains stationary over a hot spot. On Mars, a single hot spot under Olympus Mons probably pumped magma upward through the same vent for millions of years, producing one giant volcano rather than a long chain of smaller ones. The Tharsis rise and its volcanoes (see Figure 11-20, Figure 11-23*a*, and Figure 11-24*b*) may have formed from the same hot spot as gave rise to Olympus Mons; a different hot spot on the opposite side of Mars produced a smaller bulge centered on the volcano Elysium Mons, shown near the right-hand side in Figure 11-20. The same process of hot-spot volcanism presumably gave rise to large shield volcanoes on Venus like those shown in Figure 11-24*a*.

Volcanic Activity on Venus

About 80% of the surface of Venus is composed of flat plains of volcanic origin. In other words, essentially the entire planet is covered with lava! This observation shows the tremendous importance of volcanic activity in Venusian geology.

To verify the volcanic nature of the Venusian surface, it is necessary to visit the surface and examine rock samples. Figure 11-26 is a panoramic view taken in 1981 by the Soviet spacecraft *Venera 13*, one of 10 unmanned spacecraft that the Soviet Union landed successfully on the surface of Venus. Russian scientists hypothesize that this region was covered with a thin layer of lava that fractured upon cooling to create the rounded, interlocking shapes seen in the photograph. This hypothesis agrees with information obtained from chemical analyses of surface material made by the spacecraft's instruments. These analyses indicate that the surface composition is similar to lava rocks called basalt, which are common on the Earth (see Figure 9-19*a*) and in the maria of the Moon (see Figure 10-13). The results from *Venera 13* and other landers are consistent with the picture of Venus as a world whose surface and atmosphere have been shaped by volcanic activity.

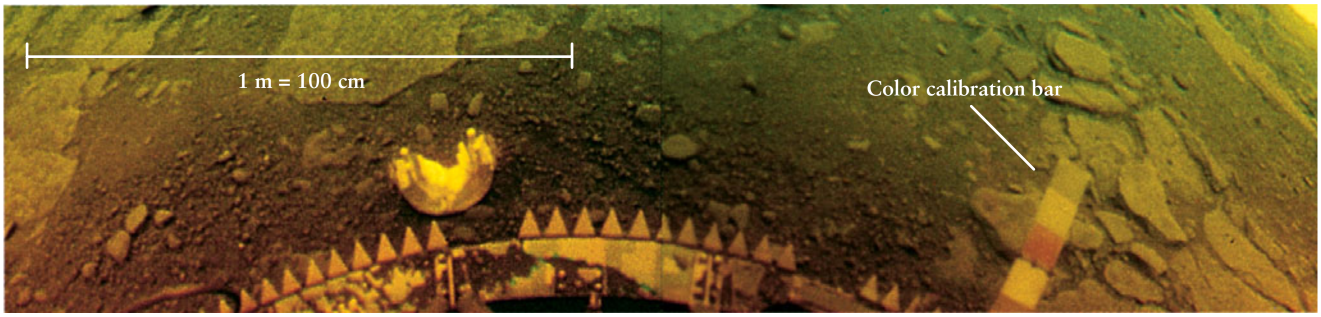
Most of the volcanoes on Venus are probably inactive at present, just as is the case with most volcanoes on Earth. But *Magellan* found evidence of recent volcanic activity, some of which may be continuing today. The key to estimating the amount of recent volcanic activity is that the radar reflectivity of volcanic materials depends on whether the material is relatively fresh or relatively old. By mapping these reflectivity variations on Venus, *Magellan* found many areas with young lava flows. Some of the youngest material found by *Magellan* caps the volcano Maat Mons (see Figure 11-24*a*). Geologists estimate that the topmost material is no more than 10 million years old and could be much younger. The presence of such young lava flows suggests that Venus, like the Earth, has some present-day volcanic activity.

Another piece of evidence for ongoing volcanic activity on Venus comes from the planet's atmosphere. An erupting volcano on Earth, like the one shown in Figure 9-15, ejects substantial amounts of sulfur dioxide, sulfuric acid, and other sulfur compounds into the air. Many of these substances are highly reactive and short-lived, forming sulfate compounds that become part of the planet's surface rocks. For these substances to be relatively abundant in a planet's atmosphere, they must be constantly replenished by new eruptions. Sulfur compounds make up about 0.015% of the Venusian atmosphere, compared to less than 0.0001% of Earth's atmosphere. This suggests that ongoing volcanic eruptions on Venus are ejecting sulfur compounds into the atmosphere to sustain the high sulfur content.

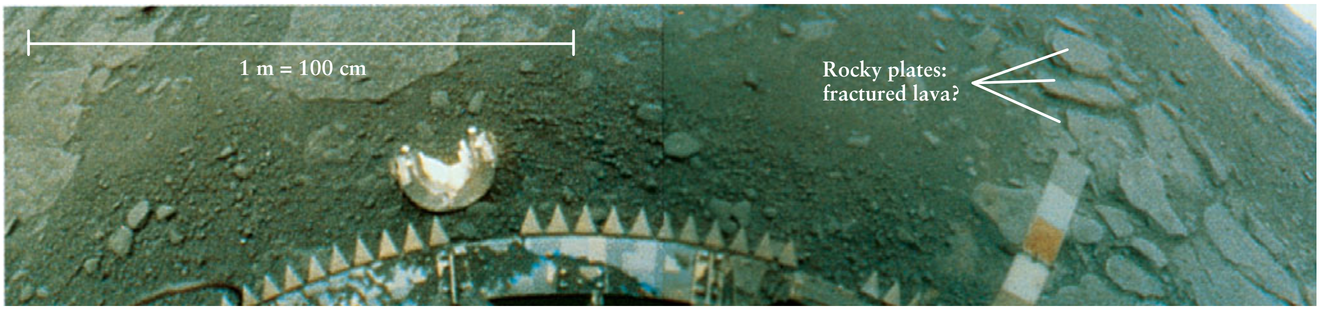
Volcanic Activity on Mars

Spectroscopic observations from Mars's orbit confirm that the planet's rocks and sands are made almost entirely of the three minerals feldspar, pyroxene, and olivine. These are the components of basalt, or solidified lava. Thus, Mars, like Venus, had a volcanic past.

Unlike lava flows on Venus, however, most of the lava flows on Mars have impact craters on them. The interpretation is that most Martian lava flows are very old and that most of the volcanoes on the red planet are no longer active. This is what we would expect from a small planet whose crust has cooled and solidified to a greater depth than on Earth, making



(a) Image from *Venera 13*



(b) Color-corrected image

Figure 11-26 R I V U X G

A Venusian Landscape (a) This wide-angle color photograph from *Venera 13* shows the rocky surface of Venus. The thick atmosphere absorbs the blue component of sunlight, giving the image an orange tint: The stripes on the spacecraft's color calibration bar that appear yellow are actually white in color. **(b)** This color-corrected view shows that the rocks are actually gray in color. The rocky plates covering the ground may be fractured segments of a thin layer of lava. (Courtesy of C. M. Pieters and the Russian Academy of Sciences)

it difficult for magma to travel from the Martian mantle to the surface.

However, a few Martian lava flows are crater-free, which suggests that they are only a few million years old. If volcanoes erupted on Mars within the past few million years, are they erupting now? Scientists have used infrared telescopes to search for telltale hot spots on the Martian surface, but have yet to discover any. Perhaps volcanism on Mars is rare but not yet wholly extinct.

Spacecraft that have landed on Mars have taught us a great deal about the geology and history of the red planet. Before we explore the Martian surface in detail, however, it is useful to examine the unique atmospheres of both Mars and Venus.

11-6 The dense atmosphere of Venus and the thin Martian atmosphere are dramatically different but have similar chemical compositions

We have seen that the three large terrestrial planets—Earth, Venus, and Mars—display very different styles of geology. As we will discover, these differences help to explain why each of these three worlds has a distinctively different atmosphere.

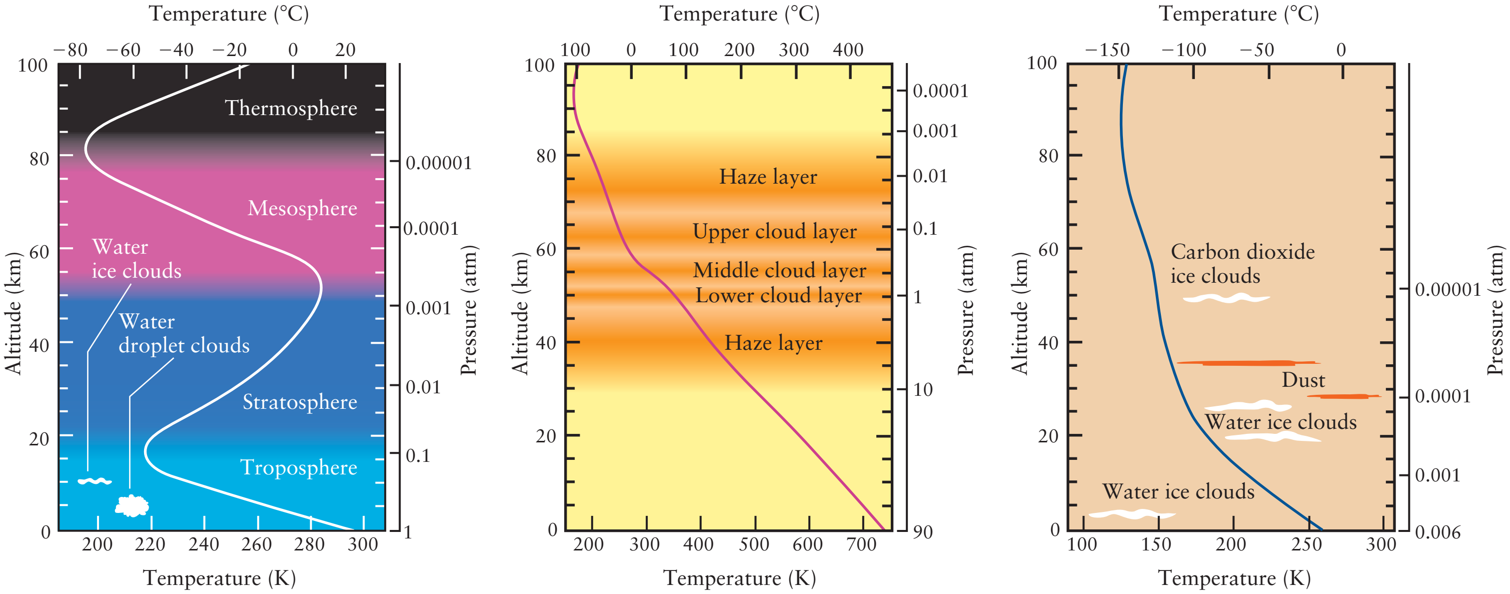
To explore a planet's atmosphere it is necessary to send a spacecraft to make measurements as it descends through that atmosphere. Both Soviet and American spacecraft have done this for Venus (see Figure 11-26), and five U.S. spacecraft have successfully landed on Mars. The results of these missions are summarized in Figure 11-27, which shows how pressure and temperature vary with altitude in the atmospheres of Earth, Venus, and Mars.

On Venus, sulfuric acid rain evaporates before reaching the ground; on Mars, it snows frozen carbon dioxide

The Venusian Atmosphere: Dense, Hot, and Corrosive

Figure 11-27*b* depicts just how dense the Venusian atmosphere is. At the surface, the pressure is 90 atmospheres—that is, 90 times greater than the average air pressure at sea level on Earth. This is about the same as the water pressure at a depth of about 1 kilometer below the surface of the Earth's oceans. The density of the atmosphere at the surface of Venus is likewise high, more than 50 times greater than the sea-level density of our atmosphere. The atmosphere is so massive that once heated by the Sun, it retains its heat throughout the long Venusian night. As a result, temperatures on the day and night sides of Venus are almost identical.

The composition of atmosphere explains why Venus's surface temperatures are so high: 96.5% of the molecules in Venus's atmosphere are carbon dioxide, with nitrogen (N_2) making up most of the remaining 3.5% (see Table 9-4 for a comparison of the atmospheres of Venus, Earth, and Mars). Because Venus's atmosphere is so thick, and because most of the atmosphere is the



(a) Earth (b) Venus (c) Mars

Figure 11-27

Atmospheres of the Terrestrial Planets In each graph the curve shows how temperature varies with altitude from 0 to 100 km above the planet's surface. The scale on the right-hand side of each graph shows how pressure varies with altitude. **(a)** Clouds in the Earth's atmosphere are seldom found above 12 km (40,000 ft). **(b)** Venus's perpetual cloud layers lie at much higher altitudes. The atmosphere is so dense that the pressure 50 km above the Venusian surface is 1 atm, the same as at sea level on Earth. **(c)** By contrast, the Martian atmosphere is so thin that the surface pressure is the same as the pressure at an altitude of 35 km on Earth. Wispy clouds can be found at extreme altitudes.

greenhouse gas CO_2, the greenhouse effect (Section 9-1) has run wild. On Earth the greenhouse gases H_2O and CO_2 together make up only about 1% of our relatively sparse atmosphere, and the greenhouse effect has elevated the surface temperature by about 33°C (59°F). But on Venus, the dense shroud of CO_2 traps infrared radiation from the surface so effectively that it has raised the surface temperature by more than 400°C (720°F).

Soviet and American spacecraft also discovered that Venus's clouds are primarily confined to three high-altitude layers. An upper cloud layer lies at altitudes between 68 and 58 km, a denser and more opaque cloud layer from 58 to 52 km, and an even more dense and opaque layer between 52 and 48 km. Above and below the clouds are 20-km-thick layers of haze. Below the lowest haze layer, the atmosphere is remarkably clear all the way down to the surface of Venus.

We saw in Section 11-5 that sulfur, which is not found in any appreciable amount in our atmosphere, plays an important role in the Venusian atmosphere. Sulfur combines with other elements to form gases such as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S), along with sulfuric acid (H_2SO_4), the same acid used in automobile batteries. While the Earth's clouds are composed of water droplets, Venusian clouds contain almost no water. Instead, they are composed of droplets of concentrated, corrosive sulfuric acid. Thanks to the high temperatures on Venus, these droplets never rain down on the planet's surface; they simply evaporate at high altitude. (You can see a similar effect on Earth. On a hot day in the desert of the American Southwest, streamers of rain called *virga* appear out of the bottoms of clouds but evaporate before reaching the ground.)

Convection in the Venusian Atmosphere

We saw in Section 9-6 that the Earth's atmosphere is in continuous motion: Hot gases rise and cooler gases sink, forming convection cells in the atmosphere. The same is true on Venus, but with some important differences. On Venus, gases in the equatorial regions are warmed by the Sun, then rise upward and travel in the upper cloud layer toward the cooler polar regions. At the polar latitudes, the cooled gases sink to the lower cloud layer, in which they are transported back toward the equator. The result is two huge convection cells, one in the northern hemisphere and another in the southern hemisphere (Figure 11-28*a*). These cells are almost entirely contained within the main cloud layers shown in Figure 11-27*b*. The circulation is so effective at transporting heat around Venus's atmosphere that there is almost no temperature difference between the planet's equator and its poles. By contrast, the Earth's atmosphere has a more complicated convection pattern (see Figure 11-28*b* and Figure 9-24) because the Earth's rotation—which is far more rapid than Venus's—distorts the convection cells.

In addition to the north-south motions due to convection, high-altitude winds with speeds of 350 km/h (220 mi/h) blow from east to west, the same direction as Venus's retrograde rotation. Thus, the upper atmosphere rotates around the planet once every 4 days. The fast-moving winds stretch out the convection cells and produce V-shaped, chevronlike patterns in the clouds (Figure 11-29). In a similar way, the Earth's rotation stretches out the convection cells in our atmosphere to produce the complicated circulation patterns shown in Figure 9-24.

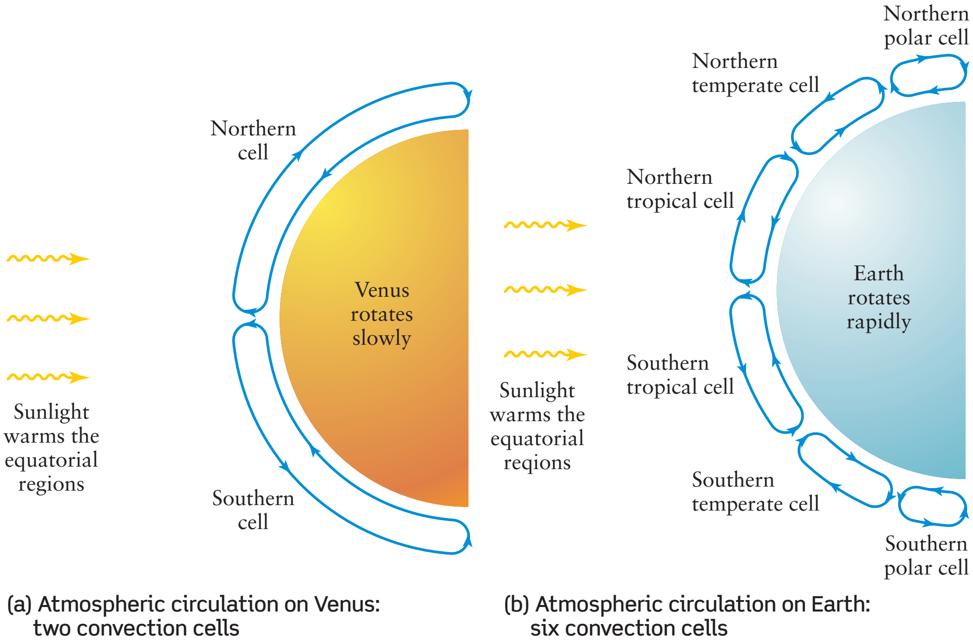


Figure 11-28

Atmospheric Circulation on Venus and Earth Solar heating causes convection in the atmospheres of both Venus and Earth, with warm air rising at the equator and cold air descending at the poles. **(a)** Because Venus rotates very slowly, it has little effect on the circulation. **(b)** Earth's rapid rotation distorts the atmospheric circulation into a more complex pattern (compare Figure 9-24).

On the Earth, friction between the atmosphere and the ground causes wind speeds at the surface to be much less than at high altitude. The same is true on Venus: The greatest wind speed measured by spacecraft on Venus's surface is only about 5 km/h (3 mi/h). Thus, only slight breezes disturb the crushing pressures and infernal temperatures found on Venus's dry, lifeless surface.

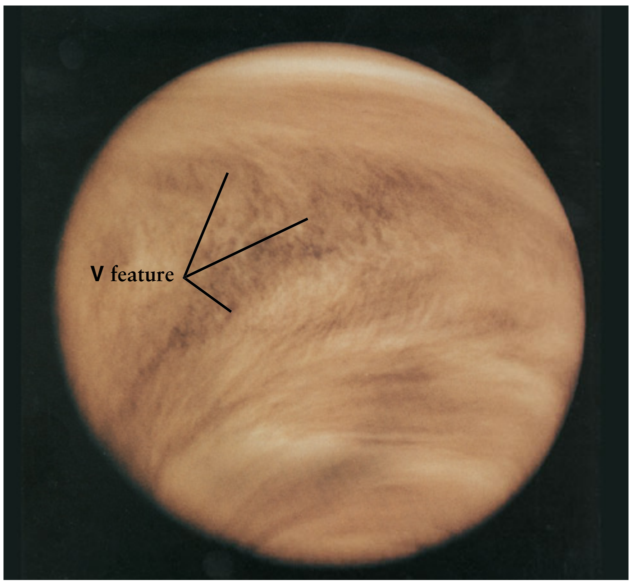


Figure 11-29 R I V **U** X G

Venus's Cloud Patterns This false-color image of Venus was made at ultraviolet wavelengths, at which the planet's atmospheric markings stand out best. The dark V feature is produced by the rapid motion of clouds around the planet's equator. The clouds move in the same retrograde direction as the rotation of the planet itself but at a much greater speed. (GSFC/NASA)

The Martian Atmosphere: Not a Drop to Drink

As Figure 11-27*c* shows, the atmosphere of Mars is very cold and thin compared to the atmosphere of either Earth or Venus: The surface pressure is a mere 0.006 atmosphere. Yet its chemical composition is very close to that of Venus: The Martian atmosphere is 95.3% carbon dioxide (versus 96.5% for Venus) and 2.7% nitrogen (versus 3.5% for Venus). The predominance of carbon dioxide means that Mars, like Earth and Venus, is warmed by the greenhouse effect. However, the Martian atmosphere is so thin that the greenhouse effect is very weak and warms the Martian surface by only 5°C (versus 33°C on Earth). While the perpetual cloud cover on Venus maintains a steady surface temperature, the thin atmosphere on Mars provides very little thermal insulation. While daytime highs on Mars can be as high as 20°C (68°F), at night the temperature can plummet to −140°C (−220°F).

Water vapor makes up about 0.03% of the Martian atmosphere (versus about 1% for the Earth), and this vapor can form clouds. Figure 11-24*b* shows clouds that form near the tops of Martian volcanoes when air moves up the volcanic slopes. The rising air cools until the water vapor condenses into ice crystals. The same process occurs on Earth, but the clouds that form in this way are made of droplets of liquid water rather than ice crystals. Why is there a difference?

The explanation is that liquid water cannot exist anywhere on the Martian surface or in the Martian atmosphere. Water is liquid over only a limited temperature range: If the temperature is too low, water becomes ice, and if the temperature is too high, it becomes water vapor. What determines this temperature range is the atmospheric pressure above a body of water or around a water drop. If the pressure is very low, molecules easily escape from the liquid's surface, causing the water to vaporize. Thus, at low pressures, water more easily becomes water vapor. The average surface temperature on Mars is only about 250 K (−23°C, or

−10°F), and the average pressure is only 0.006 atmosphere. With this combination of temperature and pressure, water can exist as a solid (ice) and as a gas (water vapor) but not as a liquid. (You can see this same situation inside a freezer, where water vapor swirls around over ice cubes.) Hence, it never rains on Mars and there are no bodies of standing water anywhere on the planet.

In order to keep water on Mars in the liquid state, it would be necessary to increase both the temperature (to keep water from freezing) and the pressure (to keep the liquid water from evaporating). Later in this chapter we will see evidence that higher temperatures and pressures did exist on Mars billions of years ago, and that there was once liquid water on the surface.

The Martian Poles: Freezing the Atmosphere

Figure 11-27*c* shows that at very high altitudes above the Martian surface, atmospheric carbon dioxide can freeze into crystals and form clouds. (Frozen carbon dioxide can be made on Earth and is called "dry ice.") Such frozen carbon dioxide is also found in larger quantities in ice caps at the north and south poles of Mars, one of which you can see in Figure 11-4*c*. Although no spacecraft has successfully landed on the ice caps, their composition can be measured from orbit by comparing the spectrum sunlight reflected from the ice caps with the known reflection spectrum of frozen carbon dioxide. (Figure 7-4 shows another application of this idea.)

The size of the ice caps varies substantially with the seasons (**Figure 11-30**). When it is winter at one of the Martian poles, temperatures there are so low that atmospheric carbon dioxide freezes and the ice cap grows. (Think of it: It gets so cold at the Martian poles that the atmosphere freezes!) With the coming of spring, much of the carbon dioxide returns to the gaseous state and the ice cap shrinks. With the arrival of summer, however, the rate of shrinkage slows abruptly and a **residual ice cap** remains solid throughout the summer. Scientists had long suspected that the north and south residual polar caps contain a large quantity of frozen water that is less easily evaporated. The European *Mars Express* spacecraft confirmed this idea in 2004. It used its infrared cameras to peer through the carbon dioxide layer at the south polar ice cap and detect the characteristic spectrum of water ice. Because we do not know the thickness of the layer of water ice, the amount of frozen water stored in the Martian polar caps is still unknown.

The wintertime freezing of atmospheric carbon dioxide was measured by the *Viking Lander 1* and *Viking Lander 2* spacecraft, which made the first successful landings on Mars in 1976. Both of these spacecraft touched down in the northern hemisphere of Mars when it was spring in that hemisphere and autumn in the southern hemisphere. (You can see the landing sites in Figure 11-20.) **Figure 11-31*a*** shows the springtime view from *Viking Lander 1*. Initially, both spacecraft measured pressures around 0.008 atmosphere. After only a few weeks on the Martian surface, however, atmospheric pressure at both landing sites was dropping steadily. Mars seemed to be rapidly losing its atmosphere, and some scientists joked that soon all the air would be gone!

The actual explanation was that winter was coming to the southern hemisphere, causing carbon dioxide to freeze in that hemisphere's atmosphere and fall as dry-ice "snow." The formation of this "snow" removed gas from the Martian atmosphere, thereby lowering the atmospheric pressure across the planet. Several months later, when spring came to the southern hemisphere, the dry-ice snow evaporated rapidly and the atmospheric pressure returned to its prewinter levels. The pressure dropped again in the southern hemisphere's summer, because it is then winter in the northern hemisphere, and dry-ice snow condenses at northern latitudes (Figure 11-31*b*). Therefore, both temperature and atmospheric pressure change significantly with the Martian seasons.

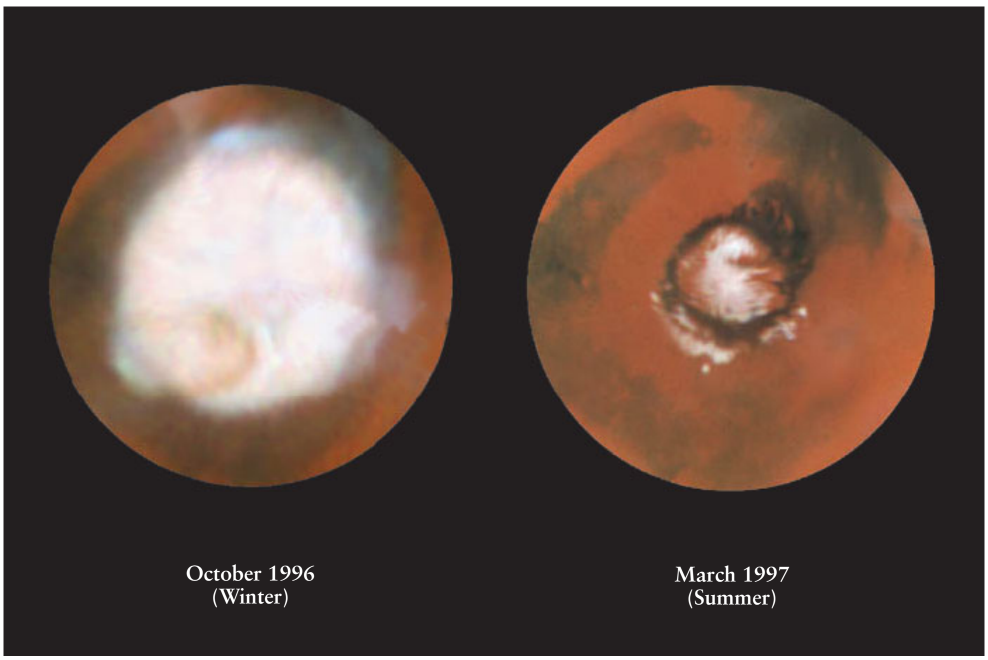
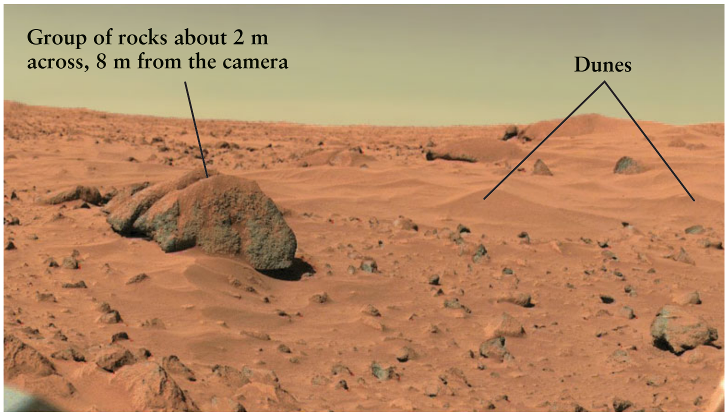


Figure 11-30 R I V U X G

Changing Seasons at the Martian North Pole
During the Martian winter, the temperature drops so low that carbon dioxide freezes out of the Martian atmosphere. A thin coating of carbon dioxide frost covers a broad region around Mars's north pole. During summer in the northern hemisphere, the ice cap is much smaller because carbon dioxide goes back into the atmosphere. The shrinking of the ice cap exposes a ring of dark sand dunes around the Martian north pole. (S. Lee/J. Bell/M. Wolff/Space Science Institute/NASA)



(a) A view from *Viking Lander 1*

(b) A wintertime view from *Viking Lander 2*

WEB LINK 11.16

Figure 11-31 R I V U X G

Seasons on the Martian Surface **(a)** This view from *Viking Lander 1* shows rocks that resemble volcanic rocks on Earth (see Figure 9-19*a*). They are thought to be part of an ancient lava flow that was broken apart by crater-forming asteroid impacts. Fine-grained debris has formed sand dunes. **(b)** This picture was taken during midwinter at the *Viking Lander 2* site. Freezing carbon dioxide adheres to water-ice crystals and dust grains in the atmosphere, causing them to fall to the ground and coat the surface with frost. This frost lasted for about a hundred days. (a: Dr. Edwin Bell II/NSSDC/GSFC/NASA; b: NASA/JPL)

Martian Dust

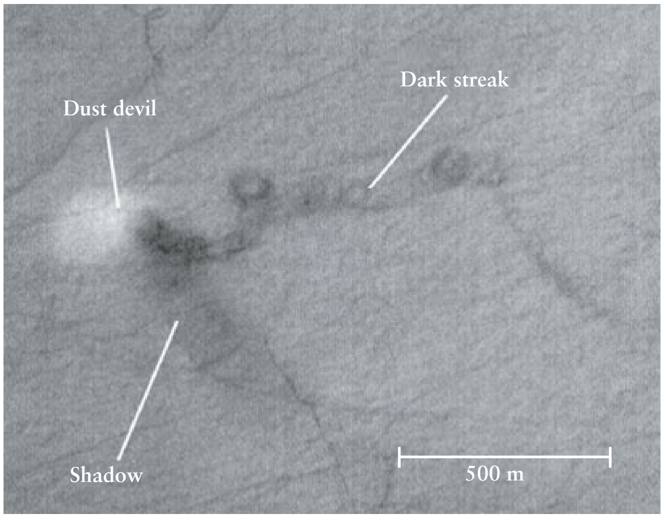
VIDEO 11.5

Figure 11-31*a* shows that the landscape around the *Viking Lander 1* is covered with a fine-grained dust. The dust particles have piled up in places to form drifts that resemble sand dunes on Earth. The dust particles are much smaller than ordinary household dust on Earth: They are only about 1 μm (10^{-6} m) across, about the size of the particles in cigarette smoke. The rocks at the *Viking Lander 2* site are also covered with dust, though it does not pile up in dunes. More recent missions to Mars have also found dust around their landing sites.

Because Martian dust is so fine, it can be carried aloft and spread over the surface by Martian winds even though the atmosphere is so tenuous. (A wind of 100 km/h, or 60 mi/h, on Mars is only about as strong as an Earth breeze of 10 km/h or 6 mi/h.) Windblown dust can sometimes be seen from Earth as a yellow haze that obscures Martian surface features. Figure 11-18 shows a dust storm that covered the entire planet, triggered by the flow of carbon dioxide evaporating from the north polar ice cap with the coming of northern spring. On Earth, stormy weather means cloudy skies, wind, and falling rain; on Mars, where no raindrop falls, stormy weather means wind and dust.

Dust also plays a role in the ordinary daily weather on Mars. Each afternoon, parcels of warm air rise from the heated surface and form whirlwinds called **dust devils.** (A similar phenomenon with the same name occurs in dry or desert terrain on Earth.) Martian dust devils can reach an altitude of 6 km (20,000 ft) and help spread dust particles across the planet's surface. All three landers measured changes in air pressure as dust devils swept past. Often several of these would pass in a single afternoon. Dust devils are large enough to be seen by spacecraft orbiting Mars (Figure 11-32). As the sun sets and afternoon turns to evening, the dust devils subside until the following day.

Airborne dust also affects the color of the Martian sky, shown in Figure 11-31. The Earth's largely dust-free sky is blue because molecules in our atmosphere scatter blue sunlight more effectively than other colors (see Box 5-4). On Mars, however, dust particles in the air do a good job of scattering all visible wavelengths, which by itself would make the sky appear white. But, in addition, the dust particles contain a mineral called magnetite, which absorbs blue light. The result is that the Martian sky has a yellowish color reminiscent of butterscotch.



VIDEO 11.6

Figure 11-32 R I V U X G

A Martian Dust Devil This *Mars Global Surveyor* image shows a dust devil as seen from almost directly above. This tower of swirling air and dust casts a long shadow in the afternoon sun. The dust devil had been moving from right to left before the picture was taken, leaving a dark, curlicue-shaped trail in its wake. (NASA/JPL/Malin Space Science Systems)

11-7 The atmospheres of Venus and Mars were very different billions of years ago

Why do Earth, Venus, and Mars have such dramatically different atmospheres? As we will see, the original atmospheres of all three worlds were essentially the same. However, each atmosphere evolved in a unique way determined by the planet's size and distance from the Sun. The *Cosmic Connections* figure summarizes the processes that led to the present-day atmospheres of the three large terrestrial planets.

The early atmospheres of Earth, Venus, and Mars were predominantly water vapor and carbon dioxide

The Origin of Atmospheres on Earth, Venus, and Mars

The original atmospheres of Earth, Venus, and Mars all derived from gases that were emitted, or *outgassed,* from volcanoes (Figure 11-33). The gases released by present-day Earth volcanoes are predominantly water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen (N_2). These gases should therefore have been important parts of the original atmospheres of all three planets. Much of the water on all three planets is thought to have come from impacts from comets, icy bodies from the outer solar system (see Section 7-5 and Section 8-5).

In fact, water probably once dominated the atmospheres of all three planets. Venus and the Earth are similar in size and mass, so Venusian volcanoes may well have outgassed as much water vapor as on the Earth, and both planets would have had about the same number of comets strike their surfaces. Studies of how stars evolve suggest that the early Sun was only about 70% as luminous as it is now, so the temperature in Venus's early atmosphere must have been quite a bit lower. Water vapor may actually have been able to liquefy and form oceans on Venus. Mars is smaller than either Earth or Venus, but its large volcanoes could also have emitted substantial amounts of water vapor. With a thicker atmosphere and hence greater pressure, liquid water could also have existed on Mars.

Figure 11-33 R I V U X G

A Volcanic Eruption on Earth The eruption of Mount St. Helens in Washington state on May 18, 1980 released a plume of ash and gas 40 km (25 mi) high. Eruptions of this kind on Earth, Venus, and Mars probably gave rise to those planets' original atmospheres. (USGS)

The Evolution of Earth's Atmosphere

On the present-day Earth most of the water is in the oceans. Nitrogen, which is not very reactive, is still in the atmosphere. By contrast, carbon dioxide dissolves in water, which can fall as rain; as a result, rain removed most of the H_2O and CO_2 out of our planet's atmosphere long ago. The dissolved CO_2 reacted with rocks in rivers and streams, and the residue was ultimately deposited on the ocean floors, where it turned into carbonate rocks, such as limestone. Consequently, most of the Earth's carbon dioxide is tied up in the Earth's crust, and only about 1 in every 3000 molecules in our atmosphere is a CO_2 molecule. If the Earth became as hot as Venus, much of its CO_2 would be boiled out of the oceans and baked out of the crust, and our planet would soon develop a thick, oppressive carbon dioxide atmosphere much like that of Venus.

The small amount of carbon dioxide in our atmosphere is sustained in part by plate tectonics. Tectonic activity causes carbonate rocks to cycle through volcanoes, where they are heated and forced to liberate their trapped CO_2. This liberated gas then rejoins the atmosphere. Without volcanoes, rainfall would remove all of the CO_2 from our atmosphere in only a few thousand years. This would dramatically reduce the greenhouse effect, our planet's surface temperature would drop precipitously, and the oceans would freeze. Plate tectonics is thus essential for maintaining our planet's livable temperatures.

The oxygen (O_2) in our atmosphere is the result of photosynthesis by plant life, which absorbs CO_2 and releases O_2. The net result is an atmosphere that is predominantly N_2 and O_2, with enough pressure and a high enough temperature (thanks to the greenhouse effect) for water to remain a liquid—and hence for life, which requires liquid water, to exist.

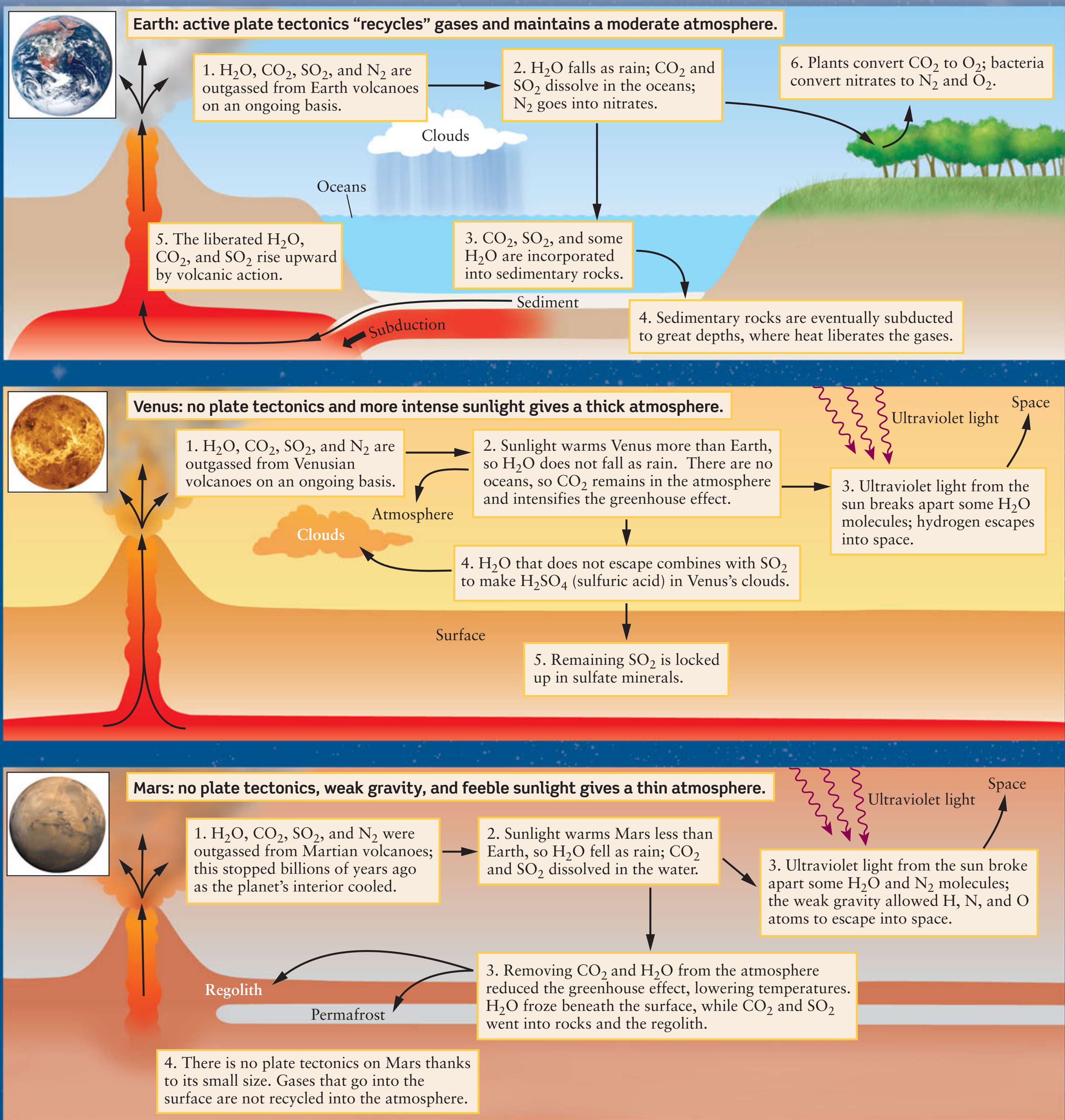
The Evolution of the Venusian Atmosphere: A Runaway Greenhouse Effect

When Venus was young and had liquid water, the amount of atmospheric CO_2 was kept in check much as on Earth today: CO_2 was released by volcanoes, then dissolved in the oceans and bound up in carbonate rocks. Enough of the liquid water would have vaporized to create a thick cover of water vapor clouds. Since water vapor is a greenhouse gas, this humid atmosphere—perhaps denser than the Earth's present-day atmosphere, but far less dense than the atmosphere that surrounds Venus today—

COSMIC CONNECTIONS

Evolution of Terrestrial Atmospheres

Earth, Venus, and Mars formed with similar original atmospheres. However, these atmospheres changed dramatically over time due to factors such as planetary size and distance from the Sun.



would have efficiently trapped heat from the Sun. At first, this would have had little effect on the oceans of Venus. Although the temperature would have climbed above 100°C, the boiling point of water at sea level on the Earth, the added atmospheric pressure from water vapor would have kept the water in Venus's oceans in the liquid state.

This hot and humid state of affairs may have persisted for several hundred million years. But as the Sun's energy output slowly increased over time, the temperature at the surface would eventually have risen above 374°C (647 K, or 705°F). Above this temperature, no matter what the atmospheric pressure, Venus's oceans would have begun to evaporate. The added water vapor in the atmosphere would have increased the greenhouse effect, making the temperature even higher and causing the oceans to evaporate faster. That would have added even more water vapor to the atmosphere, further intensifying the greenhouse effect and making the temperature climb higher still. This is an example of a **runaway greenhouse effect,** in which an increase in temperature causes a further increase in temperature, and so on.

ANALOGY A runaway greenhouse effect is like a house in which the thermostat has accidentally been connected backward. If the temperature in such a house gets above the value set on the thermostat, the heater comes on and makes the house even hotter.

Once Venus's oceans disappeared, so did the mechanism for removing carbon dioxide from the atmosphere. With no oceans to dissolve it, outgassed CO_2 began to accumulate in the atmosphere, making the greenhouse effect "run away" even faster. Temperatures eventually became high enough to "bake out" any CO_2 that was trapped in carbonate rocks. This liberated carbon dioxide formed the thick atmosphere of present-day Venus.

Sulfur dioxide (SO_2) is also a greenhouse gas released by volcanoes. Although present in far smaller amounts than carbon dioxide, it would have contributed to Venus's rising temperatures. Like CO_2, it dissolves in water, a process that helps moderate the amount of sulfur dioxide in our atmosphere. But when the oceans evaporated on Venus, the amount of atmospheric SO_2 would have increased.

The temperature in Venus's atmosphere would not have increased indefinitely. In time, solar ultraviolet radiation striking molecules of water vapor—the dominant cause of the runaway greenhouse effect—would have broken them into hydrogen and oxygen atoms. The lightweight hydrogen atoms would have then escaped into space (see Box 7-2 for a discussion of why lightweight atoms can escape a planet more easily than heavy atoms). The remaining atoms of oxygen, which is one of the most chemically active elements, would have readily combined with other substances in Venus's atmosphere. Eventually, almost all of the water vapor would have been irretrievably lost from Venus's atmosphere. With all the water vapor gone, and essentially all the carbon dioxide removed from surface rocks, the greenhouse effect would no longer have "run away," and the rising temperature would have leveled off.

Today, the infrared-absorbing properties of CO_2 have stabilized Venus's surface temperature at its present value of 460°C. Only minuscule amounts of water vapor—about 30 parts per million, or 0.003%—remain in the atmosphere. As on Earth, volcanic outgassing still adds small amounts of water vapor to the atmosphere, along with carbon dioxide and sulfur dioxide. But on Venus, these water molecules either combine with sulfur dioxide to form sulfuric acid clouds or break apart due to solar ultraviolet radiation. The great irony is that this state of affairs is the direct result of an earlier Venusian atmosphere that was predominantly water vapor!

The Evolution of the Martian Atmosphere: A Runaway Icehouse Effect

Mars probably had a thicker atmosphere 4 billion years ago. Thanks to Mars's greater distance from the Sun and hence less intense sunlight, temperatures would have been lower than on the young Earth, and any water in the atmosphere would more easily have fallen as rain or snow. This would have washed much of the planet's carbon dioxide from its atmosphere, perhaps creating carbonate minerals in which the CO_2 is today chemically bound. Measurements from Mars orbit show only small amounts of carbonate materials on the surface, suggesting that the amount of atmospheric CO_2 that rained out was small. Hence, even the original Martian atmosphere was relatively thin, though thicker than the present-day atmosphere.

Because Mars is so small, it cooled early in its history and volcanic activity came to an end. Thus, any solid carbonates were not recycled through volcanoes as they are on Earth. The depletion of carbon dioxide from the Martian atmosphere into the surface would therefore have been permanent.

As the amount of atmospheric CO_2 declined, the greenhouse effect on Mars would have weakened and temperatures begun to fall. This temperature decrease would have caused more water vapor to condense into rain or snow and fall to the surface, taking even more CO_2 with them and further weakening the greenhouse effect. Thus, a decrease in temperature would have caused a further decrease in temperature—a phenomenon sometimes called a **runaway icehouse effect.** (This is the reverse of the runaway greenhouse effect that has taken place on Venus.) Ultimately, both water vapor and most of the carbon dioxide would have been removed from the Martian atmosphere. With only a very thin CO_2 atmosphere remaining, surface temperatures on Mars eventually stabilized at their present frigid values.

As both water vapor and carbon dioxide became depleted, ultraviolet light from the Sun could penetrate the thinning Martian atmosphere to strip it of nitrogen. Nitrogen molecules (N_2) normally do not have enough thermal energy to escape from Mars, but they can acquire that energy from ultraviolet photons, which break the molecules in two. Ultraviolet photons can also split carbon dioxide and water molecules, giving their atoms enough energy to escape (Figure 13-16*b*). Indeed, in 1971 the Soviet *Mars 2* spacecraft found a stream of oxygen and hydrogen atoms (from the breakup of water molecules) escaping into space. Oxygen atoms that did not escape into space could have combined with iron-bearing minerals in the surface, forming rustlike compounds. Such compounds have a characteristic reddish-brown color and may be responsible for the overall color of the planet.

Was the early Martian atmosphere thick enough and warm enough for water to remain as a liquid on the planet's surface? As we will see in the next section, scientists have found evidence on Mars that the answer is a qualified yes.

11-8 Rovers have found evidence of ancient Martian water

Just as ancient fossils on Earth provide evidence of how life has evolved on our planet, ancient rocks and geological formations help us understand how our planet's surface and atmosphere have evolved. (For example, the oldest rocks on Earth have a chemical structure which shows that they formed in a time when there was little oxygen in the atmosphere and hence before the appearance of photosynthetic planet life.) Planetary scientists who want to learn about the history of Venus and Mars are therefore very interested in looking at ancient rocks on those worlds.

Parts of Mars are far drier than a bone, while others had standing water for extended periods

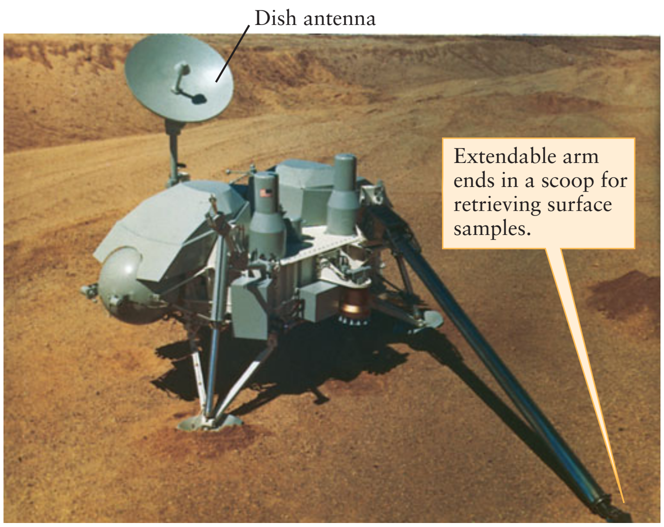
On Venus we cannot look very far into the past, since the planet's volcanic activity and flake tectonics has erased features more than about 500 million years old (see Section 11-5). On Mars, by contrast, we expect to find rocks that are billions of years old: The thin atmosphere causes very little erosion, there has been little recent volcanic activity to cover ancient rocks, and there is no subduction to drag old surface features back into the planet's interior. (The heavy cratering of the southern highlands bears testament to the great age of much of the Martian surface.) In a quest to find these ancient rocks and learn about the early history of Mars, scientists have sent spacecraft to land on the red planet and explore it at close range.

Landing on Mars

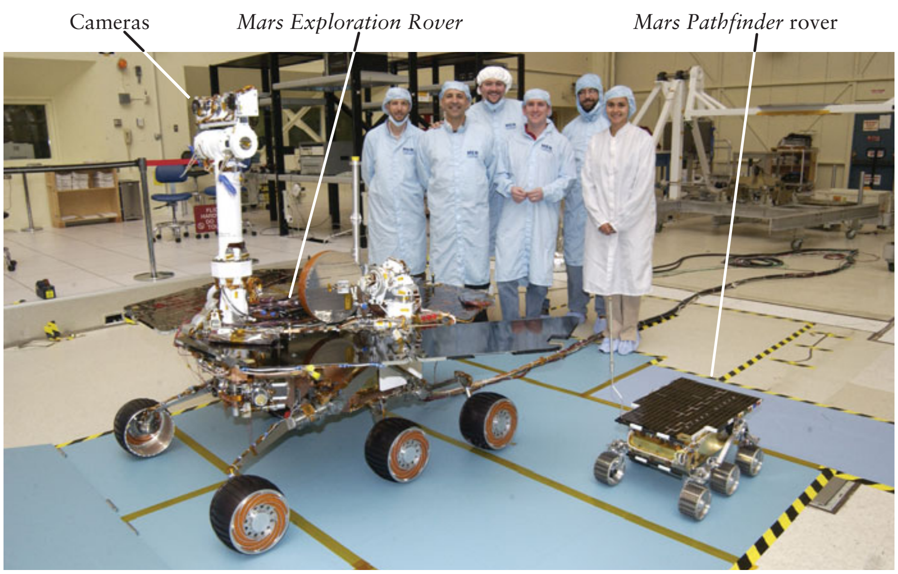
As of this writing (2006) five spacecraft have successfully landed on the Martian surface. *Viking Lander 1* and *Viking Lander 2*, which we first discussed in Section 11-6, touched down in 1976. They had no capability to move around on the surface, and so each *Viking Lander* could only study objects within reach of the scoop at the end of its mechanical arm (Figure 11-34*a*). Figure 11-31 shows the view from the two *Viking Lander* sites.

Three more recent unmanned explorers, *Mars Pathfinder* (landed 1997) and two *Mars Exploration Rovers* (landed 2004), were equipped with electrically driven wheels that allow travel over the surface (Figure 11-34*b*). Unlike the *Viking Landers*, these rovers did not have a heavy and expensive rocket engine to lower it gently to the Martian surface. Instead, the spacecraft was surrounded by airbags like those used in automobiles. Had there been anyone to watch *Mars Pathfinder* or one of the *Mars Exploration Rovers* land, they would have seen an oversized beach ball hit the surface at 50 km/h (30 mi/h), then bounce for a kilometer before finally rolling to a stop. Unharmed by its wild ride, the spacecraft then deflated its airbags and began to study the geology of Mars.

Figure 11-20 shows the landing sites of the *Mars Pathfinder* rover (named *Sojourner*) and the two *Mars Exploration Rovers* (named *Spirit* and *Opportunity*). Following directions from Earth, *Sojourner* spent three months exploring the rocks around its landing site. The *Mars Exploration Rovers* were also designed for a three-month lifetime, but both were still functioning more than $2\frac{1}{2}$ years after landing. Over that time *Spirit* and *Opportunity* had each traveled several kilometers over the Martian surface.



(a) A *Viking Lander*



(b) Two generations of rovers

WEB LINK 11.17

Figure 11-34 R I V U X G

Martian Explorers (a) Each *Viking Lander* is about 2 m (6 ft) tall from the base of its footpads to the top of its dish antenna, used for sending data to an orbiter, which in turn relayed the information back to Earth. (This photograph shows a full-size replica under test on Earth.) **(b)** The technicians in this photograph pose with one of the *Mars Exploration Rovers* and with a replica of its predecessor, the *Mars Pathfinder* rover. (a: NASA; b: NASA/JPL)

In addition to cameras, all five landers carried a device called an X-ray spectrometer to measure the chemical composition of rock samples. *Spirit* and *Opportunity* also carried a tool designed to grind holes into rocks, thus revealing parts of the rock's interior that have not been weathered by exposure to the Martian atmosphere.

The Martian Regolith

The *Viking Landers* were the first to reveal the nature of the Martian regolith, or surface material. The scoop on the extendable arm (Figure 11-34*a*) was used to dig into the regolith and retrieve samples for analysis. Bits of the regolith clung to a magnet mounted on the scoop, indicating that the regolith contains iron. The X-ray spectrometers showed that samples collected at both *Viking Lander* sites were rich in iron, silicon, and sulfur.

The *Viking Landers* each carried a miniature chemistry laboratory for analyzing the regolith. Curiously, when a small amount of water was added to a sample of regolith, the sample began to fizz and release oxygen. This experiment indicated that the regolith contains unstable chemicals called peroxides and superoxides, which break down in the presence of water to release oxygen gas.

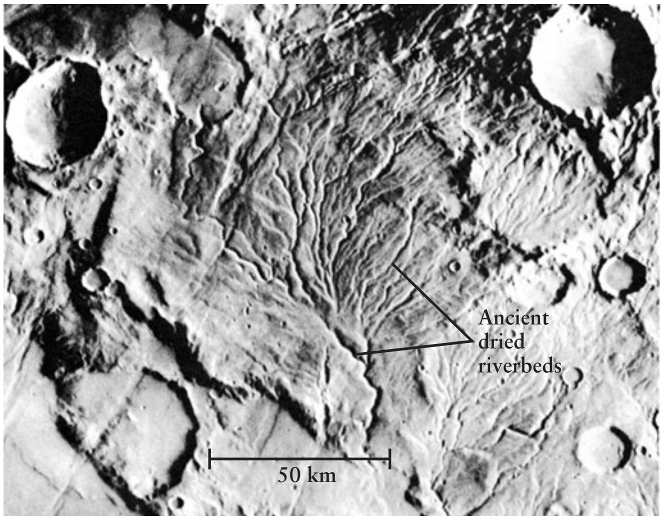
The unstable chemistry of the Martian regolith probably comes from solar ultraviolet radiation that beats down on the planet's surface. (Unlike Earth, Mars has no ozone layer to screen out ultraviolet light.) Ultraviolet photons easily break apart molecules of carbon dioxide (CO_2) and water vapor (H_2O) by knocking off oxygen atoms, which then become loosely attached to chemicals in the regolith. Ultraviolet photons also produce highly reactive ozone (O_3) and hydrogen peroxide (H_2O_2), which also become incorporated in the regolith.

Among the most important scientific goals of the *Viking Landers* was to search for evidence of life on Mars. Although it was clear that Mars has neither civilizations nor vast fields of plants, it still seemed possible that simple microorganisms could have evolved on Mars during its early brief epoch of Earthlike climate. If so, perhaps some species had survived to the present day. To test this idea, the *Viking Landers* looked for biologically significant chemical reactions in samples of the Martian regolith, but they failed to detect any reactions of this type. Perhaps life never existed on Mars, or perhaps it existed once but was destroyed by the presence of peroxides and superoxides in the regolith.

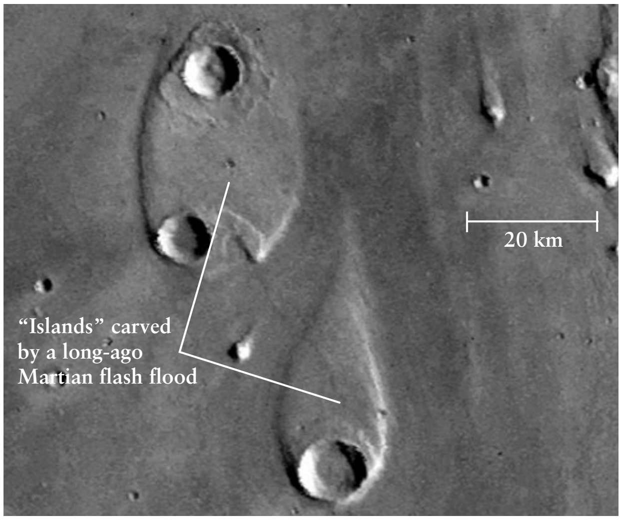
On Earth, hydrogen peroxide is commonly used as an antiseptic. When poured on a wound, it fizzes and froths as it reacts with organic material and destroys germs. Thus, the *Viking Landers* may have failed to detect any biochemistry on Mars because the regolith has literally been sterilized! Hence, we cannot yet tell whether life ever existed on Mars, or whether it might yet exist elsewhere on or beneath the planet's surface. (In Chapter 28 we discuss the *Viking Lander* experiments in detail, as well as the controversial proposal that fossil Martian microorganisms may have traveled to Earth aboard meteorites.)

Exploring Martian Rocks

Images made from Mars orbit show a number of features that suggest water flowed there in the past (Figure 11-35). To investigate these, *Mars Pathfinder* landed in an area of the northern lowlands called Ares Valles, which appears to be an ancient flood plain. Figure 11-35*b* shows a portion of this plain. Flood waters can carry rocks of all kinds great distances from their original locations, so scientists expected that this landing site (Figure 11-36) would show great geologic diversity. They were not disappointed.



(a)



(b)

Figure 11-35 R I V U X G

Sign of Ancient Martian Water **(a)** This *Viking Orbiter* image shows a network of dried riverbeds extending across the cratered southern highlands. Liquid water would evaporate in the sparse, present-day Martian atmosphere, so these must date from an earlier era when the atmosphere was thicker. **(b)** These teardrop-shaped islands rise above the floor of Ares Valles. They were carved out by a torrent of water that flowed from the bottom of the image toward the top. Similar flood-carved islands are found on Earth in eastern Washington state. (a: Michael Carr, USGS; b: NASA/USGS)

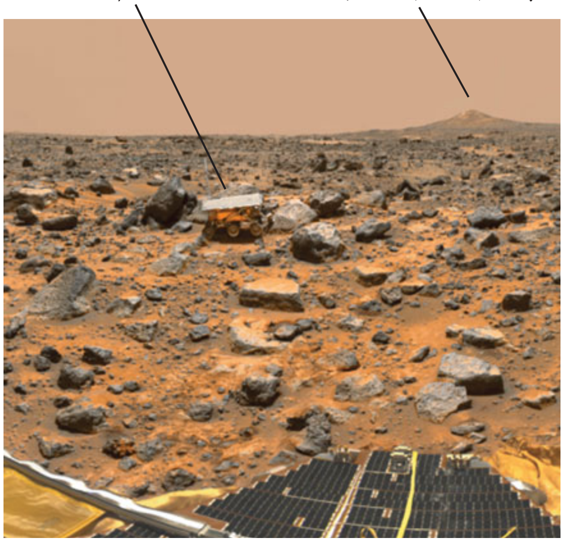


Figure 11-36 R I V U X G

Roving the Martian Surface This view from the stationary part of *Mars Pathfinder* shows the rover, called *Sojourner,* deploying its X-ray spectrometer against a rock named Moe. Scientists gave other rocks whimsical names such as Jiminy Cricket and Pooh Bear. (NASA/JPL)

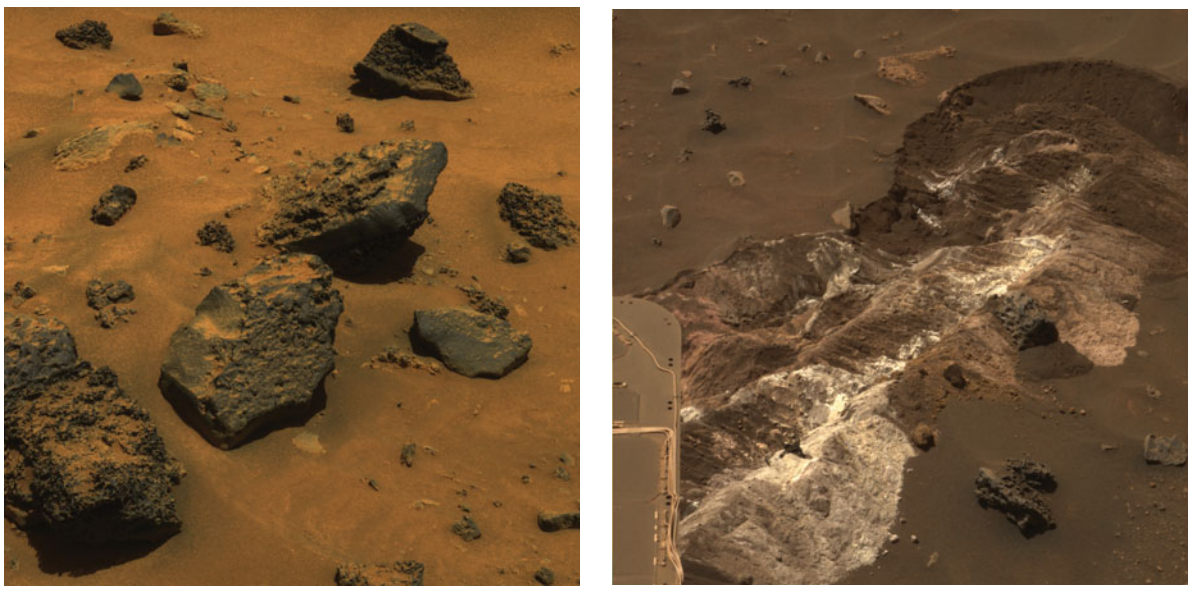
Many of the rocks appeared to be igneous rock produced by volcanic action. Other rocks, which resemble the impact breccias found in the ancient highlands of the Moon (see Figure 10-15), appear to have come from areas that were struck by crater-forming meteoroids. Still others have a layered structure like sedimentary rocks on Earth (see Figure 9-19*b*). Such rocks form gradually at the bottom of bodies of water, suggesting that liquid water was stable in at least some regions of Mars for a substantial period of time.

Searching for Martian Water

The two *Mars Exploration Rovers* also landed in sites that were suspected to have been under water in the distant past. *Spirit* touched down in Gusev Crater, a large impact basin. A valley opens into this crater, resembling a river that runs into a lake. The destination for *Opportunity* was the flat plain of Sinus Meridianii, where orbiting spectrometers had spotted evidence of hematite—a type of iron oxide that, on Earth, tends to form in wet locations.

Contrary to expectations, most of the rocks encountered by *Spirit* show *no* evidence that they have been exposed to water. The volcanic rocks found in and around Gusev Crater (Figure 11-37*a*) are composed of the minerals olivine and pyroxene, which break down if they are exposed to liquid water. In a few locations *Spirit* found deposits of sulfur salts, which can be formed by the action of water (Figure 11-37*b*). However, olivine and pyroxene were still found among the sulfur salts. While it remains a possibility that Gusev Crater was once a river-fed lake, the results from *Spirit* show that for the past billion years this region has been drier than any desert on Earth.

The results from *Opportunity* were entirely different. This rover discovered outcrops of sedimentary rocks on the plains of Sinus Meridianii (Figure 11-38). These rocks are heavily laden with sulfur compounds, strongly suggesting that they were produced by the evaporation of sulfur-rich water. *Opportunity* also found millimeter-sized spheres of hematite that, like analogous spheres found on Earth, probably formed from iron-rich water circulating through sediment. These observations suggest Sinus



(a) Volcanic rocks

(b) Sulfur salts

Figure 11-37 R I V U X G

Dry Mars At the *Spirit* landing site, both **(a)** the dusty volcanic rocks that dominate the site and **(b)** these light-colored sulfur salts contain minerals that break apart upon contact with liquid water. Hence, this area must have been dry for billions of years. (a: NASA/JPL-Caltech/Cornell; b: NASA/JPL/Cornell)

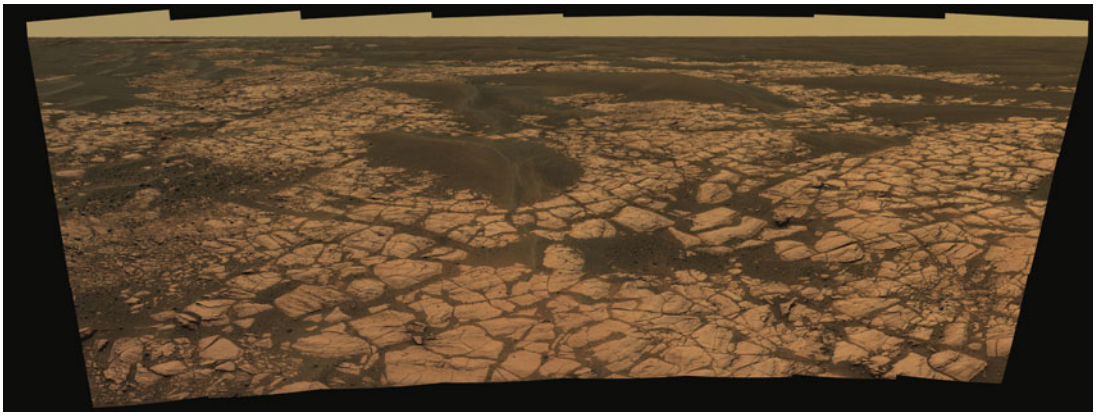


Figure 11-38 R I V U X G

Wet Mars Sedimentary rocks are formed when minerals collect in standing water. Hence, the site where *Opportunity* found this extensive outcrop of light-colored sedimentary rocks must have been under water for an extended period. This panoramic view spans about 120 degrees from side to side. (NASA/JPL-Caltech/Cornell)

Meridianii, which is among the flattest places known in the solar system, was once a lake bed. It is not known how long ago this area was under water, but the density of craters found there suggests that the surface formed 3 to 4 billion years ago.

When combined with observations from Mars orbit, the *Spirit* and *Opportunity* results show that ancient Mars was a very diverse planet. Most of the planet was probably very dry, like Gusev Crater, but there were isolated areas like Sinus Meridianii that had liquid water for some period of time. It remains a challenge to planetary scientists to explain why liquid water appeared on Mars only in certain places and at certain times.

Where Is the Water Now?

Whatever liquid water once coursed over parts of the Martian surface is presumably now frozen, either at the polar ice caps or beneath the planet's surface. To check this idea, scientists used a device on board the *Mars Odyssey* orbiter to measure the result of cosmic rays hitting Mars.

Cosmic rays are fast-moving subatomic particles that enter our solar system from interstellar space. When these particles strike and penetrate into the Martian soil, they collide with the nuclei of atoms in the soil and knock out neutrons. (Recall from Section 5-7 that atomic nuclei contain both positively charged protons and electrically neutral neutrons.) If the ejected neutrons originate within a meter or so of the surface, they can penetrate through the regolith and escape into space. However, if there are water molecules (H_2O) in the surface, the nuclei of the hydrogen atoms in these molecules will absorb the neutrons and prevent them from escaping. An instrument on board *Mars Odyssey* detects neutrons coming from Mars; where the instrument finds a *deficiency* of neutrons is where the soil contains hydrogen and, presumably, water.

The results from the *Mars Odyssey* neutron measurements show that there is abundant water beneath the surface at both Martian poles (Figure 11-39). But they also show a surprising amount of subsurface water in two regions near the equator, Arabia Terra (see Figure 11-17*a* and Figure 11-20) and another region on the opposite side of the planet. One possible explanation is that about a million years ago, gravitational forces from other planets caused a temporary change in the tilt of Mars's rotation axis. The ice caps were then exposed to more direct sunlight, causing some of the water to evaporate and eventually refreeze elsewhere on the planet.

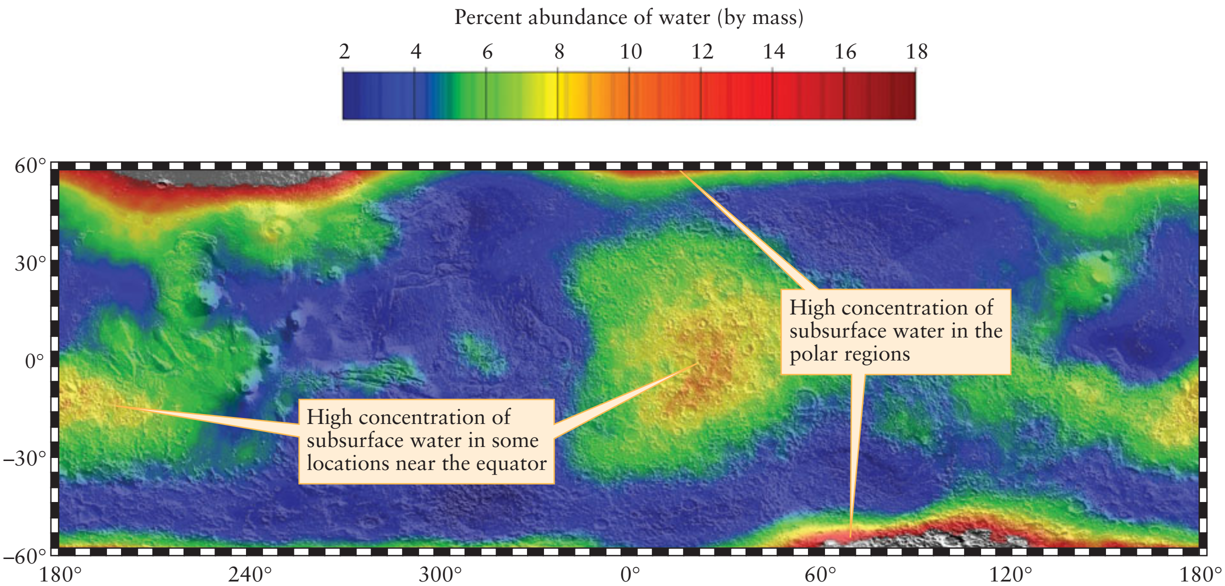


Figure 11-39

Water Beneath the Martian Surface This map of the abundance of water (probably in the form of ice) just below the surface of Mars is based on data collected from orbit by the *Mars Odyssey* spacecraft. These measurements can only reveal the presence of water or water ice to a depth of about a meter; there may be much more water at greater depths. (LANL)

There are other surprising features on Mars related to the presence of water. A number of *Mars Global Surveyor* images show gullies apparently carved by water flowing down the walls of pits or craters (**Figure 11-40**). These could have formed when water trapped underground—where the pressure is greater and water can remain a liquid—seeped onto the surface. The gullies appear to be geologically young, so it is possible that even today some liquid water survives below the Martian surface. Alternatively, these gullies may have formed during periods when the Martian climate was colder than usual and the slopes of craters were covered with a layer of dust and snow. Melting snow on the underside of this layer could have carved out gullies, which were later exposed when the climate warmed and the snow evaporated.

The total amount of water on Mars is not known. But by examining flood channels at various locations around Mars, Michael Carr of the U.S. Geological Survey has estimated that there is enough water to cover the planet to a depth of 500 meters (1500 ft). (By comparison, Earth has enough water to cover our planet to a depth of 2700 meters, or 8900 ft.) Thus, while the total amount of water on Mars is less than on Earth, there may be enough to have once formed lakes or seas—one of which may have covered the plains of Sinus Meridianii and produced the sedimentary rocks shown in Figure 11-38. Future missions to Mars will delve more deeply into the past climate and geology of the red planet.

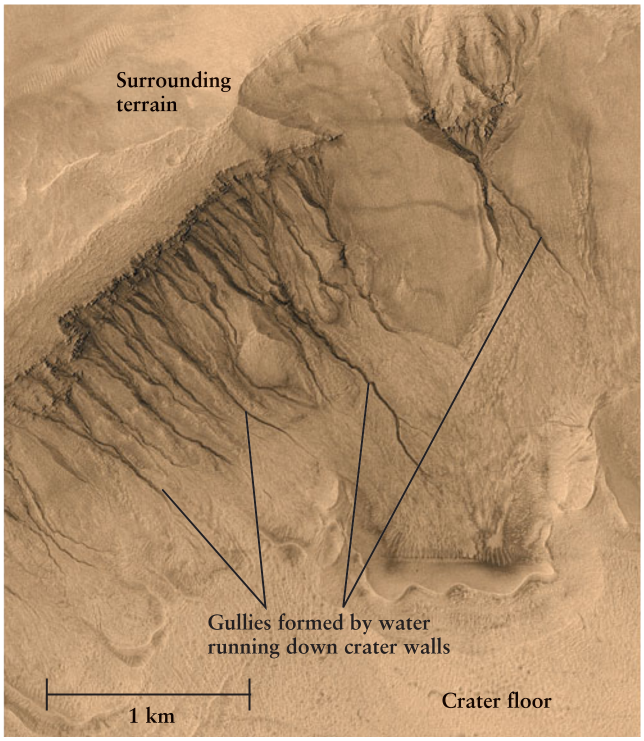


Figure 11-40 R I V U X G

Martian Gullies When the *Mars Global Surveyor* spacecraft looked straight down into this crater in the Martian southern hemisphere, it saw a series of gullies along the crater wall. These gullies may have formed by subsurface water seeping out to the surface, or by the melting of snow that fell on crater walls. (NASA/JPL/Malin Space Science Systems)

11-9 The two Martian moons resemble asteroids

WEB LINK 11.18

Two moons move around Mars in orbits close to the planet's surface. These satellites are so tiny that they were not discovered until the favorable opposition of 1877. While Schiaparelli was seeing canals, the American astronomer Asaph Hall spotted the two moons, which orbit almost directly above its equator. He named them Phobos ("fear") and Deimos ("panic"), after the mythical horses that drew the chariot of the Greek god of war.

The Orbits of Phobos and Deimos

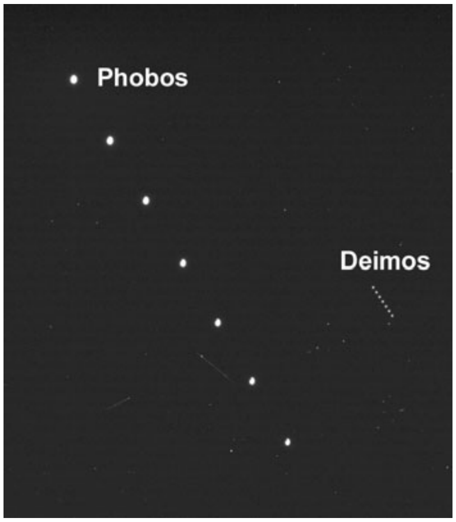
Phobos is the inner and larger of the Martian moons. It circles Mars in just 7 hours and 39 minutes at an average distance of only 9378 km (5828 mi) from the center of Mars. (Recall that our Moon orbits at an average distance of 384,400 km from the Earth's center.) This orbital period is much shorter than the Martian day; hence, Phobos rises in the *west* and gallops across the sky in only $5\frac{1}{2}$ hours, as viewed by an observer near the Martian equator. During this time, Phobos appears several times brighter in the Martian sky than Venus does from the Earth.

As seen from Mars, Deimos rises in the east but Phobos rises in the west

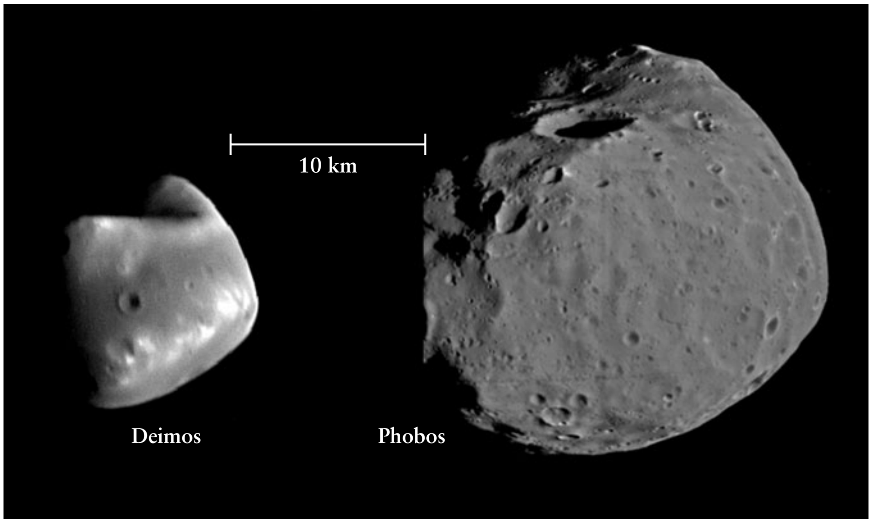
Deimos, which is farther from Mars and somewhat smaller than Phobos, appears about as bright from Mars as Venus does from the Earth. Deimos orbits at an average distance of 23,460 km (14,580 mi) from the center of Mars, slightly beyond the right distance for a synchronous orbit—an orbit in which a satellite seems to hover above a single location on the planet's equator. As seen from the Martian surface, Deimos rises in the east and takes about 3 full days to creep slowly from one horizon to the other. (**Figure 11-41*a***).

Images from spacecraft in Mars's orbit reveal Phobos and Deimos to be jagged and heavily cratered (Figure 11-41*b*). Both moons are somewhat elongated from a spherical shape: Phobos is approximately 28 by 23 by 20 km in size, while Deimos is slightly smaller, roughly 16 by 12 by 10 km. Observations from the *Viking Orbiters* showed that Phobos and Deimos are both in synchronous rotation. The tidal forces that Mars exerts on these elongated moons cause them to always keep the same sides toward Mars, just as the Earth's tidal forces ensure that the same side of the Moon always faces us (see Section 4-8).

We saw in Section 10-5 that the Moon raises a tidal bulge on the Earth. Because the Earth rotates on its axis more rapidly than the Moon orbits the Earth, this bulge is dragged ahead of a line connecting the Earth and Moon (see Figure 10-17). The gravitational force of this bulge pulls the Moon into an ever larger orbit. In the same way, and for the same reason, Deimos is slowly moving away from Mars. But for fast-moving Phobos, the situation is reversed: Mars rotates on its axis more slowly than Phobos moves around Mars. This slow rotation holds back the tidal bulge that Phobos raises in the solid body of Mars, and this bulge thus is *behind* a line connecting the centers of Mars and Phobos. (Imagine that the bulge in Figure 10-17 is tilted clockwise rather than counterclockwise.) This bulge exerts a gravitational force on



(a) As seen from Mars



(b) As seen from Mars orbit

Figure 11-41 R I V U X G

The Moons of Mars **(a)** The *Spirit* rover recorded seven images of the Martian night sky at 15-minute intervals to produce this composite view of the motions of Deimos and Phobos. **(b)** These *Viking Orbiter* images show Deimos and Phobos to the same scale. What appears to be a fold at the top of the image of Deimos is actually a side view of an impact crater 10 km across, comparable to the Moon's 22-km average diameter. An only slightly more powerful impact would have broken Deimos apart. (a: NASA/JPL/Cornell/Texas A&M; b: JPL/NASA)

Phobos that pulls it back, slowing the moon's motion and making it slowly spiral inward toward Mars. This inward spiral will cease in about 40 million years when Phobos smashes into the Martian surface.

The Nature of the Martian Moons

The origin of the Martian moons is unknown. One idea is that they are asteroids that Mars captured from the nearby asteroid belt (see Section 7-5). Like Phobos and Deimos, many asteroids reflect very little sunlight (typically less than 10%) because of a high carbon content. Phobos and Deimos also have very low densities (1900 kg/m^3 and 1760 kg/m^3, respectively), which are also characteristic of carbon-rich asteroids. Perhaps two of these asteroids wandered close enough to Mars to become permanently trapped by the planet's gravitational field. Alternatively, Phobos and Deimos may have formed in orbit around Mars out of debris left over from the formation of the planets. Some of this debris might have come from the asteroid belt, giving these two moons an asteroidlike character. Future measurements of the composition of the Martian moons—perhaps by landing spacecraft on their surfaces—may shed light on their origin.

Future Exploration of Mars

The exploration of Mars and its two moons has really just begun. Recent discoveries from orbiters and landers have only whetted our appetite to know more about Mars. Fortunately, every 25 months the Earth and Mars are ideally placed for sending a spacecraft from one planet to another with the minimum thrust. For the next several years, one or more spacecraft will be launched toward Mars at each of these opportunities. One of these spacecraft may land on Mars, collect samples with an advanced rover, and return those samples to Earth. Detailed analysis of Martian samples in laboratories on Earth could answer many open questions about the red planet, its formation, and its evolution.

It is ironic that at the end of the nineteenth century, the English novelist H. G. Wells envisioned a fleet of Martian spaceships coming to Earth on a mission of conquest. In the twenty-first century, it is we on Earth who are sending robotic spacecraft on a peaceful scientific "invasion" of Mars.

Key Words

1-to-1 spin-orbit coupling, p. 261
3-to-2 spin-orbit coupling, p. 262
cosmic rays, p. 289
crustal dichotomy, p. 273
dust devil, p. 282
favorable opposition, p. 258
flake tectonics, p. 274
greatest eastern elongation, p. 256
greatest western elongation, p. 256
hot-spot volcanism, p. 277
northern lowlands, p. 273
prograde rotation, p. 263
residual polar cap, p. 281
retrograde rotation, p. 263
rift valley, p. 276
runaway greenhouse effect, p. 285
runaway icehouse effect, p. 285
scarp, p. 265
shield volcano, p. 276
southern highlands, p. 273

Key Ideas

Motions of Mercury, Venus, and Mars in the Earth's Sky: Mercury and Venus can be seen in the morning or evening sky only, while it is possible to see Mars at any time of night depending on its position in its orbit.

• At their greatest eastern and western elongations, Mercury is only 28° from the Sun and Venus is only 47° from the Sun.

• The best Earth-based views of Mars are obtained at favorable oppositions, when Mars is simultaneously at opposition and near perihelion.

Rotation of Mercury, Venus, and Mars: Poor telescopic views of Mercury's surface led to the mistaken impression that the planet always keeps the same face toward the Sun (1-to-1 spin-orbit coupling).

• Radio and radar observations revealed that Mercury in fact has 3-to-2 spin-orbit coupling: The planet rotates on its axis three times every two orbits.

• Venus rotates slowly in a retrograde direction. Its rotation period is longer than its orbital period.

• Mars rotates at almost the same rate as the Earth, and its rotation axis is tilted by almost the same angle as the Earth's axis.

Mercury's Surface, Interior, and Magnetic Field: The Mercurian surface is pocked with craters, but there are extensive smooth plains between these craters.

• Long cliffs called scarps meander across the surface of Mercury. These probably formed as the planet's crust cooled, solidified, and shrank.

• Mercury has an iron core with a diameter equal to about $\frac{3}{4}$ of the planet's diameter. By contrast, the diameter of the Earth's core is only slightly more than $\frac{1}{2}$ of Earth's diameter.

• Mercury has a weak magnetic field, which indicates that at least part of the iron core is liquid.

Comparing Venus and Mars: Most of the surface of Venus is at about the same elevation, with just a few elevated regions. On Mars, the southern highlands rise several kilometers above the northern lowlands.

• Venus has a thick atmosphere and a volcanically active surface. Mars has a very thin atmosphere and little or no current volcanism.

• There is no evidence of plate tectonics on either Venus or Mars. On Venus, there is vigorous convection in the planet's interior, but the crust is too thin to move around in plates; instead, it wrinkles and flakes. On Mars, the planet's smaller size means the crust has cooled and become too thick to undergo subduction.

• Volcanoes on both Venus and Mars were produced by hot spots in the planet's interior.

• The entire Venusian surface is about 500 million years old and has relatively few craters. By contrast, most of the Martian surface is cratered and is probably billions of years old. The southern highlands on Mars are the most heavily cratered and hence the oldest part off the planet's surface.

The Atmospheres of Venus and Mars: Both planetary atmospheres are over 95% carbon dioxide, with a few percent of nitrogen.

• The pressure at the surface of Venus is about 90 atmospheres. The greenhouse effect is very strong, which raises the surface temperature to 460°C. The pressure at the surface of Mars is only 0.006 atmosphere, and the greenhouse effect is very weak.

• The permanent high-altitude clouds on Venus are made primarily of sulfuric acid. By contrast, the few clouds in the Martian atmosphere are composed of water ice and carbon dioxide ice.

• The circulation of the Venusian atmosphere is dominated by two huge convection currents in the cloud layers, one in the northern hemisphere and one in the southern hemisphere. The upper cloud layers of the Venusian atmosphere move rapidly around the planet in a retrograde direction, with a period of only about 4 Earth days.

• Weather on Mars is dominated by the north and south flow of carbon dioxide from pole to pole with the changing seasons. This can trigger planetwide dust storms.

Evolution of Atmospheres: Earth, Venus and Mars all began with relatively thick atmospheres of carbon dioxide, water vapor, and sulfur dioxide.

• On Earth, most of the carbon dioxide went into carbonate rocks and most of the water into the oceans. Ongoing plate tectonics recycles atmospheric gases through the crust.

• On Venus, more intense sunlight and the absence of plate tectonics led to a thick carbon dioxide atmosphere and a runaway greenhouse effect.

• On Mars, a runaway icehouse effect resulted from weaker sunlight and the absence of plate tectonics.

Water on Mars: Liquid water cannot exist on present-day Mars because the atmosphere is too thin and cold. But there is evidence for frozen water at the polar ice caps and beneath the surface of the regolith.

• Geological evidence from unmanned rovers shows that much of the Martian surface has been dry for billions of years, but some regions had substantial amounts of water.

The Moons of Mars: Mars has two small, football-shaped satellites that move in orbits close to the surface of the planet. They may be captured asteroids or may have formed in orbit around Mars out of solar system debris.

Questions

Review Questions

1. Why is it impossible to see Mercury or Venus in the sky at midnight?
2. Why are naked-eye observations of Mercury best made at dusk or dawn, while telescopic observations are best made during the day?
3. Why can't you see any surface features on Mercury when it is closest to the Earth?
4. Why is it best to view Mars near opposition? Why are some oppositions better than others?
5. Explain why Mars can best be viewed from Earth while it is undergoing retrograde motion.
6. Explain why the photograph in Figure 11-4*b* must have been made during the daytime.
7. In his 1964 science fiction story "The Coldest Place," author Larry Niven described the "dark side" of Mercury as the coldest place in the solar system. What assumption did he

make about the rotation of Mercury? Did this assumption turn out to be correct?

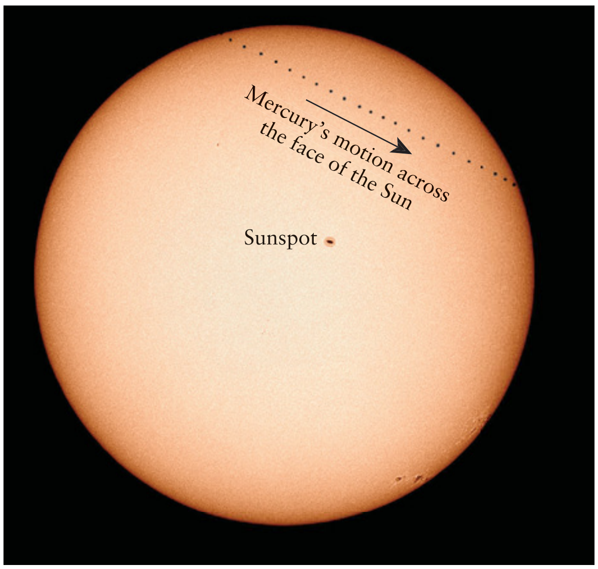
8. What is 3-to-2 spin-orbit coupling? How is the rotation period of an object exhibiting 3-to-2 spin-orbit coupling related to its orbital period? What aspects of Mercury's orbit cause it to exhibit 3-to-2 spin-orbit coupling? What telescopic observations proved this?
9. Why was it so difficult to determine the rate and direction of Venus's rotation? How were these finally determined? What is one proposed explanation for the slow, retrograde rotation of Venus?
10. Explain why Mercury does not have a substantial atmosphere.
11. What kind of surface features are found on Mercury? How do they compare to surface features on the Moon? Why are they probably much older than most surface features on the Earth?
12. How do we know that the scarps on Mercury are younger than the lava flows? How can you tell that the scarp in Figure 11-10 is younger than the vertically distorted crater at the center of the figure?
13. If Mercury is the closest planet to the Sun and has such a high average surface temperature, how is it possible that ice might exist on its surface?
14. Why do astronomers think that Mercury has a very large iron core?
15. Why is it surprising that Mercury has a global magnetic field? Why does the 58.646-day rotation period of Mercury imply that the planet can have only a weak magnetic field?
16. How is Mercury's magnetosphere similar to that of the Earth? How is it different? Why do you suppose Mercury does not have Van Allen belts?
17. Why was it difficult to determine Venus's surface temperature from Earth? How was this finally determined?
18. The *Mariner 2* spacecraft did not enter Venus's atmosphere, but it was nonetheless able to determine that the atmosphere is very dry. How was this done?
19. Why did Earth observers report that they had seen straight-line features ("canals") on Mars? How did the seasonal winds trick them into thinking that Mars had vegetation?
20. Do Venus and Mars have continents like those on Earth?
21. What is the Martian crustal dichotomy? What is the evidence that the southern highlands are older than the northern lowlands?
22. What is the evidence that the surface of Venus is only about 500 million years old?
23. What is flake tectonics? Why does Venus exhibit flake tectonics rather than plate tectonics?
24. What geologic features (or lack thereof) on Mars have convinced scientists that plate tectonics did not significantly shape the Martian surface?
25. What geologic processes are thought to have created Valles Marineris?
26. Compare the volcanoes of Venus, the Earth, and Mars. Cite evidence that hot-spot volcanism is or was active on all three worlds.
27. Describe the evidence that there has been recent volcanic activity (**a**) on Venus and (**b**) on Mars.
28. Suppose all of Venus's volcanic activity suddenly stopped. (**a**) How would this affect Venus's clouds? (**b**) How would this affect the overall Venusian environment?
29. Why are the patterns of convection in the Venusian atmosphere so different from those in our atmosphere?
30. Why is it impossible for liquid water to exist on Mars today? If liquid water existed on Mars in the past, what must have been different then?
31. Why does the atmospheric pressure on Mars vary with the seasons? What is the relationship between this pressure variation and Martian dust storms?
32. Why is it reasonable to assume that the primordial atmospheres of the Earth, Venus, and Mars were roughly the same?
33. Carbon dioxide accounts for about 95% of the present-day atmospheres of both Mars and Venus. Why, then, is there a strong greenhouse effect on Venus but only a weak greenhouse effect on Mars?
34. (**a**) What is a runaway greenhouse effect? (**b**) What is a runaway icehouse effect?
35. What is a dust devil? Why would you feel much less breeze from a Martian dust devil than from a dust devil on Earth?
36. (**a**) Why is Mars red? (**b**) Why is the Martian sky the color of butterscotch?
37. Were the *Viking Landers* able to determine whether life currently exists on Mars or whether it once existed there? Why or why not?
38. (**a**) The *Spirit* rover found the minerals olivine and pyroxene at its landing site on Mars. Explain how this shows that there has been no liquid water at that site for billions of years. (**b**) What evidence did the *Opportunity* rover find at its landing site to suggest that liquid water had once been present there?
39. How was the *Mars Odyssey* spacecraft able to detect water beneath the Martian surface without landing on the planet?
40. A full moon on Earth is bright enough to cast shadows. As seen from the Martian surface, would you expect a full Phobos or full Deimos to cast shadows? Why or why not?

Advanced Questions

Problem-solving tips and tools

We discussed the relationship between angular distance and linear distance in Box 1-1 and the idea of angular resolution in Section 6-3. You may need to refresh your memory about Kepler's third law, described in Section 4-4. You may also need to review the form of Kepler's third law that explicitly includes mass (see Section 4-7 and Box 4-4). Box 4-1 describes the relationship between a planet's sidereal orbital period and its synodic period (the time from one inferior conjunction to the next). You should recall that Wien's law (Section 5-4) relates the temperature of a blackbody to λ_{max}, its wavelength of maximum emission. Section 5-9 and Box 5-6 explain the Doppler effect and how to do calculations using it. The linear speed of a point on a planet's equator is the planet's circumference divided by its rotation period; Recall that the circumference of a circle of radius r is $2\pi r$. The volume of a sphere of radius r is $4\pi r^3/3$. The speed of light is given in Appendix 7.

41. Figure 11-1 shows Mercury with a greatest eastern elongation of 18° and a greatest western elongation of 28°. On November 25, 2006, Mercury was at a greatest western elongation of 20°. Was Mercury at perihelion, aphelion, or some other point on its orbit? Explain.
42. Venus takes 440 days to move from greatest western elongation to greatest eastern elongation, but it needs only 144 days to go from greatest eastern elongation to greatest western elongation. With the aid of a diagram like Figure 11-1, explain why.
43. Venus's sidereal rotation period is 243.01 days and its orbital period is 224.70 days. Use these data to prove that a solar day on Venus lasts 116.8 days. (*Hint:* Develop a formula relating Venus's solar day to its sidereal rotation period and orbital period similar to the first formula in Box 4-1.)
44. In Section 11-2 we described the relationship between the length of Venus's synodic period and the length of an apparent solar day on Venus. Using this and a diagram, explain why at each inferior conjunction the same side of Venus is turned toward the Earth.
45. This time-lapse photograph was taken on May 7, 2003, during a *solar transit* of Mercury. Over a period of 5 hours and 19 minutes, Mercury appeared to move across the face of the Sun. Such solar transits of Mercury occur 13 or 14 times each century; they do *not* happen each time that Mercury is at inferior conjunction. Explain why not. (*Hint*: For a solar transit to occur, the Sun, Mercury, and the Earth must be in a nearly perfect alignment. Does the orbit of Mercury lie in the plane of the ecliptic?)



R I **V** U X G

(Dominique Dierick)

46. Find the largest angular size that Mercury can have as seen from the Earth. In order for Mercury to have this apparent size, at what point in its orbit must it be?
47. (**a**) Suppose you have a telescope with an angular resolution of 1 arcsec. What is the size (in kilometers) of the smallest feature you could have seen on the Martian surface during the opposition of 2005, when Mars was 0.464 AU from Earth? (**b**) Suppose you had access to the Hubble Space Telescope, which has an angular resolution of 0.1 arcsec. What is the size (in kilometers) of the smallest feature you could have seen on Mars with the HST during the 2005 opposition?
48. For a planet to appear to the naked eye as a disk rather than as a point of light, its angular size would have to be 1 arcmin, or 60 arcsec. (This is the same as the angular separation between lines in the bottom row of an optometrist's eye chart.) (**a**) How close would you have to be to Mars in order to see it as a disk with the naked eye? Does Mars ever get this close to Earth? (**b**) Would the Earth ever be visible as a disk to an astronaut on Mars? Would she be able to see the Earth and the Moon separately, or would they always appear as a single object? Explain.
49. Using Figure 11-3, explain why oppositions of Mars are most favorable when they occur in August.
50. Imagine that you are part of the scientific team monitoring a spacecraft that has landed on Mars. At 5:00 P.M. in your control room on Earth, the spacecraft reports that the Sun is highest in the sky as seen from its location on Mars. When the Sun is next at its highest point as seen from the spacecraft, what time will it be in the control room on Earth?
51. (**a**) Mercury has a 58.646-day rotation period. What is the speed at which a point on the planet's equator moves due to this rotation? (*Hint:* Remember that speed is distance divided by time. What distance does a point on Mercury's equator travel as the planet makes one rotation?) (**b**) Use your answer to (a) to answer the following: As a result of rotation, what difference in wavelength is observed for a radio wave of wavelength 12.5 cm (such as is actually used in radar studies of Mercury) emitted from either the approaching or receding edge of the planet?
52. The orbital period of *Mariner 10* is twice that of Mercury. Use this fact to calculate the length of the semimajor axis of the spacecraft's orbit.
53. Much of the area shown in Figure 11-10 is pockmarked with small impact craters. By contrast, there are very few small craters within the large crater at the upper right of this figure. Explain why this suggests that the interior of this crater was flooded with lava while the area outside the crater was not.
54. Consider the idea that Mercury has a solid iron-bearing mantle that is permanently magnetized like a giant bar magnet. Using the fact that iron demagnetizes at temperatures above 770°C, present an argument against this explanation of Mercury's magnetic field.
55. (**a**) At what wavelength does Venus's surface emit the most radiation? (**b**) Do astronomers have telescopes that can detect this radiation? (**c**) Why can't we use such telescopes to view the planet's surface?
56. The *Mariner 2* spacecraft detected more microwave radiation when its instruments looked at the center of Venus's disk than when it looked at the edge, or limb, of the planet. (This effect is called *limb darkening*.) Explain how these observations show that the microwaves are emitted by the planet's surface rather than its atmosphere.
57. In the classic Ray Bradbury science-fiction story "All Summer in a Day," human colonists on Venus are subjected to con-

tinuous rainfall except for one day every few years when the clouds part and the Sun comes out for an hour or so. Discuss how our understanding of Venus's atmosphere has evolved since this story was first published in 1954.

58. Suppose that Venus had no atmosphere at all. How would the albedo of Venus then compare with that of Mercury or the Moon? Explain your answer.

59. A hypothetical planet has an atmosphere that is opaque to visible light but transparent to infrared radiation. How would this affect the planet's surface temperature? Contrast and compare this hypothetical planet's atmosphere with the greenhouse effect in Venus's atmosphere.

60. The Earth's northern hemisphere is 39% land and 61% water, while its southern hemisphere is only 19% land and 81% water. Thus, the southern hemisphere could also be called the "water hemisphere." The Moon also has two distinct hemispheres, the near side (which has a number of maria) and the far side (which has almost none). How are these hemispheric differences on Earth and on the Moon similar to the Martian crustal dichotomy? How are they different?

61. For a group of properly attired astronauts equipped with oxygen tanks, a climb to the summit of Olympus Mons would actually be a relatively easy (albeit long) hike rather than a true mountain climb. Give two reasons why.

62. On Mars, the difference in elevation between the highest point (the summit of Olympus Mons) and the lowest point (the bottom of the Hellas Planitia basin) is 30 km. On Earth, the corresponding elevation difference (from the peak of Mount Everest to the bottom of the deepest ocean) is only 20 km. Discuss why the maximum elevation difference is so much greater on Mars.

63. The *Mars Global Surveyor* (MGS) spacecraft is in a nearly circular orbit around Mars with an orbital period of 117 minutes. (**a**) Using the data in Table 11-3, find the radius of the orbit. (**b**) What is the average altitude of MGS above the Martian surface? (**c**) The orbit of MGS passes over the north and south poles of Mars. Explain how this makes it possible for the spacecraft to observe the entire surface of the planet.

64. The elevations in Figure 11-20 were measured using an instrument called MOLA (Mars Orbiter Laser Altimeter) on board *Mars Global Surveyor*. MOLA fires a laser beam downward, then measures how long it takes for the beam to return to the spacecraft after reflecting off the surface. Suppose MOLA measures this round-trip time for the laser beam to reflect off the summit of Olympus Mons, as well as the round-trip time to reflect off the bottom of Hellas Planitia (see Question 61). Which round-trip time is longer? How much longer is it? Do you need to know the distance from *Mars Global Surveyor* to the surface to answer this question?

65. (**a**) The Grand Canyon in Arizona was formed over 15 to 20 million years by the flowing waters of the Colorado River, as well as by rain and wind. Contrast this formation scenario to that of Valles Marineris on Mars. (**b**) Valles Marineris is sometimes called "the Grand Canyon of Mars." Is this an appropriate description? Why or why not?

66. Water has a density of 1000 kg/m^3, so a column of water n meters tall and 1 meter square at its base has a mass of $n \times$ 1000 kg. On either the Earth or Venus, which have nearly the same surface gravity, a mass of 1 kg weighs about 9.8 newtons (2.2 lb). Calculate how deep you would have to descend into the Earth's oceans for the pressure to equal the atmospheric pressure on Venus's surface, 90 atm or 9×10^6 newtons per square meter. Give your answer in meters.

67. Marine organisms produce sulfur-bearing compounds, some of which escape from the oceans into the Earth's atmosphere. (These compounds are largely responsible for the characteristic smell of the sea.) Even more sulfurous gases are injected into our atmosphere by the burning of sulfur-rich fossil fuels, such as coal, in electric power plants. Both of these processes add more sulfur compounds to the atmosphere than do volcanic eruptions. On lifeless Venus, by contrast, volcanoes are the only source for sulfurous atmospheric gases. Why, then, are sulfur compounds so much rarer in our atmosphere than in the Venusian atmosphere?

68. The classic 1950 science-fiction movie *Rocketship X-M* shows astronauts on the Martian surface with oxygen masks for breathing but wearing ordinary clothing. Would this be a sensible choice of apparel for a walk on Mars? Why or why not?

69. Suppose that the only information you had about Mars was the images of the surface in Figure 11-31. Describe at least two ways that you could tell from these images that Mars has an atmosphere.

70. Although the *Viking Lander 1* and *Viking Lander 2* landing sites are 6500 km apart and have different geologic histories, the chemical compositions of the dust at both sites are nearly identical. (**a**) What does this suggest about the ability of the Martian winds to transport dust particles? (**b**) Would you expect that larger particles such as pebbles would also have identical chemical compositions at the two *Viking Lander* sites? Why or why not?

71. Why do you suppose that Phobos and Deimos are not round like our Moon?

72. The orbit of Phobos has a semimajor axis of 9378 km. Use this information and the orbital period given in the text to calculate the mass of Mars. How does your answer compare with the mass of Mars given in Table 11-3?

73. Calculate the angular sizes of Phobos and Deimos as they pass overhead, as seen by an observer standing on the Martian equator. How do these sizes compare with that of the Moon seen from the Earth's surface? Would Phobos and Deimos appear as impressive in the Martian sky as the Moon does in our sky?

74. You are to put a spacecraft into a synchronous circular orbit around the Martian equator, so that its orbital period is equal to the planet's rotation period. Such a spacecraft would always be over the same part of the Martian surface. (**a**) Find the radius of the orbit and the altitude of the spacecraft above the Martian surface. (**b**) Suppose Mars had a third moon that was in a synchronous orbit. Would tidal forces make this moon tend to move toward Mars, away from Mars, or neither? Explain.

Discussion Questions

75. Before about 350 B.C., the ancient Greeks did not realize that Mercury seen in the morning sky (which they called Apollo) and seen in the evening sky (which they called Hermes) were actually the same planet. Discuss why you think it took some time to realize this.

76. If you were planning a new mission to Mercury, what features and observations would be of particular interest to you?
77. What evidence do we have that the surface features on Mercury were not formed during recent geological history?
78. Describe the apparent motion of the Sun during a "day" on Venus relative to (**a**) the horizon and (**b**) the background stars. (Assume that you can see through the cloud cover.)
79. If you could examine rock samples from the surface of Venus, would you expect them to be the same as rock samples from Earth? Would you expect to find igneous, sedimentary, and metamorphic rocks like those found on Earth (see Section 9-3)? Explain your answers.
80. In 1978 the *Pioneer Venus Orbiter* spacecraft arrived at Venus. It carried an ultraviolet spectrometer to measure the chemical composition of the Venusian atmosphere. This instrument recorded unexpectedly high levels of sulfur dioxide and sulfuric acid, which steadily declined over the next several years. Discuss how this observation suggests that volcanic eruptions occurred on Venus not long before *Pioneer Venus Orbiter* arrived there.
81. The total cost of the *Mars Global Surveyor* mission was about $154 million. (To put this number into perspective, in 2000 the U.S. Mint spent about $40 million to advertise its new $1 coin, which failed to be accepted by the public. Several recent Hollywood movies have had larger budgets than *Mars Global Surveyor*.) Does this expenditure seem reasonable to you? Why or why not?

Web/eBook Questions

82. **Elongations of Mercury.** Access the animation "Elongations of Mercury" in Chapter 11 of the *Universe* Web site or eBook. (**a**) View the animation and notice the dates of the greatest eastern and greatest western elongations. Which time interval is greater: from a greatest eastern elongation to a greatest western elongation, or vice versa? (**b**) Based on what you observe in the animation, draw a diagram to explain your answer to the question in (a).
83. Just as Mercury can pass in front of the Sun as seen from Earth (see Question 45), so can Venus. Transits of Venus are quite rare. The dates of the only transits in the twenty-first century are June 8, 2004, and June 6, 2012; the next ones will occur in 2117 and 2125, A number of European astronomers traveled to Asia and the Pacific islands to observe the transits of Venus in 1761 and 1769. Search the World Wide Web for information about these expeditions. Why were these events of such interest to astronomers? How definitive were the results of these observations?
84. **Surface Temperature of Venus.** Access the Active Integrated Media Module "Wien's Law" in Chapter 5 of the *Universe* Web site or eBook. (**a**) Using the Wien's Law calculator, determine Venus's approximate temperature if it emits blackbody radiation with a peak wavelength of 3866 nm. (**b**) By trial and error, find the wavelength of maximum emission for a surface temperature of 733 K (for present-day Venus) and a surface temperature of 833 K (as it might be in the event of a global catastrophe that released more greenhouse gases into Venus's atmosphere). In what part of the electromagnetic spectrum do these wavelengths lie?
85. Search the World Wide Web for information about possible manned missions to Mars. How long might such a mission take? How expensive would such a project be? What would be the advantages of a manned mission compared to an unmanned one?
86. **Conjunctions of Mars.** Access and view the animation "The Orbits of Earth and Mars" in Chapter 11 of the *Universe* Web site or eBook. (**a**) The animation highlights three dates when Mars is in opposition, so that the Earth lies directly between Mars and the Sun. By using the "Stop" and "Play" buttons in the animation, find two times during the animation when Mars is in *conjunction*, so that the Sun lies directly between Mars and the Earth (see Figure 4-6). For each conjunction, make a drawing showing the positions of the Sun, the Earth, and Mars, and record the month and year when the conjunction occurs. (*Hint:* See Figure 11-3.) (**b**) When Mars is in conjunction, at approximately what time of day does it rise as seen from Earth? At what time of day does it set? Is Mars suitably placed for telescopic observation when in conjunction?

Activities

Observing Projects

Observing tips and tools

Mercury and Venus are visible in the morning sky when it is at or near greatest western elongation and in the evening sky when at or near greatest eastern elongation. These are also the times when Venus can be seen at the highest altitude above the horizon during the hours of darkness. Mars is most easily seen around an opposition. At other times Mars may be visible only in the early morning hours before sunrise or in the early evening just after sunset. Consult such magazines as *Sky & Telescope* and *Astronomy* or their Web sites for more detailed information about when and where to look for Mercury, Venus, and Mars during a given month. You can also use the *Starry Night Enthusiast*™ program on the CD-ROM that certain printed copies of accompanies this textbook.

87. Refer to the *Universe* Web site or eBook for a link to a Web site that calculates the dates of upcoming greatest elongations of Mercury. Consult such magazines as *Sky & Telescope* and *Astronomy*, or the Web sites for these magazines, to determine if any of these greatest elongations is going to be a favorable one. If so, make plans to be one of those rare individuals who has actually seen the innermost planet of the solar system. Set

aside several evenings (or mornings) around the date of the favorable elongation to reduce the chances of being "clouded out." Select an observing site that has a clear, unobstructed view of the horizon where the Sun sets (or rises). If possible, make arrangements to have a telescope at your disposal. Search for the planet on the dates you have selected, and make a drawing of its appearance through your telescope.

88. *This observing project should be performed only under the direct supervision of an astronomer who knows how to point a telescope safely at Mercury.* Make arrangements to view Mercury during broad daylight. This is best done by visiting an observatory where the coordinates (right ascension and declination) of Mercury's position can be used to point the telescope. **DO NOT LOOK AT THE SUN! Looking directly at the Sun can cause blindness.**

89. Refer to the *Universe* Web site or eBook for a link to a Web site that calculates the dates of greatest elongations of Venus. If Venus is near a greatest elongation, view the planet through a telescope. Make a sketch of the planet's appearance. From your sketch, can you determine if Venus is closer to us or farther from us than the Sun?

90. Using a small telescope, observe Venus once a week for a month and make a sketch of the planet's appearance on each occasion. From your sketches, can you determine whether Venus is approaching us or moving away from us?

91. *This observing project should be performed only under the direct supervision of an astronomer who knows how to point a telescope safely at Venus.* Make arrangements to view Venus during broad daylight. This is best done by visiting an observatory where the coordinates (right ascension and declination) of Venus's position can be used to point the telescope. **DO NOT LOOK AT THE SUN! Looking directly at the Sun can cause blindness.**

92. If Mars is suitably placed for observation, arrange to view the planet through a telescope. Draw a picture of what you see. What magnifying power seems to give you the best image? Can you distinguish any surface features? Can you see a polar cap or dark markings? If not, can you offer an explanation for Mars's bland appearance?

93. Use the *Starry Night Enthusiast™* program to observe solar transits of Mercury (see Question 45) when the planet passes in front of the Sun as viewed from Earth. Display the entire celestial sphere (select **Guides > Atlas** in the **Favourites** menu). Open the **Find** pane and click the menu button for Mercury and select **Centre** from the menu. Using the controls at the right-hand end of the Toolbar, zoom in until the field of view is about 1° × 1°. (**a**) In the toolbar, stop time flow and set the date and time to November 8, 2006, at 12:00:00 A.M. Set the **Time Flow Rate** to **1 hour.** Step backward or forward through time using the single-step buttons (the leftmost and the rightmost buttons) and record the times at which the solar transit begins and ends. You can zoom in to a field of view of about 11 × 8 arc minutes centered upon Mercury and change the **Time Flow Rate** to **1 minute** and use the **Time Flow** controls in the toolbar to move back and forth in time to increase the accuracy of your measurement. What is the total duration of the solar transit? (**b**) Set the date and time to May 9, 2016, at 12:00:00 A.M. Again, step backward or forward through time, record the times when the solar transit begins and ends, and find the total duration of the solar transit. (**c**) The maximum duration of a solar transit of Mercury is 9 hours. Explain why the transits you observed in (a) and (b) last a substantially shorter time.

94. Use the *Starry Night Enthusiast™* program to examine Mercury. Select **Favourites > Solar System > Mercury** from the menu. Select **View > Feet** from the menu to remove the image of the astronaut's spacesuit from the view. Select **Options > Solar System > Planets-Moons. . .** from the menu to allow you to examine the complete surface of the planet. In the Planets-Moons Options dialog box, slide the control next to the label **Show dark side** all the way to the right **(Brighter)** end of the scale. Click **OK** to close the dialog box. Use the **Zoom** controls in the toolbar to zoom in and out on the view. Rotate the image of Mercury by placing the mouse cursor over the image of the planet, holding down the mouse button, and moving the mouse. (On a two-button mouse, hold down the left mouse button.) As you explore the surface of the planet Mercury, estimate the diameter of the largest craters by measuring their size on the screen with a ruler and comparing to the diameter of Mercury (see Table 11-1). (Note that the rosette patterns surrounding both planetary poles are an artifact of the technique used to produce these images).

95. Use the *Starry Night Enthusiast™* program to observe solar transits of Venus (see Question 83). Display the entire celestial sphere (select **Guides > Atlas** in the **Favourites** menu). Open the **Find** pane and click the menu button for Venus (the downward-pointing blue arrow to the left of Venus) in the list. Select **Centre** from the menu. Use the zoom controls in the toolbar to adjust the field of view to about 1° × 1°. (**a**) In the toolbar, **Stop time flow** and then set the **Time** and **Date** to June 8, 2004, at 12:00:00 A.M. Set the **Time Flow Rate** to **1 hour.** Step backward or forward through time using the single-step buttons (the leftmost and the rightmost buttons) and record the times at which the solar transit begins and ends, changing the Time Flow Rate to 1 minute and the field of view to increase the accuracy of your measurement, as necessary. What is the total duration of the solar transit? (**b**) The ecliptic appears in *Starry Night Enthusiast™* as a green line. During the transit, is Venus precisely on the ecliptic? If not, about how far off is it? (*Hint:* The Sun has an angular diameter of about 30 arcmin.) (**c**) Repeat parts (a) and (b) for the solar transit of Venus on June 6, 2012.

96. Use the *Starry Night Enthusiast™* program to observe the apparent motion of Venus on the celestial sphere. Display the entire celestial sphere (select **Guides > Atlas** in the **Favourites** menu). Open the **Find** pane and click the menu button in the list to the left of the label for the Sun. Select **Centre** from the menu that appears. Using the controls at the right-hand end of the toolbar, zoom out until the field of view is 100°. **Stop** Time Flow and in the toolbar, set the date and time to January 1, 2007, at 12:00:00 A.M. and the **Time Flow Rate** to **1 day.**

(**a**) Use the **Run Time Forward** and **Stop time** buttons to find the first date after January 1, 2007, when Venus is as far to the right of the Sun as possible, and the first date after January 1, 2007, when Venus is as far to the left of the Sun as possible. What is your interpretation of these two dates and how would you label them? (**b**) Set the date to December 1, 2007, and start the animation by clicking on the **Run Time Forward** button. Based on your observations, explain why Venus has neither a greatest western elongation nor a greatest eastern elongation during 2008.

97. Use the *Starry Night Enthusiast*™ program to compare the orbits of Venus and the Earth. Select **Options > Viewing Location. . .** from the menu. In the Viewing Location dialog box, set the **View from** to a **position moving with** the **Sun** and choose the option **Above orbital plane.** Then click the **Set Location** button to close the dialog. Click on and hold the **Increase current elevation** button in the Viewing Location section of the toolbar until the distance shown in the Viewing Location display pane is approximately **1.5 au** from the Sun. Open the **Find** pane and click both of the checkboxes on either side of the listing for the Earth and for Venus. This labels the two planets and draws their orbits in the view. Close the Find pane. **Stop** time flow and set the time and the date to 0:00:00 UT on August 19, 2007 AD. You can zoom in and zoom out on these two planets and their orbits using the buttons in the **Zoom** section of the toolbar. You can also rotate the solar system by holding down the **Shift** key and then holding down the mouse button and moving the mouse. (On a two-button mouse, hold down the left mouse button.) Are the orbits of Venus and of the Earth in the same plane? At the time shown in the image, is Venus nearest to inferior conjunction, superior conjunction, greatest eastern elongation, or greatest western elongation as seen from Earth? Explain your answers. Rotate your view to look down upon the orbits from above the pole of the Sun. Are the orbits of Earth and Venus circular?

98. Use the *Starry Night Enthusiast*™ program to observe the appearance of Mars. Select **Favourites > Guides > Atlas** from the menu. Select **View > Celestial Grid** from the menu to turn this option off. Open the **Find** pane and click the menu button for **Mars** and choose **Centre** from the menu. Close the Find pane and then use the Zoom controls in the toolbar to set a field of view of approximately **58″ × 40″.** (**a**) Set the **Time Flow Rate** to **1 hour** and then run **Time Forward.** Describe what you see. (**b**) **Stop** time flow. Change the **Time Flow Rate** to **1 lunar month. Run Time Forward** again. Describe what you see. Using a diagram like Figure 4-6, explain the changes in the apparent size of the planet. (**c**) **Stop** time flow and **zoom out** to a field of view of approximately **2′ × 1′.** Change the time and date in the toolbar to 12:00:00 A.M. on August 28, 2003, to see Mars during a very favourable opposition. You will see Mars and its two moons, Phobos and Deimos. In the toolbar, set the **Time Flow Rate** to **1 minute.** Record the date and time in the display, and note the position of Phobos (the inner moon). Click the **Run Time Forward** and single time step button (the rightmost time control button) to advance time until Phobos returns to approximately the same position relative to Mars. Record the date and time in the display. From your observations, what is the orbital period of Phobos? How does your result compare with the orbital period given in Appendix 3? (**d**) Repeat part (c) for Deimos (the outer moon).

99. Use the *Starry Night Enthusiast*™ program to compare the orbits of Mars and the Earth. **Select Options > Viewing Location. . .** from the menu. In the Viewing Location dialog box, set the **View from** to a **position moving with** the **Sun** and choose the option **Above orbital plane** and click the **Set Location** button to close the dialog. Click on and hold the **Increase current elevation** button in the Viewing Location section of the toolbar until the distance shown in the Viewing Location display pane is approximately **3.5 au** from the Sun. Open the **Find** pane and click the two checkboxes on either side of the listings for the **Earth** and for **Mars** to label these two planets and draw their orbits in the view. Close the Find pane. You can zoom in and zoom out using the buttons in the **Zoom** section of the toolbar. You can also rotate the solar system by holding down the **Shift** key and then holding down the mouse button and moving the mouse. (On a two-button mouse, hold down the left mouse button.) Stop time flow and set the time and date to 0:00:00 UT on October 16, 2005 AD. (**a**) Is Mars a few weeks before an opposition or a few weeks after an opposition at this time on this date? (*Hint:* Arrowheads on the orbits show you which way each planet moves around its orbit.) (**b**) Are the orbits of Mars and of the Earth in the same plane? Use your answer to explain the shape of the apparent path of Mars on the celestial sphere in 2011–2012, shown in Figure 4-2.

Collaborative Exercises

100. Figures 11-6*b* and 11-6*c* show a planet in synchronous rotation and Mercury with a 3-to-2 spin-orbit coupling, respectively. Stand up and demonstrate how planets move in each of these rotations by “orbiting” around a stationary classmate who represents our Sun. How would Mercury’s motion be different if it had a 4-to-2 spin-orbit coupling instead?

101. In the nineteenth century, French mathematician and astronomer U. J. J. Le Verrier led a failed search for a hypothetical planet named Vulcan (after the mythical blacksmith of the gods) orbiting closer to our Sun than Mercury. If Vulcan had an orbit with the same eccentricity as Mercury’s orbit but only one-half the size, what would have been its maximum eastern and western elongations?

102. Figure 11-7 shows prograde and retrograde rotation. Stand up and demonstrate how Venus rotates as it orbits our Sun, using a classmate as our stationary Sun. How is this different from how Earth rotates in its orbit?

103. The image of Mars that opens this chapter is from the Hubble Space Telescope. Draw a circle on your paper roughly 5 cm in diameter and, taking turns, have each person in your group sketch a different region of Mars. How is your collaborative sketch different than Schiaparelli’s drawing shown in Figure 11-16?

Robotic Geologists and the Search for Habitable Environments on Mars

by John Grotzinger

Scientists discover that which exists; engineers create that which never was.

Theodor von Kármán, founder of NASA's Jet Propulsion Lab

Humans are explorers by nature. The great quests of human history have presented grand challenges that by necessity have inspired creative design of ships of exploration. In the search to understand the history of water on Mars, and its potential role in enabling the evolution of life on the most Earthlike terrestrial planet, human imagination has been no less bridled. Since humans cannot yet travel to other planets, we have developed robots that can survive interplanetary travel and the harsh surface conditions on other planets. These robotic explorers are designed to act as geologists, which was the case for the 2004 *Mars Exploration Rover* mission.

In June 2003, two golf cart–sized rovers destined to land on the Martian surface were launched from Cape Canaveral, Florida, and began their 300-million-kilometer journey to the Red Planet. This mission succeeded beyond anyone's expectations, making 2004, 2005, and 2006 three of the greatest years in the history of space exploration. The *Mars Exploration Rovers—Spirit* and *Opportunity*—were designed to survive 3 months under the hostile Martian surface conditions and drive no farther than 300 m. Remarkably, at the time this article was written, each rover has operated for more than two and a half years, and driven a combined distance of more than 15 km! The rovers have had to survive nighttime temperatures below –150 °C, dust devils that could have tipped them over, global dust storms that diminished their solar power, and drives along rocky slopes of almost 30° and through piles of treacherous windblown sand and dust. The rovers have also discovered a treasure trove of geologic wonders. These discoveries include compelling evidence for water on the ancient Martian surface—a necessary condition for life, at least as it exists on Earth, and can be contemplated for Mars.

In particular, the rover *Opportunity* has discovered evidence from the Meridiani Planum area that water may have pooled in shallow lakes, known as playas, and infiltrated pores in sediments and soils to cause aqueous alteration. So we now know that water was present in the shallow subsurface environment and was at least intermittently present at the surface as shallow lakes and streams. But the evidence for water alone is not enough to demonstrate that life may have existed. One must also ask if the water would have had physical attributes that would have allowed life to develop.

Mars today is a forbidding place. Temperature and atmospheric pressure are so low that liquid water is not stable on the present-day Martian surface. The surface is also chemically harsh and subject to strong radiation. It is doubtful that organisms thrive today at the Martian surface. *Opportunity*'s discoveries indicate that surface environments may have, unfortunately, been biologically challenging for *most* of Mars's history. The salty and transient streams and lakes that covered Meridiani 3 to 4 billion years ago indicate that while chemical weathering and erosion provided many of the elements required for life, ambient environments were arid, acidic, and oxidizing. Terrestrial ecology suggests that microorganisms could survive many aspects of the inferred Meridiani environment, but habitability would depend critically on the time scale of sufficiently high water activity to support cell biology—a time scale that is currently unknown.

Whether Meridiani is broadly representative of the Martian surface 3 to 4 billion years ago is unknown, but remote sensing from orbiting spacecraft suggests that it could be. The sulfate minerals that are so widespread at Meridiani seem to be widespread in others areas of the planet, particularly the equatorial lowlands. However, there appear to be hints that other combinations of minerals—some dominated by clays—may be associated with the oldest rocks on Mars. From an astrobiological perspective this is encouraging because it allows for less acidic conditions. All considered, the formerly

(continued on the next page)

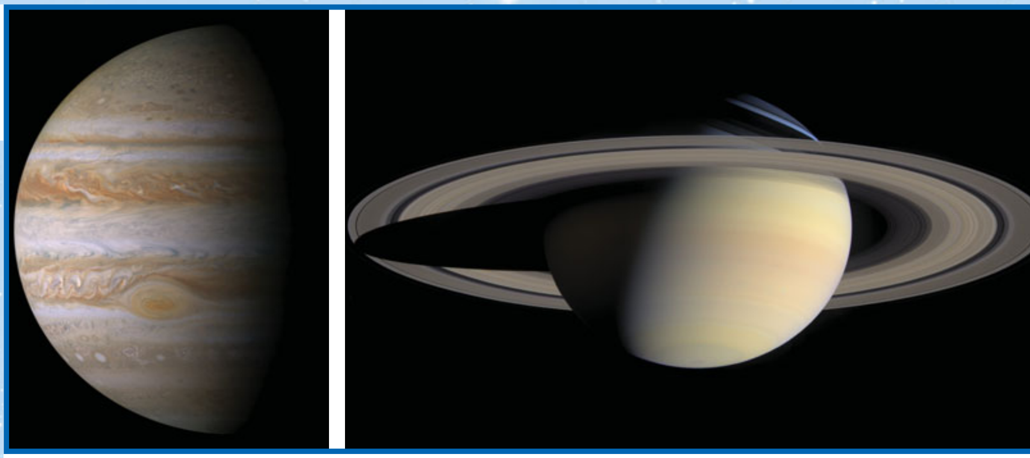
John Grotzinger is a field geologist interested in the evolution of Earth's surficial environments and biosphere. He received a B.S. in geoscience from Hobart College in 1979, an M.S. in geology from University of Montana in 1981, and a Ph.D. in geology from Virginia Tech in 1985. He currently works as a geologist on the *Mars Exploration Rover* team. This mission is the first to conduct ground-based exploration of the bedrock geology of another planet, resulting in the discovery of sedimentary rocks formed in aqueous depositional environments.

Robotic Geologists and the Search for Habitable Environments on Mars *(continued)*

water-drenched rocks at Meridiani are biologically permissive, but may record the close of a biologically favorable window in the history of Mars, not its beginning.

For future missions, such as the *Mars Science Laboratory* rover, due to launch in 2009, the most promising places to look for evidence of Mars surface life are probably sedimentary basins that preserve a record of Mars's earliest history, when water was most abundant and persistent, and both oxidation and acidity were least developed. *Mars Science Laboratory* will come with a science payload that is designed to search for large organic molecules that would provide unambiguous tests for past life. If present, their discovery would surely rank as one of the greatest benchmarks in the history of scientific exploration and would no doubt significantly influence the way that we think about the origin and evolution of life in the universe as a whole.

12 Jupiter and Saturn: Lords of the Planets



WEB LINK 12.1

R I V U X G

Jupiter (left) and Saturn (right) to scale. (NASA/JPL/Space Science Institute)

Among the most remarkable sights in our solar system are the colorful, turbulent atmosphere of Jupiter and the ethereal beauty of Saturn's rings. Both of these giant worlds dwarf our own planet: More than 1200 Earths would fit inside Jupiter's immense bulk, and more than 700 Earths inside Saturn. Unlike the Earth, both Jupiter and Saturn are composed primarily of the lightweight elements hydrogen and helium, in abundances very similar to those in the Sun.

As these images show, the rapid rotations of both Jupiter and Saturn stretch their weather systems into colorful bands that extend completely around each planet. Both planets also have intense magnetic fields that are generated in their interiors, where hydrogen is so highly compressed that it becomes a metal.

Saturn is not merely a miniature version of Jupiter, however. Its muted colors and more flattened shape are clues that Saturn's atmosphere and interior have important differences from those of Jupiter. The most striking difference is Saturn's elaborate system of rings, composed of countless numbers of icy fragments orbiting in the plane of the planet's equator. The rings display a complex and elegant structure, which is shaped by subtle gravitational influences from Saturn's retinue of moons. Jupiter, too, has rings, but they are made of dark, dustlike particles that reflect little light. These systems of rings, along with the distinctive properties of the planets themselves, make Jupiter and Saturn highlights of our tour of the solar system.

12-1 Jupiter and Saturn are the most massive planets in the solar system

Jupiter and Saturn are respectively the largest and second largest of the planets, and the largest objects in the solar system other

Learning Goals

By reading the sections of this chapter, you will learn

12-1 What observations from Earth reveal about Jupiter and Saturn

12-2 How Jupiter and Saturn rotate differently from terrestrial planets like Earth

12-3 The nature of the immense storms seen in the clouds of Jupiter and Saturn

12-4 How the internal heat of Jupiter and Saturn drives activity in their atmospheres

12-5 What the *Galileo* space probe revealed about Jupiter's atmosphere

12-6 How the shapes of Jupiter and Saturn indicate the sizes of their rocky cores

12-7 How Jupiter and Saturn's intense magnetic fields are produced by an exotic form of hydrogen

12-8 The overall structure and appearance of Saturn's ring system

12-9 What kinds of particles form the rings of Jupiter and Saturn

12-10 How spacecraft observations revealed the intricate structure of Saturn's rings

12-11 How Saturn's rings are affected by the presence of several small satellites

Table 12-1 Jupiter Data

Average distance from Sun:	5.203 AU = 7.783×10^8 km
Maximum distance from Sun:	5.455 AU = 8.160×10^8 km
Minimum distance from Sun:	4.950 AU = 7.406×10^8 km
Eccentricity of orbit:	0.048
Average orbital speed:	13.1 km/s
Orbital period:	11.86 years
Rotation period:	$9^h\ 50^m\ 28^s$ (equatorial) $9^h\ 55^m\ 29^s$ (internal)
Inclination of equator to orbit:	3.12°
Inclination of orbit to ecliptic:	1.30°
Diameter:	142,984 km = 11.209 Earth diameters (equatorial) 133,708 km = 10.482 Earth diameters (polar)
Mass:	1.899×10^{27} kg = 317.8 Earth masses
Average density:	1326 kg/m^3
Escape speed:	60.2 km/s
Surface gravity (Earth = 1):	2.36
Albedo:	0.44
Average temperature at cloudtops:	−108°C = −162°F = 165 K
Atmospheric composition (by number of molecules):	86.2% hydrogen (H_2), 13.6% helium (He), 0.2% methane (CH_4), ammonia (NH_3), water vapor (H_2O), and other gases

WEB LINK 12.2

R I V U X G

(NASA/JPL)

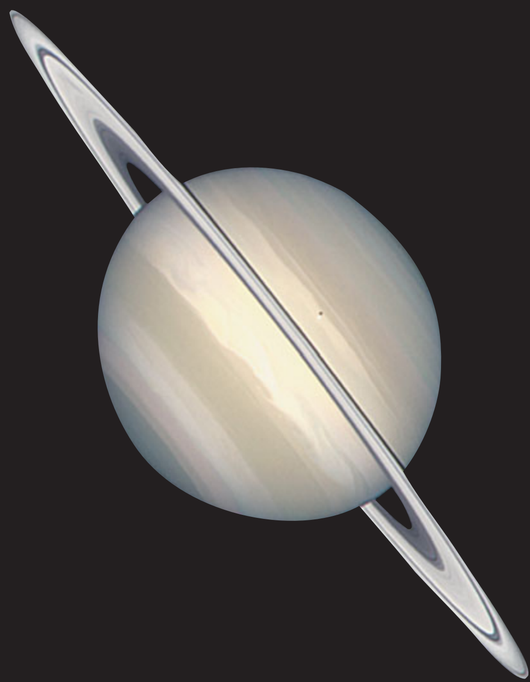
than the Sun itself. Astronomers have known for centuries about the huge diameters and immense masses of these two planets. Given the distance to each planet and their angular sizes, they used the small-angle formula (Box 1-1) to calculate that Jupiter is about 11 times larger in diameter than Earth, while Saturn's diameter is about 9 times larger than Earth's (see Figure 7-2). By observing the orbits of Jupiter's four large moons and Saturn's large moon Titan (see Table 7-2) and applying Newton's form of Kepler's third law (see Section 4-7 and Box 4-4), astronomers also determined that Jupiter and Saturn are, respectively, 318 times and 95 times more massive than the Earth. In fact, Jupiter has $2\frac{1}{2}$ times the combined mass of all the other planets, satellites, asteroids, meteoroids, and comets in the solar system. A visitor from interstellar space might well describe our solar system as the Sun, Jupiter, and some debris! Table 12-1 and Table 12-2 list some basic data about Jupiter and Saturn.

Observing Jupiter and Saturn

As for any planet whose orbit lies outside the Earth's orbit, the best time to observe Jupiter or Saturn is when they are at opposition. At opposition, Jupiter can appear nearly 3 times brighter than Sirius, the brightest star in the sky. Only the Moon and

Table 12-2 Saturn Data

Average distance from Sun:	9.572 AU = 1.432×10^9 km
Maximum distance from Sun:	10.081 AU = 1.508×10^9 km
Minimum distance from Sun:	9.063 AU = 1.356×10^9 km
Eccentricity of orbit:	0.053
Average orbital speed:	9.64 km/s
Orbital period:	29.37 years
Rotation period:	$10^h\ 13^m\ 59^s$ (equatorial) $10^h\ 39^m\ 25^s$ (internal)
Inclination of equator to orbit:	26.73°
Inclination of orbit to ecliptic:	2.48°
Diameter:	120,536 km = 9.449 Earth diameters (equatorial) 108,728 km = 8.523 Earth diameters (polar)
Mass:	5.685×10^{26} kg = 95.16 Earth masses
Average density:	687 kg/m^3
Escape speed:	35.5 km/s
Surface gravity (Earth = 1):	0.92
Albedo:	0.46
Average temperature at cloudtops:	−180°C = −292°F = 93 K
Atmospheric composition (by number of molecules):	96.3% hydrogen (H_2), 3.3% helium (He), 0.4% methane (CH_4), ammonia (NH_3), water vapor (H_2O), and other gases



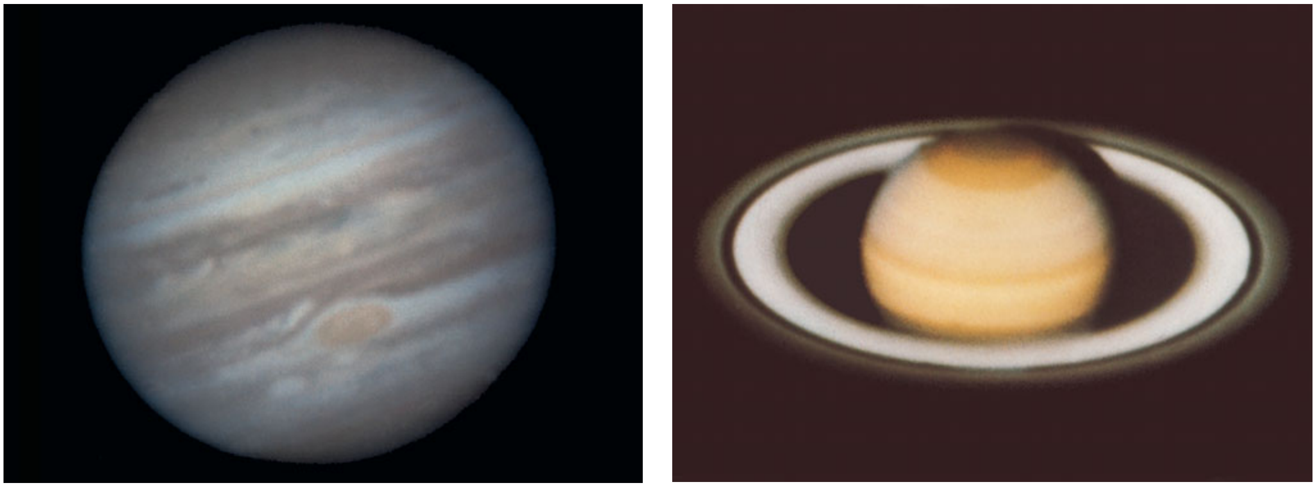
R I V U X G
(STScI/Hubble Heritage Team)

Venus can outshine Jupiter at opposition. Saturn's brightness at opposition is only about 1/7 that of Jupiter, but it still outshines all of the stars except Sirius and Canopus.

Through a telescope, Jupiter at opposition presents a disk nearly 50 arcsec in diameter, approximately twice the angular diameter of Mars under the most favorable conditions (Figure 12-1*a*). Because Jupiter takes almost a dozen Earth years to orbit the Sun, it appears to meander slowly across the 12 constellations of the zodiac at the rate of approximately one constellation per year. Successive oppositions occur at intervals of about 13 months.

Saturn's orbital period is even longer, more than 29 Earth years, so it moves even more slowly across the zodiac. If Saturn did not move at all, successive oppositions would occur exactly one Earth year apart; thanks to its slow motion, Saturn's oppositions occur at intervals of about one year and two weeks. At opposition Saturn appears as a disk about 20 arcsec in diameter, with a dramatic difference from Jupiter: Saturn is surrounded by a magnificent system of rings (Figure 12-1*b*). Later in this chapter we will examine these rings in detail.

Even a small telescope reveals colored bands on Jupiter and rings around Saturn



(a) (b)

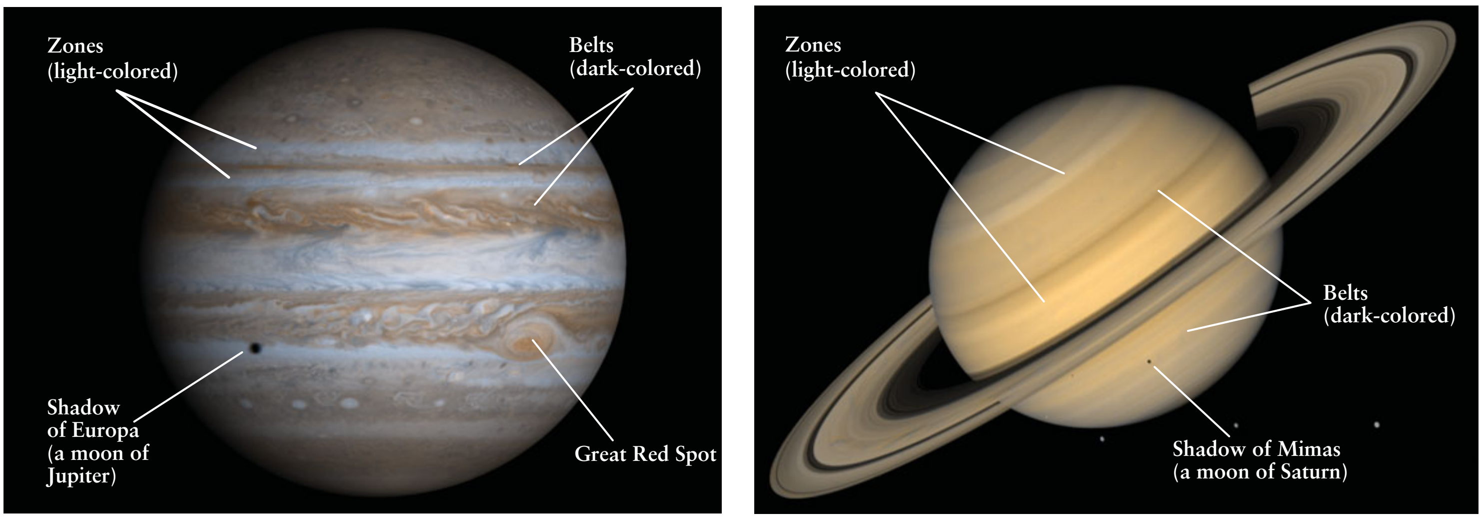
Figure 12-1 R I V U X G

Jupiter and Saturn as Viewed from Earth **(a)** The disk of Jupiter at opposition appears about $2\frac{1}{2}$ times larger than **(b)** the disk of Saturn at opposition. Both planets display dark and light bands, though these are fainter on Saturn. (a: Courtesy of Stephen Larson; b: NASA)

Dark Belts and Light Zones

As seen through an Earth-based telescope, both Jupiter and Saturn display colorful bands that extend around each planet parallel to its equator (Figure 12-1). More detailed close-up views of Jupiter from a spacecraft (Figure 12-2*a*) show alternating dark and light bands parallel to Jupiter's equator in subtle tones of red, orange, brown, and yellow. The dark, reddish bands are called **belts,** and the light-colored bands are called **zones.** The image of Saturn in Figure 12-2*b* shows similar features, but with colors that are much less pronounced. (We will see in Section 12-4 how differences between the atmospheres of Jupiter and Saturn can explain Saturn's washed-out appearance.)

In addition to these conspicuous stripes, a huge, red-orange oval called the **Great Red Spot** is often visible in Jupiter's southern hemisphere. This remarkable feature was first seen by the English scientist Robert Hooke in 1664 but may be much older. It appears to be an extraordinarily long-lived storm in the planet's



(a) Jupiter (b) Saturn

VIDEO 12.1 VIDEO 12.2

Figure 12-2 R I V U X G

Jupiter and Saturn as Viewed from Space **(a)** This view of Jupiter is a composite of four images made by the *Cassini* spacecraft as it flew past Jupiter in 2000. **(b)** Images from the *Voyager 2* spacecraft as it flew past Saturn in 1981 were combined to show the planet in approximately natural color. (a: NASA/JPL/University of Arizona; b: USGS/NASA/JPL) dynamic atmosphere. Saturn has no long-lived storm systems of this kind. However, many careful observers have reported smaller spots and blemishes in the atmospheres of both Jupiter and Saturn that last for only a few weeks or months.

12-2 Unlike the terrestrial planets, Jupiter and Saturn exhibit differential rotation

Observations of features like the Great Red Spot and smaller storms allow astronomers to determine how rapidly Jupiter and Saturn rotate. At its equator, Jupiter completes a full rotation in only 9 hours, 50 minutes, and 28 seconds, making it not only the largest and most massive planet in the solar system but also the one with the fastest rotation. However, Jupiter rotates in a strikingly different way from the Earth, the Moon, Mercury, Venus, or Mars.

Differential Rotation

If Jupiter were a solid body like a terrestrial planet (or, for that matter, a billiard ball), all parts of Jupiter's surface would rotate through one complete circle in this same amount of time (Figure 12-3*a*). But by watching features in Jupiter's cloud cover, Gian Domenico Cassini discovered in 1690 that the polar regions of the planet rotate a little more slowly than do the equatorial regions. (You may recall this Italian astronomer from Section 11-2 as the gifted observer who first determined Mars's rate of rotation.) Near the poles, the rotation period of Jupiter's atmosphere is about 9 hours, 55 minutes, and 41 seconds. Saturn, too, has a longer rotation period near its poles (10 hours, 39 minutes, and 24 seconds) than at its equator (10 hours, 13 minutes, and 59 seconds).

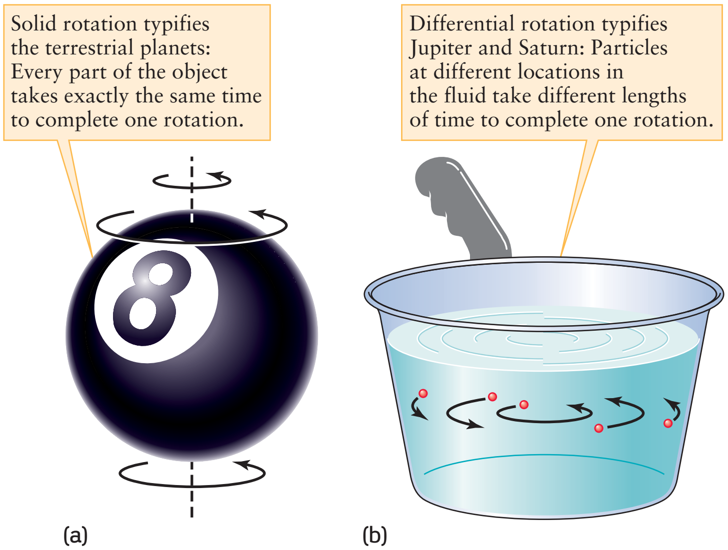


Figure 12-3

Solid Rotation versus Differential Rotation **(a)** All parts of a solid object rotate together, but **(b)** a rotating fluid displays differential rotation. To see this, put some grains of sand, bread crumbs, or other small particles in a pot of water. Stir the water with a spoon to start it rotating, then take out the spoon. The particles near the center of the pot take less time to make a complete rotation than those away from the center.

ANALOGY You can see this kind of rotation, called **differential rotation,** in the kitchen. As you stir the water in a pot, different parts of the liquid take different amounts of time to make one "rotation" around the center of the pot (Figure 12-3*b*). Differential rotation shows that neither Jupiter nor Saturn can be solid throughout their volumes: They must be at least partially fluid, like water in a pot.

The Compositions of Jupiter and Saturn

If Jupiter and Saturn have partially fluid interiors, they cannot be made of the rocky materials that constitute the terrestrial planets. An important clue to the compositions of Jupiter and Saturn are their average densities, which are only 1326 kg/m^3 for Jupiter and 687 kg/m^3 for Saturn. (By comparison, the Earth's average density is 5515 kg/m^3.) To explain these low average densities, Rupert Wildt of the University of Göttingen in Germany suggested in the 1930s that Jupiter and Saturn are composed mostly of hydrogen and helium atoms—the two lightest elements in the universe—held together by their mutual gravitational attraction to form a planet. Wildt was motivated in part by his observations of prominent absorption lines of methane and ammonia in Jupiter's spectrum. (We saw in Section 7-3 how spectroscopy plays an important role in understanding the planets.) A molecule of methane (CH_4) contains four hydrogen atoms, and a molecule of ammonia (NH_3) contains three. The presence of these hydrogen-rich molecules was strong, but indirect, evidence of abundant hydrogen in Jupiter's atmosphere.

Direct evidence for hydrogen and helium in Jupiter's atmosphere, however, was slow in coming. The problem was that neither gas produces prominent spectral lines in the visible sunlight reflected from the planet. To show the presence of these elements conclusively, astronomers had to look for spectral lines in the ultraviolet part of the spectrum. These lines are very difficult to measure from the Earth, because almost no ultraviolet light penetrates our atmosphere (see Figure 6-25). Astronomers first detected the weak spectral lines of hydrogen molecules in Jupiter's spectrum in 1960. The presence of helium on Jupiter and Saturn was finally confirmed in the 1970s and 1980s, when spacecraft first flew past these planets and measured their hydrogen spectra in detail. (Collisions between helium and hydrogen atoms cause small but measurable changes in the hydrogen spectrum, which is what the spacecraft instruments detected.)

Spacecraft observations were needed to determine the compositions of Jupiter and Saturn

Today we know that the chemical composition of Jupiter's atmosphere is 86.2% hydrogen molecules (H_2), 13.6% helium atoms, and 0.2% methane, ammonia, water vapor, and other gases. The percentages in terms of *mass* are somewhat different because a helium atom is twice as massive as a hydrogen molecule. Hence, by mass, Jupiter's atmosphere is approximately 75% hydrogen, 24% helium, and 1% other substances, quite similar to that of the Sun. We will see evidence in Section 12-6 that Jupiter has a large rocky core made of heavier elements. It is estimated that the breakdown by mass of the planet as a whole (atmosphere plus interior) is approximately 71% hydrogen, 24% helium, and 5% all heavier elements.

Saturn's Missing Helium

Like Jupiter, Saturn is thought to have a large rocky core. But unlike Jupiter, data from Earth-based telescopes and spacecraft show that the atmosphere of Saturn has a serious helium deficiency: Its chemical composition is 96.3% hydrogen molecules, 3.3% helium, and 0.4% other substances (by mass, 92% hydrogen, 6% helium, and 2% other substances). This is a puzzle because Jupiter and Saturn are thought to have formed in similar ways from the gases of the solar nebula (see Section 8-4), and so both planets (and the Sun) should have essentially the same abundances of hydrogen and helium. So where did Saturn's helium go?

The explanation may be simply that Saturn is smaller than Jupiter, and as a result Saturn probably cooled more rapidly. (We saw in Section 7-6 why a small world cools down faster than a large one.) This cooling would have triggered a process analogous to the way rain develops here on Earth. When the air is cool enough, humidity in the Earth's atmosphere condenses into raindrops that fall to the ground. On Saturn, however, it is droplets of liquid helium that condense within the planet's cold, hydrogen-rich outer layers. In this scenario, helium is deficient in Saturn's upper atmosphere simply because it has fallen farther down into the planet. By contrast, Jupiter's helium has not rained out because its upper atmosphere is warmer and the helium does not form droplets.

ANALOGY An analogy to helium "rainfall" within Saturn is what happens when you try to sweeten tea by adding sugar. If the tea is cold, the sugar does not dissolve well and tends to sink to the bottom of the glass even if you stir the tea with a spoon. But if the tea is hot, the sugar dissolves with only a little stirring. In the same way, it is thought that the descending helium droplets once again dissolve in hydrogen once they reach the warmer depths of Saturn's interior.

In this scenario, Jupiter and Saturn both have about the same overall chemical composition. But Saturn's smaller mass, less than a third that of Jupiter, means that there is less gravitational force tending to compress its hydrogen and helium. This explains why Saturn's density is only about half that of Jupiter, and is in fact the lowest of any planet in the solar system.

CAUTION! Because Jupiter and Saturn are almost entirely hydrogen and helium, it would be impossible to land a spacecraft on either planet. An astronaut foolish enough to try would notice the hydrogen and helium around the spacecraft becoming denser, the temperature rising, and the pressure increasing as the spacecraft descended. But the hydrogen and helium would never solidify into a surface on which the spacecraft could touch down. Long before reaching the planet's rocky core, the pressure of the hydrogen and helium would reach such unimaginably high levels that any spacecraft, even one made of the strongest known materials, would be crushed.

12-3 Spacecraft images show remarkable activity in the clouds of Jupiter and Saturn

Most of our detailed understanding of Jupiter and Saturn comes from a series of robotic spacecraft that have examined these remarkable planets at close range. They found striking evidence of stable, large-scale weather patterns in both planets' atmospheres, as well as evidence of dynamic changes on smaller scales.

Spacecraft to Jupiter and Saturn

WEB LINK 12.6

The first several spacecraft to visit Jupiter and Saturn each made a single flyby of the planet. *Pioneer 10* flew past Jupiter in December 1973; it was followed a year later by the nearly identical *Pioneer 11,* which went on to make the first-ever flyby of Saturn in 1979. Also in 1979, another pair of spacecraft, *Voyager 1* and *Voyager 2,* sailed past Jupiter. These spacecraft sent back spectacular close-up color pictures of Jupiter's dynamic atmosphere. Both *Voyagers* subsequently flew past Saturn.

The first spacecraft to go into Jupiter orbit was *Galileo,* which carried out an extensive program of observations from 1995 to 2003. The *Cassini* spacecraft went into orbit around Saturn in 2004. A cooperative project of NASA, the European Space Agency, and the Italian Space Agency, this spacecraft is named for astronomer Gian Domenico Cassini. On the way to its destination it viewed Jupiter at close range, recording detailed images such as Figure 12-2*a* and the image of Jupiter that opens this chapter.

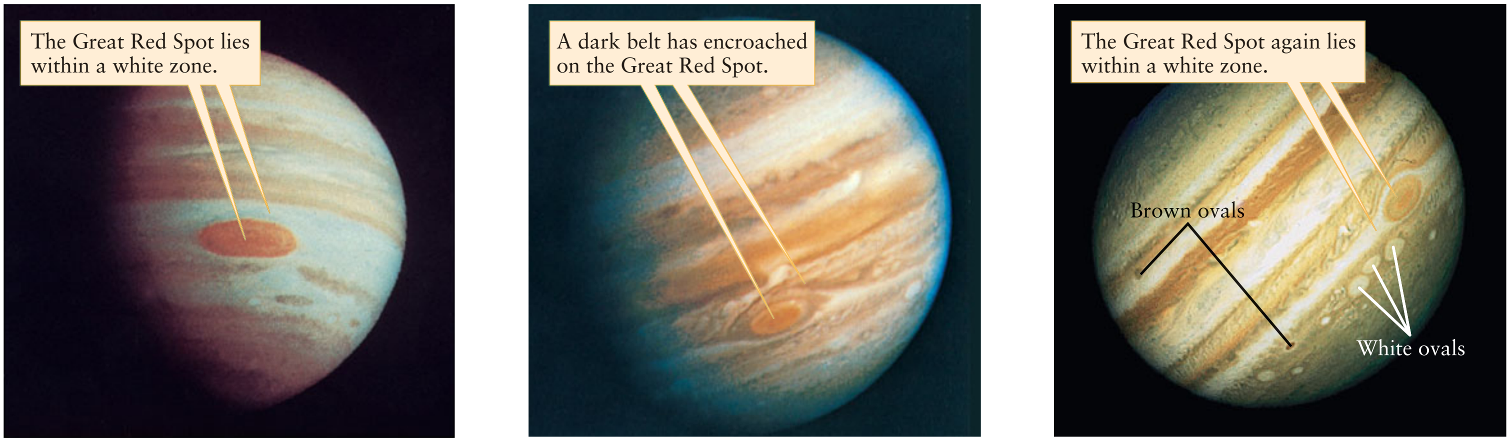
Observing Jupiter's Dynamic Atmosphere

While the general pattern of Jupiter's atmosphere stayed the same during the four years between the *Pioneer* and *Voyager* flybys, there were some remarkable changes in the area surrounding the centuries-old Great Red Spot. During the *Pioneer* flybys, the Great Red Spot was embedded in a broad white zone that dominated the planet's southern hemisphere (Figure 12-4*a*). By the time of the *Voyager* missions, a dark belt had broadened and encroached on the Great Red Spot from the north (Figure 12-4*b*). In the same way that colliding weather systems in our atmosphere can produce strong winds and turbulent air, the interaction in Jupiter's atmosphere between the belt and the Great Red Spot embroiled the entire region in turbulence (Figure 12-5). By 1995, the Great Red Spot was once again centered within a white zone (Figure 12-4*c*); when *Cassini* flew past Jupiter in 2000, the dark belt to the north of the Great Red Spot embroiled the entire region in turbulence.

Immense storms on Jupiter and Saturn can last for months or years

Over the past three centuries, Earth-based observers have reported many long-term variations in the Great Red Spot's size and color. At its largest, it measured 40,000 by 14,000 km—so large that three Earths could fit side by side across it. At other times (as in 1976 and 1977), the spot almost faded from view. During the *Voyager* flybys of 1979, the Great Red Spot was comparable in size to the Earth (see Figure 12-5).

Clouds at different levels in Jupiter's atmosphere reflect different wavelengths of infrared light. Using this effect, astronomers

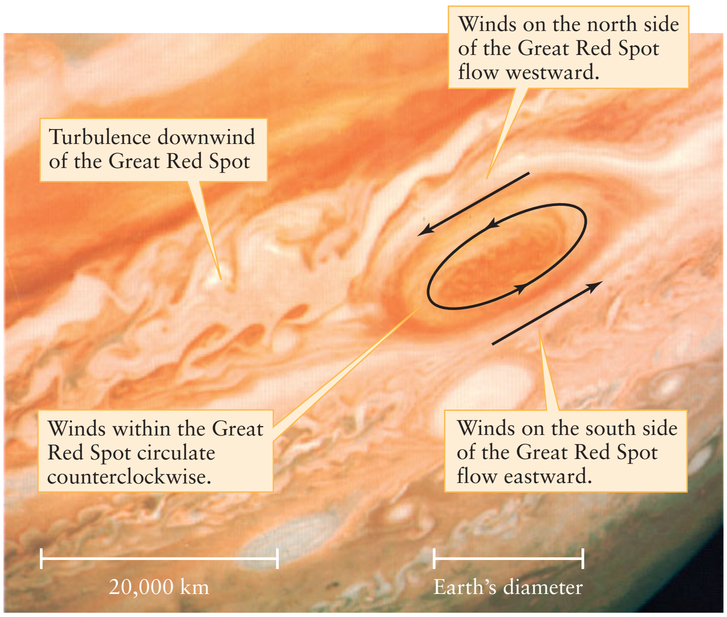


(a) *Pioneer 11*, December 1974 (b) *Voyager 2*, July 1979 (c) HST, February 1995

Figure 12-4 RIVUXG

Jupiter's Changing Appearance These images from **(a)**, **(b)** spacecraft and **(c)** the Hubble Space Telescope show major changes in the planet's upper atmosphere over a 20-year period. (a and b: NASA/JPL; c: Reta Beebe and Amy Simon, New Mexico State University, and NASA)

used an infrared telescope on board the *Galileo* spacecraft to help clarify the vertical structure of the Great Red Spot. Most of the Great Red Spot is made of clouds at relatively high altitudes, surrounded by a collar of very low-level clouds about 50 km (30 miles, or 160,000 feet) below the high clouds at the center of the spot. This same kind of structure is seen in high-pressure areas in the Earth's atmosphere, although on a very much smaller scale.



VIDEO 12.3

Figure 12-5 RIVUXG

Circulation around the Great Red Spot This 1979 image from *Voyager 2* shows atmospheric turbulence and the direction of winds around the Great Red Spot (compare Figure 12-4*b*, taken at approximately the same time). Winds within the Great Red Spot itself make it spin counterclockwise, completing a full revolution in about six days. (NASA/JPL; adapted from A. P. Ingersoll)

Cloud motions in and around the Great Red Spot reveal that the spot rotates counterclockwise with a period of about six days. Furthermore, winds to the north of the spot blow to the west, and winds south of the spot move toward the east. The circulation around the Great Red Spot is thus like a wheel spinning between two oppositely moving surfaces (see Figure 12-5). Weather patterns on the Earth tend to change character and eventually dissipate when they move between plains and mountains or between land and sea. But because no solid surface or ocean underlies Jupiter's clouds, no such changes can occur for the Great Red Spot—which may explain how this wind pattern has survived for at least three centuries.

Other persistent features in Jupiter's atmosphere are the **white ovals.** Several white ovals are visible in Figure 12-4*b*. As in the Great Red Spot, wind flow in white ovals is counterclockwise. White ovals are also apparently long-lived; Earth-based observers have reported seeing them in the same location since 1938.

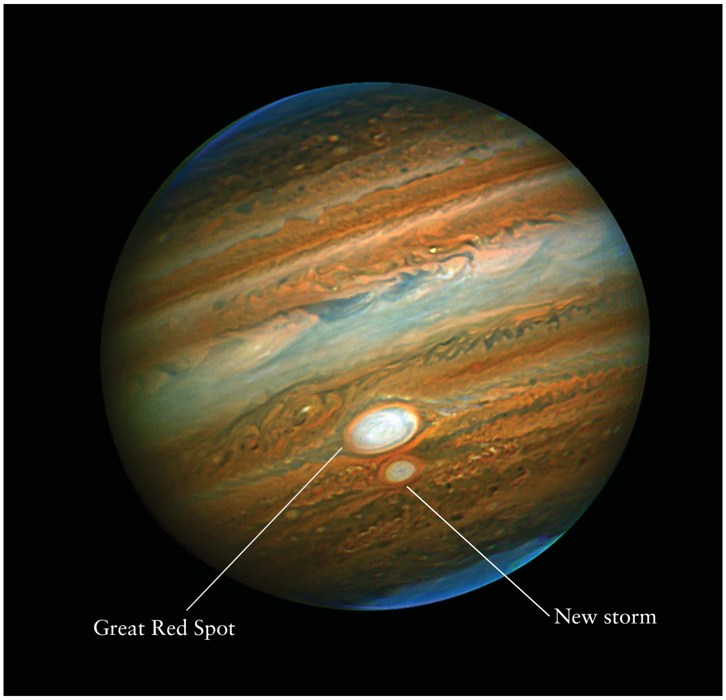
Most of the white ovals are observed in Jupiter's southern hemisphere, whereas **brown ovals** are more common in Jupiter's northern hemisphere. Brown ovals appear dark in a visible-light image like Figure 12-4*b*, but they appear bright in an infrared image. For this reason, brown ovals are understood to be holes in Jupiter's cloud cover. They permit us to see into the depths of the Jovian atmosphere, where the temperature is higher and the atmosphere emits infrared light more strongly. White ovals, by contrast, have relatively low temperatures. They are areas with cold, high-altitude clouds that block our view of the lower levels of the atmosphere.

Between 1998 and 2000 three white ovals merged in Jupiter's southern hemisphere. The merger of these ovals, each of which had been observed for 60 years, led to the formation of a massive storm about half the size of the Great Red Spot (Figure 12-6). Time will tell whether this new feature is as long-lived as its larger cousin.

WEB LINK 12.7

Figure 12-6 R I V U X G

Jupiter's "Red Spot Jr." This 2006 image of Jupiter and a new storm that formed between 1998 and 2000 was made using adaptive optics on the Gemini North telescope in Hawaii (see Section 6-3). Because Jupiter displays differential rotation (see Section 12-2), the two storms travel around Jupiter at different rates; they are not always side-by-side as shown here. (Gemini Observatory ALTAIR Adaptive Optics image/Chris Go)



Regularities in Jupiter's Atmosphere

The *Voyager*, *Galileo*, and *Cassini* images might suggest a state of incomprehensible turmoil, but, surprisingly, there is also great regularity in the Jovian atmosphere. The views in Figure 12-7 (assembled from a large number of *Cassini* images) show how Jupiter would look to someone located directly over either the planet's north pole or its south pole. Note the regular spacing of such cloud features as ripples, plumes, colored wisps, and white ovals in the southern hemisphere. These regularities are probably the result of stable, large-scale weather patterns that encircle Jupiter.

Storms on Saturn

While Saturn has belts and zones like Jupiter, it has no storm systems as long-lived as Jupiter's Great Red Spot. But about every 30 years—roughly the orbital period of Saturn—Earth-based observers have reported seeing storms in Saturn's clouds that last for

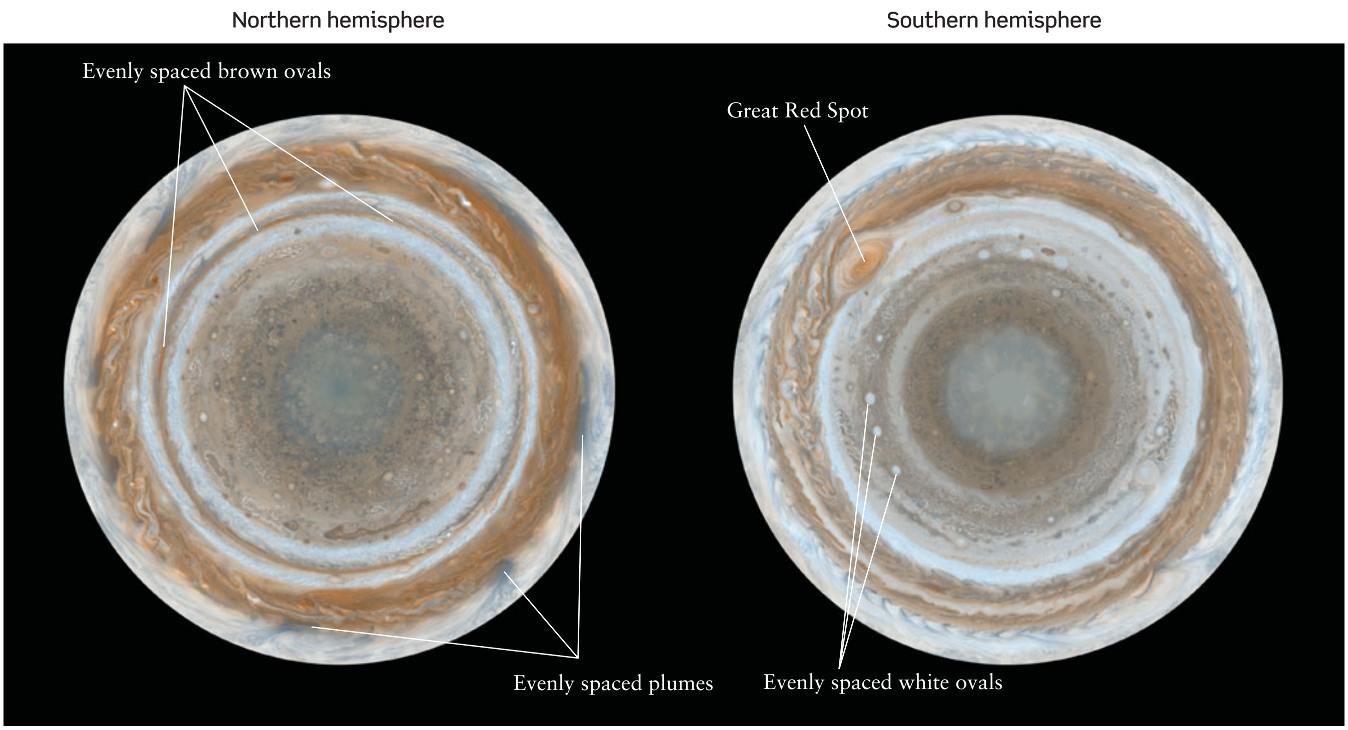
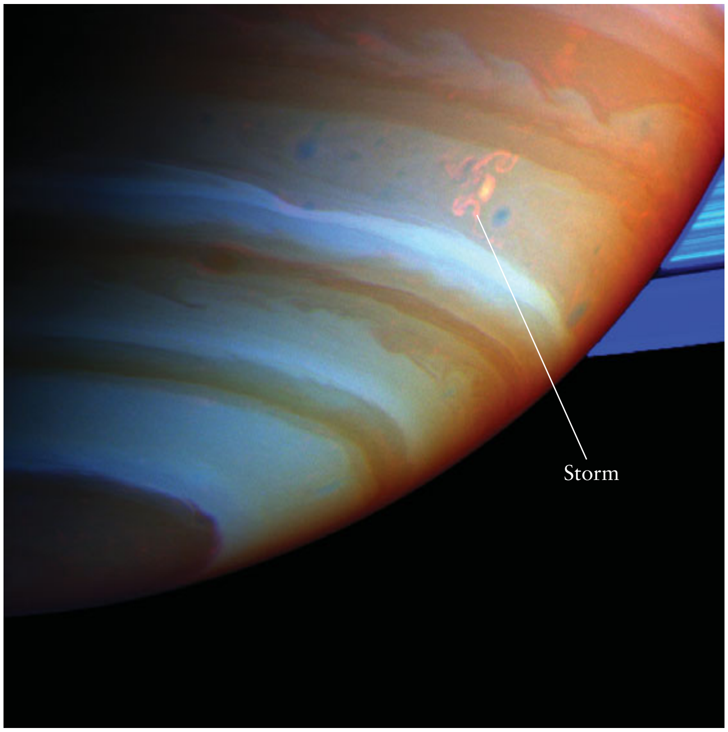


Figure 12-7 R I V U X G

Jupiter's Northern and Southern Hemispheres *Cassini* images were combined and computer processed to construct these views that look straight down onto Jupiter's north and south poles. Various cloud features are evenly spaced in longitude. (NASA/JPL/Space Science Institute)



VIDEO 12.5

Figure 12-8 R I V U X G

A New Storm on Saturn This infrared image from the *Cassini* spacecraft shows a storm the size of the Earth that appeared in Saturn's southern hemisphere in 2004. *Cassini* has observed several storms in this same region of Saturn. (NASA/JPL/Space Science Institute)

several days or even months. Figure 12-8 shows one such storm that appeared in Saturn's southern hemisphere in 2004.

VIDEO 12.4

Saturn's storms are thought to form when warm atmospheric gases rise upward and cool, causing gaseous ammonia to solidify into crystals and form white clouds. On Earth, similar rapid lifting of air occurs within thunderstorms and can cause water droplets to solidify into hailstones. Earth thunderstorms produce electrical discharges (lightning) that generate radio waves, which you hear as "static" on an AM radio. Radio receivers on board *Cassini* have recorded similar "static" emitted by storms on Saturn, which strongly reinforces the idea that these storms are like thunderstorms on Earth.

12-4 The internal heat of Jupiter and Saturn has a major effect on the planets' atmospheres

Weather patterns on Earth are the result of the motions of air masses. Winter storms in the midwestern United States occur when cold, moist air moves southward from Canada, and tropical storms in the southwest United States are caused by the northeastward motion of hot, moist air from Hawaii. All such motions, as well as the overall global circulation of our atmosphere, are powered by the Sun. Sunlight is absorbed by the Earth's surface, and the heated surface in turn warms the atmosphere and stirs it into motion (see Sections 9-1 and 9-5). The energy of sunlight also powers the motions of the atmospheres of Venus and Mars (see Section 11-6). On both Jupiter and Saturn, however, atmospheric motions are powered both by solar energy and by the internal energy of the planet.

Jupiter and Saturn: Radiating Energy into Space

In the late 1960s, astronomers using Earth-based telescopes made the remarkable discovery that Jupiter emits more energy in the form of infrared radiation than it absorbs from sunlight—in fact, about twice as much. (By comparison, the internal heat that the Earth radiates into space is only about 0.005% of what it absorbs from the Sun.) The excess heat presently escaping from Jupiter is thought to be energy left over from the formation of the planet 4.56 billion years ago. As gases from the solar nebula fell into the protoplanet, vast amounts of gravitational energy were converted into thermal energy that heated the planet's interior. Jupiter has been slowly radiating this energy into space ever since. Because Jupiter is so large, it has retained substantial thermal energy even after billions of years, and so still has plenty of energy to emit as infrared radiation.

Saturn, too, radiates into space more energy than it receives as sunlight. Because Saturn is smaller than Jupiter, it should have begun with less internal heat trapped inside, and it should have radiated that heat away more rapidly. Hence, we would expect Saturn to be radiating very little energy today. In fact, when we take Saturn's smaller mass into account, we find that Saturn releases about 25% *more* energy from its interior on a per-kilogram basis than does Jupiter. The explanation for this seeming paradox may be that helium is raining out of Saturn's upper atmosphere, as we described in Section 12-2. The helium condenses into droplets at cold upper altitudes, but generates heat at lower altitudes due to friction between the falling droplets and the surrounding gases. This heat eventually escapes from the planet's surface as infrared radiation. This "raining out" of helium from Saturn's upper layers is calculated to have begun 2 billion years ago. The amount of thermal energy released by this process adequately accounts for the extra heat radiated by Saturn since that time.

Heat naturally flows from a hot place to a colder place, never the other way around. Hence, in order for heat to flow upward through the atmospheres of Jupiter and Saturn and radiate out into space, the temperature must be warmer deep inside the atmosphere than it is at the cloudtops. Infrared measurements have confirmed that the temperature within the atmospheres of both planets does indeed increase with increasing depth (Figure 12-9).

ANALOGY You can understand the statement that "heat naturally flows from a hot place to a colder place" by visualizing an ice cube placed on a hot frying pan. Experience tells you that the hot frying pan cools down a little while the ice warms up and melts. If heat were to flow the other way, the ice would get colder and the frying pan would get hotter—which never happens in the real world.

A Convection Paradox

When a fluid is warm at the bottom and cool at the top, like water being warmed in a pot, one effective way for energy to be

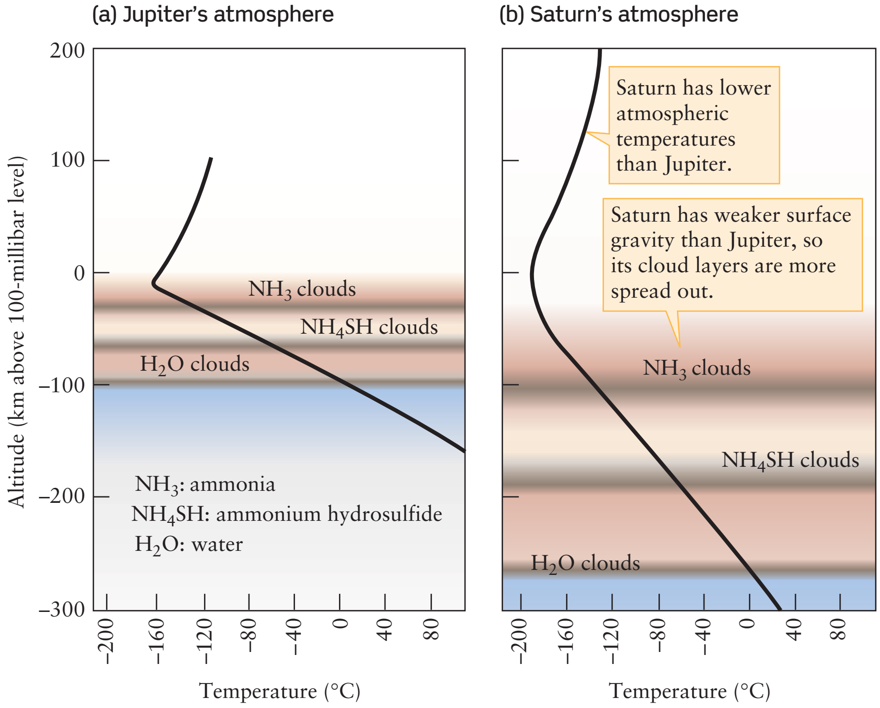


Figure 12-9

The Upper Atmospheres of Jupiter and Saturn The black curves in these graphs show temperature versus altitude in each atmosphere, as well as the probable arrangements of the cloud layers. Zero altitude in each atmosphere is chosen to be the point where the pressure is 100 millibars, or one-tenth of Earth's atmospheric pressure. Beneath both planets' cloud layers, the atmosphere is composed almost entirely of hydrogen and helium. (Adapted from A. P. Ingersoll)

distributed through the fluid is by the up-and-down motion called *convection*. (We introduced the idea of convection in Section 9-1; see, in particular, Figure 9-5.) For many years it was thought that Jupiter's light-colored zones are regions where warm gas from low levels is rising and cooling, forming high-altitude clouds, while the dark-colored belts are regions where cool high-altitude gas is descending and being heated. However, this picture has been called into question by images made by *Cassini* during its 2000–2001 flyby of Jupiter, which showed details as small as 58 km (36 mi) across. The *Cassini* images revealed numerous white cloud cells welling upward in Jupiter's atmosphere, almost all of which appeared in the dark belts.

One interpretation of these observations is that air is actually rising in the *belts* and sinking in the *zones*. Another suggestion is that air is rising in the zones and producing clouds, but these are hidden from our view by a high-altitude layer of opaque white ammonia crystals. In this model the belts are regions in which air is descending except in the localized regions where the clouds seen by *Cassini* are found.

One thing that is well known about Jupiter's atmosphere is that the belts are regions in which we can see into the atmosphere's lower levels. You can see this in Figure 12-10, which compares visible-light and infrared images of Jupiter. The cold Jovian clouds emit radiation primarily at infrared wavelengths, with an intensity that depends on the cloud temperature (see Section 5-4) and hence on the depth of the cloud within the atmosphere (see Figure 12-9*a*). The infrared image in Figure 12-10*b* shows stronger emission from the belts, where we are looking at lower-lying, warmer levels of Jupiter's atmosphere.

The Fastest Winds in the Solar System

VIDEO 12.6

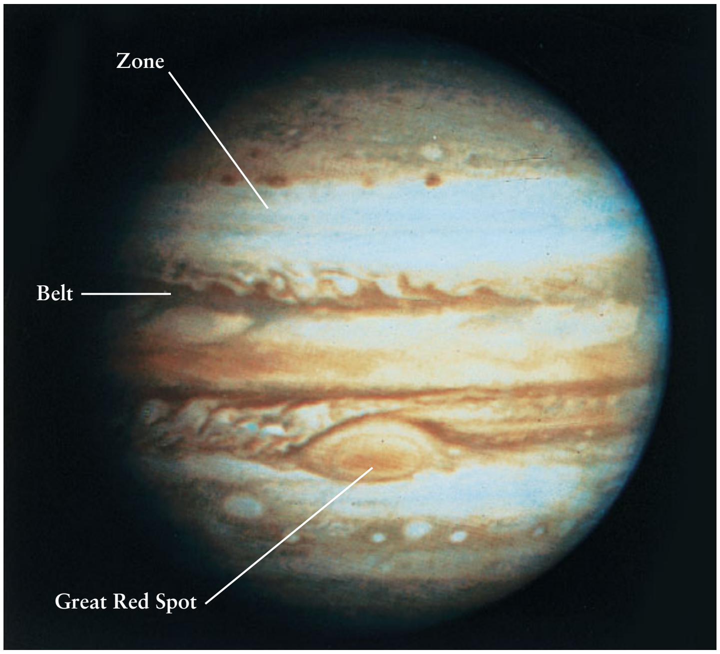
In addition to the vertical motion of gases within the belts and zones, the very rapid rotation of both Jupiter and Saturn creates a global pattern of eastward and westward **zonal winds.** Wind speeds on Jupiter can exceed 500 km/h (300 mi/h). The Earth's atmospheric circulation has a similar pattern of eastward and westward flow (see Figure 9-24), but with slower wind speeds. The faster winds on Jupiter presumably result from the planet's more rapid rotation as well as the substantial flow of heat from the planet's interior.

The zonal winds on Jupiter are generally strongest at the boundaries between belts and zones. Within a given belt or zone, the wind reverses direction between the northern and southern boundaries. As Figure 12-5 shows, such reversals in wind direction are associated with circulating storms such as the Great Red Spot.

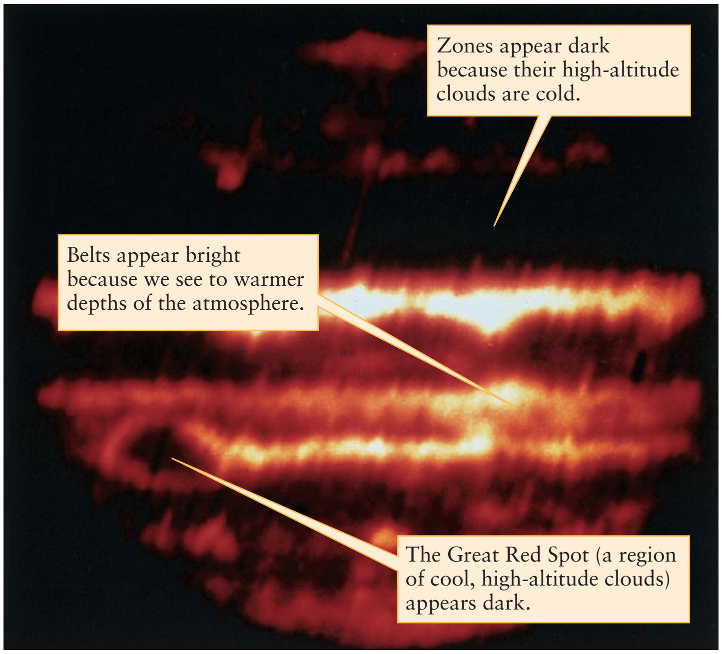
Saturn rotates at about the same rate as Jupiter, but its interior releases less heat and it receives only a quarter as much energy in sunlight as does Jupiter. With less energy available to power the motions of Saturn's atmosphere, we would expect its zonal winds to be slower than Jupiter's. Surprisingly, Saturn's winds are *faster!* In 1980 the *Voyager* spacecraft measured wind speeds near Saturn's equator that approach 1800 km/h (1100 mi/h), approximately two-thirds the speed of sound in Saturn's atmosphere and faster than winds on any other planet. Since then the equatorial winds seem to have abated somewhat: Between 1996 and 2004, astronomers using the Hubble Space Telescope showed that the wind speed had slowed to about 1000 km/h, and in 2005 *Cassini* measured wind speeds of about 1350 km/h at the equator. (These changes may be due to seasonal variations or changes in Saturn's clouds.) Why Saturn's winds should be even faster than Jupiter's is not yet completely understood.

Jupiter and Saturn's Cloud Layers

From spectroscopic observations and calculations of atmospheric temperature and pressure, scientists conclude that both Jupiter and Saturn have three main cloud layers of differing chemical



(a) Visible-light image R I V U X G



(b) Infrared image R I V U X G

Figure 12-10

Jupiter's Warm Belts and Cool Zones (a) This visible-light image of Jupiter was made by the *Voyager 1* spacecraft. **(b)** Bright and dark areas in this Earth-based infrared image, taken at the same time as the image in (a), correspond to high and low temperatures, respectively. (NASA/JPL)

composition. The uppermost cloud layer is composed of crystals of frozen ammonia. Deeper in the atmosphere, ammonia (NH_3) and hydrogen sulfide (H_2S)—a compound of hydrogen and sulfur—combine to produce ammonium hydrosulfide (NH_4SH) crystals. At even greater depths, the clouds are composed of crystals of frozen water.

Jupiter's strong surface gravity compresses these cloud layers into a region just 75 km deep in the planet's upper atmosphere (Figure 12-9*a*). But Saturn has a smaller mass and hence weaker surface gravity, so the atmosphere is less compressed and the same three cloud layers are spread out over a range of nearly 300 km (Figure 12-9*b*). The colors of Saturn's clouds are less dramatic than Jupiter's (see Figure 12-2) because deeper cloud layers are partially obscured by the hazy atmosphere above them.

The colors of clouds on Jupiter and Saturn depend on the temperatures of the clouds and, therefore, on the depth of the clouds within the atmosphere. Brown clouds are the warmest and are thus the deepest layers that we can see. Whitish clouds form the next layer up, followed by red clouds in the highest layer. The whitish zones on each planet are therefore somewhat higher than the brownish belts, while the red clouds in Jupiter's Great Red Spot are among the highest found anywhere on that planet.

Despite all the data from various spacecraft, we still do not know what gives the clouds of Jupiter and Saturn their colors. The crystals of NH_3, NH_4SH, and water ice in the three main cloud layers are all white. Thus, other chemicals must cause the browns, reds, and oranges. Certain molecules closely related to ammonium hydrosulfide, which can form into long chains that have a yellow-brown color, may play a role. Compounds of sulfur or phosphorus, which can assume many different colors, depending on their temperature, might also be involved. The Sun's ultraviolet radiation may induce the chemical reactions that produce these colorful compounds.

12-5 A space probe has explored Jupiter's deep atmosphere

By observing Jupiter's and Saturn's cloud layers from a distance, we have been able to learn a great deal about the atmospheres beneath the clouds. But there is no substitute for making measurements on site, and for many years scientists planned to send a spacecraft to explore deep into Jupiter's atmosphere. While still 81.52 million kilometers (50.66 million miles) from Jupiter, the *Galileo* spacecraft released the *Galileo Probe,* a cone-shaped body about the size of an office desk. While *Galileo* itself later fired its rockets to place itself into an orbit around Jupiter, the *Galileo Probe* continued on a course that led it on December 7, 1995, to a point in Jupiter's clouds just north of the planet's equator.

Exploring Jupiter's Atmosphere

A heat shield protected the *Galileo Probe* as air friction slowed its descent speed from 171,000 km/h (106,000 mi/h) to 40 km/h (25 mi/h) in just 3 minutes. The spacecraft then deployed a parachute and floated down through the atmosphere (Figure 12-11). For the next hour, the probe observed its surroundings and radioed its findings back to the main *Galileo* spacecraft, which in turn radioed them to Earth. The mission ceased at a point some 200 km (120 mi) below Jupiter's upper cloud layer, where the

Figure 12-11

The *Galileo Probe* Enters Jupiter's Atmosphere This artist's impression shows the *Galileo Probe* descending under a parachute through Jupiter's clouds. The jettisoned heat shield (shown to the right of the probe) protected the probe during its initial high-speed entry into the atmosphere. The *Galileo Probe* returned data for 58 minutes before it was crushed and melted by the pressure and temperature of the atmosphere. (NASA)

tremendous pressure (24 atmospheres) and high temperature (152°C = 305°F) finally overwhelmed the probe's electronics.

Although the *Galileo Probe* did not have a camera, it did carry a variety of instruments that made several new discoveries. A radio-emissions detector found evidence for lightning discharges that, while less frequent than on Earth, are individually much stronger than lightning bolts in our atmosphere. Other measurements showed that Jupiter's winds, which are brisk in the atmosphere above the clouds, are even stronger beneath the clouds: The *Galileo Probe* measured a nearly constant wind speed of 650 km/h (400 mi/h) throughout its descent. This shows convincingly that the energy source for the winds is Jupiter's interior heat. If the winds were driven primarily by solar heating, as is the case on Earth, the wind speed would have decreased with increasing depth.

A central purpose of the *Galileo Probe* mission was to test the three-layer cloud model depicted in Figure 12-9*a* by making direct measurements of Jupiter's clouds. But the probe saw only traces of the NH_3 and NH_4SH cloud layers and found no sign at all of the low-lying water clouds. One explanation of this surprising result is that the probe by sheer chance entered a **hot spot,** an unusually warm and cloud-free part of Jupiter's atmosphere. Indeed, observations from the Earth showed strong infrared emission from the probe entry site, as would be expected where a break in the cloud cover allows a view of Jupiter's warm interior (see Figure 12-10*b*).

The *Galileo Probe* also made measurements of the chemical composition of Jupiter's atmosphere. These revealed that the relative proportions of hydrogen and helium are almost exactly the same as in the Sun, in line with the accepted picture of how Jupiter formed from the solar nebula (see Section 8-4). But a number of heavy elements, including carbon, nitrogen, and sulfur, were found to be significantly more abundant on Jupiter than in the Sun. This was an expected result. Over the past several billion years, Jupiter's strong gravity should have pulled in many pieces of interplanetary debris, thus building up a small but appreciable abundance of heavy elements.

Water is a major constituent of small bodies in the outer solar system and thus should likewise be present inside Jupiter in noticeable quantities. Surprisingly, the amount of water actually detected by the *Galileo Probe* was less than half the expected amount. One proposed explanation for this disparity is that the hot spot where the probe entered the atmosphere was also unusually dry. If this explanation is correct, Jupiter's hot spots are analogous to hot, dry deserts on Earth. An alternative idea is that more water than expected has rained out of Jupiter's upper atmosphere and coalesced deep within the planet. For now, the enigma of Jupiter's missing water remains unresolved.

Noble Gases and the Origin of Jupiter

Another surprising and potentially important result from the *Galileo Probe* concerns three elements, argon (Ar), krypton (Kr), and xenon (Xe). These elements are three of the so-called **noble gases,** which do not combine with other atoms to form molecules. (The noble gases, which also include helium, appear in the rightmost column of the periodic table in Box 5-5.) All three of these elements appear in tiny amounts in the Earth's atmosphere and in the Sun, and so must also have been present in the solar nebula. But the *Galileo Probe* found that argon, krypton, and xenon are about 3 times as abundant in Jupiter's atmosphere as in the Sun's.

If these elements were incorporated into Jupiter directly from the gases of the solar nebula, they should be equally as abundant in Jupiter as in the Sun (which formed from the gas at the center of the solar nebula; see Section 8-3). So, the excess amounts of argon, krypton, and xenon must have entered Jupiter in the form of solid planetesimals, just as did carbon, nitrogen, and sulfur. But at Jupiter's distance from the Sun, the presumed temperature of the solar nebula was too high to permit argon, krypton, or xenon to solidify. How, then, did the excess amounts of these noble gases become part of Jupiter?

Measuring trace amounts of rare gases on Jupiter provides clues about the origins of the planets

Several hypotheses have been proposed to explain these results. One idea is that icy bodies, including solid argon, krypton, and xenon, formed in an interstellar cloud even before the cloud collapsed to form the solar nebula. A second notion is that the solar nebula may actually have been colder than previously thought. If either of these ideas proves to be correct, it would mean that Jovian planets can form closer to their stars than had heretofore been thought. This would help to explain why astronomers find massive, presumably Jovian planets orbiting close to stars other than the Sun (see Section 8-5).

A third hypothesis proposes that our models of the solar nebula are correct, but that Jupiter originally formed much farther from the Sun. Out in the cold, remote reaches of the solar nebula, argon, krypton, and xenon could have solidified into icy particles and fallen into the young Jupiter, thus enriching it in those elements. Interactions between Jupiter and the material of the solar nebula could then have forced the planet to spiral inward, eventually reaching its present distance from the Sun. As we saw in Section 8-5, a model of this kind has been proposed to explain why extrasolar planets orbit so close to their stars. More research will be needed to decide which of these hypotheses is closest to the truth.

The story of the *Galileo Probe* exemplifies two of the most remarkable aspects of scientific research. First, when new scientific observations are made, the results often pose many new questions at the same time that they provide answers to some old ones. And second, it sometimes happens that investigating what might seem to be trivial details—such as the abundances of trace elements in Jupiter's atmosphere—can reveal clues about truly grand issues, such as how the planets formed.

12-6 The oblateness of Jupiter and Saturn reveals their rocky cores

The *Galileo Probe* penetrated only a few hundred kilometers into Jupiter's atmosphere before being crushed. To learn about Jupiter's structure at greater depths as well as that of Saturn, astronomers must use indirect clues. The shapes of Jupiter and Saturn are important clues, since they indicate the size of the rocky cores at the centers of the planets.

Oblateness and Rotation

Even a casual glance through a small telescope shows that Jupiter and Saturn are not spherical but slightly flattened or **oblate.** (You can see this in Figures 12-1 and 12-2.) The diameter across Jupiter's equator (142,980 km) is 6.5% larger than its diameter from pole to pole (133,700 km). Thus, Jupiter is said to have an **oblateness** of 6.5%, or 0.065. Saturn has an even larger oblateness of 9.8%, or 0.098, making it the most oblate of all the planets. By comparison, the oblateness of the Earth is just 0.34%, or 0.0034.

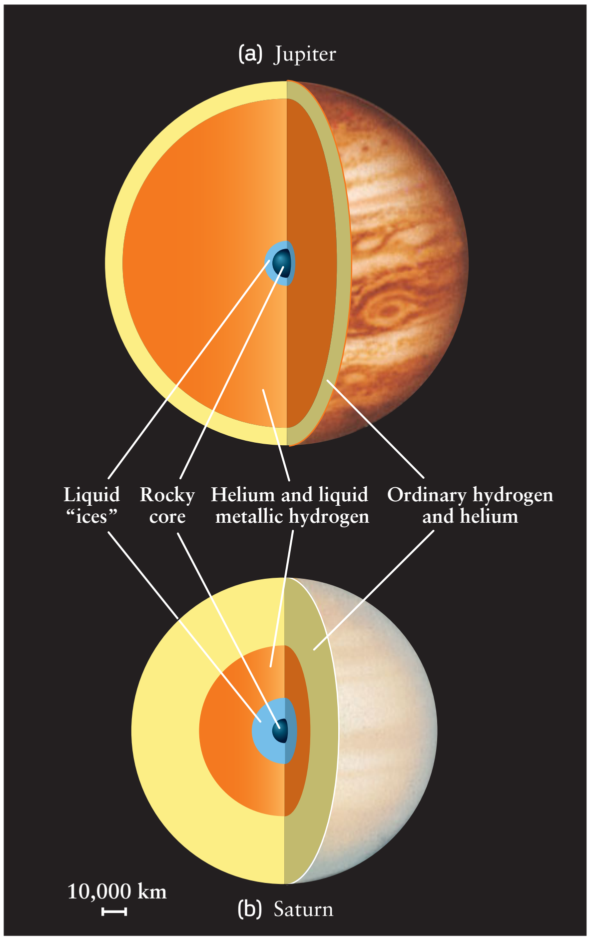
If Jupiter and Saturn did not rotate, both would be perfect spheres. A massive, nonrotating object naturally settles into a spherical shape so that every atom on its surface experiences the same gravitational pull aimed directly at the object's center. Because Jupiter and Saturn do rotate, however, the body of each planet tends to fly outward and away from the axis of rotation.

ANALOGY You can demonstrate this effect for yourself. Stand with your arms hanging limp at your sides, then spin yourself around. Your arms will naturally tend to fly outward, away from the vertical axis of rotation of your body. Likewise, if you drive your car around a circular road, you feel thrown toward the outside of the circle; the car as a whole is rotating around the center of the circle, and you tend to move away from the rotation axis. (We discussed the physical principles behind this in Box 4-3.) For Jupiter and Saturn, this same effect deforms the planets into their nonspherical, oblate shapes.

Modeling Jupiter and Saturn's Interiors

The oblateness of a planet depends both on its rotation rate and on how the planet's mass is distributed over its volume. The challenge to planetary scientists is to create a model of a planet's mass distribution that gives the right value for the oblateness. One such model for Jupiter suggests that 2.6% of its mass is concentrated in a dense, rocky core (Figure 12-12*a*). Although this core has about 8 times the mass of the Earth, the crushing weight of the remaining bulk of Jupiter compresses it to a diameter of just 11,000 km, slightly smaller than the Earth's diameter of 12,800 km. The pressure at the center of the core is estimated to be about 70 million atmospheres, and the central temperature is probably about 22,000 K. By contrast, the temperature at Jupiter's cloudtops is only 165 K.

If Jupiter formed by accretion of gases onto a rocky "seed," the present-day core is presumably that very seed. However, additional amounts of rocky material were presumably added later



INTERACTIVE EXERCISE 12.1

Figure 12-12

The Internal Structures of Jupiter and Saturn These diagrams of the interiors of Jupiter and Saturn are drawn to the same scale. Each planet's rocky core is surrounded by an outer core of liquid "ices," a layer of helium and liquid metallic hydrogen, and a layer of helium and ordinary molecular hydrogen (H_2). Saturn's rocky core contains a larger fraction of the planet's mass than does Jupiter's, while Saturn has a smaller volume of liquid metallic hydrogen than does Jupiter.

by meteoritic material that fell into the planet and sank to the center. (If Jupiter formed directly from the gases of the solar nebula, this additional material makes up the present-day core.) Material from icy planetesimals, too, would have sunk deep within Jupiter and added to the core. In the model we have been describing, these "ices"—principally water (H_2O), methane (CH_4), ammonia (NH_3), and other molecules made by chemical reactions among these substances—form a layer some 3000 km thick that surrounds the rocky core. (Because these substances are less dense than rock, they "float" on top of the rocky core.) Despite the high pressures in this layer, the temperature is so high that the "ices" are probably in a liquid state.

Saturn rotates at about the same rate as Jupiter but has less mass, and therefore less gravity to pull its material inward. Hence, Saturn's rotation should cause material at its equator to bulge outward more than on Jupiter, giving Saturn a greater oblateness. In fact, if Saturn and Jupiter had the same internal structure, we would actually expect Saturn to be even more oblate than it really is. We can account for this discrepancy if Saturn has a different mass distribution than Jupiter. Detailed calculations suggest that about 10% of Saturn's mass is contained in its rocky core, compared to 2.6% for Jupiter's rocky core (see Figure 12-12*b*). As for Jupiter, the rocky core of Saturn is probably surrounded by an outer core of liquid "ices."

12-7 Metallic hydrogen inside Jupiter and Saturn endows the planets with strong magnetic fields

The oblateness of Jupiter and Saturn gives information about the size of the planets' rocky cores. It does not, however, provide much insight into the planets' bulk between their cores and their colorful cloudtops. Most of our knowledge of these parts of the interiors of Jupiter and Saturn comes from observations with radio telescopes. By using these telescopes to detect radio waves from Jupiter and Saturn, astronomers have found evidence of electric currents flowing within both planets' hydrogen-rich interiors.

Radio Emissions from Jupiter

Astronomers began discovering radio emissions coming from Jupiter in the 1950s. A small portion of these emissions is **thermal radiation,** with the sort of spectrum that would be expected from an opaque object due to its temperature. (We discussed the electromagnetic radiation from heated objects in Sections 5-3 and 5-4.) However, most of the radio energy emitted from Jupiter is **nonthermal radiation.** This has a very different sort of spectrum from radiation from a heated object and is found in two distinct wavelength ranges.

At wavelengths of a few meters, Jupiter emits sporadic bursts of radio waves. This **decametric** (10-meter) **radiation** is probably caused by electrical discharges associated with powerful electric currents in Jupiter's ionosphere. These discharges result from electromagnetic interactions between Jupiter and its large satellite Io. At shorter wavelengths of a few tenths of a meter, Jupiter emits a nearly constant stream of electromagnetic radiation. The properties of this **decimetric** (tenth-meter) **radiation** show that it is emitted by electrons moving through a strong magnetic field at speeds comparable to the speed of light. The magnetic field deflects the electrons into spiral-shaped trajectories, and the spiraling electrons radiate energy like miniature radio antennas. Energy produced in this fashion is called **synchrotron radiation.** Astronomers now realize that synchrotron radiation is very important in a wide range of situations throughout the universe, including radio emissions from entire galaxies.

Jupiter's Magnetic Field

If some of Jupiter's radiation is indeed synchrotron radiation, then Jupiter must have a magnetic field. Measurements by the *Pioneer* and *Voyager* spacecraft verified this and indicated that the field at Jupiter's equator is 14 times stronger than at the Earth's equator. Like the Earth's magnetic field, Jupiter's field is thought to be generated by motions of an electrically conducting fluid in the planet's interior. But wholly unlike Earth, the moving fluid within Jupiter is an exotic form of hydrogen called **liquid metallic hydrogen.**

As we discussed in Section 7-7, hydrogen becomes a liquid metal only when the pressure exceeds about 1.4 million atmospheres. This occurs at depths more than about 7000 km below Jupiter's cloudtops. Thus, the internal structure of Jupiter consists of four distinct regions, as shown in Figure 12-12*a*: a rocky core, a roughly 3000-km thick layer of liquid "ices," a layer of helium and liquid metallic hydrogen about 56,000 km thick, and a layer of helium and ordinary hydrogen about 7000 km thick. The colorful cloud patterns that we can see through telescopes are located in the outermost 100 km of the outer layer.

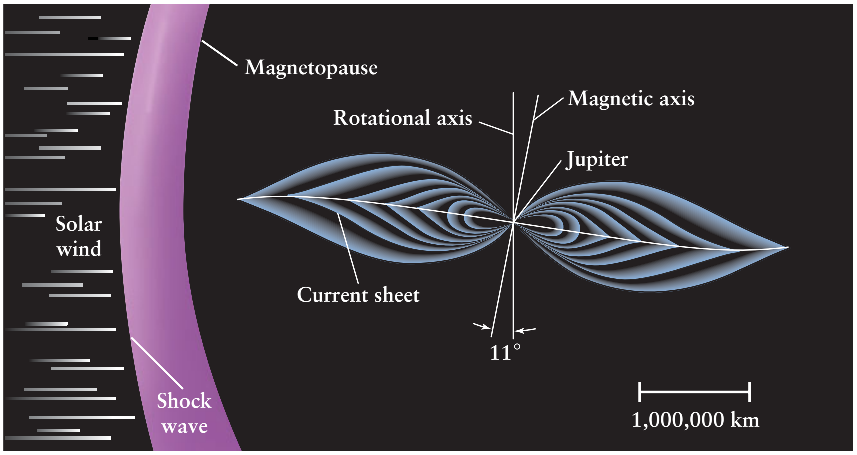
Figure 12-12*a* shows that much of the enormous bulk of Jupiter is composed of liquid metallic hydrogen. Jupiter's rapid rotation sets the liquid metallic hydrogen into motion, giving rise to a powerful dynamo 20,000 times stronger than Earth's and generating an intense magnetic field.

Saturn's Magnetic Field

Saturn also has a substantial magnetic field, but it pales by Jupiter standards: Saturn's internal dynamo is only 3% as strong as Jupiter's. (To be fair, it is still 600 times stronger than Earth's dynamo.) This difference between the planets suggests that even though Saturn rotates nearly as rapidly as Jupiter, there must be far less liquid metallic hydrogen within Saturn to be stirred up by the rotation and thereby generate a magnetic field. This makes sense: Compared to Jupiter, Saturn has less mass, less gravity, and less internal pressure to compress ordinary hydrogen into liquid metallic hydrogen. As a consequence, as Figure 10-14*b* shows, liquid metallic hydrogen probably makes up only a relatively small fraction of Saturn's bulk.

Jupiter's Magnetosphere

Jupiter's strong magnetic field surrounds the planet with a magnetosphere so large that it envelops the orbits of many of its moons. The *Pioneer* and *Voyager* spacecraft, which carried instruments to detect charged particles and magnetic fields, revealed the awesome dimensions of the Jovian magnetosphere. The shock wave that surrounds Jupiter's magnetosphere is nearly 30 million



INTERACTIVE EXERCISE 12.2

Figure 12-13

Jupiter's Magnetosphere The shock wave marks where the supersonic solar wind is abruptly slowed to subsonic speeds. Most solar wind particles are deflected around Jupiter in the turbulent region (shown in purple) between the shock wave and magnetopause (where the pressure within the magnetosphere balances the pressure of the solar wind). Particles trapped inside Jupiter's magnetosphere are spread out into a vast current sheet by the planet's rapid rotation.

kilometers across. If you could see Jupiter's magnetosphere from the Earth, it would cover an area in the sky 16 times larger than the Moon. Figure 12-13 shows the structure of Jupiter's magnetosphere. (Compare to Earth's much smaller magnetosphere, shown in Figure 9-19.)

Both Jupiter and Saturn have magnetospheres that are millions of kilometers across

The outer boundary of Jupiter's magnetosphere (on the left in Figure 12-13) lies at distances ranging from 3 to 7 million kilometers (2 to 4 million miles) above the planet. The "downstream" side of the magnetosphere (on the right in Figure 12-13) extends for more than a billion kilometers (650 million miles), even beyond the orbit of Saturn.

The inner regions of the Earth's magnetosphere are dominated by two huge Van Allen belts (recall Figure 9-20), which are filled with charged particles. In a similar manner, Jupiter entraps immense quantities of charged particles in belts of its own. An astronaut venturing into these belts would quickly receive a lethal dose of radiation. In addition, Jupiter's rapid rotation spews the charged particles out into a huge **current sheet,** which lies close to the plane of Jupiter's magnetic equator (see Figure 12-13). Jupiter's magnetic axis is inclined 11° from the planet's axis of rotation, and the orientation of Jupiter's magnetic field is the reverse of the Earth's magnetic field—a compass would point toward the south on Jupiter.

Figure 12-14 shows radio emissions from charged particles in the densest regions of Jupiter's magnetosphere. These emissions vary slightly with a period of 9 hours, 55 minutes, and 30 seconds, as Jupiter's rotation changes the angle at which we view its magnetic field. Because the magnetic field is anchored deep within the planet, this variation reveals Jupiter's **internal rotation period.** This period, indicative of the rotation of the bulk of the planet's mass, is slightly slower than the atmospheric rotation at the equator (period 9 hours, 50 minutes, 28 seconds) but about the same as the atmospheric rotation at the poles (period 9 hours, 55 minutes, 41 seconds). The faster motion of the atmosphere at the equator relative to the interior is driven by Jupiter's internal heat.

The *Voyager* spacecraft discovered that the inner regions of Jupiter's magnetosphere contain a hot, gaslike mixture of charged particles called a **plasma.** A plasma is formed when a gas is heated to such extremely high temperatures that electrons are torn off the atoms of the gas. As a result, a plasma is a mixture of positively charged ions and negatively charged electrons. The plasma that envelops Jupiter consists primarily of electrons and protons, with some ions of helium, sulfur, and oxygen. A major source of these particles is Jupiter's volcanically active moon Io (see Table 7-2), which lies deep within the magnetosphere. Io ejects a ton of material into Jupiter's magnetosphere each second from its surface and volcanic plumes. These charged particles are caught up in Jupiter's rapidly rotating magnetic field and are accelerated to high speeds.

The fast-moving particles in Jupiter's plasma exert a substantial pressure that holds off the solar wind. The *Voyager* data suggest that the pressure balance between the solar wind and the hot plasma inside the Jovian magnetosphere is precarious. A gust in the solar wind can blow away some of the plasma, at which point the magnetosphere deflates rapidly to as little as one-half its

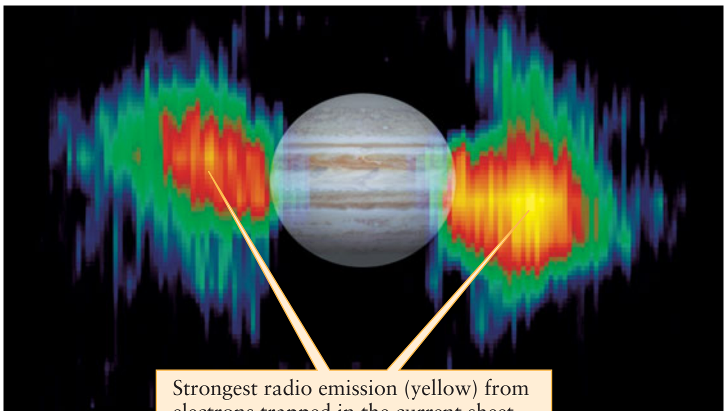


Figure 12-14 R I V U X G

A Radio View of Jupiter Instruments on board the *Cassini* spacecraft recorded this false-color map of decimetric emission from Jupiter at a wavelength of 2.2 cm. The emission comes from a region elongated parallel to the planet's magnetic equator, which is tilted relative to its geographic equator. A visible-light image of Jupiter is superimposed on the radio image. (NASA/JPL) original size. However, additional electrons and ions accelerated by Jupiter's rotating magnetic field soon replenish the plasma, and the magnetosphere expands again.

Saturn's Magnetosphere

Saturn's magnetosphere is similar to Jupiter's, but is only about 10 to 20% as large and contains far fewer charged particles than Jupiter's. There are two reasons for this deficiency. First, Saturn lacks a highly volcanic moon like Io to inject particles into the magnetosphere. Second, and more important, many charged particles are absorbed by the icy particles that make up Saturn's rings (see Section 12-10). The charged particles that do exist in Saturn's magnetosphere are concentrated in radiation belts similar to the Van Allen belts in the Earth's magnetosphere.

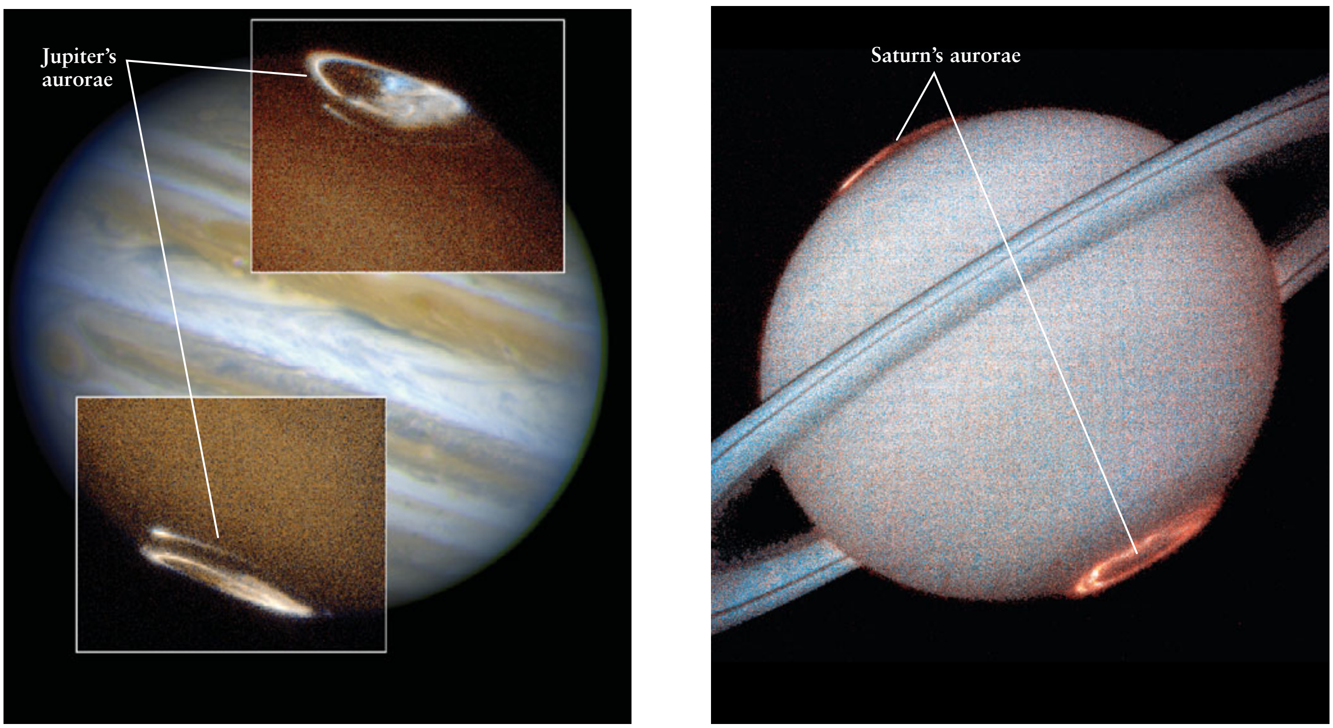
Cassini measurements show, however, that the moons of Saturn do influence the magnetosphere. The inner magnetosphere is dominated by water and atomic oxygen, material that is thought to come from the planet's icy moons (which we will discuss in Chapter 13), as well as from Saturn's rings (which we will learn about later in this chapter).

WEB LINK 12.8

As for Jupiter, the motion of Saturn's magnetic field allows us to track the planet's internal rotation. *Voyager* measurements in 1980 showed Saturn is similar to Jupiter in that its internal rotation period (10 hours, 39 minutes, and 25 seconds) is slower than the rotation period of the visible surface at the equator (10 hours, 13 minutes, and 59 seconds). Surprisingly, when *Cassini* repeated these measurements in 2003–2004, it found that the magnetosphere's rotation had slowed down: The new rotation period is 10 hours, 45 minutes, and 45 seconds, more than 6 minutes longer than in 1980. It seems unlikely that the rotation of the planet's interior could have slowed so much in such a short time. Instead, the magnetic field inside Saturn may have slipped and reattached itself at higher latitudes, where the differentially rotating planet spins at a slower rate. The reason for this slippage is not known.

Aurorae on Jupiter and Saturn

On Earth, particles trapped in our planet's magnetic field stream onto the north and south magnetic poles, creating the aurora (see Section 9-4). The same effect takes place on both Jupiter and Saturn. **Figure 12-15** shows images from the Hubble Space Telescope that reveal glowing auroral rings centered on the north and south magnetic poles of Jupiter and of Saturn. As on Earth, the emission comes from a region high in each planet's atmosphere, hundreds of kilometers above the cloudtops.



(a) Jupiter R I V U X G

(b) Saturn R I V U X G

Figure 12-15

Aurorae on Jupiter and Saturn On both Jupiter and Saturn, charged particles from the magnetosphere are funneled onto the planet's magnetic poles. When the particles collide with and excite molecules in the upper atmosphere, the molecules emit ultraviolet light. (The ultraviolet images in (a) are superimposed on a visible-light image of Jupiter.) (a: J. Clarke, University of Michigan, and NASA; b: J. Trauger, JPL, and NASA)

12-8 Earth-based observations reveal three broad rings encircling Saturn

Compared to Saturn, Jupiter is unquestionably larger, more massive, more colorful, and more dynamic in both its atmosphere and magnetosphere. But as seen through even a small telescope, Saturn stands out as perhaps the most beautiful of all the worlds of the solar system, thanks to its majestic rings (Figure 12-16). As we will see in Section 12-9, Jupiter also has rings, but they are so faint that they were not discovered until spacecraft could observe Jupiter at close range.

Discovering Saturn's Rings

In 1610, Galileo became the first person to see Saturn through a telescope. He saw few details, but he did notice two puzzling lumps protruding from opposite edges of the planet's disk. Curiously, these lumps disappeared in 1612, only to reappear in 1613. Other observers saw similar appearances and disappearances over the next several decades.

In 1655, the Dutch astronomer Christiaan Huygens began to observe Saturn with a better telescope than was available to any of his predecessors. (We discussed in Section 11-2 how Huygens used this same telescope to observe Mars.) On the basis of his observations, Huygens suggested that Saturn was surrounded by a thin, flattened ring. At times this ring was edge-on as viewed from the Earth, making it almost impossible to see. At other times Earth observers viewed Saturn from an angle either above or below the plane of the ring, and the ring was visible, as in Figure 12-1. (The lumps that Galileo saw were the parts of the ring to either side of Saturn, blurred by the poor resolution of his rather small telescope.) Astronomers confirmed this brilliant deduction over the next several years as they watched the ring's appearance change just as Huygens had predicted.

As the quality of telescopes improved, astronomers realized that Saturn's "ring" is actually a *system* of rings, as Figure 12-16 shows. In 1675, the Italian astronomer Cassini discovered a dark division in the ring. The **Cassini division** is an apparent gap about 4500 kilometers wide that separates the outer **A ring** from the brighter **B ring** closer to the planet. In the mid-1800s, astronomers managed to identify the faint **C ring,** or *crepe* ring, that lies just inside the B ring.

Saturn and its rings are best seen when the planet is at or near opposition. A modest telescope gives a good view of the A and B rings, but a large telescope and excellent observing conditions are needed to see the C ring.

How the Rings Appear from Earth

Earth-based views of the Saturnian ring system change as Saturn slowly orbits the Sun. Huygens was the first to understand that this change occurs because the rings lie in the plane of Saturn's equator, and this plane is tilted 27° from the plane of Saturn's orbit. As Saturn orbits the Sun, its rotation axis and the plane of its equator maintain the same orientation in space. (The same is true for the Earth; see Figure 2-12.) Hence, over the course of a Saturnian year, an Earth-based observer views the rings from various angles (Figure 12-17). At certain times Saturn's north pole is tilted toward the Earth and the observer looks "down" on the "top side" of the rings. Half a Saturnian year later, Saturn's south pole is tilted toward us and the "underside" of the rings is exposed to our Earth-based view.

As seen from Earth, Saturn's rings change their orientation as the planet orbits the Sun

When our line of sight to Saturn is in the plane of the rings, the rings are viewed edge-on and seem to disappear entirely (see the images at the upper left and lower right corners of Figure 12-17).

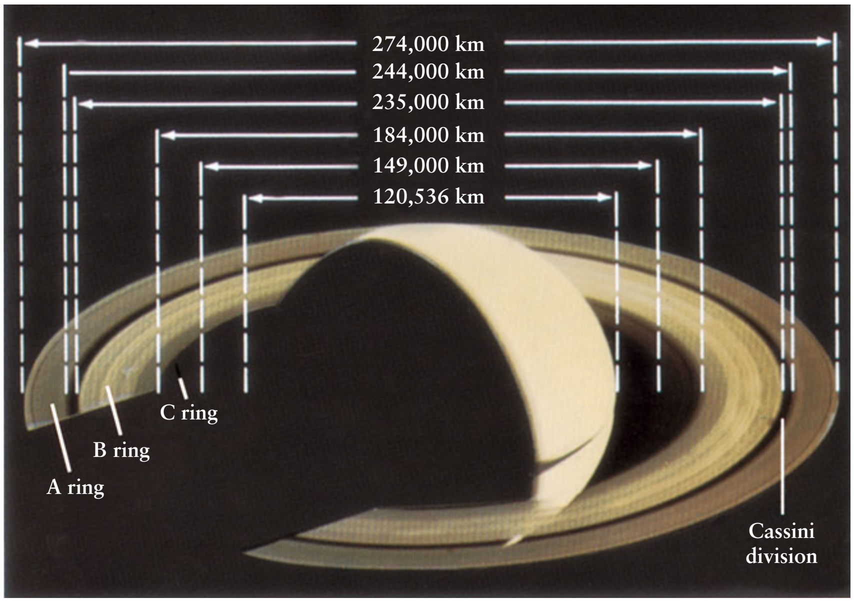
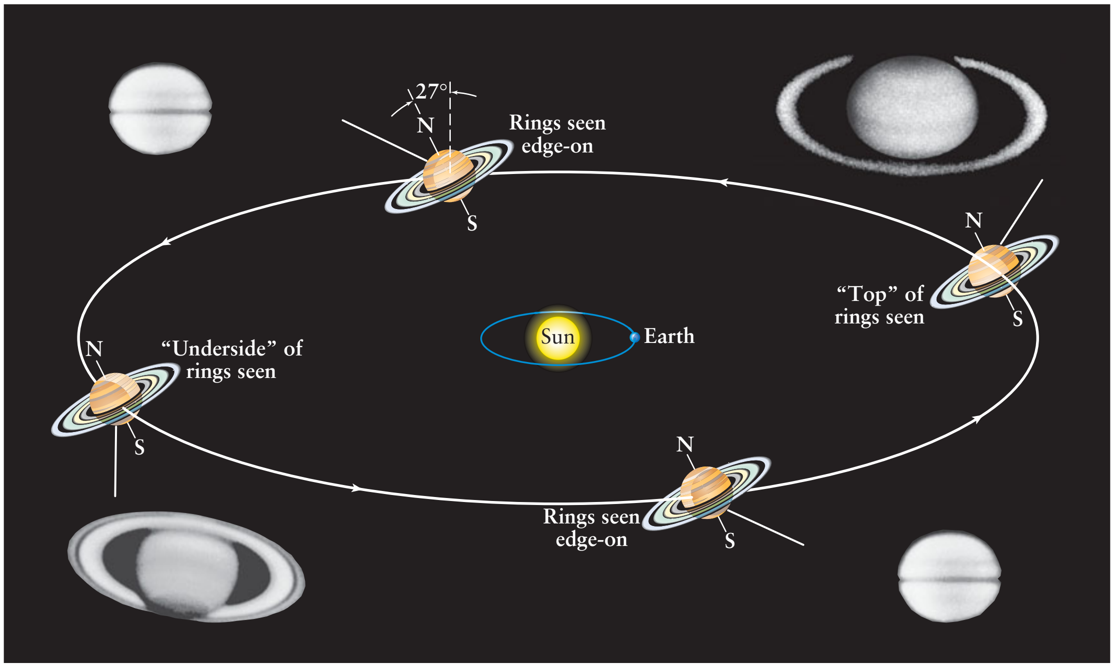


Figure 12-16 R I V U X G

Saturn's System of Rings This *Voyager 1* image shows many details of Saturn's rings. Saturn's equatorial diameter is labeled, as are the diameters of the inner and outer edges of the rings. The C ring is so faint that it is almost invisible in this view. Saturn is visible through the rings (look near the bottom of the image), which shows that the rings are not solid. (NASA/JPL)



ANIMATION 12.1

Figure 12-17 R I V U X G

The Changing Appearance of Saturn's Rings Saturn's rings are aligned with its equator, which is tilted 27° from Saturn's orbital plane. As Saturn moves around its orbit, the rings maintain the same orientation in space, so observers on Earth see the rings at various angles. The accompanying Earth-based photographs show Saturn at various points in its orbit. Note that the rings seem to disappear entirely when viewed edge-on, which occurs about every 15 years. (Lowell Observatory)

This disappearance indicates that the rings are very thin. In fact, they are thought to be only a few tens of meters thick. In proportion to their diameter, Saturn's rings are thousands of times thinner than the sheets of paper used to print this book.

The last edge-on presentation of Saturn's rings of the 20th century was in 1995–1996; the first two of the 21st century are in 2008–2009 and in 2025. From 1996 to 2008, we Earth observers see the "underside" of the rings (as in the image at the lower left corner of Figure 12-17); from 2009 until 2025 we see the "top" of the rings.

12-9 Saturn's rings are composed of numerous icy fragments, while Jupiter's rings are made of small rocky particles

Astronomers have long known that Saturn's rings could not possibly be solid sheets of matter. In 1857, the Scottish physicist James Clerk Maxwell (whom we last encountered in Section 5-2) proved theoretically that if the rings were solid, differences in Saturn's gravitational pull on different parts of the rings would cause the rings to tear apart. He concluded that Saturn's rings are made of "an indefinite number of unconnected particles."

Ring Particles

In 1895, James Keeler at the Allegheny Observatory in Pittsburgh became the first to confirm by observation that the rings are not rigid. He did this by photographing the spectrum of sunlight reflected from Saturn's rings. As the rings orbit Saturn, the spectral lines from the side approaching us are blueshifted by the Doppler effect (recall Section 5-9, especially Figure 5-26). At the same time, spectral lines from the receding side of the rings are redshifted. Keeler noted that the size of the wavelength shift increased inward across the rings—the closer to the planet, the greater the shift. This variation in Doppler shift proved that the inner portions of Saturn's rings are moving around the planet more rapidly than the outer portions. Indeed, the orbital speeds across the rings are in complete agreement with Kepler's third law: The square of the orbital period about Saturn at any place in the rings is proportional to the cube of the distance from Saturn's center (see Section 4-7 and Box 4-4). This is exactly what would be expected if the rings consisted of numerous tiny "moonlets," or **ring particles,** each individually circling Saturn.

Saturn's rings are quite bright; they reflect 80% of the sunlight that falls on them. (By comparison, Saturn itself reflects 46% of incoming sunlight.) Astronomers therefore long suspected that the ring particles are made of ice and ice-coated rock. This hunch was confirmed in the 1970s, when the American astronomers Gerard P. Kuiper and Carl Pilcher identified absorption features of frozen water in the rings' near-infrared spectrum. The *Voyager* and *Cassini* spacecraft have made even more detailed infrared measurements that indicate the temperature of the rings ranges from –180°C (–290°F) in the sunshine to less than –200°C (–330°F) in Saturn's shadow. Water ice is in no danger of melting or evaporating at these temperatures.

To determine the sizes of the particles that make up Saturn's rings, astronomers analyzed the radio signals received from a spacecraft as it passes behind the rings. How easily radio waves can travel through the rings depends on the relationship between the wavelength and the particle size. The results show that most of the particles range in size from pebble-sized fragments about 1 cm in diameter to chunks about 5 m across, the size of large boulders. Most abundant are snowball-sized particles about 10 cm in diameter.

The Roche Limit

All of Saturn's material may be ancient debris that failed to accrete (fall together) into satellites. The total amount of material in the rings is quite small. If Saturn's entire ring system were compressed together to make a satellite, it would be no more than 100 km (60 mi) in diameter. But, in fact, the ring particles are so close to Saturn that they will never be able to form moons.

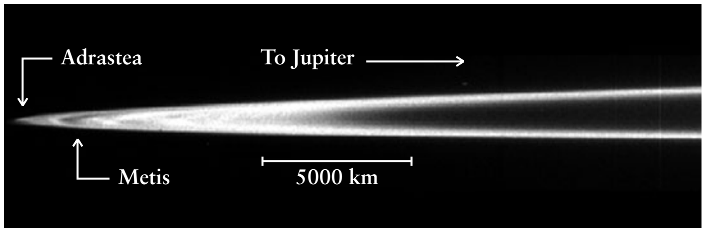
To see why, imagine a collection of small particles orbiting a planet. Gravitational attraction between neighboring particles tends to pull the particles together. However, because the various particles are at differing distances from the parent planet, they also experience different amounts of gravitational pull from the planet. This difference in gravitational pull is a **tidal force** that tends to keep the particles separated. (We discussed tidal forces in detail in Section 4-8. You may want to review that section, and in particular Figure 4-24.)

Tidal forces prevent the material of Saturn's rings from coalescing into a moon

The closer a pair of particles is to the planet, the greater the tidal force that tries to pull the pair apart. At a certain distance from the planet's center, called the **Roche limit,** the disruptive tidal force is just as strong as the gravitational force between the particles. (The concept of this limit was developed in the mid-1800s by the French mathematician Edouard Roche.) Inside the Roche limit, the tidal force overwhelms the gravitational pull between neighboring particles, and these particles cannot accrete to form a larger body. Instead, they tend to spread out into a ring around the planet. (The *Cosmic Connections* figure on the next page depicts this process.) Indeed, most of Saturn's system of rings visible in Figure 12-16 lies within the planet's Roche limit.

All large planetary satellites are found outside their planet's Roche limit. If any large satellite were to come inside its planet's Roche limit, the planet's tidal forces would cause the satellite to break up into fragments. We will see in Chapter 14 that such a catastrophic tidal disruption may be the eventual fate of Neptune's large satellite, Triton.

CAUTION! It may seem that it would be impossible for any object to hold together inside a planet's Roche limit. But the ring particles inside Saturn's Roche limit survive and do not break apart. The reason is that the Roche limit applies only to objects held together by the *gravitational* attraction of each part of the object for the other parts. By contrast, the forces that hold a rock or a ball of ice together are *chemical* bonds between the object's atoms and molecules. These chemical forces are much stronger than the disruptive tidal force of a nearby planet, so the rock or ball of ice does not break apart. In the same way, people walking around on the Earth's surface (which is inside the Earth's Roche limit) are in no danger of coming apart, because we are held together by comparatively strong chemical forces rather than gravity.



VIDEO 12.7 **Figure 12-18** R I V U X G

Jupiter's Main Ring This *Galileo* image shows Jupiter's main ring almost edge-on. The ring's outer radius, about 129,000 km from the center of Jupiter, is close to the orbit of Adrastea, the second closest (after Metis) of Jupiter's moons. Not shown is an even larger and even more tenuous pair of "gossamer rings," one of which extends out to 181,000 km and the other out to 222,000 km. (NASA/JPL; Cornell University)

Jupiter's Ring and the Roche Limit

When the *Voyager 1* spacecraft flew past Jupiter in 1979, it trained its cameras not just on the planet but also on the space around the planet's equator. It discovered that Jupiter, too, has a system of rings that lies within its Roche limit (Figure 12-18). These rings differ from Saturn's in two important ways. First, Jupiter's rings are composed of tiny particles of rock with an average size of only about 1 μm (= 0.001 mm = 10^{-6} m) and that reflect less than 5% of the sunlight that falls on them. Second, there is very little material in the rings of Jupiter, less than 1/100,000 (10^{-5}) the amount of material in Saturn's rings. As a result, Jupiter's rings are extremely faint, which explains why their presence was first revealed by a spacecraft rather than an Earth-based telescope. The ring particles are thought to originate from meteorite impacts on Jupiter's four small, inner satellites, two of which are visible in Figure 12-18.

We will see in Chapter 14 that the rings of Uranus and Neptune are also made of many individual particles orbiting inside each planet's Roche limit. Like the rings of Jupiter, these rings are quite dim and difficult to see from Earth.

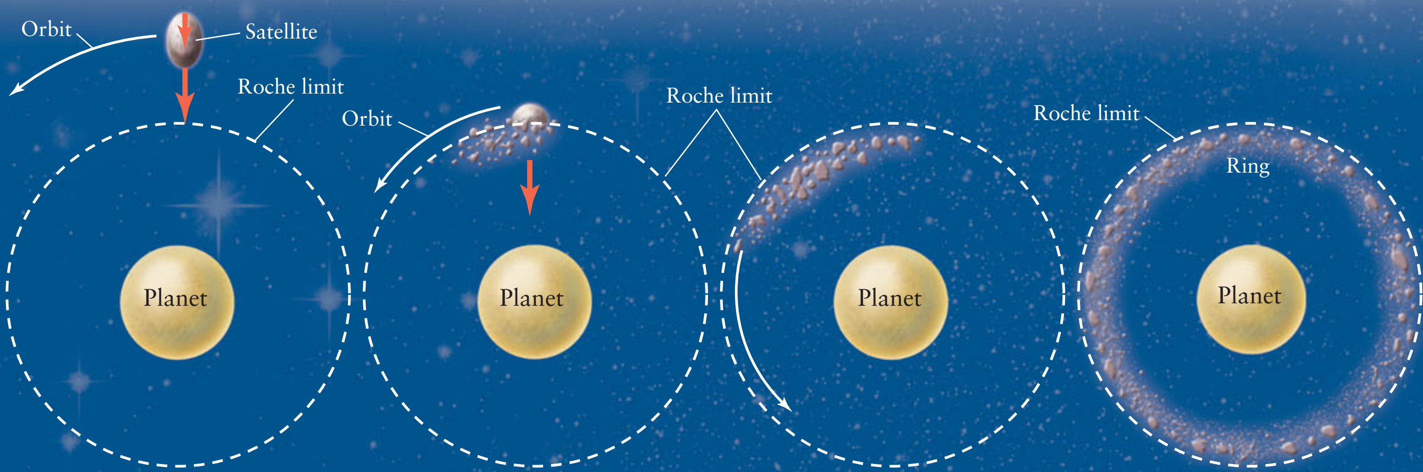
12-10 Saturn's rings consist of thousands of narrow, closely spaced ringlets

The photograph in Figure 12-1*b*, which was made in 1974, indicates what astronomers understood about the structure of Saturn's rings in the mid-1970s. Each of the A, B, and C rings appeared to be rather uniform, with little or no evidence of any internal structure. Within a few years, however, close-up observations from spacecraft revealed the true complexity of the rings, as well as their chemical composition.

COSMIC CONNECTIONS

Planetary Rings and the Roche Limit

If a small moon wanders too close to a planet, tidal forces tear the moon into smaller particles. These particles form a ring around the planet. The critical distance from the planet at which this happens is called the Roche limit. This helps us understand why the rings of Jupiter and Saturn are made of small particles, as are the rings of Uranus and Neptune (discussed in Chapter 14).



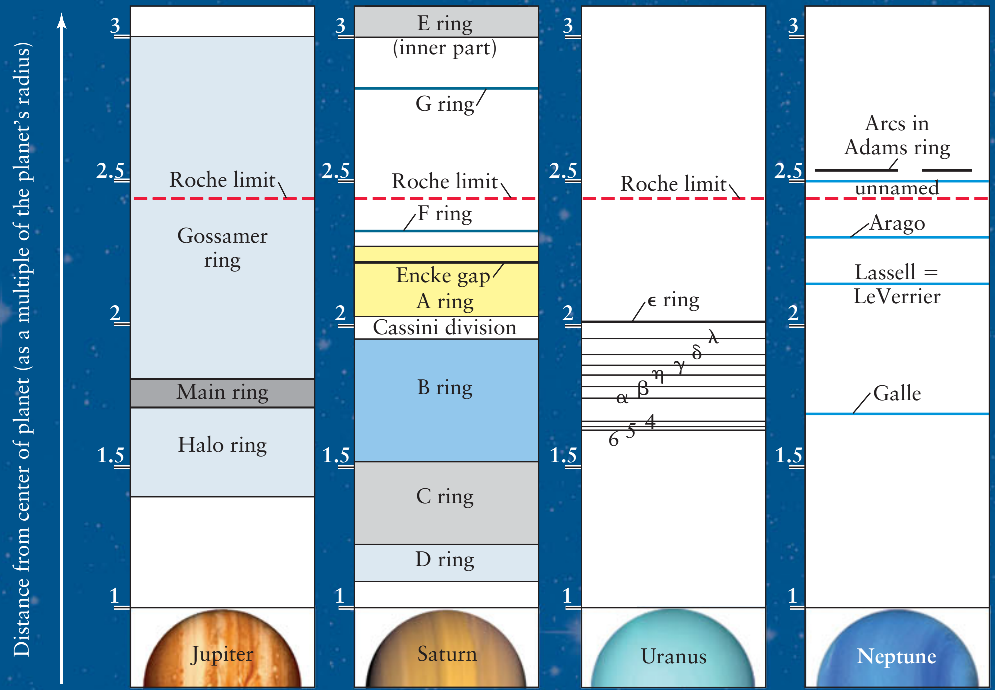
If a satellite is outside the planet's Roche limit, the tidal forces exerted by the planet may deform the satellite but will not tear it apart.

If the satellite crosses the planet's Roche limit, the tidal forces overwhelm the gravitational forces that hold the satellite together and the satellite fragments.

Fragments that are closer to the planet orbit faster (in accordance with Kepler's third law). This spreads the fragments around the planet...

...and the result is a ring.

Jupiter, Saturn, Uranus, and Neptune all have systems of rings that lie mostly within the Roche limit. This diagram shows each of the four ring systems scaled to the radius of the planet.



A planet's Roche limit is about 2.4 times the radius of the planet, provided the material orbiting the planet has the same density as the planet itself. For denser material the Roche limit is closer to the planet.

Spacecraft Views of Saturn's Rings

Pioneer 11, Voyager 1, and *Voyager 2* recorded images of Saturn's rings during their flybys in 1979, 1980, and 1981 respectively. *Pioneer 11* had only a relatively limited capability to make images, but cameras on board the two *Voyager* spacecraft sent back a number of pictures showing the detailed structure of Saturn's rings. Since entering Saturn orbit in 2004, the *Cassini* spacecraft has provided scientists with even higher-resolution images of the rings.

Figure 12-19 shows a *Voyager 1* image. Some of the features seen in this image were expected, including the **Encke gap,** a 270-km-wide division in the outer A ring observed by the German astronomer Johann Franz Encke in 1838. But to the amazement of scientists, images like the one in Figure 12-19 revealed that the broad A, B, and C rings are not uniform at all but instead consist of hundreds upon hundreds of closely spaced bands or **ringlets.** These ringlets are arrangements of ring particles that have evolved from the combined gravitational forces of neighboring particles, of Saturn's moons, and of the planet itself.

Pioneer 11 first detected the narrow **F ring,** which you can see in Figure 12-19. It is only about 100 km wide and lies 4000 km beyond the outer edge of the A ring. Close-up views from the *Voyagers* and *Cassini* show that the F ring is made up of several narrow ringlets. Small moons that orbit close to the F ring exert gravitational forces on the ring particles, thus warping and deforming these ringlets (Figure 12-20).

Exploring Saturn's Ring Particles

Spacecraft have done more than show Saturn's rings in greater detail; they have also viewed the rings from perspectives not possible from Earth. Through Earth-based telescopes, we can see only

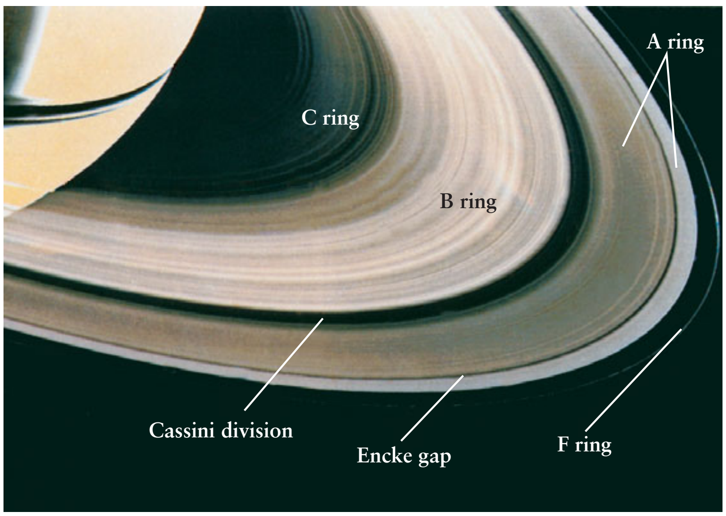
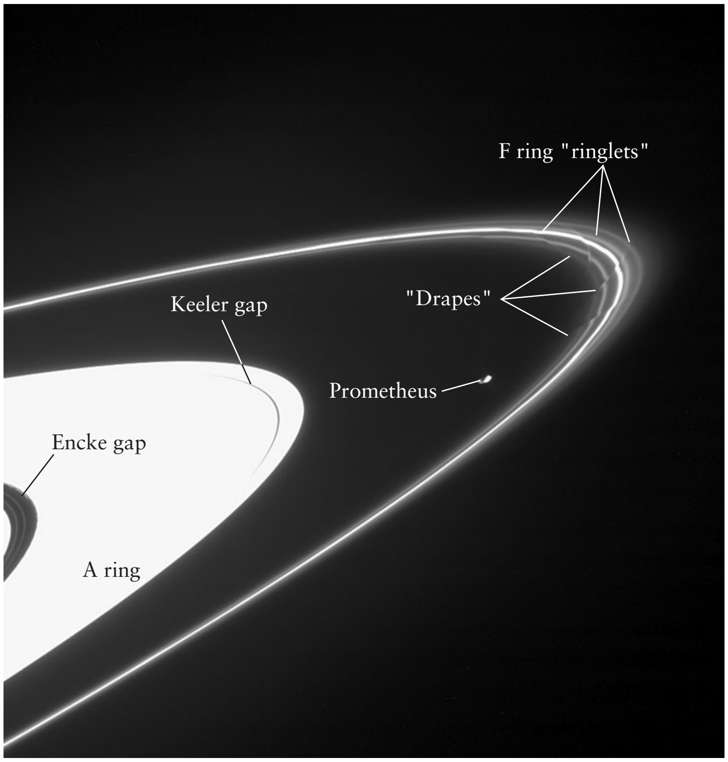


Figure 12-19 R I V U X G

Details of Saturn's Rings The colors in this *Voyager 1* image have been enhanced to emphasize small differences between different portions of the rings. The broad Cassini division is clearly visible, as is the narrow Encke gap in the outer A ring. The very thin F ring lies just beyond the outer edge of the A ring. (NASA/JPL)



VIDEO 12.8

Figure 12-20 R I V U X G

Details of Saturn's F Ring This *Cassini* image shows Saturn's F ring (compare Figure 12-19). The bright central ringlet is about 50 km wide. As the small satellite Prometheus orbits just inside the F ring, its gravitational pull causes disturbances called "drapes" in the ringlets. The narrowness of the F ring is the result of gravitational forces exerted by Prometheus and another small satellite called Pandora (see Section 12-11). This image also shows two divisions in the A ring, the Encke gap and the Keeler gap. (NASA/JPL/Space Science Institute)

the sunlit side of the rings. From this perspective, the B ring appears very bright, the A ring moderately bright, the C ring dim, and the Cassini division dark (see Figure 12-19). The fraction of sunlight reflected back toward the Sun (the *albedo*) is directly related to the concentration and size of the particles in the ring. The B ring is bright because it has a high concentration of relatively large, icy, reflective particles, whereas the darker Cassini division has a lower concentration of such particles.

The *Voyagers* and *Cassini* have expanded our knowledge of the ring particles by imaging the shaded side of the rings, which cannot be seen from Earth. Figure 12-21 shows such an image. Because the spacecraft was looking back toward the Sun, this picture shows sunlight that has passed through the rings. The B ring looks darkest in this image because little sunlight gets through its dense collection of particles. If the Cassini division were completely empty, it would look black, because we would then see through it to the blackness of empty space. But the Cassini division looks *bright* in Figure 12-21. This shows that the Cassini division is not empty but contains a relatively small

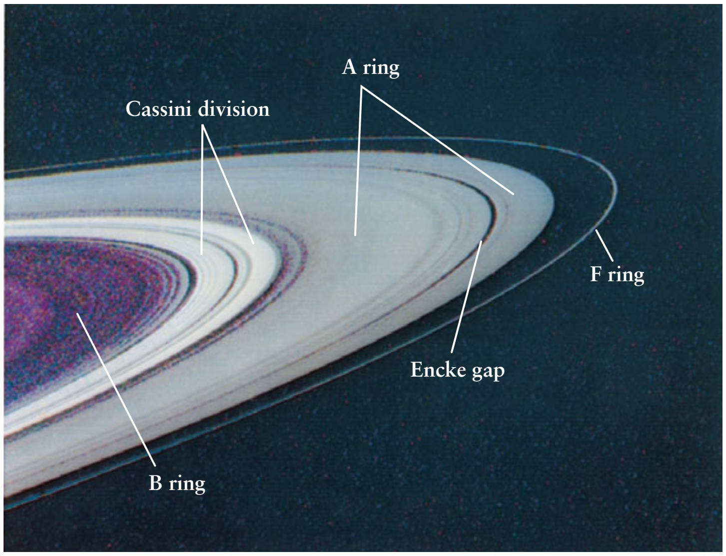


Figure 12-21 R I V U X G

The View from the Far Side of Saturn's Rings This false-color view of the side of the rings away from the Sun was taken by *Voyager 1*. The Cassini division appears white, not black like the empty gap between the A and F rings. Hence, the Cassini division cannot be empty, but must contain a number of relatively small particles that scatter sunlight like dust motes. (NASA/JPL)

number of particles. (In the same way, dust particles in the air in your room become visible when a shaft of sunlight passes through them.)

The process by which light bounces off particles in its path is called **light scattering.** The proportion of light scattered in various directions depends upon both the size of the particles and the wavelength of the light. (See Box 5-4 for examples of light scattering on Earth.) Because visible light has a much smaller wavelength than radio waves, light scattering allows scientists to measure the sizes of particles too small to detect using the radio technique described in Section 12-10. As an example, by measuring the amount of light scattered from the rings at various wavelengths and from different angles as the two *Voyager* spacecraft sped past Saturn, scientists showed that the F ring contains a substantial number of tiny particles about 1 μm (= 10^{-6} m) in diameter. This is about the same size as the particles found in smoke.

There are also subtle differences in color from one ring to the next, as the computer-enhanced image in Figure 12-22 shows. Although the main chemical constituent of the ring particles is frozen water, trace amounts of other chemicals—perhaps coating the surfaces of the ice particles—are probably responsible for the different colors. These trace chemicals have not yet been identified.

The color variations in Figure 12-22 suggest that the icy particles do not migrate substantially from one ringlet to another. Had such migration taken place, the color differences would have been smeared out over time. The color differences may also indicate that different sorts of material were added to the rings at different times. In this scenario, the rings did not all form at the same time as Saturn but were added to over an extended period. New ring material could have come from small satellites that shattered after being hit by a stray asteroid or comet.

Different colors in the rings reveal variations in chemical composition

Discovering New Ring Systems

In addition to revealing new details about the A, B, C, and F rings, the *Voyager* cameras also discovered three new ring systems: the D, E, and G rings. The drawing in Figure 12-23 shows the layout of all of Saturn's known rings along with the orbits of some of Saturn's satellites. The **D ring** is Saturn's innermost ring system. It consists of a series of extremely faint ringlets located between the inner edge of the C ring and the Saturnian cloudtops. The **E ring** and the **G ring** both lie far from the planet, well beyond the narrow F ring. Both of these outer ring systems are extremely faint, fuzzy, and tenuous. Each lacks the ringlet structure so prominent in the main ring systems. The E ring encloses the orbit of Enceladus, one of Saturn's icy satellites. Some scientists suspect that water geysers on Enceladus are the source of ice particles in the E ring, much as Io's volcanoes supply material to Jupiter's magnetosphere (see Section 12-8).

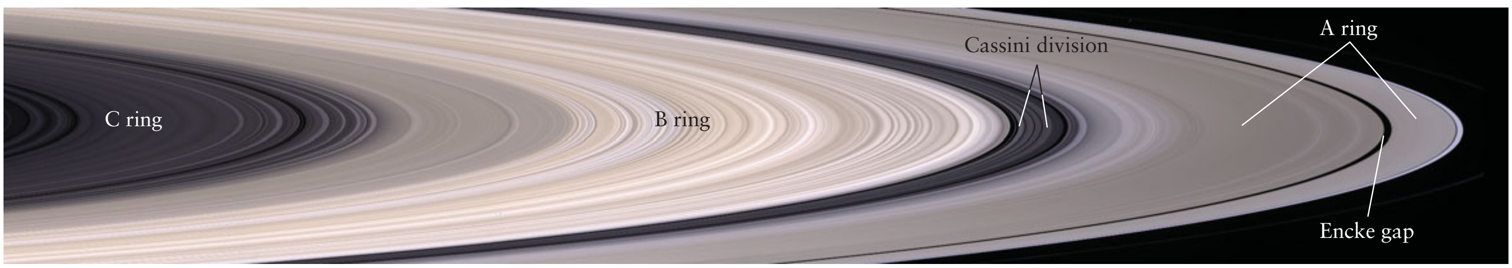
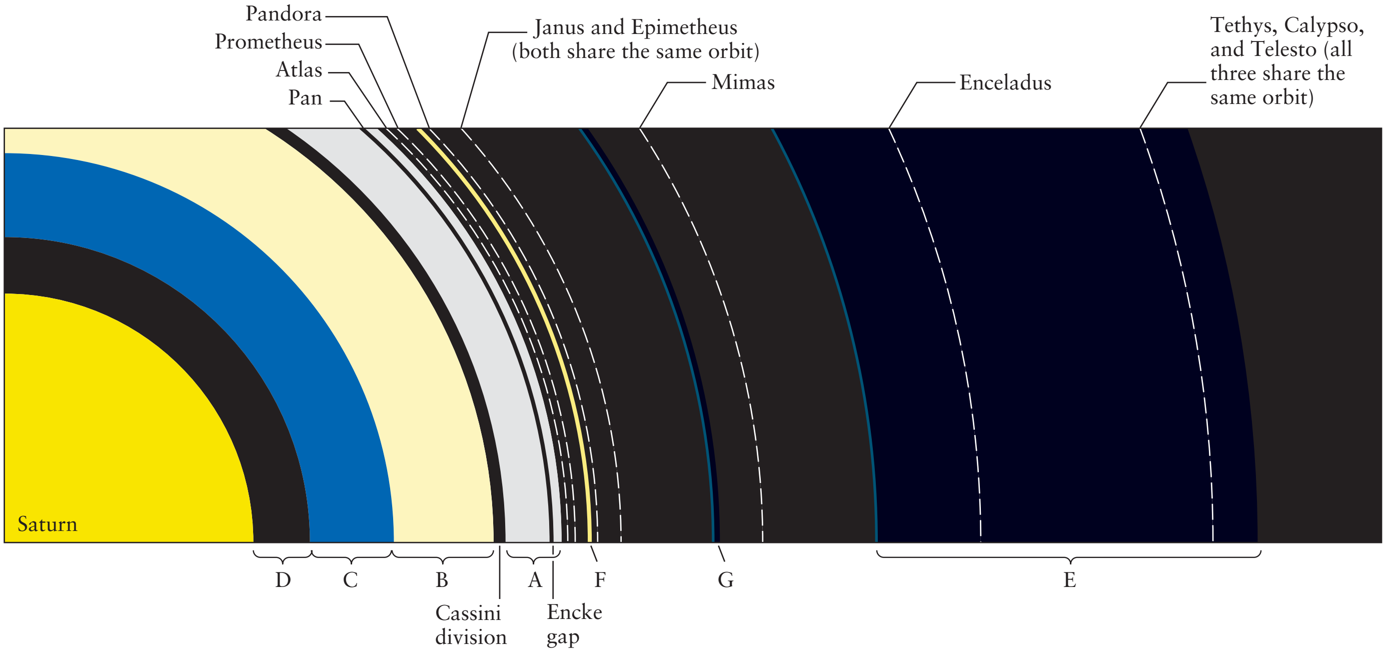


Figure 12-22 R I V U X G

Color Variations in Saturn's Rings This mosaic of *Cassini* images shows the rings in natural color. The color variations are indicative of slight differences in chemical composition among particles in different parts of the rings. (NASA/JPL/Space Science Institute)



INTERACTIVE EXERCISE 12.3

Figure 12-23

The Arrangement of Saturn's Rings This scale drawing shows the location of Saturn's rings along with the orbits of the 11 inner satellites. Only the A, B, and C rings can readily be seen from the Earth. The remaining rings are very faint, and their existence was only confirmed by spacecraft flybys.

12-11 Saturn's inner satellites affect the appearance and structure of its rings

Why do Saturn's rings have such a complex structure? The answer is that, like any object in the universe, the particles that make up the rings are affected by the force of gravity. Saturn's gravitational pull keeps the ring particles in orbit around the planet. But the satellites of Saturn also exert gravitational forces on the rings. These forces can shape the orbits of the ring particles and help give rise to the rings' structure.

Resonance and Shepherd Satellites

Astronomers have long known that one of Saturn's moons, Mimas, has a gravitational effect on its ring system. Mimas is a moderate-sized satellite that orbits Saturn every 22.6 hours. According to Kepler's third law, ring particles in the Cassini division should orbit Saturn approximately every 11.3 hours. Consequently, a given set of ring particles in the Cassini division will find itself between Saturn and Mimas on every second orbit (that is, every 22.6 hours). In other words, particles in the Cassini division are in a 2-to-1 resonance with Mimas. Because of these repeated alignments, the combined gravitational forces of Saturn and Mimas cause small particles to deviate from their original orbits, sweeping them out of the Cassini division. This helps explain why the Cassini division is relatively empty (although not completely so, as Figure 12-21 shows).

While Mimas tends to spread ring particles apart, other satellites exert gravitational forces that herd particles together. The *Voyager* spacecraft discovered two such satellites orbiting on either side of the narrow F ring (Figure 12-24). Pandora, the outer of the two satellites, moves around Saturn at a slightly slower speed than the particles in the ring. As ring particles pass Pandora, they experience a tiny gravitational tug that slows them

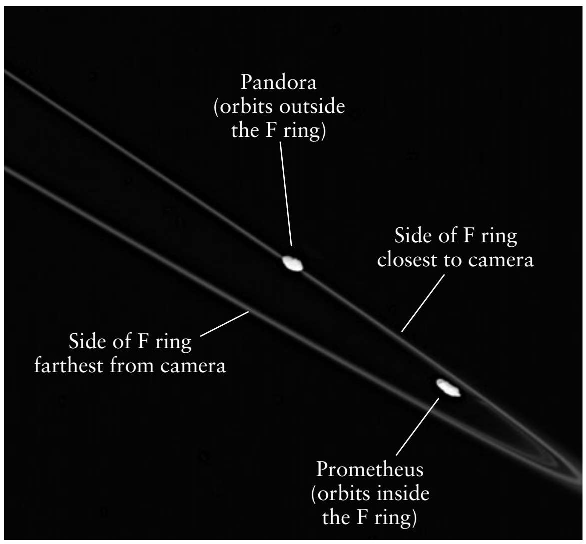
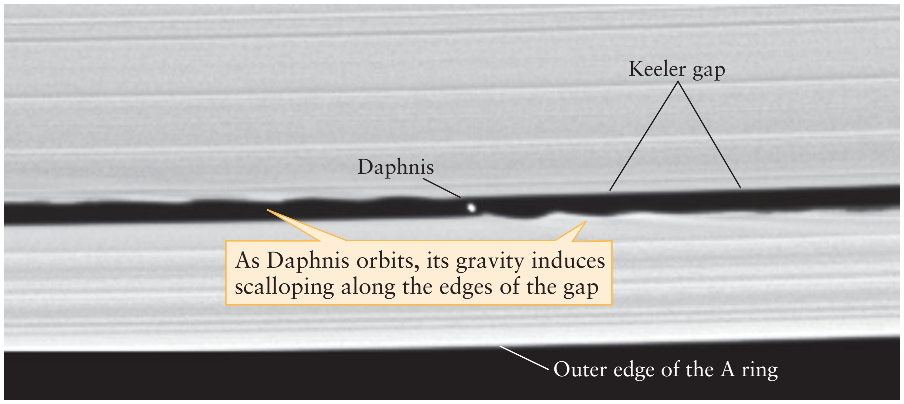


Figure 12-24 R I V U X G

Saturn's F Ring and Its Two Shepherds This *Cassini* image shows the tiny satellites Prometheus (102 km across) and Pandora (84 km across). (Compare with Figure 12-20.) These orbit Saturn on either side of its F ring, shepherding the ring particles into a narrow band. The satellites lap each other every 25 days. (NASA/JPL/Space Science Institute)

Figure 12-25 RIVUXG

VIDEO 12.9



Daphnis and the Keeler Gap This *Cassini* spacecraft shows Saturn's tiny moon Daphnis orbiting within the Keeler gap (see also Figure 12-20). Although it is just 7 km across, Daphnis exerts enough gravitational force to keep the 42-km wide gap open and induce wavelike disturbances in the two edges of the gap. (NASA/JPL/Space Science Institute)

down slightly. Hence, these particles lose a little energy and fall into orbits a bit closer to Saturn. At the same time, Prometheus, the inner satellite, orbits the planet somewhat faster than the F ring particles. The gravitational pull of Prometheus makes the ring particles speed up a little, giving them some extra energy and nudging them into slightly higher orbits. The competition between the pulls exerted by these two satellites focuses the F ring particles into a well-defined, narrow band.

Because of their confining influence, Prometheus and Pandora are called **shepherd satellites.** We will see in Chapter 14 that Uranus is encircled by narrow rings that are likewise kept confined by shepherd satellites.

An effect similar to shepherding explains two divisions in the A ring, the Encke gap and the even narrower Keeler gap (Figure 12-20). In 2005, *Cassini* images revealed a miniature moon, Daphnis, which actually orbits inside the Keeler gap (Figure 12-25). In a fashion similar to the F ring's shepherds, Daphnis's gravitational forces cause ring particles outside its orbit to move farther out and cause those inside its orbit to move farther inward toward Saturn. In this way, Daphnis helps to maintain a gap in the rings that is 42 km (26 mi) wide, many times wider than Daphnis's 7-km (4-mi) diameter. In a similar way, a 20-km wide moon called Pan orbits within and maintains the 270-km wide Encke gap. Both of these moons cause wavelike disturbances in the ring material on either side of the gap through which they travel (see Figure 12-25).

Gravitational effects carve gaps in the rings and focus ring particles into narrow ringlets

In addition to their dynamic ring systems, Jupiter and Saturn together have an exotic collection of moons. These include Saturn's moon Titan, with a thick atmosphere rich in hydrocarbons; Jupiter's satellite Io, the most volcanic world in the solar system; and Saturn's satellite Enceladus, which has exotic geysers that spew a mixture of water vapor and ice. We will examine these alien worlds in Chapter 13.

Key Words

A ring, p. 317
B ring, p. 317
belts, p. 304
brown oval, p. 307
C ring, p. 317
Cassini division, p. 317
current sheet, p. 315
D ring, p. 322
decametric radiation, p. 314
decimetric radiation, p. 314
differential rotation, p. 305
E ring, p. 322
Encke gap, p. 321
F ring, p. 321
G ring, p. 322
Great Red Spot, p. 304
hot spot, p. 312
internal rotation period, p. 315
light scattering, p. 322
liquid metallic hydrogen, p. 314
noble gases, p. 312
nonthermal radiation, p. 314
oblate, oblateness, p. 313
plasma, p. 315
ring particles, p. 318
ringlets, p. 321
Roche limit, p. 319
shepherd satellite, p. 324
synchrotron radiation, p. 314
thermal radiation, p. 314
tidal force, p. 319
white oval, p. 307
zonal winds, p. 310
zones, p. 304

Key Ideas

Composition and Structure: Jupiter and Saturn are both much larger than Earth. Each is composed of 71% hydrogen, 24% helium, and 5% all other elements by mass. Both planets have a higher percentage of heavy elements than does the Sun.

• Jupiter probably has a rocky core several times more massive than the Earth. The core is surrounded by a layer of liquid "ices" (water, ammonia, methane, and associated compounds). On top of this is a layer of helium and liquid metallic hydrogen and an outermost layer composed primarily of ordinary hydrogen and helium. All of Jupiter's visible features are near the top of this outermost layer.

• Saturn's internal structure is similar to that of Jupiter, but its core makes up a larger fraction of its volume and its liquid metallic hydrogen mantle is shallower than that of Jupiter.

• Jupiter and Saturn both rotate so rapidly that the planets are noticeably flattened. The rotation of both planets' interiors is revealed by variations in the radio emissions from the planets.

• Both Jupiter and Saturn emit more energy than they receive from the Sun. Presumably both planets are still cooling.

Atmospheres: The visible "surfaces" of Jupiter and Saturn are actually the tops of their clouds. The rapid rotation of the planets twists the clouds into dark belts and light zones that run parallel to the equator. Strong zonal winds run along the belts and zones.

• The outer layers of both planets' atmospheres show differential rotation: The equatorial regions rotate slightly faster than the polar regions. For both Jupiter and Saturn, the polar rotation rate is nearly the same as the internal rotation rate.

• The colored ovals visible in the Jovian atmosphere represent gigantic storms. Some, such as the Great Red Spot, are quite stable and persist for many years. Storms in Saturn's atmosphere seem to be shorter-lived.

• There are presumed to be three cloud layers in the atmospheres of Jupiter and Saturn. The reasons for the distinctive colors of these different layers are not yet known. The cloud layers in Saturn's atmosphere are spread out over a greater range of altitude than those of Jupiter, giving Saturn a more washed-out appearance.

• Saturn's atmosphere contains less helium than Jupiter's atmosphere. This lower abundance may be the result of helium raining downward into the planet. Helium "rainfall" may also account for Saturn's surprisingly strong heat output.

Magnetic Fields and Magnetospheres: Jupiter has a strong magnetic field created by currents in the metallic hydrogen layer. Its huge magnetosphere contains a vast current sheet of electrically charged particles. Charged particles in the densest portions of Jupiter's magnetosphere emit synchrotron radiation at radio wavelengths.

• The Jovian magnetosphere encloses a low-density plasma of charged particles. The magnetosphere exists in a delicate balance between pressures from the plasma and from the solar wind. When this balance is disturbed, the size of the magnetosphere fluctuates drastically.

• Saturn's magnetic field and magnetosphere are much less extensive than Jupiter's.

Rings: Saturn is circled by a system of thin, broad rings lying in the plane of the planet's equator. This system is tilted away from the plane of Saturn's orbit, which causes the rings to be seen at various angles by an Earth-based observer over the course of a Saturnian year.

Structure of the Rings: Saturn has three major, broad rings (A, B, and C) that can be seen from Earth. Other, fainter rings were found by the *Voyager* spacecraft.

• The principal rings of Saturn are composed of numerous particles of ice and ice-coated rock ranging in size from a few micrometers to about 10 m. Most of the rings exist inside the Roche limit of Saturn, where disruptive tidal forces are stronger than the gravitational forces attracting the ring particles to each other.

• Each of Saturn's major rings is composed of a great many narrow ringlets. The faint F ring, which is just outside the A ring, is kept narrow by the gravitational pull of shepherd satellites.

• Jupiter's faint rings are composed of a relatively small amount of small, dark, rocky particles that reflect very little light.

Questions

Review Questions

1. Mars passes closer to the Earth than Jupiter does, but with an Earth-based telescope it is easier to see details on Jupiter than on Mars. Why is this?
2. Saturn is the most distant of the planets visible without a telescope. Is there any way we could infer this from naked-eye observations? Explain. (*Hint:* Think about how Saturn's position on the celestial sphere must change over the course of weeks or months.)
3. As seen from Earth, does Jupiter or Saturn undergo retrograde motion more frequently? Explain your answer.
4. In what ways are the motions of Jupiter's atmosphere like the motion of water stirred in a pot (see Figure 12-3*b*)? In what ways are they different?
5. Is the chemical composition of Jupiter as a whole the same as that of its atmosphere? Explain any differences.
6. Astronomers can detect the presence of hydrogen in stars by looking for the characteristic absorption lines of hydrogen in the star's visible spectrum (Figure 5-21). They can also detect hydrogen in glowing gas clouds by looking for hydrogen's characteristic emission lines (Figure 5-18). Explain why neither of these techniques helped Earth-based astronomers to detect hydrogen in Jupiter's atmosphere.
7. On a warm, humid day, water vapor remains in the atmosphere. But if the temperature drops suddenly, the water vapor forms droplets, clouds appear, and it begins to rain. Relate this observation to why there is relatively little helium in Saturn's atmosphere compared to the atmosphere of Jupiter.
8. What would happen if you tried to land a spacecraft on the surface of Jupiter?
9. What are the belts and zones in the atmospheres of Jupiter and Saturn? Is the Great Red Spot more like a belt or a zone? Explain your answer.
10. Give one possible explanation why weather systems on Jupiter are longer-lived than weather systems on Earth.
11. What are white ovals and brown ovals? What can we infer about them from infrared observations?
12. Compare and contrast the source of energy for motions in the Earth's atmosphere with the energy source for motions in the atmospheres of Jupiter and Saturn.
13. Both Jupiter and Saturn emit more energy than they receive from the Sun in the form of sunlight. Compare the internal energy sources of the two planets that produce this emission.
14. What observations from the *Cassini* spacecraft contradict the accepted picture of convection in Jupiter's atmosphere?
15. Compare the atmospheres of Jupiter and Saturn. Why does Saturn's atmosphere look "washed out" in comparison to that of Jupiter?
16. Which data from the *Galileo Probe* were in agreement with astronomers' predictions? Which data were surprising?
17. Fewer than one in every 10^5 atoms in Jupiter's atmosphere is an argon atom, and fewer than one in 10^8 is an atom of krypton or xenon. If these atoms are so rare, why are scientists concerned about them? How do the abundances of these elements in Jupiter's atmosphere compare to the abundances in the Sun? What hypotheses have been offered to explain these observations?
18. Why is Jupiter oblate? What do astronomers learn from the value of Jupiter's oblateness?
19. What is liquid metallic hydrogen? What is its significance for Jupiter?
20. Describe the internal structures of Jupiter and Saturn, and compare them with the internal structure of the Earth.

21. Explain why Saturn is more oblate than Jupiter, even though Saturn rotates more slowly.

22. If Jupiter does not have any observable solid surface and its atmosphere rotates differentially, how are astronomers able to determine the planet's internal rotation rate?

23. Compare and contrast Jupiter's magnetosphere with the magnetosphere of a terrestrial planet like Earth. Why is the size of the Jovian magnetosphere highly variable, while that of the Earth's magnetosphere is not?

24. What is a plasma? Where are plasmas found in the vicinity of Jupiter?

25. Why is Saturn's magnetosphere less extensive than Jupiter's?

26. What observations of Saturn's rings proved that they are not solid?

27. If Saturn's rings are not solid, why do they look solid when viewed through a telescope?

28. Although the *Voyager* and *Cassini* spacecraft did not collect any samples of Saturn's ring particles, measurements from these spacecraft allowed scientists to determine the sizes of the particles. Explain how this was done.

29. The Space Shuttle and other spacecraft orbit the Earth well within the Earth's Roche limit. Explain why these spacecraft are not torn apart by tidal forces.

30. How do Jupiter's rings differ from those of Saturn?

31. Describe the structure of Saturn's rings. What evidence is there that ring particles do not migrate significantly between ringlets?

32. During the planning stages for the *Pioneer 11* mission, when relatively little was known about Saturn's rings, it was proposed to have the spacecraft fly through the Cassini division. Why would this have been a bad idea?

33. What is the relationship between Saturn's satellite Mimas and the Cassini division?

34. Why is the term "shepherd satellite" appropriate for the objects so named? Explain how a shepherd satellite operates.

Advanced Questions

The question preceded by an asterisk (*) involves topics discussed in Box 7-2.

Problem-solving tips and tools

Box 4-4 describes how to use Newton's form of Kepler's third law. Newton's universal law of gravitation, discussed in Section 4-7, is the basic equation from which you can calculate a planet's surface gravity. Box 7-2 discusses escape speed, and Sections 5-3 and 5-4 discuss the properties of thermal radiation (including the Stefan-Boltzmann law, which relates the temperature of a body to the amount of thermal radiation that it emits).

35. The angular diameter of Jupiter at opposition varies little from one opposition to the next. By contrast, the angular diameter of Mars at opposition is quite variable. Explain why there is a difference between these two planets.

36. Jupiter was at opposition on June 5, 2007. On that date Jupiter appeared to be in the constellation Ophiuchus. Approximately when will Jupiter next be at opposition in this same region of the celestial sphere? Explain your answer.

37. Jupiter's equatorial diameter and the rotation period at Jupiter's equator are both given in Table 12-1. Use these data to calculate the speed at which an object at the cloudtops along Jupiter's equator moves around the center of the planet.

38. Using orbital data for a Jovian satellite of your choice (see Appendix 3), calculate the mass of Jupiter. How does your answer compare with the mass quoted in Table 12-1?

39. It has been claimed that Saturn would float if one had a large enough bathtub. Using the mass and size of Saturn given in Table 12-2, confirm that the planet's average density is about 690 kg/m^3, and comment on this somewhat fanciful claim.

40. Roughly speaking, Jupiter's composition (by mass) is three-quarters hydrogen and one-quarter helium. The mass of a single hydrogen atom is given in Appendix 7; the mass of a single helium atom is about 4 times greater. Use these numbers to calculate how many hydrogen atoms and how many helium atoms there are in Jupiter.

41. Use the information given in Section 12-3 to estimate the wind velocities in the Great Red Spot, which rotates with a period of about 6 days.

42. An astronaut floating above Saturn's cloudtops would see a blue sky, even though Saturn's atmosphere has a very different chemical composition than Earth's. Explain why. (*Hint:* See Box 5-4.)

43. If Jupiter emitted just as much energy per second (as infrared radiation) as it receives from the Sun, the average temperature of the planet's cloudtops would be about 107 K. Given that Jupiter actually emits twice this much energy per second, calculate what the average temperature must actually be.

44. (**a**) From Figure 12-9*a*, by how much does the temperature increase as you descend from the 100-millibar level in Jupiter's atmosphere to an altitude 100 km below that level? (**b**) Use Figure 12-9*b* to answer the same question for Saturn's atmosphere. (**c**) In the Earth's troposphere (see Section 9-5), the air temperature increases by 6.4°C for each kilometer that you descend. In which planet's atmosphere—Earth, Jupiter, or Saturn—does the temperature increase most rapidly with decreasing altitude?

***45.** Consider a hypothetical future spacecraft that would float, suspended from a balloon, for extended periods in Jupiter's upper atmosphere. If we want this spacecraft to return to Earth after completing its mission, calculate the speed at which the spacecraft's rocket motor would have to accelerate it in order to escape Jupiter's gravitational pull. Compare with the escape speed from the Earth, equal to 11.2 km/s.

46. The *Galileo Probe* had a mass of 339 kg. On Earth, its weight (the gravitational force exerted on it by Earth) was 3320 newtons, or 747 lb. What was the gravitational force that Jupiter exerted on the *Galileo Probe* when it entered Jupiter's clouds?

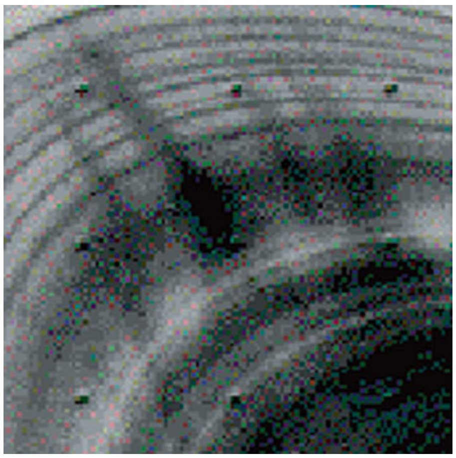
47. From the information given in Section 12-6, calculate the average density of Jupiter's rocky core. How does this compare with the average density of the Earth? With the average density of the Earth's solid inner core? (See Table 9-1 and Table 9-2 for data about the Earth.)

48. In the outermost part of Jupiter's outer layer (shown in yellow in the upper part of Figure 12-12), hydrogen is principally in the form of molecules (H_2). Deep within the liquid metallic hydrogen layer (shown in orange in Figure 12-12), hydrogen is in the form of single atoms. Recent laboratory experiments suggest that there is a gradual transition between these two states, and that the transition layer overlaps the boundary between the ordinary hydrogen and liquid metallic hydrogen layers. Use this information to redraw the upper part of Figure 12-12 and to label the following regions in Jupiter's interior: (i) ordinary (nonmetallic) hydrogen molecules; (ii) nonmetallic hydrogen with a mixture of atoms and molecules; (iii) liquid metallic hydrogen with a mixture of atoms and molecules; (iv) liquid metallic hydrogen atoms.

49. When Saturn is at different points in its orbit, we see different aspects of its rings because the planet has a 27° tilt. If the tilt angle were different, would it be possible to see the upper and lower sides of the rings at all points in Saturn's orbit? If so, what would the tilt angle have to be? Explain your answers.

50. As seen from Earth, the intervals between successive edge-on presentations of Saturn's rings alternate between about 13 years, 9 months, and about 15 years, 9 months. Why do you think these two intervals are not equal?

51. (**a**) Use Newton's form of Kepler's third law to calculate the orbital periods of particles at the outer edge of Saturn's A ring and at the inner edge of the B ring. (**b**) Saturn's rings orbit in the same direction as Saturn's rotation. If you were floating along with the cloudtops at Saturn's equator, would the outer edge of the A ring and the inner edge of the B ring appear to move in the same or opposite directions? Explain.



VIDEO 12.10 R I V U X G

(NASA/JPL)

52. The above *Voyager 2* close-up image of Saturn's rings shows a number of dark, straight features called *spokes*. As these features orbit around Saturn, they tend to retain their shape like the rigid spokes on a rotating bicycle wheel. (The black dots were added by the *Voyager* camera system to help scientists calibrate the electronic image.) The spokes rotate at the same rate as Saturn's magnetic field and are thought to be clouds of tiny, electrically charged particles kept in orbit by magnetic forces. Explain why the spokes could *not* maintain their shape if they were kept in orbit by gravitational forces alone.

53. The Cassini division involves a 2-to-1 resonance with Mimas. Does the location of the Encke gap—133,500 km from Saturn's center—correspond to a resonance with one of the other satellites? If so, which one? (See Appendix 3.)

Discussion Questions

54. Describe some of the semipermanent features in Jupiter's atmosphere. Compare and contrast these long-lived features with some of the transient phenomena seen in Jupiter's clouds.

55. Suppose you were asked to design a mission to Jupiter involving an unmanned airplanelike vehicle that would spend many days (months?) flying through the Jovian clouds. What observations, measurements, and analyses should this aircraft be prepared to make? What dangers might the aircraft encounter, and what design problems would you have to overcome?

56. What sort of experiment or space mission would you design in order to establish definitively whether Jupiter has a rocky core?

57. The classic science-fiction films *2001: A Space Odyssey* and *2010: The Year We Make Contact* both involve manned spacecraft in orbit around Jupiter. What kinds of observations could humans make on such a mission that cannot be made by robotic spacecraft? What would be the risks associated with such a mission? Do you think that a manned Jupiter mission would be as worthwhile as a manned mission to Mars? Explain your answers.

58. Suppose that Saturn were somehow moved to an orbit around the Sun with semimajor axis 1 AU, the same as the Earth's. Discuss what long-term effects this would have on the planet and its rings.

Web/eBook Questions

59. On Jupiter, the noble gases argon, krypton, and xenon provide important clues about Jupiter's past. On Earth, xenon is used in electronic strobe lamps because it emits a very white light when excited by an electric current. Argon, by contrast, is one of the gases used to fill ordinary incandescent lightbulbs. Search the World Wide Web for information about why argon is used in this way. Why do premium, long-life lightbulbs use krypton rather than argon?

60. Search the World Wide Web, especially the Web sites for NASA's Jet Propulsion Laboratory and the European Space Agency, for information about the current status of the *Cassini* mission. What recent discoveries has *Cassini* made? What ideas are being considered for the *Cassini* extended mission, to begin in 2008?

61. The two *Voyager* spacecraft were launched from Earth along a trajectory that took them directly to Jupiter. The force of Jupiter's gravity then gave the two spacecraft a "kick" that helped push them onward to Saturn. The much larger *Cassini* spacecraft, by contrast, was first launched on a trajectory that took it past Venus. Search the World Wide Web, especially the Web sites for NASA's Jet Propulsion Laboratory and the European Space Agency, for information about the trajectory that *Cassini* took through the solar system to reach

Saturn. Explain why this trajectory was so different from that of the *Voyagers*.

VIDEO 12.5

62. The Rotation Rate of Saturn. Access and view the video "Saturn from the Hubble Space Telescope" in Chapter 12 of the *Universe* Web site or eBook. The total amount of time that actually elapses in this video is 42.6 hours. Using this information, identify and follow an atmospheric feature and determine the rotation period of Saturn. How does your answer compare with the value given in Table 12-2?

Activities

Observing Projects

> **Observing tips and tools**
>
> WEB LINK 12.3 WEB LINK 12.4 WEB LINK 12.9
>
> Like Mars, Jupiter and Saturn are most easily seen around opposition. (The dates of Jupiter's and Saturn's oppositions are available on the World Wide Web.) Each planet is visible in the night sky for several months before or after its opposition. At other times, Jupiter and Saturn may be visible in either the predawn morning sky or the early evening sky. Consult such magazines as *Sky & Telescope* and *Astronomy* or their Web sites for more detailed information about when and where to look for Jupiter during a given month. You can also use the *Starry Night Enthusiast*™ program on the CD-ROM that accompanies selected copies of this textbook. A relatively small telescope with an objective diameter of 15 to 20 cm (6 to 8 inches), used with a medium-power eyepiece to give a magnification of 25X or so, should enable you to see some of the dark belts on Jupiter and the rings of Saturn.

63. If Jupiter is visible in the night sky, make arrangements to view the planet through a telescope. What magnifying power seems to give you the best view? Draw a picture of what you see. Can you see any belts and zones? How many? Can you see the Great Red Spot?

64. Make arrangements to view Jupiter's Great Red Spot through a telescope. Consult the *Sky & Telescope* Web site, which lists the times when the center of the Great Red Spot passes across Jupiter's central meridian. The Great Red Spot is well placed for viewing for 50 minutes before and after this happens. You will need a refractor with an objective of at least 15 cm (6 in.) diameter or a reflector with an objective of at least 20 cm (8 in.) diameter. Using a pale blue or green filter can increase the color contrast and make the spot more visible. For other useful hints, see the article "Tracking Jupiter's Great Red Spot" by Alan MacRobert (*Sky & Telescope*, September 1997).

65. View Saturn through a small telescope. Make a sketch of what you see. Estimate the angle at which the rings are tilted to your line of sight. Can you see the Cassini division? Can you see any belts or zones in Saturn's clouds? Is there a faint, starlike object near Saturn that might be Saturn's satellite Titan? What observations could you perform to test whether the starlike object is a Saturnian satellite?

STARRY NIGHT

66. Use the *Starry Night Enthusiast*™ program to observe the appearance of Jupiter. Select **Favourites > Guides > Atlas** from the menu. Open the **Find** pane and click the menu button for **Jupiter** and select **Magnify** from the drop-down menu. **Stop** time flow and, in the toolbar, set the date and time to **March 4, 2004, at 12:00:00 A.M.** to see Jupiter at opposition. Set the **Time Flow Rate** to **1 minute.** Then **Run Time Forward.** Use the Time Flow controls to determine the rotation period of the planet. (*Hint:* You may want to track the motion of an easily recognizable feature, such as the Great Red Spot.) How does your answer compare with the rotation period given in Table 12-1?

STARRY NIGHT

67. Use the *Starry Night Enthusiast*™ program to observe the appearance of Saturn. Select **Favourites > Guides > Atlas** from the menu. Open the **Find** pane and click the menu button for **Saturn** and select **Magnify** from the drop-down menu. **Stop** time flow. Set the **Time Flow Rate** to 1 lunar month. Then **Run Time Forward.** Describe how Saturn's appearance changes over time. Explain what causes these changes.

STARRY NIGHT

68. Use the *Starry Night Enthusiast*™ program to examine Jupiter and Saturn. (**a**) Select **Favourites > Solar System > Jupiter** from the menu. Select **View > Feet** to remove the image of the spacesuit. You can zoom in and zoom out on the view and you can also rotate Jupiter by putting the mouse cursor over the image, holding down the mouse button, and moving the mouse. (On a two-button mouse, hold down the left mouse button.) How many white ovals and brown ovals can you count in Jupiter's southern hemisphere (the hemisphere in which the Great Red Spot is located)? How many white ovals and brown ovals can you count in the northern hemisphere? What general rule can you state about the abundance of these storms in the two hemispheres? (**b**) Select **Favourites > Solar System > Saturn** from the menu. Select **View > Feet** to remove the image of the spacesuit. You can zoom in and zoom out on the view and you can also rotate Saturn by placing the mouse cursor over the image, holding down the mouse button, and moving the mouse. (On a two-button mouse, hold down the left mouse button.) Rotate Saturn so that you are looking straight down on the plane of the rings. Draw a copy of what you see and label the different rings and divisions. (Compare Figure 12-23.)

Collaborative Exercises

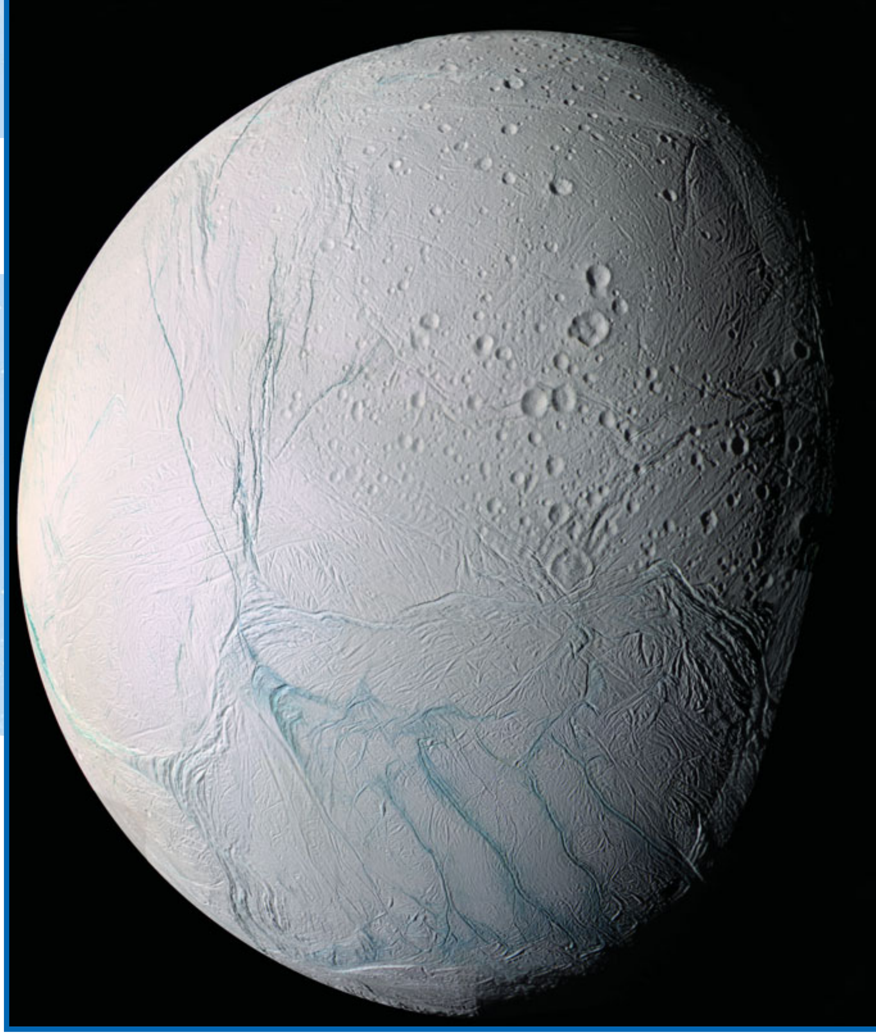
69. Using a ruler with millimeter markings on five various images of Jupiter in the text, Figures 12-1*a*, 12-2*a*, and 12-4, determine the ratio of the longest width of the Great Red Spot to the full diameter of Jupiter. Each group member should measure a different image and all values should be averaged.

70. The text provides different years that spacecraft have flown by Jupiter and Saturn. List these dates and create a time line by listing one important event that was occurring on Earth during each of those years.

71. If the largest circle you can draw on a piece of paper represents the largest diameter of Saturn's rings, about how large would Saturn be if scaled appropriately? Which item in a group member's backpack is closest to this size?

13

Jupiter and Saturn's Satellites of Fire and Ice



WEB LINK 13.1

R I V U X G

A color-enhanced view of Saturn's satellite Enceladus. (NASA/JPL/Space Science Institute)

The delicately colored world shown here is neither the creation of an abstract artist nor the product of a science fiction writer's imagination. It is Enceladus, a satellite of Saturn whose icy surface has a split personality: One hemisphere is ancient and covered with impact craters, while the other hemisphere is nearly crater-free and crisscrossed by stress faults and fractures. The latter hemisphere is actually the site of active volcanoes that eject icy particles rather than lava.

Enceladus is not the only satellite of the giant planets to display exotic geologic activity. Io, a large satellite of Jupiter discovered by Galileo in 1610, is the most geologically active world in the solar system. Its surface is covered with colorful sulfur compounds deposited by dozens of active volcanoes. Europa, another of Jupiter's large satellites, has no volcanoes but does have a weirdly cracked surface of ice. Beneath Europa's ice there may be a worldwide ocean, within which there could possibly be single-celled organisms.

No less exotic is Saturn's large satellite Titan, which is enveloped by a thick, nitrogen-rich atmosphere from which liquid hydrocarbons fall as rain. In this chapter we will explore these and other intriguing aspects of Jupiter and Saturn's extensive collection of satellites.

13-1 Jupiter's Galilean satellites are easily seen with Earth-based telescopes

When Galileo trained his telescope on Jupiter in January 1610, he became the first person to observe satellites orbiting another planet (see Section 4-5). He called them the Medicean Stars, in

Learning Goals

By reading the sections of this chapter, you will learn

- **13-1** What the Galilean satellites are and how they orbit Jupiter
- **13-2** The similarities and differences among the Galilean satellites
- **13-3** How the Galilean satellites formed
- **13-4** Why Io is the most volcanically active world in the solar system
- **13-5** How Io interacts with Jupiter's magnetic field
- **13-6** The evidence that Europa may have an ocean beneath its surface
- **13-7** The kinds of geologic activity found on Ganymede and Callisto
- **13-8** The nature of Titan's thick, hydrocarbon-rich atmosphere
- **13-9** Why most of Jupiter's moons orbit in the "wrong" direction
- **13-10** What powers the volcanoes on Saturn's icy moon Enceladus

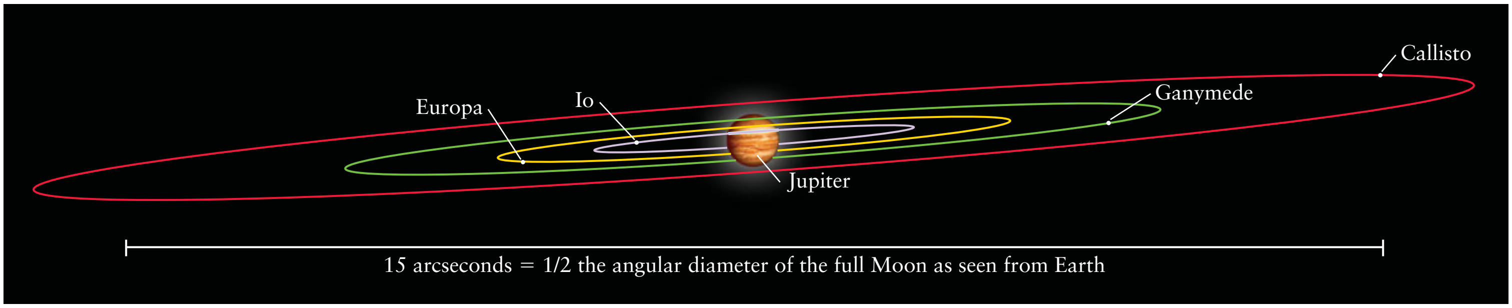


Figure 13-1

The Orbits of the Galilean Satellites This illustration shows the orbits of the four Galilean satellites as seen from Earth. All four orbits lie in nearly the same plane as Jupiter's equator. The apparent angular size and orientation of the orbits depends on the relative positions of Earth and Jupiter.

order to curry the favor of a wealthy Florentine patron of the arts and sciences. We now call them the **Galilean satellites.** Individually, they are named Io, Europa, Ganymede, and Callisto, after four mythical lovers and companions of the god whom the Greeks called Zeus and the Romans called Jupiter.

When viewed through an Earth-based telescope, the Galilean satellites look like pinpoints of light (see Figure 4-16). All four satellites orbit Jupiter in nearly the same plane as the planet's equator (**Figure 13-1**). From Earth, we always see that plane nearly edge-on, so the satellites appear to move back and forth relative to Jupiter (see Figure 4-17). The orbital periods are fairly short, ranging from 1.8 (Earth) days for Io to 16.7 days for Callisto, so we can easily see the satellites move from one night to the next and even during a single night. These motions led Galileo to realize that he was seeing objects orbiting around Jupiter, in much the same way that Copernicus said that planets move around the Sun (see Section 4-2).

Each of the four Galilean satellites is bright enough to be visible to the naked eye. Why, then, did Galileo need a telescope to discover them? The reason is that as seen from the Earth, the angular separation between Jupiter and the satellites is quite small—never more than 10 arcminutes for Callisto and even less for the other three Galilean satellites. To the naked eye, these satellites are lost in the overwhelming glare of Jupiter. But a small telescope or even binoculars increases the apparent angular separation by enough to make the Galilean satellites visible.

Synchronous Rotation

The brightness of each satellite varies slightly as it orbits Jupiter. This is because the satellites also spin on their axes as they orbit Jupiter, and dark and light areas on their surfaces are alternately exposed to and hidden from our view. Remarkably, each Galilean satellite goes through one complete cycle of brightness during one orbital period. This tells us that each satellite is in *synchronous rotation,* so that it rotates exactly once on its axis during each trip around its orbit (see Figure 3-4*b*). As we saw in Section 4-8, our Moon's synchronous rotation is the result of gravitational forces exerted on the Moon by Earth. Likewise, Jupiter's gravitational forces keep the Galilean satellites in synchronous rotation.

ANIMATION 13.1

Synchronous rotation means that the rotation period and orbital period are in a 1-to-1 ratio for each Galilean satellite. Remarkably, there is also a simple ratio of the different orbital periods of the three inner Galilean satellites, Io, Europa, and Ganymede. During the 7.155 days that Ganymede takes to complete one orbit around Jupiter, Europa makes two orbits and Io makes four orbits. Thus, the orbital periods of Io, Europa, and Ganymede are in the ratio 1:2:4, which you can verify from the data in **Table 13-1**.

This special relationship among the satellites' orbits is maintained by the gravitational forces that they exert on one another. Those forces can be quite strong, because the three inner Galilean satellites pass relatively close to one another; at their closest approach, Io and Europa are separated by only two-thirds the distance from the Earth to the Moon. Such a close approach occurs once for every two of Io's orbits, so Europa's gravitational pull acts on Io in a rhythmic way. Indeed, Io, Europa, and Ganymede all exert rhythmic gravitational tugs on one another. Just as a drummer's rhythm keeps musicians on the same beat, this gravitational rhythm maintains the simple ratio of orbital periods among the satellites.

Gravitational interactions between Io, Europa, and Ganymede induce a rhythmic relationship among their orbits

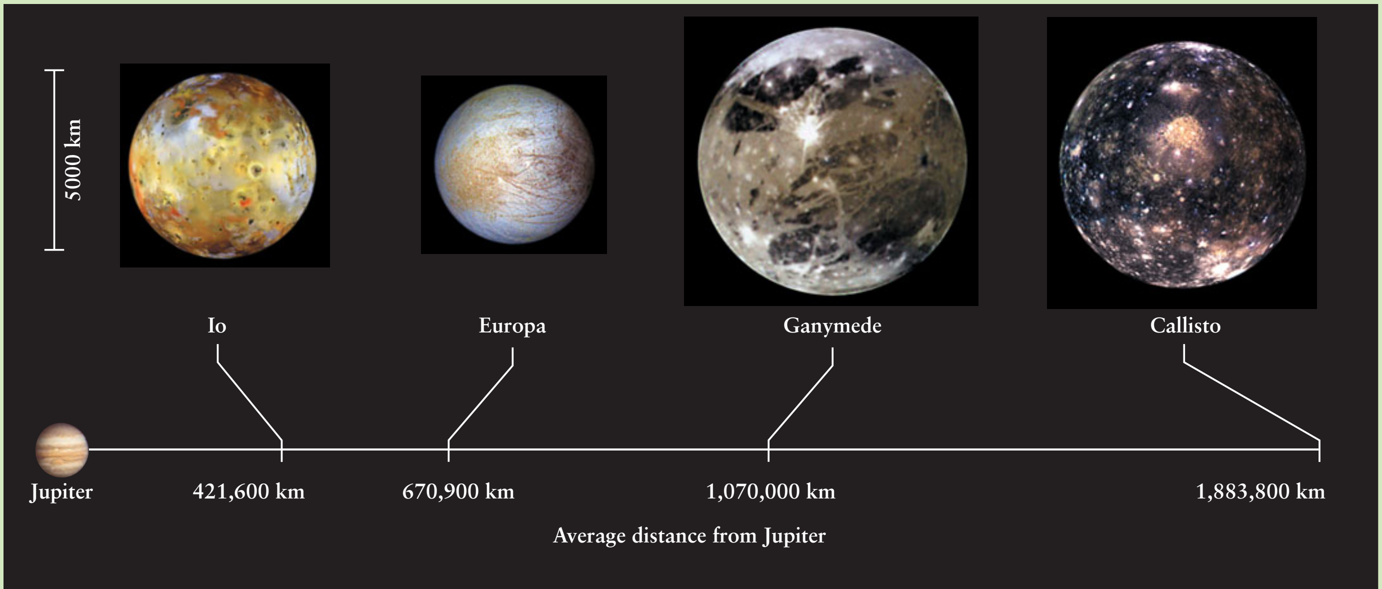
By contrast, Callisto orbits at a relatively large distance from the other three large satellites. Hence, the gravitational forces on Callisto from the other satellites are relatively weak, and there is no simple relationship between Callisto's orbital period and the period of Io, Europa, or Ganymede.

Transits, Eclipses, and Occultations

Because the orbital planes of the Galilean satellites are nearly edge-on to our line of sight, we see these satellites undergoing transits, eclipses, and occultations. In a *transit,* a satellite passes between us and Jupiter, and we see the satellite's shadow as a black dot against the planet's colorful cloudtops. (Figure 12-2*a* shows Europa's shadow on Jupiter.) In an *eclipse,* one of the satellites disappears and then reappears as it passes into and out of Jupiter's enormous shadow. In an **occultation,** a satellite passes

Table 13-1 Jupiter's Galilean Satellites Compared with the Moon, Mercury, and Mars

	Average distance from Jupiter (km)	Orbital period (days)	Diameter (km)	Mass (kg)	Mass (Moon = 1)	Average density (kg/m^3)	Albedo
Io	421,600	1.769	3642	8.932×10^{22}	1.22	3529	0.63
Europa	670,900	3.551	3120	4.791×10^{22}	0. 65	3018	0.64
Ganymede	1,070,000	7.155	5268	1.482×10^{23}	2.02	1936	0.43
Callisto	1,883,000	16.689	4800	1.077×10^{23}	1.47	1851	0.17
Moon	—	—	3476	7.349×10^{22}	1.00	3344	0.11
Mercury	—	—	4880	3.302×10^{23}	4.49	5430	0.12
Mars	—	—	6794	6.419×10^{23}	8.73	3934	0.15



Note: Jupiter is shown to the same scale as the distances of the satellites from Jupiter. Compared to this scale, the images of the satellites themselves have been enlarged 74×.

WEB LINK 13.2

R I V U X G

(NASA/JPL)

completely behind Jupiter, and the satellite is temporarily blocked from our Earth-based view. (The word *occultation* comes from a Latin verb meaning "to cover.")

Before spacecraft first ventured to Jupiter, astronomers used eclipses to estimate the diameters of the Galilean satellites. When a satellite emerges from Jupiter's shadow, it does not blink on instantly. Instead, there is a brief interval during which the satellite gets progressively brighter as more of its surface is exposed to sunlight. The satellite's diameter is calculated from the duration of this interval and the satellite's orbital speed (which is known from Kepler's laws).

Occultations can also be used to determine the diameter of a satellite by measuring the time it takes to disappear behind Jupiter or to reappear from behind the planet. In addition, the Galilean satellites occasionally occult one another, because all four orbit Jupiter in the plane of the planet's equator. Every six years, when the Earth passes through this equatorial plane, there is a period of a few months during which Earth observers can see mutual occultations of the satellites. Once again, timing the occultations enables astronomers to calculate the diameters of the satellites.

As Table 13-1 shows, the smallest Galilean satellite (Europa) is slightly smaller than our Moon; the largest satellite (Ganymede) is larger than Mercury and more than three-quarters the size of Mars. Thus, the Galilean satellites truly are worlds in their own right.

13-2 Data from spacecraft reveal the unique properties of the Galilean satellites

WEB LINK 13.3

Even the finest images made with Earth-based telescopes have revealed relatively few details about the Galilean satellites. Almost everything we know about these satellites has come from observations made at close range by spacecraft.

The first close-range observations of the Galilean satellites were made by the *Pioneer 10* and *Pioneer 11* spacecraft as they flew past Jupiter in 1973 and 1974. The images from these missions were of relatively low resolution, however, and much more information has come from three subsequent missions. *Voyager 1* and *Voyager 2* flew past Jupiter in 1979 and recorded tens of thousands of images, one of which is shown in Figure 13-2. The *Galileo* spacecraft, which made 35 orbits around Jupiter between 1995 and 2003, carried out an even more extensive investigation of Jupiter's satellites.

Measuring Satellite Densities

One key goal of these missions was to determine the densities of the Galilean satellites to very high accuracy. Given the density of a planet or satellite, astronomers can draw conclusions about its chemical composition and internal structure. To find the densities, scientists first determined the satellite masses. They did this by measuring how the gravity of Io, Europa, Ganymede, and Callisto deflected the trajectories of the *Voyager* and *Galileo* spacecraft. Given the masses and diameters of the satellites, they then calculated each satellite's average density (mass divided by volume). Table 13-1 lists our current knowledge about the sizes and masses of the Galilean satellites.

Of the four Galilean satellites, Europa proves to be the least massive: Its mass is only two-thirds that of our Moon. Ganymede is by far the most massive of the four, with more than double the mass of our Moon. In fact, Ganymede is the most massive satellite anywhere in the solar system. In second place is Callisto, with about $1\frac{1}{2}$ times the Moon's mass.

However, Ganymede and Callisto are *not* merely larger versions of our Moon. The reason is that both Ganymede and Callisto have very low average densities of less than 2000 kg/m^3. By comparison, typical rocks in the Earth's crust have densities around 3000 kg/m^3, and the average density of our Moon is 3344 kg/m^3. The low densities of Ganymede and Callisto mean that these satellites cannot be composed primarily of rock. Instead, they are probably roughly equal parts of rock and water ice. Water ice is substantially less dense than rock, but it becomes as rigid as rock under high pressure (such as is found in the interiors of the Galilean satellites). Furthermore, water molecules are relatively common in the solar system. Enough water would have been available in the early solar system to make up a substantial portion of a large satellite such as Ganymede or Callisto.

Three of the Galilean satellites are made of a mixture of ice and rock; only Io is ice-free

Water ice cannot be a major constituent of the two inner Galilean satellites, however. The innermost satellite, Io, has the highest average density, 3529 kg/m^3, slightly greater than the density of our Moon. The next satellite out, Europa, has an average density of 3018 kg/m^3. Both of these values are close to the densities of typical rocks in the Earth's crust. Hence, it is reasonable to suppose that both Io and Europa are made primarily of rocky material.

The most definitive evidence for water ice on Jupiter's satellites has come from spectroscopic observations. The spectra of sunlight reflected from Europa, Ganymede, and Callisto show absorption at the infrared wavelengths characteristic of water ice molecules. You can see this in Figure 7-4, which compares the spectrum of Europa to the spectrum of ice. Europa's density shows that it is composed mostly of rock, so its ice must be limited to the satellite's outer regions. Among the Galilean satellites, only Io shows no trace of water ice on its surface or in its interior.

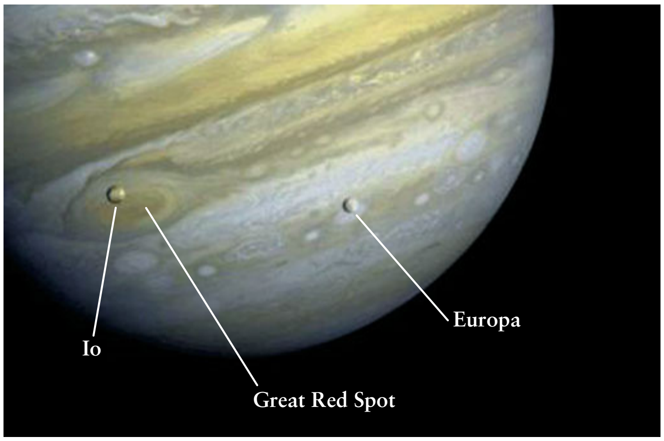


Figure 13-2 R I V U X G

Io and Europa from *Voyager 1* *Voyager 1* recorded this image of Jupiter and the Galilean satellites Io and Europa in February 1979, when it was 20 million kilometers (12.4 million miles) from the giant planet. The satellites are actually smaller than some of Jupiter's cloud features, such as the Great Red Spot (see Section 14-3). *Voyager 1* and *Voyager 2* also recorded many images of the Galilean satellites at closer range. (NASA/JPL)

13-3 The Galilean satellites formed like a solar system in miniature

As Table 13-1 shows, the more distant a Galilean satellite is from Jupiter, the greater the proportion of ice within the satellite and the lower its average density. But why should this be? An important clue is that the average densities of the planets show a similar trend: Moving outward from the Sun, the average density of the planets steadily decreases, from more than 5000 kg/m^3 for Mercury to less than 1000 kg/m^3 for Saturn (recall Table 7-1). The best explanation for this similarity is that the Galilean satellites formed around Jupiter in much the same way that the planets formed around the Sun, although on a much smaller scale.

The differences in composition among the Galilean satellites mimic those among planets orbiting the Sun

We saw in Section 8-4 that dust grains in the solar nebula played an important role in planet formation. In the inner parts of the nebula, close to the glowing protosun, only dense, rocky grains were able to survive. These accumulated over time into the dense, rocky inner planets. But in the cold outer reaches of the nebula, dust grains were able to retain icy coatings of low-density material like water and ammonia. Hence, when the Jovian planets formed in the outer solar nebula and incorporated these ice-coated grains, the planets ended up with both rock and ices in their cores as well as substantial amounts of ammonia and water throughout their interiors and atmospheres (see Section 14-1 and Section 14-6).

As Jupiter coalesced, the gas accumulating around it formed a rotating "Jovian nebula." The central part of this nebula became the huge envelope of hydrogen and helium that makes up most of Jupiter's bulk. But in the outer parts of this nebula, dust grains could have accreted to form small solid bodies. These grew to become the Galilean satellites.

Although the "Jovian nebula" was far from the protosun, not all of it was cold. Jupiter, like the protosun, must have emitted substantial amounts of radiation due to Kelvin-Helmholtz contraction, which we discussed in Section 8-3. (We saw in Section 12-4 that even today, Jupiter emits more energy due to its internal heat than it absorbs from sunlight.) Hence, temperatures very close to Jupiter must have been substantially higher than at locations farther from the planet. Calculations show that only rocky material would condense at the orbital distances of Io and Europa, but frozen water could be retained and incorporated into satellites at the distances of Ganymede and Callisto. In this way Jupiter ended up with two distinct classes of Galilean satellites (Figure 13-3).

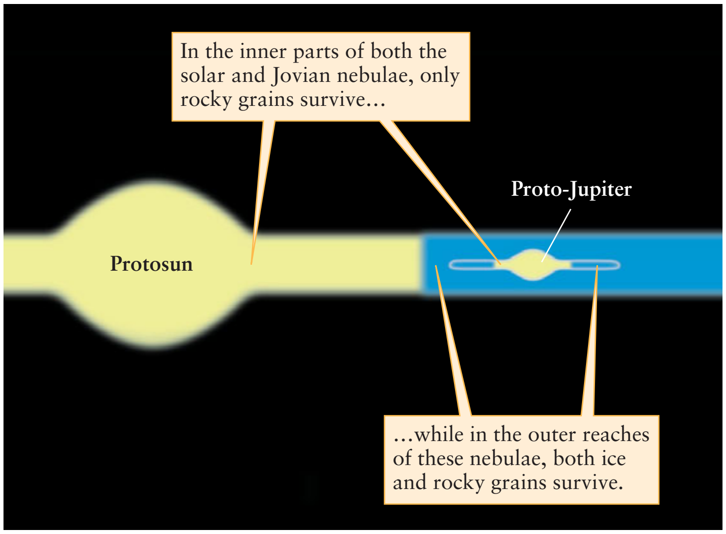


Figure 13-3

Formation of the Galilean Satellites Heat from the protosun made it impossible for icy grains to survive within the innermost 2.5 to 4 AU of the solar nebula. In the same way, Jupiter's heat evaporated any icy grains that were too close to the center of the "Jovian nebula." Hence, the two inner Galilean satellites were formed primarily from rock, while the outer two incorporated both rock and ice.

The analogy between the solar nebula and the "Jovian nebula" is not exact. Unlike the Sun, Jupiter is a "failed star." Its internal temperatures and pressures never became high enough to ignite nuclear reactions that convert hydrogen into helium. (Jupiter's mass would have had to be about 80 times larger for these reactions to have begun.) Furthermore, the icy worlds that formed in the outer region of the "Jovian nebula"—namely, Ganymede and Callisto—were of relatively small mass. Hence, they were unable to attract gas from the nebula and become Jovian planets in their own right. Nonetheless, it is remarkable how the main processes of "planet" formation seem to have occurred twice in our solar system: once in the solar nebula around the Sun, and once in microcosm in the gas cloud around Jupiter.

The diverse densities of the Galilean satellites suggest that these four worlds may be equally diverse in their geology. This turns out to be entirely correct. Because each of the Galilean satellites is unique, we devote the next several sections to each satellite in turn.

13-4 Io is covered with colorful sulfur compounds ejected from active volcanoes

WEB LINK 13.4

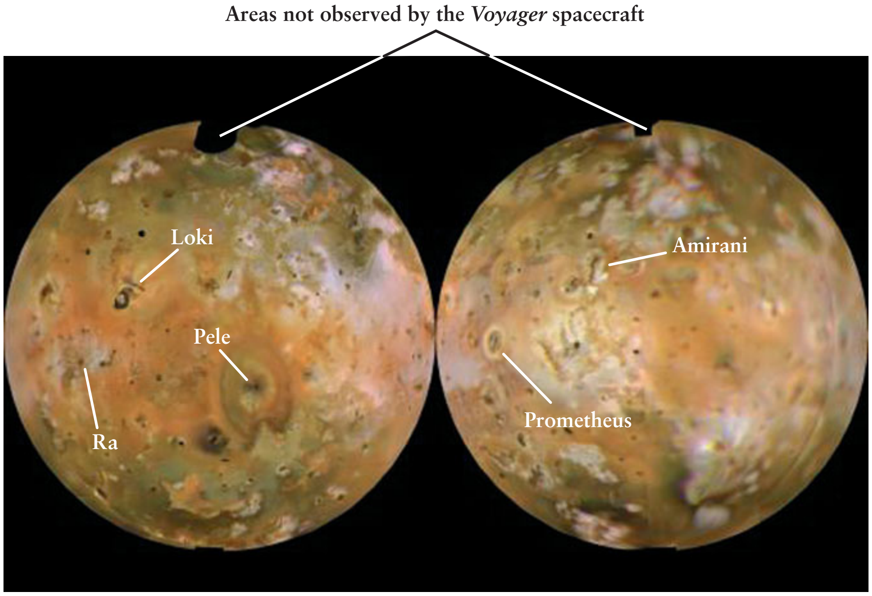
Before the two *Voyager* spacecraft flew past Jupiter, the nature of Io was largely unknown. On the basis of Io's size and density, however, it was expected that Io would be a world much like our own Moon—geologically dead, with little internal heat available to power tectonic or volcanic activity (see Section 7-6). Hence, it was thought that Io's surface would be extensively cratered, because there would have been little geologic activity to erase those craters over the satellite's history.

Io proved to be utterly different from these naive predictions. On March 5, 1979, *Voyager 1* came within 21,000 kilometers (13,000 miles) of Io and began sending back a series of bizarre and unexpected pictures of the satellite (Figure 13-4). These images showed that Io has *no* impact craters at all! Instead, the surface is pockmarked by irregularly shaped pits and is blotched with color.

The scientists were seeing confirmation of a prediction published in the journal *Science* just three days before *Voyager 1* flew past Io. In this article, Stanton Peale of the University of California, Santa Barbara, and Patrick Cassen and Ray Reynolds of NASA's Ames Research Center reported their conclusion that Io's interior must be kept hot by Jupiter's tidal forces, and that this should lead to intense volcanic activity.

Tidal Heating on Io

As we saw in Section 4-8, tidal forces are differences in the gravitational pull on different parts of a planet or satellite. These forces tend to deform the shape of the planet or satellite (see Figure 4-25). Io, for example, is somewhat distorted from a spherical shape by tidal forces from Jupiter. If Io were in a perfectly circular orbit so that it traveled around Jupiter at a steady speed, Io's rotation would always be in lockstep with its orbital motion. In this case, Io would be in perfect synchronous rotation, with its long axis always pointed directly toward Jupiter. But as Io moves



VIDEO 13.1

Figure 13-4 R I V U X G

Io These mosaics of Io's two hemispheres were built up from individual *Voyager* images. The extraordinary colors are probably caused by deposits of sulfur and sulfur compounds ejected from Io's numerous volcanoes. The labels show several of these volcanoes, which are named for sun gods and fire gods of different cultures. (NASA/JPL)

around its orbit, Europa and Ganymede exert gravitational tugs on it in a regular, rhythmic fashion, thanks to the 1:2:4 ratio among the orbital periods of these three satellites. These tugs distort Io's orbit into an ellipse, and so its speed varies as it moves around its orbit. Consequently, Io's long axis "nods" back and forth by about ½° as seen from Jupiter. Due to this "nodding," the tidal stresses that Jupiter exerts on Io vary rhythmically as Io moves around its orbit. These varying tidal stresses alternately squeeze and flex Io. Just as a ball of clay or bread dough gets warm as you knead it between your fingers, this squeezing and flexing causes **tidal heating** of Io's interior. (The Earth's Moon also "nods" as it orbits our planet, but experiences almost no tidal heating because the Earth's tidal forces are very weak compared to those of massive Jupiter.)

The theory of tidal forces helped predict Io's volcanic nature

Tidal heating adds energy to Io at a rate of about 10^{14} watts, equivalent to 24 tons of TNT exploding every second. As this energy makes its way to the satellite's surface, it provides about 2.5 watts of power to each square meter of Io's surface. By comparison, the average global heat flow through the Earth's crust is 0.06 watts per square meter. Only in volcanically active areas on Earth do we find heat flows that even come close to Io's average. Thus, Peale, Cassen, and Reynolds predicted "widespread and recurrent surface volcanism" on Io.

Io's Active Volcanoes

No one expected that *Voyager 1* would obtain images of erupting volcanoes on Io. After all, a spacecraft making a single trip past the Earth would be highly unlikely to catch a large volcano actually erupting. But, in fact, *Voyager 1* images of Io revealed *eight* different giant plumes of gas from volcanic eruptions. (Figure 13-5*a* shows two of these.) More recently, the *Galileo* spacecraft, which came as close as 200 km to Io's surface during its eight years in orbit around Jupiter, returned detailed images of several such plumes (Figure 13-5*b*). These observations resoundingly confirm the Peale-Cassen-Reynolds prediction: Io is by far the most volcanic world in the solar system.

Io's volcanic plumes rise to astonishing heights of 70 to 280 km above Io's surface. To reach such altitudes, the material must emerge from volcanic vents with speeds between 300 and 1000 m/s (1100 to 3600 km/h, or 700 to 2200 mi/h). Even the most violent terrestrial volcanoes have eruption speeds of only around 100 m/s (360 km/h, or 220 mi/h). Scientists thus began to suspect that Io's volcanic activity must be fundamentally different from volcanism here on Earth.

The Nature of Io's Volcanic Eruptions

An important clue about volcanism on Io came from the infrared spectrometers aboard *Voyager 1,* which detected abundant sulfur and sulfur dioxide in Io's volcanic plumes. This led to the idea that the plumes are actually more like geysers than volcanic eruptions. In a geyser on Earth, water seeps down to volcanically heated rocks, where it changes to steam and erupts explosively through a vent. Planetary geologists Susan Kieffer, Eugene Shoemaker, and Bradford Smith suggested that sulfur dioxide rather than water could be the principal propulsive agent driving volcanic plumes on Io. Sulfur dioxide is a solid at the frigid temperatures found on most of Io's surface, but it should be molten at depths of only a few kilometers. Just as the explosive conversion of water into steam produces a geyser on the Earth, the conversion of liquid sulfur dioxide into a high-pressure gas could result in eruption velocities of up to 1000 m/s.

VIDEO 13.2

Io's dramatic coloration (see Figure 13-4) is probably due to sulfur and sulfur dioxide, which are ejected in volcanic plumes and later fall back to the surface. Sulfur is normally bright yellow, which explains the dominant color of Io's surface. But if sulfur is heated and suddenly cooled, as would happen if it were ejected from a volcanic vent and allowed to fall to the surface, it can assume a range of colors from orange