When temperatures are measured in kelvins, the average thermal energy of particles is proportional to the measured temperature. The average thermal energy of the atoms in an object with a temperature of 200 K is twice the average thermal energy of the atoms in an object with a temperature of 100 K.

Temperature, Luminosity, and Color

We have seen the way discrete atoms emit and absorb radiation, which leads to a useful understanding of emission lines and absorption lines that tell us about the physical state and motion of distant objects. But not all objects have spectra that are dominated by discrete spectral lines. As you saw in Figure 5.13a, if you pass the light from a lightbulb through a prism, instead of discrete bright and dark bands you will see light spread out smoothly from the blue end of the spectrum to the red. Similarly, if you look closely at the spectrum of the Sun, you will see absorption lines, but mostly you will see light smoothly spread out across all colors of the spectrum—a type of spectrum called a **continuous spectrum**.

We can think of a dense material as being composed of a collection of charged particles that are being jostled as their thermal motions cause them to run into their neighbors. The hotter the material is, the more violently its particles are being jostled. Recall that any time a charged particle is subjected to an acceleration, it radiates. So the jostling of particles due to their thermal motions causes them to give off a continuous spectrum of electromagnetic radiation. This is why any material that is sufficiently dense for its atoms to be jostled by their neighbors emits light simply because of its temperature. Radiation of this sort is called **thermal radiation**.

The radiation from an object changes as the object heats up or cools down. **Luminosity** is the amount of light *leaving* a source; that is, the total amount of light emitted (energy per second, measured in watts, W). The hotter the object, the more energetically the charged particles within it move, and the more energy they emit in the form of electromagnetic radiation. So as an object gets hotter, the light that it emits becomes more intense. Here is our first point about thermal radiation: *an object is more luminous when it is hotter.*

Now let's move to the question of what color light an object emits. As the object gets hotter, the thermal motions of its particles become more energetic, which produce more energetic photons. The average energy of the photons that it emits increases, the average wavelength of the emitted photons gets shorter, and the light from the object gets bluer. Here is our second point about thermal radiation: *hotter objects are bluer.* If you heat a piece of metal, the metal will glow—first a dull red, then orange, then yellow. The hotter the metal becomes, the more the highly energetic blue photons become mixed with the less energetic red photons, and the color of the light shifts from red toward blue. The light becomes more intense and bluer as the metal becomes hotter.

Blackbodies are objects that emit electromagnetic radiation only because of their temperature, not their composition. Blackbodies emit just as much thermal radiation as they absorb from their surroundings. Physicist Max Planck (1858–1947) graphed the intensity of the emitted radiation across all wavelengths and obtained the characteristic curves that we now call **Planck spectra** or **blackbody spectra**. **Figure 5.22** shows blackbody spectra for objects at several different temperatures.

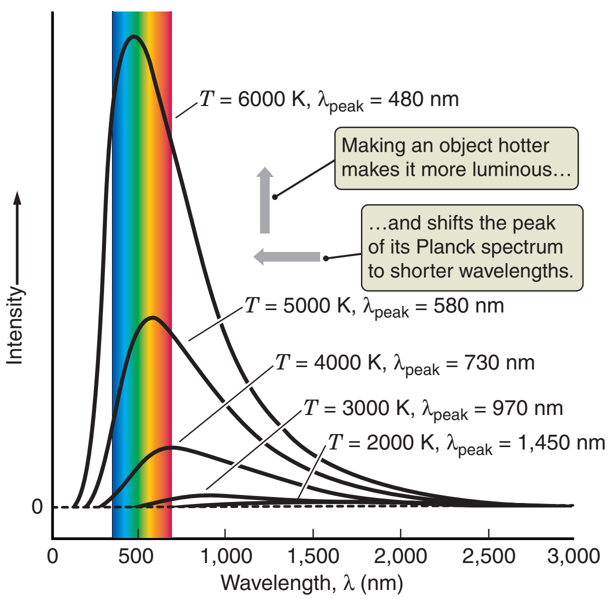


Figure 5.22 This illustration shows blackbody spectra emitted by sources with temperatures of 2000 K, 3000 K, 4000 K, 5000 K, and 6000 K. At higher temperatures, the peak of the spectrum shifts toward shorter wavelengths, and the amount of energy radiated per second from each square meter of the source increases.

Blackbody Laws

In the real world, the light from stars such as the Sun and the thermal radiation from a planet often come close to having blackbody spectra. So these objects follow two blackbody laws that relate luminosity with temperature and temperature with color, respectively.

Stefan-Boltzmann Law As the temperature of an object increases, the object gives off more radiation at every wavelength, so the luminosity of the object should increase. Adding up all of the energy in a blackbody spectrum shows that the increase in luminosity is proportional to the fourth power of the temperature: Luminosity $\propto T^4$, known as the **Stefan-Boltzmann law**. This law was discovered in the laboratory by physicist Josef Stefan (1835–1893) and derived mathematically by his student Ludwig Boltzmann (1844–1906).

It is difficult to measure all of the photons emitted by Earth or the Sun in all possible directions, but it is easier to measure the *flux*. The amount of energy radiated by each square meter of the surface of an object each second is called the **flux**, abbreviated $\mathcal{F}$. The flux is proportional to the luminosity. You can find the luminosity by multiplying the flux by the total surface area. The Stefan-Boltzmann law says that the flux is given by the following equation: $\mathcal{F} = \sigma T^4$. The constant σ (the Greek letter sigma), which is called the **Stefan-Boltzmann constant**, equals 5.67×10^{-8} W/(m^2 K^4), where 1 watt = 1 joule per second (J/s).

The Stefan-Boltzmann law says that an object rapidly becomes more luminous as its temperature increases. If the temperature of an object doubles, the amount of energy being radiated each second increases by a factor of 2^4, or 16. If the temperature of an object goes up by a factor of 3, then the energy being radiated by the object each second goes up by a factor of 3^4, or 81. A lightbulb with a filament temperature of 3000 K radiates 16 times as much light as it would if the filament temperature were 1500 K. Even modest changes in temperature can result in large changes in the amount of luminosity radiated by an object.

Astronomy in Action: Wien's Law

Wien's Law Look again at Figure 5.22. The wavelength where the blackbody spectrum is at its peak, λ_{peak}, is where the electromagnetic radiation from an object is greatest. As the temperature, T, increases, the peak of the spectrum shifts toward shorter wavelengths. For example, compare the peak wavelengths of a 3000 K object and a 6000 K object. Photon energy and wavelength are inversely related; thus, as the peak wavelength becomes shorter, the average photon energy becomes greater. The object becomes bluer. The physicist Wilhelm Wien (1864–1928) found that the peak wavelength in the spectrum is inversely proportional to the temperature of the object. **Wien's law** states that if you double the temperature, the peak wavelength becomes half of what it was. If you increase the temperature by a factor of 3, the peak wavelength becomes a third of what it was. Stefan-Boltzmann's law and Wien's law are further explored in **Working It Out 5.3**. We will return to these laws later in the chapter when we use them to estimate the temperatures of the planets.

Nebraska Simulation: Blackbody Curves

CHECK YOUR UNDERSTANDING 5.5

When you look at the sky on a dark night and see stars of different colors, which are the hottest? (a) orange; (b) red-orange; (c) yellow; (d); red; (e) blue

5.3 Working It Out Working with the Stefan-Boltzmann Law and Wien's Law

Stefan-Boltzmann's law can be used to estimate the flux and luminosity of Earth. Earth's average temperature is 288 K, so the flux from its surface is

$$\mathcal{F} = \sigma T^4$$

$$\mathcal{F} = (5.67 \times 10^{-8}\ \mathrm{W/m^2\,K^4}) \times (288\ \mathrm{K})^4$$

$$\mathcal{F} = 390\ \mathrm{W/m^2}$$

The luminosity is the flux multiplied by the surface area (A) of Earth. Surface area is given by $4\pi R^2$, and the radius of Earth is 6,378 km, or 6.378×10^6 meters. So the luminosity is

$$L = \mathcal{F} \times A = \mathcal{F} \times 4\pi R^2$$

$$L = (390\ \mathrm{W/m^2}) \times [4\pi(6.378 \times 10^6\ \mathrm{m})^2]$$

$$L \approx 2 \times 10^{17}\ \mathrm{W}$$

Earth emits the equivalent of the energy used by 2,000,000,000,000,000 (2 million billion) hundred-watt lightbulbs. This is still not anywhere close to the amount emitted by the Sun.

Wien's law also proves useful to astronomers. If they measure the spectrum of an object emitting thermal radiation and find where the peak in the spectrum is, Wien's law can be used to calculate the temperature of the object. Wien's law can be written as

$$T = \frac{2{,}900{,}000\ \mathrm{nm\,K}}{\lambda_{\mathrm{peak}}}$$

For example, the spectrum of the light coming from the Sun peaks at a wavelength of $\lambda_{\mathrm{peak}} = 500$ nm, so

$$T = \frac{2{,}900{,}000\ \mathrm{nm\,K}}{500\ \mathrm{nm}} = 5800\ \mathrm{K}$$

This is how you can know the surface temperature of the Sun.

Suppose you want to calculate the peak wavelength at which Earth radiates. Using Earth's average temperature of 288 K in Wien's law gives

$$\lambda_{\mathrm{peak}} = \frac{2{,}900{,}000\ \mathrm{nm\,K}}{288\ \mathrm{K}} = 10{,}100\ \mathrm{nm} = 10.1\ \mathrm{microns}$$

Earth's radiation peaks in the infrared region of the spectrum.

5.5 The Brightness of Light Depends on the Luminosity and Distance of the Source

Recall that luminosity refers to the amount of light leaving a source. By contrast, the **brightness** of electromagnetic radiation is the amount of light that is arriving at a particular location. Therefore, brightness depends on the luminosity and the distance of the light source. For example, replacing a 50-W lightbulb with a 100-W bulb makes a room twice as bright because it doubles the light reaching any point in the room. But brightness also depends on the distance from a source of electromagnetic radiation. If you needed more light to read this book, you could replace the bulb in your lamp with a more luminous bulb or you can move the book closer to the light. Conversely, if a light is too bright, you can move away from it. Our everyday experience teaches us that as we move away from a light, its brightness decreases.

The particle description of light provides another way to think about the brightness of radiation and how brightness depends on distance. Suppose you had a piece of cardboard that measured 1 meter by 1 meter. To make the light falling on the cardboard twice as bright, you would need to double the number of photons that hit the cardboard each second. Tripling the brightness of the light would mean increasing the number of photons hitting the cardboard each second by a factor of 3, and so on. Brightness depends on the number of photons falling on each square meter of a surface each second.

Now imagine a lightbulb sitting at the center of a spherical shell, illustrated in **Figure 5.23**. Photons from the bulb travel in all directions and land on the inside of the shell. To find the number of photons landing on each square meter of the shell during each second, that is, to determine the brightness of the light, take the *total* number of photons given off by the lightbulb each second and divide by the number of square meters over which those photons have to be spread. The surface area of a sphere is given by the formula $A = 4\pi r^2$, where r is the distance between the bulb and the surface of the sphere (that is, r = the radius of the sphere). The number of photons striking one square meter each second is equal to the total number of photons emitted each second divided by the surface area $4\pi r^2$.

Now change the size of the spherical shell while keeping the total number of photons given off by the lightbulb each second the same. As the shell becomes larger, the photons from the lightbulb must spread out to cover a larger surface area. Each square meter of the shell receives fewer photons each second, so the brightness of the light decreases. If the shell's surface is moved twice as far from the light, the area over which the light must spread increases by a factor of $2^2 = 2 \times 2 = 4$. The photons from the bulb spread out over 4 times as much area, so the number of photons falling on each square meter each second becomes $\frac{1}{4}$ of what it was. If the surface of the sphere is 3 times as far from the light, the area over which the light must spread increases by a factor of $3^2 = 3 \times 3 = 9$, and the number of photons per second falling on each square meter becomes $\frac{1}{9}$ of what it was originally. This is the same kind of inverse square relationship you saw for gravity in Chapter 4. The brightness of the light from an object is inversely proportional to the square of the distance from the object. Twice as far means one-fourth as bright.

This idea of photons streaming and spreading onto a surface from a light explains why brightness follows an inverse square law. In practice, however, it is usually more convenient to talk about the *energy* coming to a surface each second, rather than the number of photons arriving.

The luminosity of an object is the total number of photons given off by the object multiplied by the energy of each photon. So instead of thinking about how the number of photons must spread out to cover the surface of a sphere, we can think about how the energy carried by the photons must spread out to cover the surface of a sphere. The brightness of the light is the amount of energy falling on a square meter in a second, and it equals the luminosity L divided by the area of the sphere, which depends on the radius squared. This tells us, for example, that the brightness of the Sun will depend on the inverse square of the planet's distance from the Sun. This will factor in as we estimate the equilibrium temperatures of the planets in **Working It Out 5.4**.

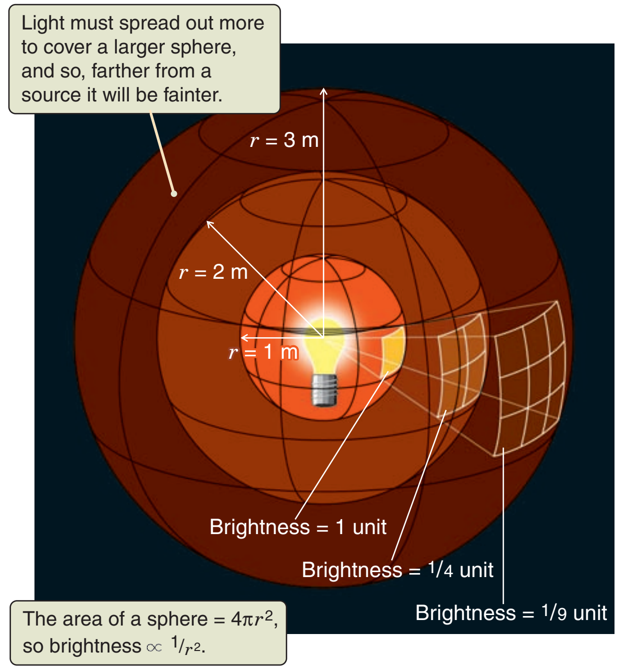


Figure 5.23 Light obeys an inverse square law as it spreads away from a source. Twice as far means one-fourth as bright.

Astronomy in Action: Inverse Square Law

CHECK YOUR UNDERSTANDING 5.6

The average distance of Mars from the Sun is 1.4 AU. How bright is the Sun on Mars compared with its brightness on Earth? (a) 1.4 times brighter; (b) about 2 times brighter; (c) about 2 times fainter; (d) 1.4 times fainter

5.4 Working It Out Using Radiation Laws to Calculate Equilibrium Temperatures of Planets

The temperature of a planet is determined by a balance between the amount of sunlight being absorbed and the amount of energy being radiated back into space. We begin with the amount of sunlight being absorbed. When viewed from the Sun, a planet looks like a circular disk with a radius equal to the radius of the planet, R_{planet}. The area of the planet that is lit by the Sun is

$$\text{Absorbing area of planet} = \pi R^2_{\text{planet}}$$

The amount of energy striking a planet also depends on the brightness of sunlight at the distance at which the planet orbits. The brightness of sunlight at a distance d from the Sun is equal to the luminosity of the Sun (L_{Sun}, in watts) divided by $4\pi d^2$ (we use d here to avoid confusion with the planet's radius, R_{planet}):

$$\text{Brightness of sunlight} = \frac{L_{\text{Sun}}}{4\pi d^2}$$

A planet does not absorb all the sunlight that falls on it. **Albedo**, a, is the fraction of the sunlight that reflects from a planet. The corresponding fraction of the sunlight that is absorbed by the planet is 1 minus the albedo. A planet covered entirely in snow would have a high albedo (close to 1), while a planet covered entirely by black rocks would have a low albedo, close to 0:

$$\text{Fraction of sunlight absorbed} = 1 - a$$

We can now calculate the energy absorbed by the planet each second. Writing this relationship as an equation, we say that

$$\begin{pmatrix}\text{Energy absorbed}\\ \text{by the planet}\\ \text{each second}\end{pmatrix} = \begin{pmatrix}\text{Absorbing}\\ \text{area of}\\ \text{the planet}\end{pmatrix} \times \begin{pmatrix}\text{Brightness}\\ \text{of sunlight}\end{pmatrix} \times \begin{pmatrix}\text{Fraction}\\ \text{of sunlight}\\ \text{absorbed}\end{pmatrix}$$

$$= \pi R^2_{\text{planet}} \times \frac{L_{\text{Sun}}}{4\pi d^2} \times (1 - a)$$

Now let's turn to the other piece of the equilibrium: the amount of energy that the planet radiates away into space each second. We can calculate this amount by multiplying the number of square meters of the planet's total surface area by the energy radiated by each square meter each second. The surface area for the planet is given by $4\pi R^2_{\text{planet}}$. The Stefan-Boltzmann law tells us that the energy radiated by each square meter each second is given by σT^4. So we can say that

$$\begin{pmatrix}\text{Energy radiated}\\ \text{by the planet}\\ \text{each second}\end{pmatrix} = \begin{pmatrix}\text{Surface}\\ \text{area of}\\ \text{the planet}\end{pmatrix} \times \begin{pmatrix}\text{Energy radiated}\\ \text{per square meter}\\ \text{per second}\end{pmatrix}$$

$$= 4\pi R^2_{\text{planet}} \times \sigma T^4$$

If the planet's temperature is to remain stable—not heating up or cooling down—then each second the "Energy radiated" must be equal to "Energy absorbed." When we set these two quantities equal to each other, we arrive at the expression

$$\begin{pmatrix}\text{Energy radiated}\\ \text{by the planet}\\ \text{each second}\end{pmatrix} = \begin{pmatrix}\text{Energy absorbed}\\ \text{by the planet}\\ \text{each second}\end{pmatrix}$$

or

$$4\pi R^2_{\text{planet}}\sigma T^4 = \pi R^2_{\text{planet}}\frac{L_{\text{Sun}}}{4\pi d^2}(1 - a)$$

Canceling out πR^2_{planet} on both sides, and rearranging this equation to put T on one side and everything else on the other gives

$$T^4 = \frac{L_{\text{Sun}}(1 - a)}{16\sigma\pi d^2}$$

If we take the fourth root of each side, we get

$$T = \left(\frac{L_{\text{Sun}}(1 - a)}{16\sigma\pi d^2}\right)^{1/4}$$

Putting in the appropriate numbers for the known luminosity of the Sun, L_{Sun}, and the constants π and σ yields this simpler equation:

$$T = 279\ \text{K} \times \left(\frac{1 - a}{d^2_{\text{AU}}}\right)^{1/4}$$

where d_{AU} is the distance of the planet from the Sun in astronomical units.

To use this equation, we would need to know a planet's distance from the Sun and its average albedo. For a blackbody ($a = 0$) at 1 AU from the Sun, the temperature is 279 K. For Earth, with an albedo of 0.3 and a distance from the Sun of 1 AU, the temperature is

$$T = 279\ \text{K} \times \left(\frac{1 - 0.3}{1^2}\right)^{1/4} = 255\ \text{K}$$

(Calculator hint: To take a fourth root, you can take the square root twice, or use the x^y button with $y = 0.25$).

Earth is cooler than a blackbody at 1 AU from the Sun because its average albedo is greater than zero. If Earth's albedo changed or the Sun's luminosity changed, that would affect the result. When we examine planets around other stars, we will need to use the luminosity of the particular star in the equation, instead of the Sun's luminosity, so the temperature at 1 AU will be different than what is it for Earth.

Origins

Temperatures of Planets

In the previous chapters, we discussed how a planet's axial tilt and its orbital shape can affect its temperature, and thus its prospects for life. Now let's get more specific about the temperatures of planets, using what you learned in this chapter about thermal radiation. For a planet at an equilibrium temperature, the energy radiated by a planet exactly balances the energy absorbed by the planet. If the planet is hotter than this equilibrium temperature, it will radiate energy faster than it absorbs sunlight, and its temperature will fall. If the planet is cooler than this temperature, it will radiate energy slower than it absorbs sunlight, and its temperature will rise.

Planets at different distances from the Sun will have different temperatures, and the temperature should be inversely proportional to the square root of the distance, as you saw in Working It Out 5.4. **Figure 5.24** plots the actual and predicted temperatures of nine solar system objects. Each vertical orange bar shows the range of temperatures found on the surface of the planet or, in the case of the giant planets, at the top of the planet's clouds. The black dots show the predictions made using the equation in Working It Out 5.4. For most planets, the predictions are not too far off; indicating that our basic understanding of *why* planets have the temperatures they have is probably pretty good. The data for Mercury, Mars, and Pluto agree particularly well.

In some cases, however, the predictions are wrong. For Earth, the actual measured temperature is a bit higher than the predicted temperature, and for Venus the actual surface temperature is much higher than the prediction.

The predicted values assume that the temperature of the planet is the same everywhere. However, planets are likely to be hotter on the day side than on the night side. The predictions also assume that a planet's only source of energy is sunlight, and that the fraction of sunlight reflected is constant over the surface of each planet. There is also the assumption that the planets absorb and radiate energy into space as blackbodies.

The discrepancies between the calculated and the measured temperatures of some of the planets indicate that for these planets, some or all of these assumptions are incorrect. For example, the planet may have its own source of energy besides sunlight, or it may have an atmosphere. Understanding the temperatures of planets makes it possible to hypothesize why life may have evolved here on Earth, instead of on a different planet in the Solar System.

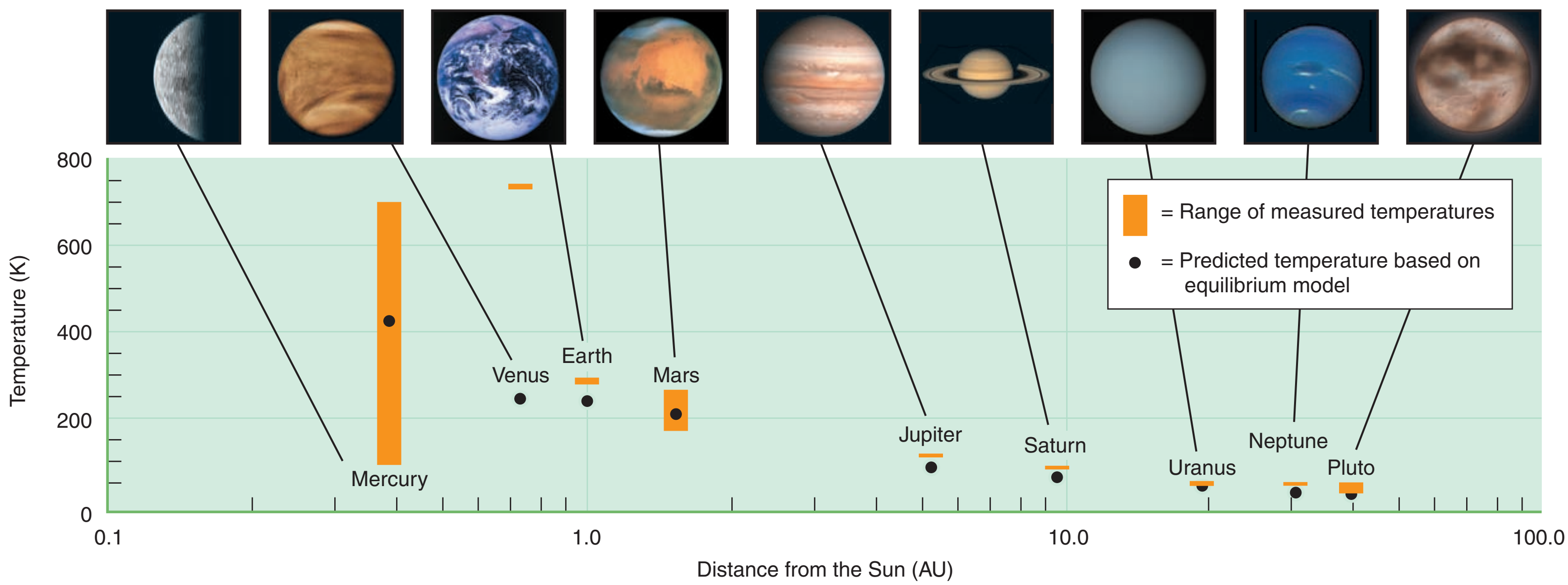


Figure 5.24 Predicted temperatures for the planets and dwarf planet Pluto are based on the equilibrium between absorbed sunlight and thermal radiation into space. These temperatures are compared with ranges of observed surface temperatures.

ARTICLES QUESTIONS

This press release from the European Southern Observatory (ESO) in Chile was widely reprinted in news sites around the world.

A Study in Scarlet

ESO

This new image from ESO's La Silla Observatory in Chile reveals a cloud of hydrogen called Gum 41 (**Figure 5.25**). In the middle of this little-known nebula, brilliant hot young stars are giving off energetic radiation that causes the surrounding hydrogen to glow with a characteristic red hue.

Figure 5.25 The Gum 41 Nebula.

This area of the southern sky, in the constellation of Centaurus (The Centaur), is home to many bright nebulae, each associated with hot newborn stars that formed out of the clouds of hydrogen gas. The intense radiation from the stellar newborns excites the remaining hydrogen around them, making the gas glow in the distinctive shade of red typical of star-forming regions. Another famous example of this phenomenon is the Lagoon Nebula, a vast cloud that glows in similar bright shades of scarlet.

The nebula in this picture is located some 7,300 light-years from Earth. Australian astronomer Colin Gum discovered it on photographs taken at the Mount Stromlo Observatory near Canberra, and included it in his catalog of 84 emission nebulae, published in 1955. Gum 41 is actually one small part of a bigger structure called the Lambda Centauri Nebula, also known by the more exotic name of the Running Chicken Nebula. Gum died at a tragically early age in a skiing accident in Switzerland in 1960.

In this picture of Gum 41, the clouds appear to be quite thick and bright, but this is actually misleading. If a hypothetical human space traveler could pass through this nebula, it is likely that they would not notice it as—even at close quarters—it would be too faint for the human eye to see. This helps to explain why this large object had to wait until the mid-twentieth century to be discovered—its light is spread very thinly and the red glow cannot be well seen visually.

This new portrait of Gum 41—likely one of the best so far of this elusive object—has been created using data from the Wide Field Imager (WFI) on the MPG/ESO 2.2-meter telescope at the La Silla Observatory in Chile. It is a combination of images taken through blue, green, and red filters, along with an image using a special filter designed to pick out the red glow from hydrogen.

ARTICLES QUESTIONS

1. How long has it taken the light from this nebula to reach us?
2. Why are the young stars blue?
3. What type of spectra would you expect to get from the stars and from the gas?
4. Refer to the spectrum of hydrogen in Figure 5.15. Why is the excited hydrogen gas in the image of Gum 41 glowing red?
5. Would you be able to see Gum 41 from your location? Why or why not?

Summary

Light carries both information and energy throughout the universe. The speed of light in a vacuum is 300,000 km/s; nothing can travel faster. Visible light is only a tiny portion of the entire electromagnetic spectrum. Atoms absorb and emit radiation at unique wavelengths like spectral fingerprints. A planet's temperature depends on its distance from its star, its albedo, and the luminosity of its star.

LG 1 **Describe the wave and particle properties of light, and describe the electromagnetic spectrum.** Light is both a particle and a wave. Light is simultaneously a stream of particles called photons and an electromagnetic wave. Different types of electromagnetic radiation, from gamma rays to visible light to radio waves, are electromagnetic waves that differ in frequency and wavelength.

LG 2 **Describe how to measure the composition of distant objects using the unique spectral lines of different types of atoms.** Nearly all matter is composed of atoms, and light can reveal the identity of the types of atoms that are present in matter. Each type of atom has a different spacing of its electron energy levels, and the emission of photons is related to the electron changing levels. As a result, we can identify different chemical elements and molecules in distant objects.

LG 3 **Describe the Doppler effect and how it can be used to measure the motion of distant objects.** Because of the Doppler effect, light from receding objects is redshifted to longer wavelengths, and light from approaching objects is blueshifted to shorter wavelengths. The wavelength shifts of the spectral lines indicate how fast an astronomical object is moving toward or away from Earth.

LG 4 **Explain how the spectrum of light that an object emits depends on its temperature.** Temperature is a measure of how energetically particles are moving in an object. A light source that emits electromagnetic radiation because of its temperature is called a blackbody. A blackbody emits a continuous spectrum. The total amount of energy emitted is proportional to the temperature to the fourth power, and the peak wavelength, which determines its color, is inversely proportional to the temperature.

LG 5 **Differentiate luminosity from brightness, and illustrate how distance affects each.** The light output, or luminosity, of an object is the amount of light the object emits. The brightness of an object is proportional to its luminosity divided by its distance squared. Thus, the brightness of the Sun is different when measured from each Solar System planet but the luminosity is the same.

? UNANSWERED QUESTIONS

- Has the speed of light always been 300,000 km/s? Some theoretical physicists have questioned whether light traveled much faster earlier in the history of our universe. The observational evidence that may test this idea comes from studying the spectra of the most distant objects—whose light has been traveling for billions of years—and determining whether billions of years ago chemical elements absorbed light somewhat differently than they do today. So far, there is no evidence that the speed of light changes.
- Will it ever be possible to travel faster than the speed of light? Our current understanding of the science says no. A staple of science fiction films and stories is spaceships that go into "warp speed" or "hyperdrive"—moving faster than light—to traverse the huge distances of space (and visit a different planetary system every week). If this premise is simply fictional and the speed of light is a true universal limit, then travel between the stars will take many years. Because all electromagnetic radiation travels at the speed of light, even an electromagnetic signal sent to another planetary system would take many years to get there. Interstellar visits (and interstellar conversations) will be quite prolonged.

Questions and Problems

Test Your Understanding

1. If the Sun instantaneously stopped giving off light, what would happen on Earth?
   a. Earth would immediately get dark.
   b. Earth would get dark 8 minutes later.
   c. Earth would get dark 27 minutes later.
   d. Earth would get dark 1 hour later.
2. Why is an iron atom a different element from a sodium atom?
   a. A sodium atom has fewer neutrons in its nucleus than an iron atom has.
   b. An iron atom has more protons in its nucleus than a sodium atom has.
   c. A sodium atom is bigger than an iron atom.
   d. A sodium atom has more electrons.

3. Suppose an atom has three energy levels, specified in arbitrary units as 10, 7, and 5. In these units, which of the following energies might an emitted photon have? (Select all that apply.)
   a. 3
   b. 2
   c. 5
   d. 4

4. When a boat moves through the water, the waves in front of the boat bunch up, while the waves behind the boat spread out. This is an example of
   a. the Bohr model.
   b. the wave nature of light.
   c. emission and absorption.
   d. the Doppler effect.

5. As a blackbody becomes hotter, it also becomes ________ and ________ .
   a. more luminous; redder
   b. more luminous; bluer
   c. less luminous; redder
   d. less luminous; bluer

6. Which of the following factors does *not* directly influence the temperature of a planet?
   a. the luminosity of the Sun
   b. the distance from the planet to the Sun
   c. the albedo of the planet
   d. the size of the planet

7. Two stars are of equal luminosity. Star A is 3 times as far from you as star B. Star A appears ________ star B.
   a. 9 times brighter than
   b. 3 times brighter than
   c. the same brightness as
   d. $\frac{1}{3}$ as bright as
   e. $\frac{1}{9}$ as bright as

8. When less energy radiates from a planet, its ________ increases until a new ________ is achieved.
   a. temperature; equilibrium
   b. size; temperature
   c. equilibrium; size
   d. temperature; size

9. How does the speed of light in a medium compare to the speed in a vacuum?
   a. The speed is the same in both a medium and a vacuum, as the speed of light is a constant.
   b. The speed in the medium is always faster than the speed in a vacuum.
   c. The speed in the medium is always slower than the speed in a vacuum.
   d. The speed in the medium may be faster or slower, depending on the medium.

10. When an electron moves from a higher energy level in an atom to a lower energy level,
    a. a continuous spectrum is emitted.
    b. a photon is emitted.
    c. a photon is absorbed.
    d. a redshifted spectrum is emitted.

11. In Figure 5.15, the red photons come from the transition from E_3 to E_2. These photons will have the ________ wavelengths because they have the ________ energy compared to the other photons.
    a. shortest; least
    b. shortest; most
    c. longest; least
    d. longest; most

12. Star A and star B appear equally bright in the sky. Star A is twice as far away from Earth as star B. How do the luminosities of stars A and B compare?
    a. Star A is 4 times as luminous as star B.
    b. Star A is 2 times as luminous as star B.
    c. Star B is 2 times as luminous as star A.
    d. Star B is 4 times as luminous as star A.

13. What is the surface temperature of a star that has a peak wavelength of 290 nm?
    a. 1000 K
    b. 2000 K
    c. 5000 K
    d. 10,000 K
    e. 100,000 K

14. If a planet is in thermal equilibrium,
    a. no energy is leaving the planet.
    b. no energy is arriving on the planet.
    c. the amount of energy leaving equals the amount of energy arriving.
    d. the temperature is very low.

15. The temperature of an object has a very specific meaning as it relates to the object's atoms. A high temperature means that the atoms
    a. are very large.
    b. are moving very fast.
    c. are all moving together.
    d. have a lot of energy.

Thinking about the Concepts

16. We know that the speed of light in a vacuum is 3×10^5 km/s. Is it possible for light to travel at a lower speed? Explain your answer.

17. Is light a wave or a particle or both? Explain your answer.

18. Referring to the Process of Science Figure, if any of these experiments had *not* agreed with the others, what would that mean for the conclusion that light has a finite, constant speed?

19. If photons of blue light have more energy than photons of red light, how can a beam of red light carry as much energy as a beam of blue light?

20. Patterns of emission or absorption lines in spectra can uniquely identify individual atomic elements. Explain how positive identification of atomic elements can be used as one way of testing the validity of the cosmological principle discussed in Chapter 1.

21. An atom in an excited state can drop to a lower energy state by emitting a photon. Is it possible to predict exactly how long the atom will remain in the higher energy state? Explain your answer.

22. Spectra of astronomical objects show both bright and dark lines. Describe what these lines indicate about the atoms responsible for the spectral lines.

23. Astronomers describe certain celestial objects as being *redshifted* or *blueshifted*. What do these terms indicate about the objects?

24. An object somewhere near you is emitting a pure tone at middle C on the octave scale (262 Hz). You, having perfect pitch, hear the tone as A above middle C (440 Hz). Describe the motion of this object relative to where you are standing.

25. During a popular art exhibition, the museum staff finds it necessary to protect the artwork by limiting the total number of viewers in the museum at any particular time. New viewers are admitted at the same rate that others leave. Is this an example of static equilibrium or of dynamic equilibrium? Explain.

26. A favorite object for amateur astronomers is the double star Albireo, with one of its components a golden yellow and the other a bright blue. What do these colors tell you about the relative temperatures of the two stars?

27. The stars you see in the night sky cover a large range of brightness. What does that range tell you about the distances of the various stars? Explain your answer.

28. Why is it not surprising that sunlight peaks in the "visible"?

29. Study Figure 5.24. For which planet is the range of measured temperatures furthest from the predicted value? What accounts for this difference?

30. Suppose you want to find a planet with the same temperature as Earth. What could you say about the size of the orbit of such a planet if it is orbiting a red star? A yellow star? A blue star?

Applying the Concepts

31. You are tuned to 790 on AM radio. This station is broadcasting at a frequency of 790 kHz (7.90×10^5 Hz). You switch to 98.3 on FM radio. This station is broadcasting at a frequency of 98.3 MHz (9.83×10^7 Hz).
    a. What are the wavelengths of the AM and FM radio signals?
    b. Which broadcasts at higher frequencies: AM or FM?
    c. What are the photon energies of the two broadcasts?

32. Your microwave oven cooks by vibrating water molecules at a frequency of 2.45 gigahertz (GHz), or 2.45×10^9 Hz. What is the wavelength, in centimeters, of the microwave's electromagnetic radiation?

33. You observe a spectral line of hydrogen at a wavelength of 502.3 nm in a distant galaxy. The rest wavelength of this line is 486.1 nm. What is the radial velocity of this galaxy? Is it moving toward you or away from you?

34. Assume that an object emitting a pure tone of 440 Hz is on a vehicle approaching you at a speed of 25 m/s. If the speed of sound at this particular atmospheric temperature and pressure is 340 m/s, what will be the frequency of the sound that you hear? (Hint: Keep in mind that frequency is inversely proportional to wavelength.)

35. If half of the phosphorescent atoms in a glow-in-the-dark toy give up a photon every 30 minutes, how bright (relative to its original brightness) will the toy be after 2 hours?

36. How bright would the Sun appear from Neptune, 30 AU from the Sun, compared to its brightness as seen from Earth? The spacecraft *Voyager 1* is now about 130 AU from the Sun and heading out of the Solar System. Compare the brightness of the Sun seen by *Voyager 1* with that seen from Earth.

37. On a dark night you notice that a distant lightbulb happens to have the same brightness as a firefly that is 5 meters away from you. If the lightbulb is a million times more luminous than the firefly, how far away is the lightbulb?

38. Two stars appear to have the same brightness, but one star is 3 times more distant than the other. How much more luminous is the more distant star?

39. A panel with an area of 1 square meter (m^2) is heated to a temperature of 500 K. How many watts is it radiating into its surroundings?

40. The Sun has a radius of 6.96×10^5 km and a blackbody temperature of 5780 K. Calculate the Sun's luminosity.

41. Some of the hottest stars known have a blackbody temperature of 100,000 K. What is the peak wavelength of their radiation? What type of radiation is this?

42. Your body, at a temperature of about 37°C (98.6°F), emits radiation in the infrared region of the spectrum.
    a. What is the peak wavelength, in microns, of your emitted radiation?
    b. Assuming an exposed body surface area of 0.25 m^2, how many watts of power do you radiate?

43. A planet with no atmosphere at 1 AU from the Sun would have an average blackbody surface temperature of 279 K if it absorbed all the Sun's electromagnetic energy falling on it (albedo = 0).
    a. What would be the average temperature on this planet if its albedo were 0.1, typical of a rock-covered surface?
    b. What would be the average temperature if its albedo were 0.9, typical of a snow-covered surface?

44. The orbit of Eris, a dwarf planet, carries it out to a maximum distance of 97.7 AU from the Sun. Assuming an albedo of 0.8, what is the average temperature of Eris when it is farthest from the Sun?

45. Suppose our Sun had 10 times its current luminosity. What would be the average blackbody surface temperature of Earth, assuming Earth had the same albedo?

USING THE WEB

46. a. Go to the website for NASA's Astronomy Picture of the Day (http://apod.nasa.gov/apod/ap101027.html) and study the picture of the Andromeda Galaxy in visible light and in ultraviolet light. Which light represents a hotter temperature? What differences do you see in the two images?
    b. Go to the APOD archive (http://apod.nasa.gov/cgi-bin/apod/apod_search) and enter "false color" in the search box. Examine a few images that come up in the search. What does *false color* mean in this context? What wavelength(s) were the pictures exposed in? What is the color coding; that is, what wavelength does each color in the image represent? You can read more about false color here: http://chandra.harvard.edu/photo/false_color.html.

47. Crime scene investigators may use different types of light to examine a crime scene. Search for "forensic lighting" in your browser. What wavelengths of light are used to search for blood and saliva? For fingerprints? Why is it useful for an investigator to have access to different kinds of light? Search on "forensic spectroscopy" and select a recent report. How is spectroscopy being used in crime scene investigations?

48. Using Google Images or an equivalent website, search for "night vision imaging" and "thermal imaging." How do night vision goggles and thermal-imaging devices work differently from regular binoculars or cameras? When are these useful?

49. The Transportation Security Administration (TSA) uses several types of imaging devices to screen passengers in airports. Search for "TSA imaging" in your browser. What wavelengths of light are being used in these devices? What concerns do passengers have about some of these imaging devices?

50. Go to the NASA Earth Observations website (http://neo.sci.gsfc.nasa.gov) and look at the current map of Earth's albedo (click on "albedo" in the menu for "energy" or "land" if it didn't come up). Compare this map with those of 2, 4, 6, 8, and 10 months ago. Which parts of Earth have the lowest and highest albedos? In which parts do the albedos seem to change the most with the time of the year? Would you expect ice, snow, oceans, clouds, forests, and deserts to add or subtract in each case from the total Earth albedo? Which parts of Earth are not showing up on this map?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

EXPLORATION Light as a Wave, Light as a Photon

digital.wwnorton.com/astro5

Visit the Student Site at the Digital Landing Page, and open the "Light as a Wave, Light as a Photon" AstroTour in Chapter 5. Watch the first section and then click through, using the "Play" button, until you reach "Section 2 of 3."

Here we will explore the following questions: How many properties does a wave have? Are any of these properties related to each other?

Work your way to the experimental section, where you can adjust the properties of the wave. Watch for a moment to see how fast the frequency counter increases.

1 Increase the wavelength by pressing the arrow key. What happens to the rate of the frequency counter?

2 Reset the simulation and then decrease the wavelength. What happens to the rate of the frequency counter?

3 How are the wavelength and frequency related to each other?

4 Imagine that you increase the frequency instead of the wavelength. How should the wavelength change when you increase the frequency?

5 Reset the simulation, and increase the frequency. Did the wavelength change in the way you expected?

6 Reset the simulation, and increase the amplitude. What happens to the wavelength and the frequency counter?

7 Decrease the amplitude. What happens to the wavelength and the frequency counter?

8 Is the amplitude related to the wavelength or frequency?

9 Why can't you change the speed of this wave?

6 The Tools of the Astronomer

In the previous chapter, you saw that astronomers learn about the physical and chemical properties of distant planets, stars, and galaxies by studying the light from these objects. This electromagnetic radiation must first be collected and processed before it can be analyzed and converted to useful knowledge. In this chapter, you will learn about the tools that astronomers use to capture and scrutinize that information.

LEARNING GOALS

By the conclusion of this chapter, you should be able to:

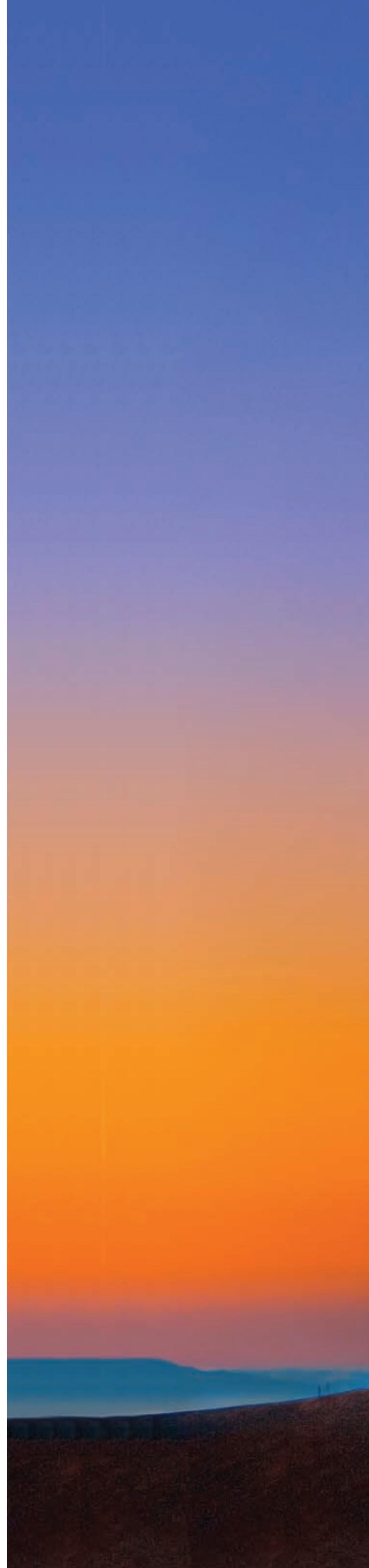
LG 1 Compare the two main types of optical telescopes and how they gather and focus light.

LG 2 Summarize the main types of detectors that are used on telescopes.

LG 3 Explain why some wavelengths of radiation must be observed from space.

LG 4 Explain the benefits of sending spacecraft to study the planets and moons of our Solar System.

LG 5 Describe other astronomical tools that contribute to the study of the universe.



The twin 10-meter Keck reflectors on Mauna Kea, Hawaii, have a multiple mirror, compact design. ▶▶▶

Why are most telescopes on remote mountaintops?

6.1 The Optical Telescope Revolutionized Astronomy

Astronomical observations began with the human eye—information about the overall colors of stars and their brightness in the night sky is apparent even to the naked eye, unassisted by binoculars or telescopes or filters. The development of **telescopes**—devices for collecting and focusing light—in the 17th century greatly increased the amount of light that can be collected from astronomical objects. With modern telescopes, astronomers can detect light that has been traveling across space for billions of years—even electromagnetic radiation from soon after the Big Bang, the beginning of the universe itself.

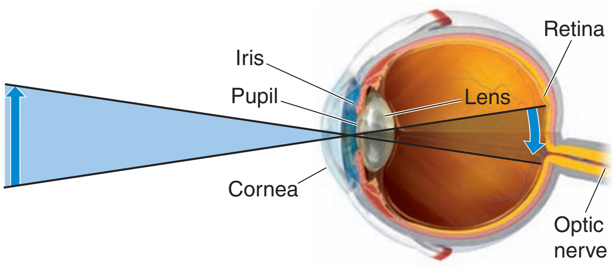


Figure 6.1 A schematic view of the human eye, creating an image of an object (the blue arrow).

The Eye

Human eyes are sensitive to light with wavelengths ranging from about 350 nanometers (deep violet) to 750 nanometers (far red). A simplified schematic of the human eye is shown in **Figure 6.1**. The part of the human eye that detects light is called the retina, and the individual receptor cells that respond to light falling on the retina are called rods and cones. The center of the human retina consists solely of cones, which detect color and provide the greatest visual acuity. Away from the center, rods and cones intermingle, with rods dominating far from the center, where they are responsible for peripheral vision.

Nebraska Simulation: Snell's Law Demonstrator

Our vision is limited by the eye's angular **resolution**, which refers to how close two points of light can be to each other before we can no longer distinguish them. Unaided, the best human eyes can resolve objects separated by 1 arcminute (1/60 of a degree), an angular distance of about 1/30 the diameter of the full Moon. (A more in-depth description of angular units—radians, degrees, arcminutes, and arcseconds—can be found in Appendix 1.4.) This may seem small, but when we look at the sky, thousands of stars and galaxies may reside within a patch of sky with this diameter.

Refracting Telescopes

Optical telescopes come in two primary types: **refracting telescopes**, which use lenses; and **reflecting telescopes**, which use mirrors. For all telescopes, the "size" of the telescope refers to the diameter of the largest mirror or lens, which determines the light-collecting area. This diameter is called the **aperture**. The light-gathering power of a telescope is proportional to the area of its aperture; that is, to the square of its diameter. The larger the aperture, the more light the telescope can collect. A "1-meter telescope" has a primary mirror (or lens) that is 1 meter in diameter. The aperture of the human eye is about 6–7 millimeters.

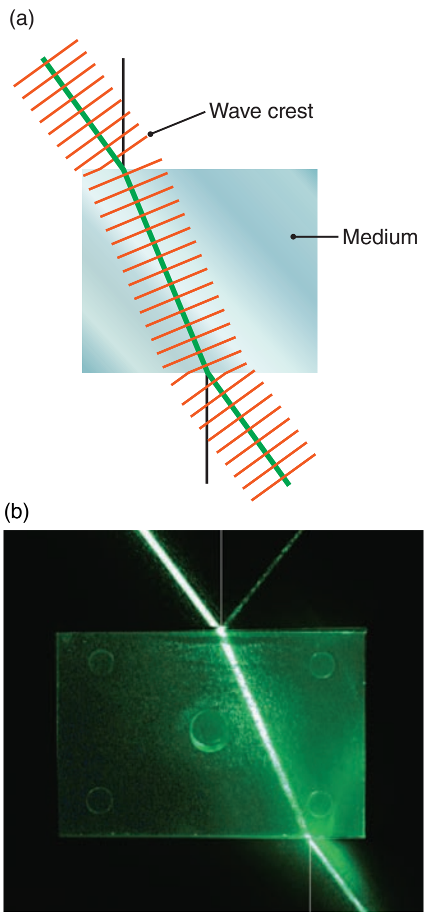


Figure 6.2 (a) When wavefronts enter a new medium, they bend in a new direction relative to a line perpendicular to the surface (black lines). (b) An actual light ray entering and leaving a medium.

In the late 13th century, craftsmen in Venice were making small lentil-shaped disks of glass that could be mounted in frames and worn over the eyes to improve vision. More than 300 years later, Hans Lippershey (1570–1619), a spectacle maker living in the Netherlands, put two of his lenses together in a tube. With this new instrument, he saw distant objects magnified and could see farther. Galileo Galilei heard news of this invention, and he constructed one of his own. Recall from Chapter 3 that by 1610, Galileo had become the first to see the phases of Venus and the moons of Jupiter, and among the first to see craters on the Moon. He was also the first to realize that the Milky Way is made up of large numbers of individual stars. The refracting telescope—one that uses lenses—quickly revolutionized the science of astronomy.

Refraction is the basis for the refracting telescope. Recall from Chapter 5 that the speed of light is constant in a vacuum, but through a medium such as air or glass, the speed of light is always lower. As light enters a new medium, its speed changes. If the light strikes the surface at an angle, some of the crest of the wave arrives at the surface earlier and some arrives later. You can see this in **Figure 6.2a**, a schematic diagram of wave crests (red lines) striking a medium at an angle. Figure 6.2b shows an actual light ray passing into and out of a medium, in this case glass. The ray bends each time the medium changes. This bending of light when it changes the medium through which it travels is called **refraction**.

The amount of refraction is determined by the properties of the medium. A medium's index of refraction (n) is equal to the ratio of the speed of light in a vacuum (c) to its speed in a medium (v). This can be expressed by the equation $n = c/v$. For example, most glass has an index of refraction of approximately 1.5, so the speed of light in glass is 300,000 kilometers per second (km/s) divided by 1.5, or 200,000 km/s. The light bends by an amount that depends on the index of refraction of the materials involved and the angle at which the light strikes.

The primary lens in a refracting telescope is a simple convex lens, called the **objective lens**, shown in **Figure 6.3**, whose curved surfaces refract the light from a distant object. This refracted light forms an image on the telescope's **focal plane**, which is perpendicular to the *optical axis*—the path that light takes through the center of the lens. Because the telescope's glass lens is curved, light at the outer edges of the lens strikes the surface more obliquely than light near the center. Therefore, light at the outer edges of the lens is refracted more than light near its center. The lens concentrates the light rays entering the telescope, bringing them to a sharp focus at a distance called the **focal length**. Sometimes focal length is specified on a telescope as *focal ratio*, which equals focal length divided by aperture size; this term may be familiar to you from lenses used in photography.

Figure 6.4 illustrates how a telescope uses the light that passes through its lenses. Figure 6.4a shows the light from two stars passing through a lens and converging at the focal plane of the lens. Figure 6.4b shows the same situation for a lens with a longer focal length. Longer focal lengths increase the size and separation of objects in the focal plane. Aperture and focal length are the two most important parameters of a telescope. The image can be viewed with an **eyepiece**—a changeable lens whose focal length determines the magnification (**Working It Out 6.1**). In modern research, however, the images are sent directly to a camera or other detector.

Refracting telescopes have two major shortcomings. First, there are physical limits on the size of refracting telescopes. The larger the area of the objective lens, the more light-gathering power it has and the fainter the stars we can observe. However, as objective lenses get larger, they get heavier, and a massive piece of glass at the end of a very long tube sags too much under the force of gravity. Refracting telescopes grew in size until the 1897 completion of the Yerkes 1-meter refractor (**Figure 6.5**), the world's largest operational refracting telescope. Located in

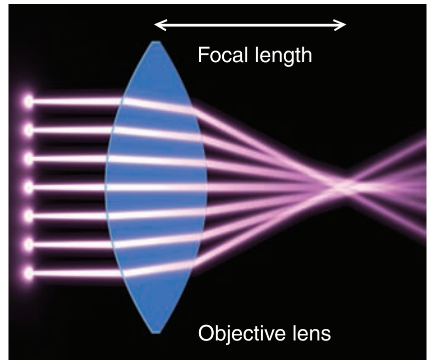


Figure 6.3 For a curved lens like the one shown, refraction causes the light to focus to a point. This point is in a slightly different location for different wavelengths (colors) of light.

Nebraska Simulation: Telescope Simulator

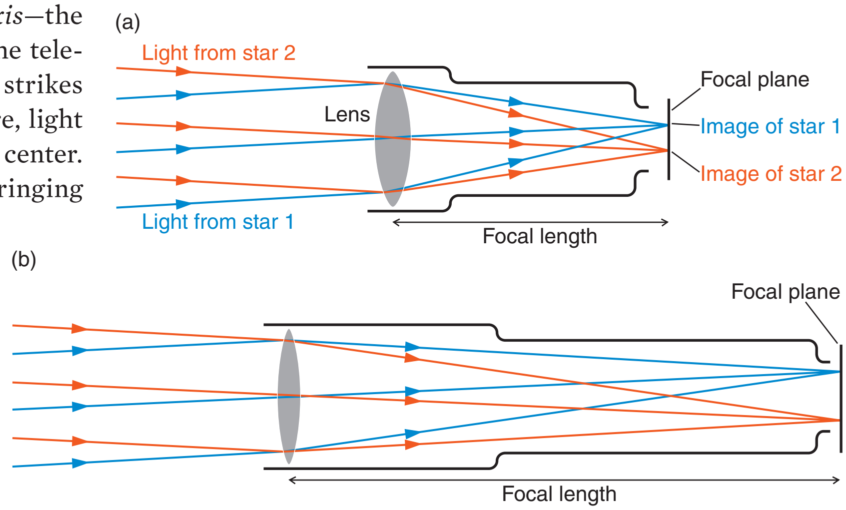


Figure 6.4 (a) A refracting telescope uses a lens to collect and focus light from two stars, forming images of the stars on its focal plane. (b) Telescopes with longer focal length produce larger images.

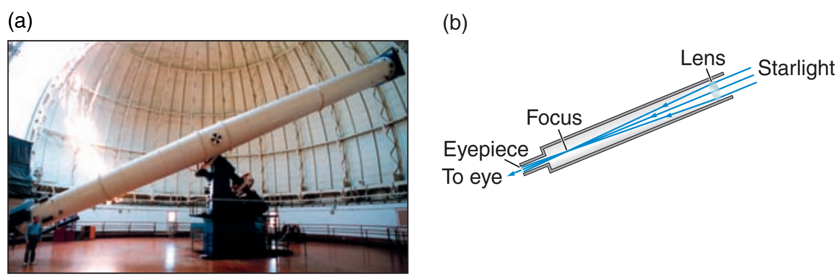


Figure 6.5 (a) The Yerkes 1-meter refractor is the world's largest refracting telescope. (b) This sketch shows the parts of a refractor.

6.1 Working It Out Telescope Aperture and Magnification

If you were shopping for a telescope, you would likely be told to consider aperture and magnification. Here we will look briefly at each.

Aperture

The light-gathering power is proportional to the area of the mirror or lens, and thus to the square of the aperture, $\pi \times (D/2)^2$. A telescope with a larger aperture collects more light than does one with a smaller aperture. We can compare a 200-millimeter (mm), or 8-inch, diameter telescope with the light-gathering power of the pupil of your eye, which is about 6 mm in the dark:

$$\text{Light-gathering power of telescope} = \frac{\pi}{4} \times (200\text{ mm})^2$$

and

$$\text{Light-gathering power of eye} = \frac{\pi}{4} \times (6\text{ mm})^2$$

So, to compare:

$$\frac{\text{Light-gathering power of telescope}}{\text{Light-gathering power of eye}} = \frac{\cancel{\frac{\pi}{4}}(200\text{ mm})^2}{\cancel{\frac{\pi}{4}}(6\text{ mm})^2} = \left(\frac{200}{6}\right)^2 = 1{,}000$$

A typical 8-inch telescope has more than 1,000 times the light-gathering power of your eye.

Comparing this 8-inch telescope to the Keck 10-meter telescope shows why bigger is better: 200 mm = 0.2 meter, and we cancel out the $\frac{\pi}{4}$ again to obtain

$$\frac{\text{Light-gathering power of Keck}}{\text{Light-gathering power of 8-inch telescope}} = \left(\frac{10\text{ m}}{0.2\text{ m}}\right)^2 = 2{,}500$$

Even larger telescopes, 25–40 meters in diameter, are currently under construction.

Magnification

Most telescopes have a set focal length and come with a collection of eyepieces. The magnification of the image in the telescope is given by

$$\text{Magnification} = \frac{\text{Telescope focal length}}{\text{Eyepiece focal length}}$$

Suppose the focal length of the 200-mm telescope in the preceding example is 2,000 mm. Combined with the focal length of a standard eyepiece, 25 mm, this telescope will give the following magnification:

$$\text{Magnification} = \frac{2{,}000\text{ mm}}{25\text{ mm}} = 80$$

This telescope and eyepiece combination has a magnifying power of 80, meaning that a crater on the Moon will appear 80 times (80×) larger in the telescope's eyepiece than it does when viewed by the naked eye. An eyepiece that has a focal length of 8 mm will have about 3 times more magnifying power, or 250.

A higher magnification will not necessarily let you see the object better. A faint and fuzzy image will not look clearer when magnified.

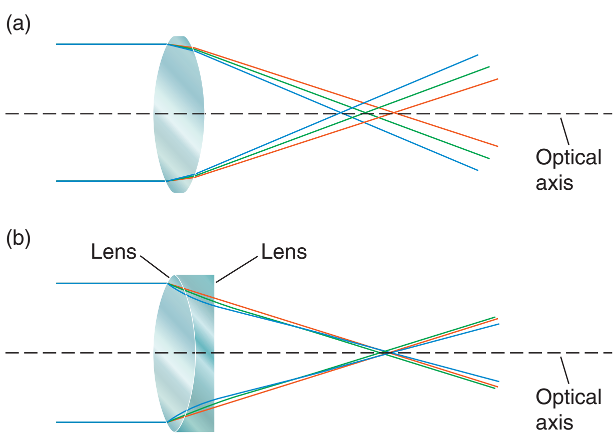


Figure 6.6 (a) Different wavelengths of light come to different foci along the optical axis of a simple lens, causing chromatic aberration. (b) A compound lens using two types of glass with different indices of refraction can compensate for much of the chromatic aberration, so different colors of light all come to a focus at the same point.

Williams Bay, Wisconsin, the Yerkes telescope carries a 450-kilogram (kg) objective lens mounted at the end of a 19.2-meter tube.

The second major shortcoming of refracting telescopes is **chromatic aberration**. Starlight is made up of all the colors of the rainbow, and each color refracts at a slightly different angle because the index of refraction depends on the wavelength of the light. As seen in **Figure 6.6a**, shorter (bluer) wavelengths are refracted more strongly than longer (redder) wavelengths. This wavelength-dependent difference in refraction, which spreads the white light out into its spectral colors, is called **dispersion**. Dispersion causes bluer light to come to a shorter focus than that of the longer visible wavelengths, creating chromatic aberration. In a refracting telescope with a simple convex lens, chromatic aberration produces haloed images around the star. Manufacturers of quality cameras and telescopes use a **compound lens** composed of two types of glass to correct for chromatic aberration (Figure 6.6b).

Reflecting Telescopes

Another property of light is **reflection**, the basis for reflecting telescopes. When light encounters a different medium—in this case going from air to glass—there

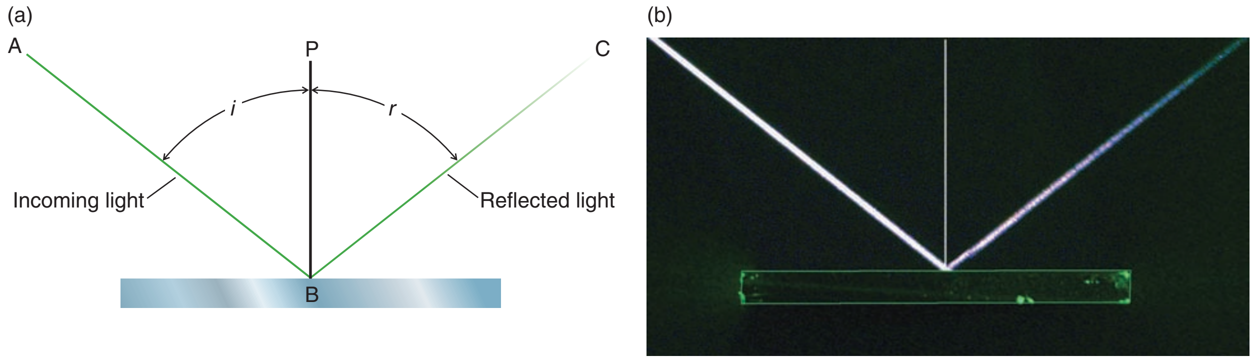


Figure 6.7 (a) When a ray of incoming light (AB) shines on a flat surface, it reflects from the surface, becoming the reflected ray BC. The angle between AB and PB, the perpendicular to the surface, is the angle of incidence (*i*). The angle between BC and PB is the angle of reflection (*r*). The angles of incidence and reflection are always equal. (b) Light from a laser beam is reflected from a flat glass surface.

will be an amount of light reflected from the surface of the new medium. In other words, some of the light will reverse its direction of travel. The most common example occurs when light encounters an ordinary flat mirror. As shown in **Figure 6.7**, the angle of the incoming light and the angle of outgoing light are always equal. A reflected image from a mirror is a good representation of what falls on it, although left and right are interchanged.

In 1668, Isaac Newton designed a reflecting telescope, which uses mirrors instead of lenses (**Figure 6.8a**). The direction of reflected light does not depend on the wavelength of light; therefore, chromatic aberration is not a problem in reflecting telescopes. A sketch of parts of Newton's reflecting telescope is presented in Figure 6.8b. To make this reflecting telescope, Newton cast a 2-inch primary mirror made of copper and tin and polished it to a special curvature. He then placed this primary mirror at the bottom of a tube with a secondary flat mirror mounted above it at a 45° angle. The second mirror directed the focused light to an eyepiece on the outside of the tube.

Astronomers use mirrors with a surface that curves inward toward the incoming light, called concave mirrors. The same rules of incidence and reflection hold here for each ray of light, but in this case the reflected rays do not maintain the same angle with respect to each other as they do with a flat mirror. Concave mirrors will reflect the rays so that they converge to form an image, as shown in **Figure 6.9**. If the incoming light rays are parallel, as from a distant source like a star, the reflected light rays cross at the focal length of the mirror. The light path from the primary mirror to the focal plane can be "folded" by using a secondary mirror, which enables a significant reduction in the length and weight of the telescope. In many modern telescopes, the primary mirror has a hole so that light can pass back through it; the eyepiece is on the back of the tube of the telescope, and the tube can be shortened.

Large reflecting telescopes did not become common until the latter half of the 18th century. But then the size of the primary mirrors in reflecting telescopes continued to grow; and they became larger every decade. Primary mirrors can be supported from the back, and they can be made thinner and therefore less massive than the objective lenses found in refracting telescopes. The limitation on the size of reflecting telescopes is the cost of their fabrication and support structure.

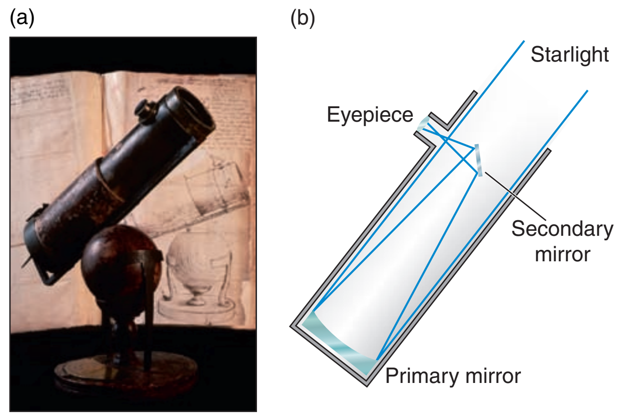


Figure 6.8 Newton's reflecting telescope (a) has parts shown in the sketch (b).

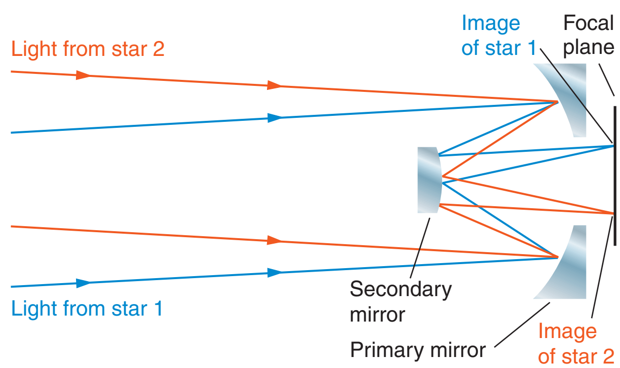


Figure 6.9 Large reflecting telescopes often use a secondary mirror that directs the light back through a hole in the primary mirror to an accessible focal plane behind the primary mirror. Parallel rays of light that strike a concave parabolic mirror are brought to a focus in the mirror's focal plane.

TABLE 6.1 The World's Largest Optical Telescopes

Mirror Diameter (meters)	Telescope	Sponsor(s)	Location	Operational Date
39.3	European Extremely Large Telescope (E-ELT)	European Southern Observatory (Europe, Chile, Brazil)	Cerro Armazones, Chile	Under construction
30.0	Thirty Meter Telescope (TMT)	International collaboration led by Caltech, U. of California, U. of Hawaii, China, Japan, India, and Canada	Mauna Kea, Hawaii	Under construction
24.5	Giant Magellan Telescope (GMT)	Carnegie Institution, Harvard U., Smithsonian Institution, U. of Arizona, U. of Texas, Texas A&M, U. of Chicago, Australian National U., Astronomy Australia Ltd., Korea Astronomy and Space Science Institute	Cerro Las Campanas, Chile	Under construction
11.0	South African Large Telescope (SALT)	South Africa, USA, UK, Germany, Poland, New Zealand, India	Sutherland, South Africa	2005
10.4	Gran Telescopio CANARIAS (GTC)	Spain, Mexico, U. of Florida	Canary Islands	2007
10	Keck I	Caltech, U. of California, NASA	Mauna Kea, Hawaii	1993
10	Keck II	Caltech, U. of California, NASA	Mauna Kea, Hawaii	1996
9.2	Hobby-Eberly Telescope (HET)	U. of Texas, Penn State U., Stanford U., Germany	Mount Fowlkes, Texas	1999
8.4 × 2	Large Binocular Telescope (LBT)	U. of Arizona, Ohio State U., Italy, Germany, Arizona State, and others	Mount Graham, Arizona	2008
8.4	Large Synoptic Survey Telescope (LSST)	Many partners	Cerro Pachón	Under construction
8.3	Subaru Telescope	Japan	Mauna Kea, Hawaii	1999
8.2 × 4	Very Large Telescope (VLT)	European Southern Observatory	Cerro Paranal, Chile	2000
8.1	Gemini North	USA, UK, Canada, Chile, Brazil, Argentina, Australia	Mauna Kea, Hawaii	1999
8.1	Gemini South	USA, UK, Canada, Chile, Brazil, Argentina, Australia	Cerro Pachón, Chile	2000
6.5	MMT	Smithsonian Institution, U. of Arizona	Tucson, Arizona	2000
6.5	Magellan I	Carnegie Institution, U. of Arizona, Harvard U., U. of Michigan, MIT	Cerro Las Campanas, Chile	2000
6.5	Magellan II	Carnegie Institution, U. of Arizona, Harvard U., U. of Michigan, MIT	Cerro Las Campanas, Chile	2002

▶II **AstroTour:** Geometric Optics and Lenses

Table 6.1 lists the world's largest optical telescopes. All are reflecting telescopes. The largest single mirrors constructed today are 8 meters in diameter, but reflecting telescopes even bigger than this are designed to make use of an array of smaller segments. The primary mirror of each of the 10-meter, twin Keck telescopes is made up of 36 hexagon-shaped segments that are 1.8 meters in diameter (**Figure 6.10**). Located on 4,100-meter-high Mauna Kea in Hawaii, the Keck telescopes are among the world's largest reflecting telescopes. Each one has 4 million times the light-gathering power of the human eye.

CHECK YOUR UNDERSTANDING 6.1

Which of the following is a reason that all large astronomical telescopes are reflectors (choose all that apply): (a) chromatic aberration is minimized; (b) they are not as heavy; (c) they can be shorter; (d) the glass doesn't need to be curved.

Optical and Atmospheric Limitations

Another important characteristic of a telescope is its *resolution*—how close two points of light can be to each other before they are indistinguishable. The concept of resolution is illustrated in **Figure 6.11**. Review Figure 6.4a to see the path followed by rays of light from two distant stars as they pass through the lens of a refracting telescope. Figure 6.4b illustrated that increasing the focal length increases the size of and separation between the images that a telescope produces. This is one reason why telescopes provide a much clearer view of the stars than that obtained with the naked eye. The focal length of a human eye is typically about 20 mm, whereas telescopes used by professional astronomers often have focal lengths of tens or even hundreds of meters. Such telescopes make images that are far larger than those formed by the human eye, and consequently they contain far more detail.

Focal length explains only one difference between the resolution of telescopes and that of the unaided eye. The other difference results from the wave nature of light. **Figure 6.12** shows what happens when light waves pass through the aperture of a telescope: they spread out from the edges of the lens or mirror. The distortion that occurs as light passes the edge of an opaque object is called **diffraction**. Diffraction "diverts" some of the light from its path, slightly blurring the image made by the telescope. The degree of blurring depends on the wavelength of the light and the telescope's aperture. The larger the aperture, the smaller the problem posed by diffraction. The best resolution that a given telescope can achieve is known as the **diffraction limit** (**Working It Out 6.2**).

Larger telescopes have better resolution and can distinguish objects that appear closer together. Theoretically, the 10-meter Keck telescopes have a diffraction-limited resolution of 0.0113 arcseconds (arcsec) in visible light, which would be good enough for you to read newspaper headlines 60 km away. But for telescopes with apertures larger than about a meter, Earth's atmosphere stands in the way of better resolution. If you have ever looked out across a large asphalt parking lot on a summer day, you have seen the distant horizon shimmer as light is bent this way and that by turbulent bubbles of warm air rising off the hot

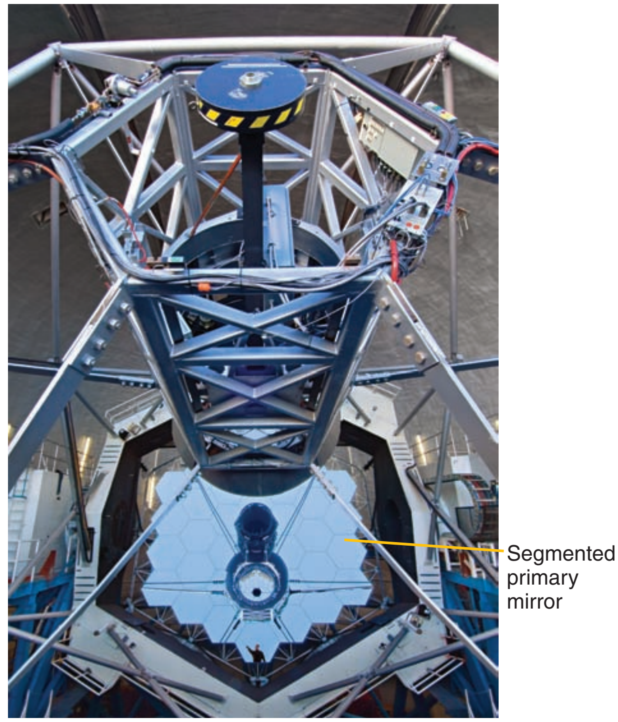


Figure 6.10 Each of the Keck 10-meter reflectors uses an aligned group of 36 hexagonal mirrors to collect light.

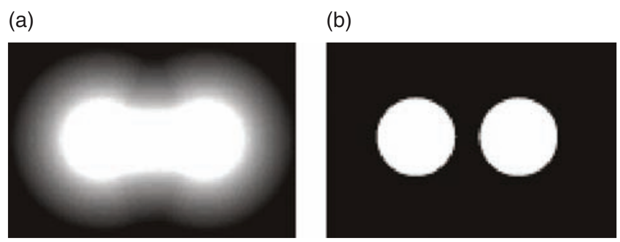


Figure 6.11 Resolution is the ability to separate two images that appear close together. When resolution is lower (a), the two images blend together. When resolution is higher (b), individual images can be seen.

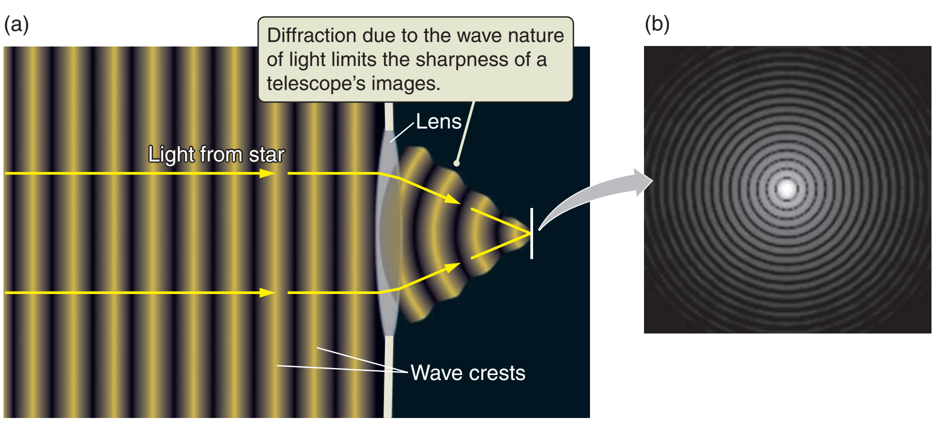


Figure 6.12 (a) Light waves from a star are diffracted by the edges of a telescope's lens or mirror. (b) This diffraction causes the stellar image to be blurred, limiting a telescope's ability to resolve objects.

6.2 Working It Out Diffraction Limit

The practical limit on the angular resolution, θ, of a telescope is called the diffraction limit. This limit is determined by the ratio of the wavelength of light, λ, passing through the telescope to the diameter of the aperture, D:

$$\theta = 2.06 \times 10^5 \left(\frac{\lambda}{D}\right) \text{arcsec}$$

With the constant, 2.06×10^5, the units are arcseconds (arcsec). An **arcsecond** is a tiny angular measure found by first dividing the sky into 360 degrees, and then dividing a degree by 60 to get arcminutes, and then by 60 again to get arcseconds. An arcsecond is 1/1,800 of the size of the Moon in the sky, or about the size of a tennis ball if you could see it from 8 miles away.

Both λ and D must be expressed in the same units, usually meters. The smaller the ratio of λ/D, the better the resolution. For example, the size of the human pupil (see Figure 6.1) ranges from about 2 mm in bright light to 8 mm in the dark. A typical pupil size in the dark is about 6 mm, or 0.006 meter. Visible (green) light has a wavelength (λ) of 550 nanometers (nm); that is, 550×10^{-9} meter, or 5.5×10^{-7} meter. Using these values for the aperture and the wavelength gives

$$\theta = 2.06 \times 10^5 \left(\frac{5.5 \times 10^{-7}\,\text{m}}{0.006\,\text{m}}\right) \text{arcsec} = 19\,\text{arcsec}$$

or about 0.5 arcmin. The typical resolution of the human eye is 2 arcmin. We do not achieve the theoretical resolution with our eyes because the physical properties of our eyes are not perfect.

How does the resolution of the human eye compare to that of a telescope? Consider the Hubble Space Telescope, when operating in the visible part of the spectrum. Its primary mirror has a diameter of 2.4 meters. Substituting this value for D and again using visible (green) light gives

$$\theta = 2.06 \times 10^5 \left(\frac{5.5 \times 10^{-7}\,\text{m}}{2.4\,\text{m}}\right) \text{arcsec} = 0.047\,\text{arcsec}$$

or about 600 times better than the theoretical resolving power of the human eye.

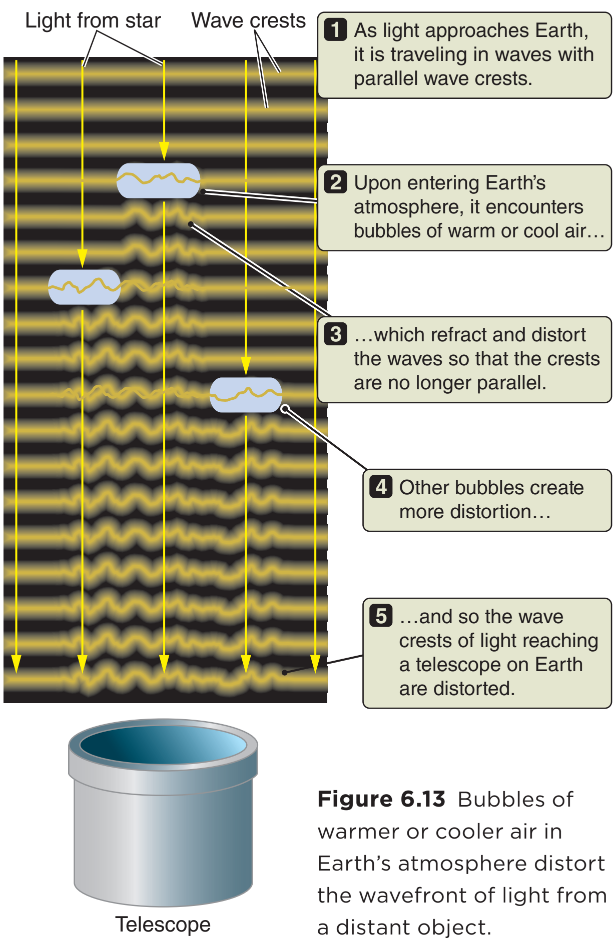


Figure 6.13 Bubbles of warmer or cooler air in Earth's atmosphere distort the wavefront of light from a distant object.

pavement. The problem of the shimmering atmosphere is less pronounced when we look overhead, but the twinkling of stars in the night sky is caused by the same phenomenon. As telescopes magnify the angular diameter of an object, they also magnify the shimmering effects of the atmosphere. The limit on the resolution of a telescope on the surface of Earth caused by this atmospheric distortion is called **astronomical seeing**. One advantage of launching telescopes such as the Hubble Space Telescope into orbit around Earth above the atmosphere is that they are not hindered by astronomical seeing.

Modern technology has improved ground-based telescopes with computer-controlled **adaptive optics** that compensate for much of the atmosphere's distortion. To understand how adaptive optics work, we need to look more closely at how Earth's atmosphere smears out an otherwise perfect stellar image. Light from a distant star arrives at the top of Earth's atmosphere with flat, parallel wave crests. If Earth's atmosphere were perfectly uniform, the crests would remain flat as they reached the objective lens or primary mirror of a ground-based telescope. After making its way through the telescope's optical system, the crests would produce a tiny diffraction disk in the focal plane, as shown in Figure 6.12b. But Earth's atmosphere is not uniform. It is filled with bubbles of air that have slightly different temperatures than those of their surroundings. Different temperatures mean different densities, and different densities mean different refractive properties, so each bubble bends light differently.

These air bubbles act as weak lenses, and by the time the waves reach the telescope they are far from flat, as shown in **Figure 6.13**. Instead of a tiny diffraction disk, the image in the telescope's focal plane is distorted and swollen, degrading the resolution. Adaptive optics flatten out this distortion. First, an optical device within the telescope constantly measures the wave crests. Then, before reaching the telescope's focal plane, the light is reflected off yet another mirror, which has a flexible surface. A computer analyzes the light and bends the flexible mirror so that it accurately corrects for the distortion caused by the air bubbles. **Figure 6.14** shows an example of an image corrected by adaptive optics. The widespread use of adaptive optics has made the image quality of ground-based telescopes competitive with the quality of Hubble images from space at some wavelengths.

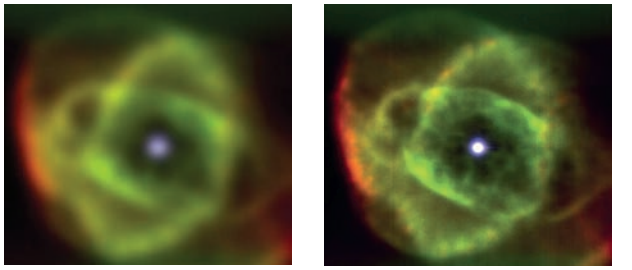


Figure 6.14 These images of the Cat's Eye Nebula from the Palomar Observatory telescope without (left) and with (right) adaptive optics show the benefit of the technique.

Observatory Locations

What makes a good location for a telescope on Earth? Look back at Table 6.1—what do these locations have in common? Astronomers look for sites that are high, dry, and dark. The best sites are far away from the lights of cities, in locations with little moisture, humidity, or rain, and where the atmosphere is relatively still. Telescopes are located as high as possible so that they get above a significant part of Earth's atmosphere, which distorts images and blocks infrared light. Many telescopes are situated on remote, high mountaintops surrounded by desert or ocean. Recall from Chapter 2 that the stars that can be seen throughout the year depend on latitude, and only at the equator would a telescope have access to all of the stars in the sky. But equatorial latitudes have tropical weather—wet, humid, and stormy—and thus are poor locations for a telescope. So, to cover the entire sky, astronomers have built telescopes in both northern and southern locations. In the United States, large telescopes are located in California, Arizona, New Mexico, Texas, and Hawaii. The largest southern-sky observatories are found in Chile, South Africa, and Australia. The twin Gemini telescopes, designed to be a matched pair, are located in Hawaii in the Northern Hemisphere and in Chile in the Southern Hemisphere.

Figure 6.15 This is an artist's rendering of the Thirty Meter Telescope, a planned reflecting telescope.

Newer and larger telescopes are planned for many of the same locations that are listed in Table 6.1. The 8-meter Large Synoptic Survey Telescope (LSST) is headed for Cerro Pachón in Chile, current site of the Gemini South telescope. The Giant Magellan Telescope (GMT), consisting of seven 8-meter mirrors in a pattern equivalent to a 24.5-meter mirror, will be constructed at Cerro Las Campanas in Chile. The Thirty Meter Telescope (TMT) (**Figure 6.15**) is planned for Mauna Kea in Hawaii, current site of the twin Keck telescopes; and the European Southern Observatory (ESO) is building the 39-meter European Extremely Large Telescope (E-ELT) at Cerro Armazones in Chile. As telescopes get larger—and more expensive—international collaboration becomes even more important.

Today's professional astronomers rarely look through the eyepiece of a telescope because they learn much more and make better use of observing time by permanently recording an object's image at a variety of wavelengths or seeing its light spread out into a revealing spectrum. Some astronomers no longer travel to telescopes at all, instead observing remotely from the base of the mountain or far away at their own institutions.

Figure 6.16 This satellite image of the United States at night shows that few populated areas are free from light pollution.

Professional and amateur astronomers alike are concerned about loss of the dark sky. As cities and suburbs grow and expand around the world, the use of outdoor artificial light becomes more widespread. Pictures from space show how bright many areas of Earth are at night. In the United States, two-thirds of the population resides in an area that is too bright to see the Milky Way in the sky at night (**Figure 6.16**), and it has been estimated that by 2025 there will be almost no dark skies in the continental United States. Increased air pollution also dims the view of the night sky in many locations. The U.S. National Park Service now advertises evening astronomy programs in natural, unpolluted dark skies as one of the reasons to visit some parks. Several international astronomy associations are working with UNESCO (the United Nations Educational, Scientific and Cultural Organization) to promote the "right to starlight," arguing that for historical, cultural, and scientific reasons, it would be a huge loss if humanity could no longer view the stars. These organizations are encouraging countries to create starlight reserves and starlight parks where people can experience increasingly rare dark skies and a natural nocturnal environment.

CHECK YOUR UNDERSTANDING 6.2

In practice, the smallest angular size that one can resolve with a 10-inch telescope is governed by the: (a) blurring caused by Earth's atmosphere; (b) diffraction limit of the telescope; (c) size of the primary mirror; (d) magnification of the telescope.

6.2 Optical Detectors and Instruments Used with Telescopes

Beginning in the 1800s, the development of film photography, and later digital photography, revolutionized astronomy, allowing astronomers to detect fainter and more distant objects than possible to detect with the eye alone. In this section, we will examine some of the more common types of detectors.

Integration Time and Quantum Efficiency

Originally, the retina of the human eye was the only astronomical detector. The limit of the faintest stars we can see with our unaided eyes is determined in part by two factors that are characteristic of all detectors: *integration time* and *quantum efficiency*.

Integration time is the limited time interval during which the eye can add up photons—this is analogous to leaving the shutter open on a camera. The brain "reads out" the information gathered by the eye about every 100 milliseconds (ms). Anything that happens faster than that appears to happen all at once. If two images on a computer screen appear 30 ms apart, you will see them as a single image because your eyes will add up (or integrate) whatever they see over an interval of 100 ms or less. However, if the images occur 200 ms apart, you will see them as separate images. This relatively brief integration time is the most important factor limiting our nighttime vision. Stars too faint to be seen with the unaided eye are those from which you receive too few photons for your eyes to process in 100 ms.

Quantum efficiency determines how many responses occur for each photon received. For the human eye, 10 photons must strike a cone within 100 ms to activate a single response. So the quantum efficiency of our eyes is about 10 percent: for every 10 events, the eye sends one signal to the brain. Together, integration time and quantum efficiency determine the rate at which photons must arrive at the retina before the brain says, "Aha, I see something." Astronomers seek to use detectors with longer integration times and higher quantum efficiency than those of our eyes.

From Photographic Plates to Charge-Coupled Devices

For more than two centuries after the invention of the telescope, astronomers struggled with the problem of surface brightness. Only *point sources* such as stars appear brighter in a telescope; extended astronomical objects like the Moon appear bigger in the eyepiece, but their surfaces are no brighter than they appear to the unaided eye. Even when astronomers built larger telescopes, nebulae and galaxies appeared larger, but the details of these faint objects remained elusive. The problem was not with the telescopes but with the limitations of optics and the human eye. Only with the longer exposure times made possible by the invention of photography and the later development of electronic cameras were astronomers finally able to discern intricate details in faint objects.

Figure 6.17 A photograph of the Moon taken by John W. Draper in 1840.

In 1840, John W. Draper (1811–1882), a New York chemistry professor, created the earliest known astronomical photograph (**Figure 6.17**). By the late 1800s, astronomers had created thousands of photographic plates with permanent images of planets, nebulae, and galaxies. The quantum efficiency of most photographic systems used in astronomy was poorer than that of the human eye—typically 1–3 percent. But unlike the eye, photography can overcome poor quantum efficiency by leaving the shutter open on the camera, increasing the integration time to many hours of exposure. Photography made it possible for astronomers to record and study objects that were invisible to the human eye. However, one problem is that the response of photography to light is not linear, especially at long exposures, so if you doubled the exposure time, you did not get twice as much light on your image. By the middle of the 20th century, the search was on for electronic detectors that would overcome the sensitivity, spectral range, and nonlinearity problems of photography.

In 1969, scientists at Bell Laboratories invented a detector called a **charge-coupled device**, or **CCD**. By the late 1970s, the CCD had become the detector of choice in almost all astronomical-imaging applications. CCDs are linear, so doubling the exposure means you record twice as much light. Therefore, they are good for measuring objects that vary in brightness, as well as for faint objects that require long exposures. CCDs have a quantum efficiency far superior to that of photography or the eye, up to 80 percent at some wavelengths. This improvement dramatically increases the ability to view faint objects with short exposure times.

A CCD is an ultrathin wafer of silicon—less than the thickness of a human hair—that is divided into a two-dimensional array of picture elements, or **pixels**, as seen in **Figure 6.18a**. When a photon strikes a pixel, it creates a small electric charge within the silicon. As each CCD pixel is read out, the digital signal that flows to the computer is nearly proportional to the accumulated charge. This is what we mean when we say that the CCD is a linear device. However, if a CCD is exposed to too much light, it can lose its linearity.

Liquid nitrogen or helium is used to cool the CCDs down to very low temperatures to reduce noise caused by the movement of the charge-carrying atoms within the silicon wafer. The first astronomical CCDs were small arrays containing a few hundred thousand pixels. The larger CCDs used in astronomy today may contain more than 100 million pixels (Figure 6.18b). Still larger arrays are under development as ever-faster computing power keeps up with image-processing demands.

(a)

(b)

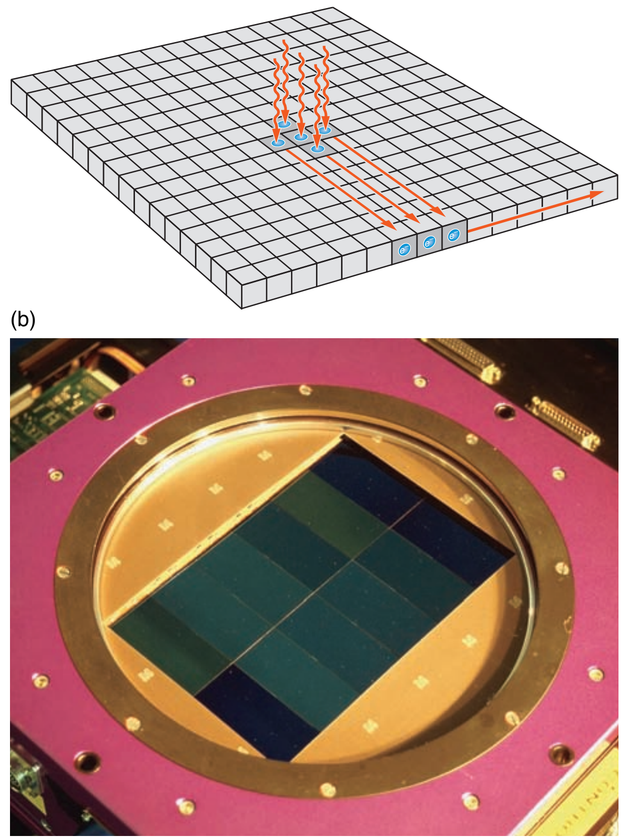


Figure 6.18 (a) In this simplified diagram of a charge-coupled device (CCD), photons from a star land on pixels (represented by gray squares) and produce free electrons within the silicon. The electron charges are electronically moved sequentially to the collecting register at the bottom. Each row is then moved out to the right to an electronic amplifier, which converts the electric charge of each pixel into a digital signal. (b) This large CCD (about 6 inches across) contains 12,288 × 8,192 pixels.

Nebraska Simulation: CCD Simulator

(a)

(b)

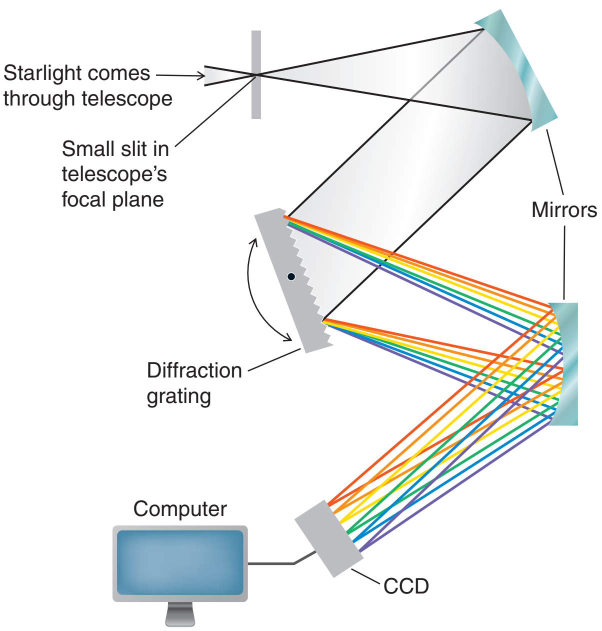


Figure 6.19 (a) A spectrum is created by the reflection of light from the closely spaced tracks of a CD. (b) In a grating spectrograph, light goes through the telescope and then a slit, where it is reflected to the diffraction grating and split into components. The spectrum is recorded on the CCD.

The output from a CCD is a digital signal that can be sent directly from the telescope to image-processing software or stored electronically for later analysis. Nearly every spectacular astronomical image in ultraviolet, visible, or infrared wavelength that you find online was recorded by a CCD in a telescope either on the ground or in space. CCDs are found in many common devices such as digital cameras, digital video cameras, and camera phones.

Your cell phone takes color pictures by using a grid of CCD pixels arranged in groups of three. Each pixel in a group is constructed to respond to only a particular range of colors—only to red light, for example. This is also true for digital image displays. You can see this for yourself if you place a small drop of water on the screen of your smartphone or tablet and turn it on. The water magnifies the grid of pixels so that you can see them individually. This grid degrades the angular resolution of the camera because each spot in the final image requires three pixels of information. Astronomers choose instead to use all the pixels on the camera to measure the number of photons that fall on each pixel, without regard to color. They put filters in front of the camera to allow light of only particular wavelengths to pass through, such as the light of a specific spectral line. Color pictures like those from the Hubble Space Telescope are constructed by taking multiple pictures, coloring each one, and then carefully aligning and overlapping them to produce beautiful and informative images. Sometimes the colors are "true"; that is, they are close to the colors you would see if you were actually looking at the object with your eyes. Other times "false" colors represent different portions of the electromagnetic spectrum and tell you the temperature or composition of different parts of the object. Using changeable filters instead of designated color pixels gives astronomers greater flexibility and greater resolution.

Spectrographs

Spectroscopy is the study of an object's *spectrum* (plural: *spectra*)—its electromagnetic radiation split into component wavelengths. **Spectrographs** (sometimes called **spectrometers**) are instruments that take the spectrum of an object and then record it. The first spectrographs used prisms to disperse the light. Modern spectrographs use a **diffraction grating**, which is made by engraving closely spaced lines on glass to disperse incoming light into its constituent wavelengths. **Figure 6.19a** shows the light reflected from a CD or DVD; the closely spaced tracks act as a grating and create a spectrum. Figure 6.19b shows a grating spectrograph: light from an astronomical object enters a telescope and passes through a slit. The light is reflected onto the diffraction grating, which creates a spectrum like the one shown in Figure 5.14. The spectra are recorded on a CCD and then analyzed. Some modern spectrographs use bundles of optical fibers, or masks with multiple slits, to obtain spectra simultaneously from multiple objects in the field of view of the telescope.

CHECK YOUR UNDERSTANDING 6.3

CCD cameras have much higher quantum efficiency than other detectors. This means that CCD cameras: (a) can collect photons for longer times; (b) can collect photons of different energies; (c) can generate a signal from fewer photons; (d) can split light into different colors.

6.3 Astronomers Observe in Wavelengths Beyond the Visible

Recall from Chapter 5 that an object's temperature can be found from the peak wavelength of its continuous spectrum. Extending beyond visible light, radio or infrared telescopes are used to study cool objects, like clouds of dust, whereas X-ray or gamma-ray telescopes are used to study violently hot gas. Therefore, astronomers must utilize telescopes that observe at all the wavelengths of the electromagnetic spectrum. However, not all of these wavelengths reach Earth, so some telescopes must be put into space. **Figure 6.20** shows that Earth has a few **atmospheric windows** that let in parts of the spectrum. The largest window is in radio wavelengths, including microwaves at the short-wavelength end of the radio window. These telescopes can be built on the ground. However, gamma-ray, X-ray, ultraviolet, and most of the infrared light arriving at Earth fails to reach the ground because it is partially or completely absorbed by ozone, water vapor, carbon dioxide, and other molecules in Earth's atmosphere. Light at these wavelengths has to be observed from space.

Nebraska Simulation: EM Spectrum Module

Radio Telescopes

Karl Jansky (1905–1950), a young physicist working for Bell Laboratories in the early 1930s, identified a radio source in the Milky Way in the direction of the galactic center, in the constellation Sagittarius. Jansky's discovery marked the birth

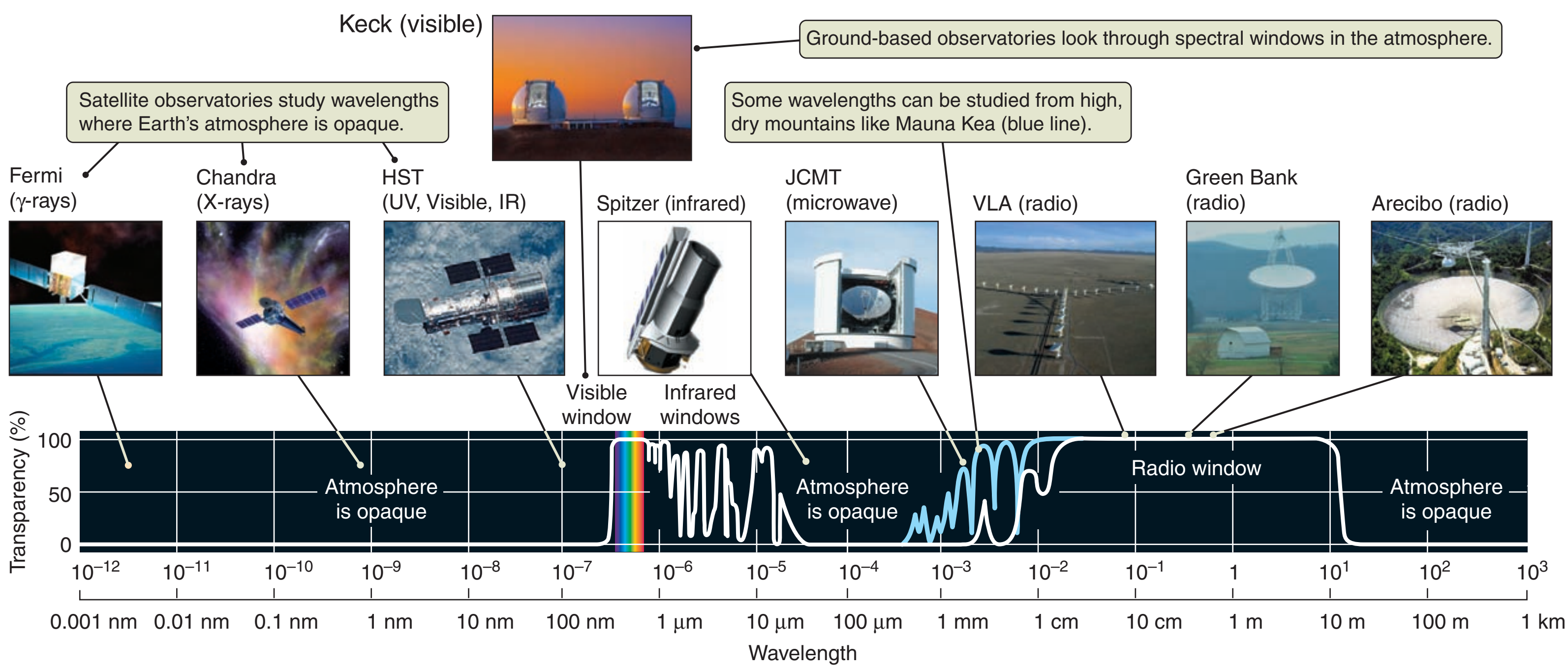


Figure 6.20 Earth's atmosphere blocks most electromagnetic radiation. Fermi = Fermi Gamma-ray Space Telescope (orbiting); Chandra = Chandra X-ray Observatory (orbiting); HST = Hubble Space Telescope (orbiting); Keck = Keck Observatory (Hawaii); Spitzer = Spitzer Space Telescope (orbiting); JCMT = James Clerk Maxwell Telescope (Hawaii); VLA = Very Large Array (New Mexico); Green Bank = Robert C. Byrd Green Bank Telescope (West Virginia); Arecibo = Arecibo Observatory (Puerto Rico).

(a)

(b)

Figure 6.21 (a) The Parkes radio telescope in Australia. (b) The Arecibo radio telescope is the world's largest. The steerable receiver suspended above the dish permits limited pointing toward celestial targets as they pass close to the zenith.

Figure 6.22 The VLA in New Mexico combines signals from 27 different telescopes so that they act as one "very large" telescope.

of radio astronomy, and in his honor, the basic unit for the strength of a radio source is called the **jansky (Jy)**. A few years later, Grote Reber (1911–2002), a radio engineer and ham radio operator, built his own radio telescope and conducted the first survey of the sky at radio frequencies. Reber was largely responsible for the rapid advancement in radio astronomy that blossomed in the post–World War II era.

Most radio telescopes are large, steerable dishes, typically tens of meters in diameter, like the one shown in **Figure 6.21a**. The world's largest single-dish radio telescope is the 305-meter Arecibo dish built into a natural bowl-shaped depression in Puerto Rico (Figure 6.21b). (China is constructing a 500-meter single-dish radio telescope with a similar design.) The Arecibo telescope is not steerable, so it can only observe sources that pass within 20° of the zenith as Earth's rotation carries them overhead.

As large as radio telescopes are, they have relatively poor angular resolution. Recall that a telescope's angular resolution is determined by the ratio λ/D, so a larger ratio means poorer resolution. Radio telescopes have diameters much larger than the apertures of most optical telescopes. However, the wavelengths of radio waves range from about 1 centimeter (cm) to 10 meters, or up to several hundred thousand times greater than the wavelengths of visible light, which makes the ratio larger. Radio telescopes are thus limited by the very long wavelengths they are designed to receive. For example, the resolution of the huge Arecibo dish in Figure 6.21b is typically about 1 arcmin, little better than the unaided human eye.

Radio astronomers have had to develop ways to improve resolution. Mathematically combining the signals from two radio telescopes turns them into a telescope with a diameter equal to the separation between them. For example, if two 10-meter telescopes are located 1,000 meters apart, the D in λ/D is 1,000, not 10. This combination of two (or more) telescopes is called an **interferometer**, and it makes use of the wavelike properties of light. Usually, several telescopes are used in an arrangement called an **interferometric array**. Through the use of very large arrays, radio astronomers can better observe bright sources and exceed the angular resolution possible with optical telescopes.

The Very Large Array (VLA) in New Mexico (**Figure 6.22**) is an interferometric array made up of 27 movable dishes spread out in a Y-shaped configuration up to 36 km across. At a wavelength of 10 cm, this array reaches resolutions of less than 1 arcsec. The Very Long Baseline Array (VLBA) uses 10 radio telescopes spread out over more than 8,000 km from the Virgin Islands in the Caribbean to Hawaii in the Pacific. At a wavelength of 10 cm, this array can attain resolutions of better than 0.003 arcsec. A radio telescope put into near-Earth orbit as part of a Space Very Long Baseline Interferometer (SVLBI) overcomes even this limit. The new Event Horizon Telescope will combine many of the most advanced existing radio telescopes, from Greenland to the South Pole, to make an *Earth-sized* interferometer. A few nights each year, all the telescopes would all observe the same object, with a combined resolution that may be good enough to image the objects near the center of the Milky Way.

Some radio telescopes use large numbers of small dishes. The Atacama Large Millimeter/submillimeter Array (ALMA; **Figure 6.23**), located at an elevation of 5,000 meters in the Atacama Desert in Chile, was completed in 2013. This project, an international collaboration of astronomers from Europe, North America, East Asia, and Chile, consists of sixty-six 12- and 7-meter dishes for observations in the 0.3- to 9.6-mm wavelength range. The Square Kilometre Array (SKA) is designed to have *thousands* of small radio dishes, which together will act as one dish with a collecting area of 1 square kilometer (km^2). Twenty countries are supporting this telescope, which will be located in Australia and South Africa and is scheduled to be built by 2024.

Optical telescopes can also be combined in an array to yield resolutions greater than those of single telescopes, although for technical reasons the individual units cannot be spread as far apart as radio telescopes. The Very Large Telescope Interferometer (VLTI) in Chile, operated by ESO, combines the four Very Large Telescope (VLT) 8-meter telescopes with four movable 1.8-meter auxiliary telescopes. It has a baseline of up to 200 meters, yielding angular resolution of about 0.001 arcsec. The six-telescope Center for High Angular Resolution Astronomy (CHARA) array in California works in visible and near-infrared and has a baseline of 330 meters with similar resolution.

Figure 6.23 The new Atacama Large Millimeter/submillimeter Array (ALMA) telescope in the Atacama Desert in northern Chile has many international partners.

Infrared Telescopes

Molecules such as water vapor in Earth's atmosphere block infrared (IR) photons from reaching astronomical telescopes on the ground, so telescopes that observe in the infrared (0.75–30 microns; μm) are at the highest locations. Mauna Kea, a dormant volcano and home of the Mauna Kea Observatories (MKO), rises 4,200 meters above the Pacific Ocean. At this altitude, the MKO telescopes sit above 40 percent of Earth's atmosphere; but more important, 90 percent of Earth's atmospheric water vapor lies below. Still, for the infrared astronomer the remaining 10 percent is troublesome.

Airborne observatories overcome atmospheric absorption of infrared light by placing telescopes above most of the water vapor in the atmosphere. NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) (**Figure 6.24**), a joint project with the German Aerospace Center (DLR), is a modified 747 airplane that carries a 2.5-meter telescope and works in the far-infrared region of the spectrum, from 1 to 650 μm. It flies in the stratosphere at an altitude of about 12 km, above 99 percent of the water vapor in Earth's lower atmosphere. Because airplanes are highly mobile, SOFIA can observe in both the Northern and Southern hemispheres. Other infrared wavelengths must be observed from space.

Figure 6.24 SOFIA is a 2.5-meter infrared telescope that is mounted in a Boeing 747 aircraft.

Orbiting Observatories

Gaining full access to the complete electromagnetic spectrum requires getting completely above Earth's atmosphere. The first astronomical satellite was the British Ariel 1, launched in 1962 to study solar UV and X-ray radiation. Today, a multitude of orbiting astronomical telescopes cover the electromagnetic spectrum from gamma rays to microwaves, with more in the planning stage (**Table 6.2**). Optical telescopes, such as the 2.4-meter Hubble Space Telescope (HST), operate successfully at low Earth orbit, 600 km above Earth's surface. Launched in 1990, HST has been the workhorse for UV, visible, and IR space astronomy for more than 25 years. Low Earth orbit is also the region where the International Space Station (ISS) and many scientific satellites orbit. For certain other satellites and space telescopes, 600 km is not high enough.

The Chandra X-ray Observatory, NASA's X-ray telescope, cannot see through even the tiniest traces of atmosphere and therefore orbits more than 16,000 km above Earth's surface. NASA's Spitzer Space Telescope, an infrared telescope, is so sensitive that it needs to be completely free from Earth's own infrared

TABLE 6.2 Selected Current and Future Space Observatories

Telescope	Sponsor(s)	Description	Launch Year
Hubble Space Telescope (HST)	NASA, ESA	Optical, infrared, ultraviolet observations	1990
Chandra X-ray Observatory	NASA	X-ray imaging and spectroscopy	1999
X-ray Multi-Mirror Mission (XMM-Newton)	ESA	X-ray spectroscopy	1999
Galaxy Evolution Explorer (GALEX)	NASA	Ultraviolet observations	2003
Spitzer Space Telescope	NASA	Infrared observations	2004
Swift Gamma-Ray Burst Mission	NASA	Gamma-ray bursts	2004
Convection Rotation and Planetary Transits (COROT) space telescope	CNES (France)	Planet finder	2006
Fermi Gamma-ray Space Telescope	NASA, European partners	Gamma-ray imaging and gamma-ray bursts	2008
Planck telescope	ESA	Cosmic microwave background radiation	2009
Herschel Space Observatory	ESA	Far-infrared and submillimeter observations	2009
Kepler telescope	NASA	Planet finder	2009
Solar Dynamics Observatory (SDO)	NASA	Sun, solar weather	2010
RadioAstron	Russia	Very-long-baseline interferometry in space	2011
Nuclear Spectroscopic Telescopic Array (NuSTAR)	NASA	High-energy X-ray	2012
Gaia	ESA	Optical, digital 3D space camera	2013
James Webb Space Telescope (JWST)	NASA, ESA, Canadian Space Agency	Optical and infrared; replacement for HST	2018

radiation. The solution was to put it into a *solar* orbit, trailing tens of millions of kilometers behind Earth. The James Webb Space Telescope, scheduled to replace the HST, will observe primarily in infrared wavelengths. It will be located 1.5 million miles away from Earth, orbiting the Sun at a fixed distance from the Sun and Earth.

Orbiting telescopes located above the atmosphere are not affected by atmospheric image distortions, weather, or brightening night skies. But space observatories are much more expensive than ground-based observatories and can be difficult or impossible to repair. The HST required several servicing missions, but such missions are not possible for the observatories in more distant Earth orbits. Ground-based telescopes at even the most remote mountaintop locations can receive shipments of replacement parts in a few days; space telescopes cannot. Of course, some wavelengths can be observed from space only. But issues of cost and repair are the reason why ground-based telescopes are much more prevalent.

CHECK YOUR UNDERSTANDING 6.4

Which of the following is the biggest disadvantage of putting a telescope in space? (a) Astronomers don't have as much control in choosing what to observe. (b) Astronomers have to wait until the telescopes come back to Earth to get their images. (c) Space telescopes can only observe in certain parts of the electromagnetic spectrum. (d) Space telescopes are much more expensive than similar ground-based telescopes.

6.4 Planetary Spacecraft Explore the Solar System

Recall from Chapter 2 that everyone always sees the same face of the Moon from Earth because the Moon's orbital and rotational periods are equal. The first view of the "far" side was in 1959, when the Soviet flyby mission *Luna 3* sent back pictures showing that the far side of the Moon was very different from its Earth-facing half. No matter how powerful our ground-based or Earth-orbiting telescopes, sometimes we need to send a spacecraft for a different view.

Only in the past half century has the technology existed to explore the Solar System. Spacecraft have now visited all of the planets and some of their moons, as well as a few comets and asteroids, providing the first close-up views of these distant worlds. The study of the Solar System from space is an international collaboration involving NASA, the European Space Agency (ESA), the Russian Federal Space Agency (Roscosmos), the Japan Aerospace Exploration Agency (JAXA), the China National Space Administration (CNSA), and the Indian Space Research Organisation (ISRO). Other countries may soon join the endeavor. In this section, we will look at the different types of spacecraft used to explore our Solar System.

Flybys and Orbiters

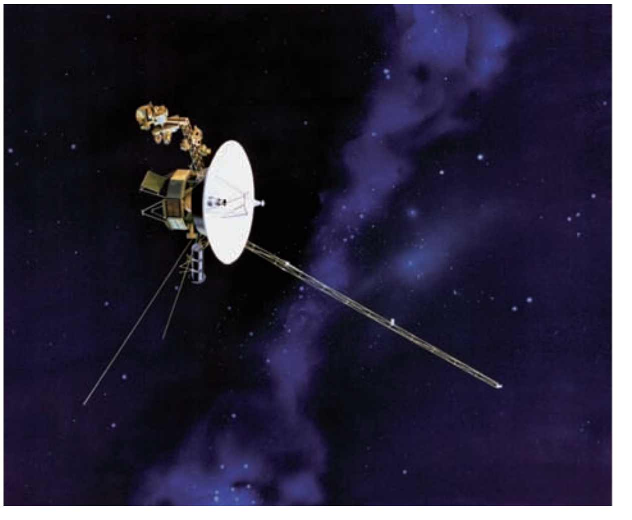
Exploration of the Solar System began with a reconnaissance phase, using spacecraft to fly by or orbit a planet or other body. A **flyby** is a spacecraft that first approaches and then continues flying past the target. As these spacecraft speed by, instruments aboard them briefly probe the physical and chemical properties of the target and its environment.

Flyby missions are the most common first phase of exploration. They cost less than orbiters or landers and are easier to design and execute. Flyby spacecraft such as *Voyager* are sometimes able to visit several different worlds during their travels (**Figure 6.25**). The downside of flyby missions is that because of the physics of orbits, these spacecraft must move by very swiftly. They are limited to just a few hours or at most a few days in which to conduct close-up studies of their targets. Flyby spacecraft provide astronomers with their first close-up views of Solar System objects, and sometimes the data obtained are then used for planning follow-up studies.

More detailed reconnaissance work is done by spacecraft known as **orbiters** because they orbit around their target. These missions are intrinsically more difficult than flyby missions because they have to make risky maneuvers and use up fuel to change their speed to enter an orbit. But orbiters can linger, looking in detail at more of the surfaces of the objects they are orbiting and studying things that change with time, like planetary weather.

Orbiters use remote-sensing instrumentation like that used by Earth-orbiting satellites to study our own planet. These instruments include tools such as cameras that take images at different wavelength ranges, radar that can map surfaces hidden beneath obscuring layers of clouds, and spectrographs that analyze the electromagnetic spectrum. These instruments enable planetary scientists to map other worlds, measure the heights of mountains, identify geological features and rock types, watch weather patterns develop, measure the composition of atmospheres, and get a general sense of the place. Additional instruments make

(a)



(b)

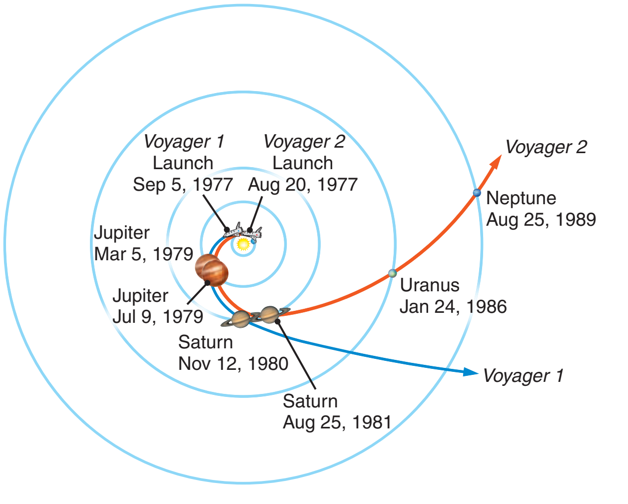


Figure 6.25 The *Voyager* spacecraft (a) flew past the outer planets and (b) are now near the boundary of our Solar System.

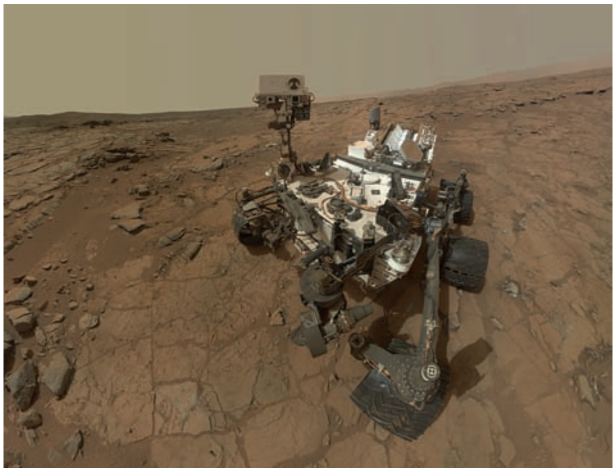


Figure 6.26 The robotic rover *Curiosity* took this photograph of itself on the surface of Mars.

measurements of the extended atmospheres and space environment through which they travel.

Landers, Rovers, and Atmospheric Probes

Reconnaissance spacecraft provide a wealth of information about a planet, but there is no better way of exploring a planet than within a planet's atmosphere or on solid ground. Spacecraft have landed on the Moon, Mars, Venus, Saturn's large moon Titan, several asteroids, and a comet. These spacecraft have taken pictures of planetary surfaces, measured surface chemistry, and conducted experiments to determine the physical properties of the surface rocks and soils.

There are several disadvantages of using **landers**—spacecraft that touch down and remain on the surface. Because of the expense, only a few landings in limited areas are practical. Given this limitation, the results may apply only to the small area around the landing site. Imagine, for example, what a different picture of Earth you might get from a spacecraft that landed in Antarctica, as opposed to a spacecraft that landed in a volcano or on the floor of a dry riverbed. Sites to be explored with landed spacecraft must be very carefully chosen on the basis of reconnaissance data. Some landers have wheels and can explore the vicinity of the landing site. Such remote-controlled vehicles, called **rovers**, were used first by the Soviet Union on the Moon four decades ago and more recently by the United States on Mars. **Figure 6.26** shows a self-portrait of the *Curiosity* rover on Mars.

Atmospheric probes descend into the atmospheres of planets and continually measure and send back data on temperature, pressure, and wind speed, along with other properties, such as chemical composition. Atmospheric probes have survived all the way to the solid surfaces of Venus and Saturn's moon Titan, sending back streams of data during their descent. An atmospheric probe sent into Jupiter's atmosphere never reached that planet's surface because, as we will discuss later in the book, Jupiter does not have a solid surface in the same sense that terrestrial planets and moons do. After sending back its data, the Jupiter probe eventually melted and vaporized as it descended into the hotter layers of the planet's atmosphere.

Sample Returns

If you pick up a rock from the side of a mountain road, you might learn a lot from the rock using tools that you could carry in your pocket or your car. But it would be much better to pick up a few samples and carry them back to a laboratory equipped with a full range of state-of-the-art instruments capable of measuring chemical composition, mineral type, age, and other information needed to reconstruct the story of your rock sample's origin and evolution. The same is true of Solar System exploration. One of the most powerful methods for investigating remote objects is to collect samples of the objects and bring them back to Earth for detailed study. So far, only samples of the Moon, a comet, and streams of charged particles from the Sun have been collected and returned to Earth. Scientists have found meteorites on Earth that are likely pieces of Mars that were blasted loose by objects that crashed into Mars. Someday, there may be unmanned "sample and return" missions to Mars.

The missions discussed so far in this section have all been conducted with robotic spacecraft. The only spacecraft that took people to another world were the *Apollo* missions to the Moon. This program ran from 1961 to 1972 and included several missions before the actual Moon landings. The *Apollo 8* astronauts brought back the famous picture of Earth viewed over the surface of the Moon (see the opening figure of Chapter 1). Each mission from *Apollo 11* through *Apollo 17* had three astronauts—two to land on the Moon and one to remain in orbit. One mission (*Apollo 13*) did not reach the Moon but returned to Earth safely. Twelve American astronauts walked on the Moon between 1969 and 1972 and brought back a total of 382 kg of rocks and other material.

The return of extraterrestrial samples to Earth is governed by international treaties and standards to ensure that these samples do not contaminate Earth. For example, before the lunar samples brought back by the *Apollo* missions could be studied, they (and the astronauts) had to be placed in quarantine and tested for alien life-forms. The same international standards apply to spacecraft landing on other planets. The goal of these standards is to avoid transporting life-forms from Earth to another planet. If there is life on other planets, there is concern about introducing potential harm, and we do not want to "discover" life that we, in fact, introduced.

With numerous missions under way and others on the horizon, unmanned exploration of the Solar System is an ongoing, dynamic activity. Appendix 5 summarizes some recent and current missions. Information on the latest discoveries can be found on mission websites and in science news sources.

CHECK YOUR UNDERSTANDING 6.5

Spacecraft are the most effective way to study planets in our Solar System because: (a) planets move too fast across the sky for us to image them well from Earth; (b) planets cannot be imaged from Earth; (c) they can collect more information than is available just from images from Earth; (d) space missions are easier than long observing campaigns.

6.5 Other Tools Contribute to the Study of the Universe

High-profile space missions have sent back stunning images and data from across the electromagnetic spectrum, but astronomers use other tools as well, including particle accelerators and colliders, neutrino and gravitational-wave detectors, and high-speed computers.

Particle Accelerators

Ever since the early years of the 20th century, physicists have been peering into the structure of the atom by observing what happens when small particles collide. By the 1930s, physicists had developed the technology to accelerate charged subatomic particles such as protons to very high speeds and then observe what happens when they slam into a target. From such experiments, physicists have discovered many kinds of subatomic particles and learned about their physical properties. High-energy particle colliders have proved to be an essential tool for physicists studying the basic building blocks of matter.

Astronomers have realized that to understand the very largest structures seen in the universe, it is important to understand the physics that took place during

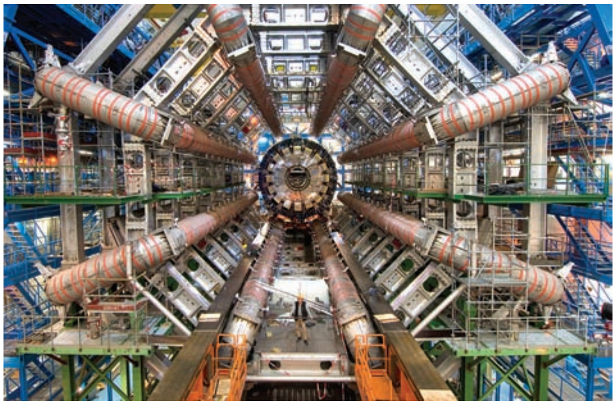


Figure 6.27 The ATLAS particle detector at CERN's Large Hadron Collider near Geneva, Switzerland. The enormous size of this instrument is evident from the person standing near the bottom center of the picture.

the earliest moments in the universe, when everything was extremely hot and dense. High-energy particle colliders that physicists use today are designed to approach the energies of the early universe. The effectiveness of particle accelerators is determined by the energy they can achieve and the number of particles they can accelerate. Modern particle colliders such as the Large Hadron Collider near Geneva, Switzerland (**Figure 6.27**), reach very high energies. Particles can also be studied from space. The Alpha Magnetic Spectrometer, installed on the International Space Station in 2011, searches for some of the most exotic forms of matter, such as dark matter, antimatter, and high-energy particles called cosmic rays.

Neutrinos and Gravitational Waves

The **neutrino** is an elusive elementary particle that plays a major role in the physics of the interiors of stars. Neutrinos are extremely difficult to detect. In less time than it takes you to read this sentence, a thousand trillion (10^{15}) solar neutrinos from the Sun are passing through your body, even during the night. Neutrinos are so nonreactive with matter that they can pass right through Earth (and you) as though it (or you) weren't there at all. A neutrino has to interact with a detector to be observed. Neutrino detectors typically record only one out of every 10^{22} (10 billion trillion) neutrinos passing though them, but that's enough to reveal processes deep within the Sun or the violent death of a star 160,000 light-years away.

Experiments designed to look for neutrinos originating outside of Earth are buried deep underground in mines or caverns or under the ocean or ice to ensure that only neutrinos are detected. For example, the ANTARES experiment uses the Mediterranean Sea as a neutrino telescope. Detectors located 2.5 km under the sea, off the coast of France, observe neutrinos that originated in objects visible in southern skies and passed through Earth. In the IceCube neutrino observatory located at the South Pole in Antarctica, the neutrino detectors are 1.5–2.5 km under the ice, and they observe neutrinos that originated in objects visible in northern skies (**Figure 6.28**).

Another elusive phenomenon is the **gravitational wave**. Gravitational waves are disturbances in a gravitational field, similar to the waves that spread out from the disturbance you create when you toss a pebble onto the quiet surface of a pond. There is strong, although indirect, observational evidence for the existence of gravitational waves, but they are so elusive that they have not yet actually been detected (**Process of Science Figure**). Several facilities, including the Laser Interferometer Gravitational-Wave Observatory (LIGO), have been constructed to detect gravitational waves. Scientists are eager to detect gravitational waves—to confirm their existence and to study the physical phenomena they are likely to reveal, such as the birth and evolution of the universe, stellar evolution, or the very force of gravity itself.

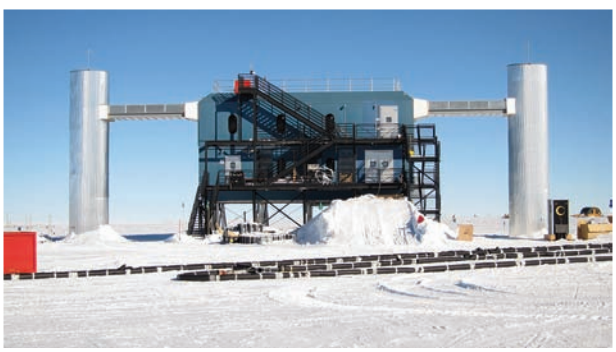


Figure 6.28 The IceCube neutrino telescope at the South Pole, Antarctica.

Computers

Astronomers use powerful computers for data gathering, analysis, and interpretation. A single CCD image may contain as many as 100 million pixels, with each pixel displaying roughly 30,000 levels of brightness. That adds up to several trillion pieces of information in each image. To analyze their data, astronomers typically do calculations on *every single pixel* of an image in order to remove unwanted contributions from Earth's atmosphere or to correct for instrumental effects. Astronomers conduct many different types of sky surveys—in which one or more

Process of Science

TECHNOLOGY AND SCIENCE ARE SYMBIOTIC

Scientists have been searching for waves that carry gravitational information for nearly 100 years, but the accuracy of their measurements is limited by the available technology.

Take 1

Weber Bar

Precision-machined bars of metal that should "ring" as a gravitational wave passes by.

Sensitive only to extremely powerful gravitational waves.

No detection.

Take 2

LIGO

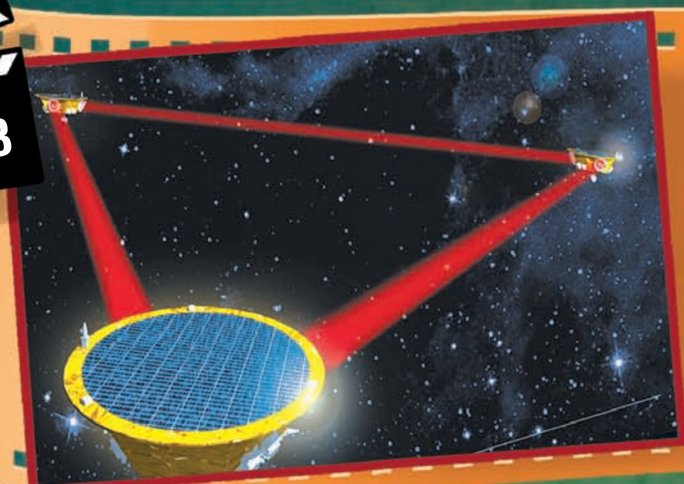
New Technology: Lasers

Lasers should interfere as gravitational waves pass by.

Roughly 100 times more sensitive than Weber bar measurements.

No detection (yet).

Take 3



Future Science Mission

Lasers will interfere as gravitational waves pass by.

Sensitive to more types of objects than LIGO is.

Technology and science develop together. New technologies enable humans to ask new scientific questions. Asking scientific questions pushes the development of better instrumentation. Deeper scientific understanding leads to new technologies.

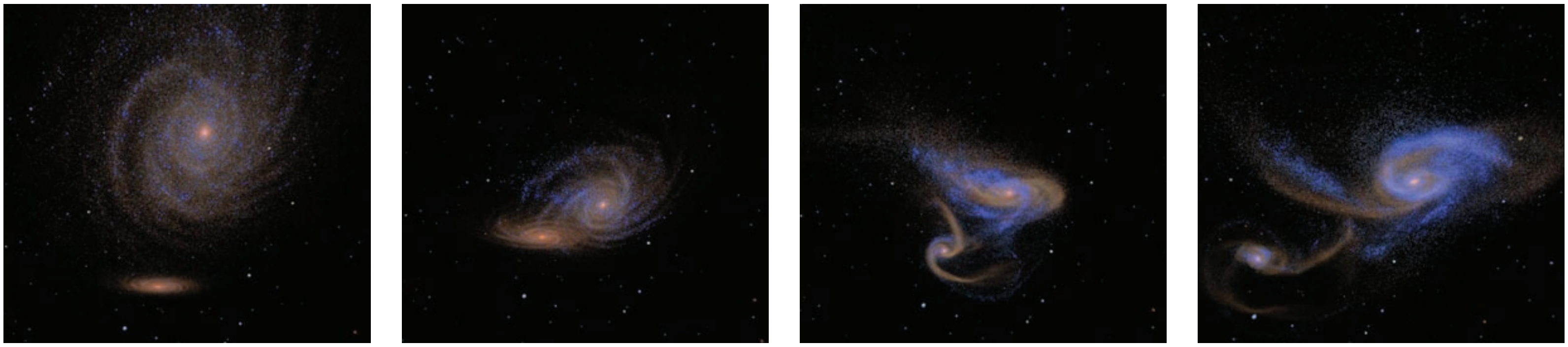


Figure 6.29 These images show supercomputer simulations of the collision of two galaxies. Astronomers compare simulations like these with telescopic observations.

telescopes survey a specific part of the sky—yielding thousands of images that need to be analyzed.

High-speed computers also play an essential role in generating and testing theoretical models of astronomical objects. Even when we completely understand the underlying physical laws that govern the behavior of a particular object, often the object is so complex that it would be impossible to calculate its properties and behavior without the assistance of high-speed computers. For example, as you learned in Chapter 4, you can use Newton's laws to compute the orbits of two stars that are gravitationally bound to one another, because their orbits take the form of simple ellipses. However, it is not so easy to understand the orbits of the several hundred billion stars that make up the Milky Way Galaxy, even though the underlying physical laws are the same.

Computer modeling is used to determine the interior properties of stars and planets, including Earth. Although astronomers cannot see beneath the surfaces of these bodies, they have a surprisingly good understanding of the interiors of these bodies, as we will describe in later chapters. Astronomers start a model by assigning well-understood physical properties to tiny volumes within a planet or star. The computer assembles an enormous number of these individual elements into an overall representation. When it is all put together, the result is a rather good picture of what the interior of the star or planet is like.

Astronomers also use supercomputers to study the evolution of astronomical objects, systems of objects, or the universe as a whole over time. For example, astronomers create models of galaxies, and then run computer simulations to study how those galaxies might change over billions of years. **Figure 6.29** shows a simulation of the collision of two galaxies. The results of the computer simulations are then compared with telescopic observations. If the simulations do not match the observations, then adjustments are made to the model and the simulations are run again until there is general agreement between them.

CHECK YOUR UNDERSTANDING 6.6

High-speed computers have become one of an astronomer's most important tools. Which of the following require the use of a high-speed computer? (Choose all that apply.) (a) analyzing images taken with very large CCDs; (b) generating and testing theoretical models; (c) pointing a telescope from object to object; (d) studying the evolution of astronomical objects or systems over time.

Origins

Microwave Telescopes Detect Radiation from the Big Bang

In this chapter, we explored the tools of the astronomer, from basic optical telescopes to instruments that observe in different wavelengths. Now let's examine in more detail one type of telescope that has aided the study of the origin of the universe. Recall from Chapter 1 that astronomers think the universe originated with a hot Big Bang. The multiple strands of evidence for this conclusion will be discussed in Chapter 21. Here, we look at one piece: the observation of faint microwave radiation left over from the early hot universe. Two Bell Laboratories physicists, Arno Penzias (1933–) and Robert Wilson (1936–), were working on satellite communications when they first accidentally detected this radiation in 1964 with a microwave dish antenna in New Jersey. Today, we routinely use cell phones and handheld GPS systems that communicate directly with satellites, but at the time, this capability was at the limit of technology.

Penzias and Wilson needed a very sensitive microwave telescope for the work they were doing for Bell Labs, because any spurious signals coming from the telescope itself might wash out the faint signals bounced off a satellite. To that end, they were working very hard to eliminate all possible sources of interference originating from within their instrument, including keeping the telescope free of bird droppings. They found that no matter how carefully they tried to eliminate sources of extraneous noise, they always still detected a faint signal at microwave wavelengths. This faint signal was the same in every direction and turned out to be from the Big Bang. Penzias and Wilson shared the 1978 Nobel Prize in Physics for the discovery of this **cosmic microwave background radiation (CMB)** left over from the Big Bang itself.

Since 1964, astronomers from around the world have designed increasingly precise instruments to measure this radiation from the ground, from high-altitude balloons, from rockets, and from satellites. The Russian experiment RELIKT-1, launched in 1983, found some limits on the variation of the CMB. The COBE (Cosmic Background Explorer) satellite, launched in 1989, showed that the spectrum of this radiation precisely matched that of a blackbody with a temperature of 2.73 K—exactly what was predicted for the radiation left over from the Big Bang. (Compare **Figure 6.30** with the curves in Figure 5.22.) The data also showed some slight differences in temperature—small fractions of a degree—over the map of the sky. These slight variations tell us about how the universe evolved from one that was dominated by radiation to one that contains structures such as galaxies, stars, planets, and us. John Mather and George Smoot shared the 2006 Nobel Prize in Physics for this work.

In 1998 and 2003, a high-altitude balloon experiment called BOOMERANG (short for "balloon observations of millimetric extragalactic radiation and geophysics") flew over Antarctica at an altitude of 42 km to study CMB variations and estimate the overall geometry of the universe. The *WMAP* (Wilkinson Microwave Anisotropy Probe) satellite, launched in 2001, created an even more detailed map of the temperature variations in this radiation, yielding more precise values for the age and shape of the universe and the presence of dark matter and dark energy. The Atacama Cosmology Telescope (Chile) and the South Pole Telescope (Antarctica) study this radiation to look for evidence of when galaxy clusters formed. The newest microwave observatory in space, the Planck telescope, was launched in 2009 by the European Space Agency. Planck has much greater sensitivity than *WMAP* and studied these CMB variations in even more precise detail. These experiments and observations have opened up the current era of precision cosmology, in which astronomers can make detailed models of how the universe was born, eventually leading to stars, planets, and us.

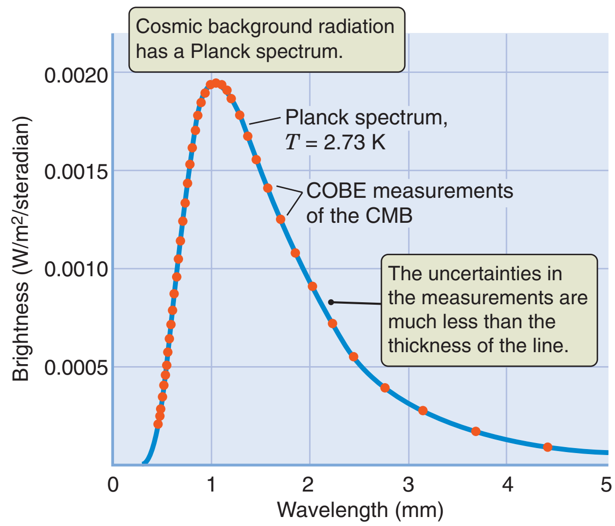


Figure 6.30 This graph shows the spectrum of the cosmic microwave background radiation (CMB) as measured by the COBE satellite (red dots). A steradian is a unit of solid angle. The uncertainty in the measurement at each wavelength is much less than the size of a dot. The line running through the data is a Planck blackbody spectrum with a temperature of 2.73 K.

Planning to build a new large telescope can involve many complications, including negotiations among different countries and among people who live near the site of the telescope.

ARTICLES QUESTIONS

Big Mirrors, High Hopes: Extremely Large Telescope Is a Go

By **CALEB A. SCHARF**

In astronomy, bigger is almost always better. The size of a telescope's aperture (or primary optical element) not only determines how many pesky little photons it can capture, but also the ultimate resolution of the image that can be formed. The challenge is to fabricate optics on large scales, find somewhere really good to put them, and to build the massive structure to house them and the sensitive instruments to analyze the photons that come out of the pipeline.

Now one of the world's next generation of huge telescopes has been given the green light to push ahead with construction and operation. At an astonishing 39.3 meters in diameter, the European Extremely Large Telescope, or E-ELT (one can only hope a more poetic name is eventually chosen), will hold the crown for sheer girth among optical and infrared sensitive telescopes. With an authorized spending of about a billion euros (about $1.24B) the project can move ahead, with an anticipated "first light" sometime in 2024.

Although E-ELT is not alone in the race for so-called "30-meter class" telescopes (with the Thirty Meter Telescope and Giant Magellan observatories also on track, and also extraordinarily powerful), it's definitely the Hulk of the bunch.

Observatories on this scale will have profound impact on how we study the universe around us, from cosmology to planets.

A telescope like E-ELT will peer at the faintest, most distant objects in the young cosmos, and it'll be capable of sensing the atmospheric signatures of life in a few nearby terrestrial-type exoplanets (including the presence of oxygen). These tasks require an enormous "light bucket" to catch enough photons, but perhaps one of the most vivid examples of the gain of a big telescope comes from considering the resolving power.

Equipped with adaptive optics, E-ELT should, for example, be able to routinely study Jupiter down to scales of about 20 kilometers—by comparison the Great Red Spot is at present about 20,000 kilometers across. Mars can be imaged to roughly 5-kilometer resolution (depending of course on the relative separation of Earth). In other words, on a nightly basis we will be able to monitor the worlds in our Solar System with a fidelity comparable to flyby missions of yore.

Preparations have already begun. In June 2014, explosives were used to help level the mountaintop where E-ELT will sit—Cerro Armazones in northern Chile, a dry peak at about 3,000 meters altitude where the night skies are cloudless 89 percent of the time.

What rises there over the next 10 years will help take our understanding of the universe to a whole new level.

ARTICLES QUESTIONS

1. Why do astronomers want to build at this particular location?
2. What are the advantages of larger telescopes?
3. How can adaptive optics yield images as good as those from old space missions?
4. Why will this telescope observe only in optical and infrared wavelengths?
5. Do a Web search to see the status of this project. What countries are partners? Is there any local opposition to the project in the host country?

Summary

Earth's atmosphere blocks many spectral regions and distorts telescopic images. Telescopes are sited to be above as much of the atmosphere as possible. Telescopes are matched to the wavelengths of observation, with different technologies required for each region of the spectrum. The aperture of a telescope both determines its light-gathering power and limits its resolution; larger telescopes are better in both measures. Modern CCD cameras have improved quantum efficiency and longer integration times, which allow astronomers to study fainter and more distant objects than were observable with prior detectors. Telescopes observing at microwave wavelengths have detected radiation left over from the Big Bang.

LG 1 **Compare the two main types of optical telescopes and how they gather and focus light.** The telescope is the astronomer's most important tool. Ground-based telescopes that observe in visible wavelengths come in two basic types: refractors (lenses) and reflectors (mirrors). All large astronomical telescopes are reflectors. Large telescopes collect more light and have greater resolution. The diffraction limit is the limiting resolution of a telescope.

LG 2 **Summarize the main types of detectors that are used on telescopes.** Photography improved the ability of astronomers to record details of faint objects seen in telescopes. CCDs are today's astronomical detector of choice because they are much more linear, have a broader spectral response, and can send electronic images directly to a computer. Spectrographs are specialized instruments that take the spectrum of an object to reveal what the object is made of and many other physical properties.

LG 3 **Explain why some wavelengths of radiation must be observed from space.** Radio telescopes are able to see through our atmosphere. Radio, near-infrared, and optical telescopes can be arrayed to greatly increase angular resolution. Putting telescopes in space solves problems created by Earth's atmosphere.

LG 4 **Explain the benefits of sending spacecraft to study the planets and moons of our Solar System.** Most of what is known about the planets and moons comes from observations by spacecraft. Flyby and orbiting missions obtain data from space, and landers and rovers collect data from the ground.

LG 5 **Describe other astronomical tools that contribute to the study of the universe.** Astronomers also use particle accelerators, neutrino detectors, and gravitational-wave detectors to study the universe. High-speed computers are essential to the acquisition, analysis, and interpretation of astronomical data.

? UNANSWERED QUESTIONS

- Will telescopes be placed on the Moon? The Moon has no atmosphere to make stars twinkle, cause weather, or block certain wavelengths of light from reaching its surface. The far side of the Moon faces away from the light and radio radiation of Earth, and all parts of the Moon have nights that last for two Earth weeks. One proposal calls for a Lunar Array for Radio Cosmology (LARC), an array of hundreds of radio telescopes that would be deployed on the Moon—after the year 2025—to study the earliest formation of stars and galaxies. Another proposal is for the Lunar Liquid Mirror Telescope (LLMT), with a diameter of 20–100 meters, to be located at one of the Moon's poles. Gravity would settle the rotating liquid into the necessary parabolic shape, and these liquid mirror telescopes are much simpler than are arrays of telescopes with large glass mirrors. The LLMT would observe extremely distant protostars and protogalaxies in infrared wavelengths. Astronomers debate whether telescopes on the Moon would be easier to service and repair than those in space and whether problems caused by lunar dust would outweigh any advantages.
- Will there be human exploration of the Solar System within your lifetime? Since the *Apollo* program, humans have not returned to the Moon or traveled to other planets or moons in the Solar System. Sending humans to the worlds of the Solar System is much more complicated, risky, and more expensive than sending robotic spacecraft. Humans need life support such as air, water, and food. Radiation in space can be dangerous. Furthermore, human explorers would expect to return to Earth, whereas most spacecraft do not come back. Astronomers and space scientists have heated debates about human spaceflight versus robotic exploration. Some argue that true exploration requires that human eyes and brains actually go there; others argue that the costs and risks are too high for the potential additional scientific knowledge. Beyond basic exploration, we also do not know whether humans will ever permanently colonize space.

Questions and Problems

Test Your Understanding

1. You are shopping for telescopes online. You find two in your price range. One of these has an aperture of 20 cm, and the other has an aperture of 30 cm. If aperture size is the only difference, which should you choose, and why?
   a. The 20 cm, because the light-gathering power will be better.
   b. The 20 cm, because the image size will be larger.
   c. The 30 cm, because the light-gathering power will be better.
   d. The 30 cm, because the image size will be larger.

2. Which of the following can be observed from Earth's surface? (Choose all that apply.)
   a. radio waves
   b. gamma radiation
   c. far UV light
   d. X-ray light
   e. visible light

3. Match the following properties of telescopes (lettered) with their corresponding definitions (numbered).

a. aperture	(1) two or more telescopes connected to act as one
b. resolution	(2) distance from lens to focal plane
c. focal length	(3) diameter
d. chromatic aberration	(4) ability to distinguish close objects
e. diffraction	(5) computer-controlled atmospheric distortion correction
f. interferometer	(6) color-separating effect
g. adaptive optics	(7) smearing effect due to sharp edge

4. The two Keck 10-meter telescopes, separated by a distance of 85 meters, can operate as an optical interferometer. What is its resolution when it observes in the infrared at a wavelength of 2 microns?
   a. 0.01 arcsec
   b. 0.005 arcsec
   c. 0.2 arsec
   d. 0.05 arcsec

5. Arrays of radio telescopes can produce much better resolution than single-dish telescopes because they work based on the principle of
   a. reflection.
   b. refraction.
   c. diffraction.
   d. interference.

6. Refraction is caused by
   a. light bouncing off a surface.
   b. light changing colors as it enters a new medium.
   c. light changing speed as it enters a new medium.
   d. two light beams interfering.

7. The light-gathering power of a 4-meter telescope is ___________ than that of a 2-meter telescope.
   a. 8 times larger
   b. 4 times larger
   c. 16 times smaller
   d. 2 times smaller

8. Improved resolution is helpful to astronomers because
   a. they often want to look in detail at small features of an object.
   b. they often want to look at very distant objects.
   c. they often want to look at many objects close together.
   d. all of the above

9. The part of the human eye that acts as the detector is the
   a. retina.
   b. pupil.
   c. lens.
   d. iris.

10. Cameras that use adaptive optics provide higher-spatial-resolution images primarily because
    a. they operate above Earth's atmosphere.
    b. deformable mirrors are used to correct the blurring due to Earth's atmosphere.
    c. composite lenses correct for chromatic aberration.
    d. they simulate a much larger telescope.

11. The advantage of an interferometer is that
    a. the resolution is dramatically improved.
    b. the focal length is dramatically increased.
    c. the light-gathering power is dramatically increased.
    d. diffraction effects are dramatically decreased.
    e. chromatic aberration is dramatically decreased.

12. The angular resolution of a ground-based telescope is usually determined by
    a. diffraction.
    b. the focal length.
    c. refraction.
    d. atmospheric seeing.

13. A grating is able to spread white light out into a spectrum of colors because of the property of
    a. reflection.
    b. diffraction.
    c. dispersion.
    d. interference.

14. Why would astronomers put telescopes in airplanes?
    a. to get the telescopes closer to the stars
    b. to get the telescopes above the majority of the water vapor in Earth's atmosphere
    c. to be able to observe one object for more than 24 hours without stopping
    d. to allow the telescopes to observe the full spectrum of light

15. If we could increase the quantum efficiency of the human eye, it would
    a. allow humans to see a larger range of wavelengths.
    b. allow humans to see better at night or in other low-light conditions.
    c. increase the resolution of the human eye.
    d. decrease the resolution of the human eye.

Thinking about the Concepts

16. Galileo's telescope used simple lenses. What is the primary disadvantage of using a simple lens in a refracting telescope?

17. The largest astronomical refractor has an aperture of 1 meter. List several reasons why it would be impractical to build a larger refractor with twice this aperture.

18. Your camera may have a zoom lens, ranging between wide angle (short focal length) and telephoto (long focal length). How does the size of an object in the camera's focal plane differ between wide angle and telephoto?

19. Optical telescopes reveal much about the nature of astronomical objects. Why do astronomers also need information provided by gamma-ray, X-ray, infrared, and radio telescopes?

20. For light reflecting from a flat surface, the angles of incidence and reflection are the same. This is also true for light reflecting from the curved surface of a reflecting telescope's primary mirror. Sketch a curved mirror and several of these reflecting rays.

21. Consider two optically perfect telescopes having different diameters but the same focal length. Is the image of a star larger or smaller in the focal plane of the larger telescope? Explain your answer.

22. Study the Process of Science Figure. Make a flowchart for the symbiosis between technology and science that led to the development of the CCD camera as discussed in Section 6.2.

23. Explain adaptive optics and how they improve a telescope's image quality.

24. Explain integration time and quantum efficiency and how each contributes to the detection of faint astronomical objects.

25. Some people believe that we put astronomical telescopes on high mountaintops or in orbit because doing so gets them closer to the objects they are observing. Explain what is wrong with this popular misconception, and give the actual reason telescopes are located in these places.

26. Humans have sent various kinds of spacecraft—including flybys, orbiters, and landers—to all of the planets in our Solar System. Explain the advantages and disadvantages of each of these types of spacecraft.

27. If there are meteorites that are pieces of Mars on Earth, why is it so important to go to Mars and bring back samples of the martian surface?

28. Humans had a first look at the far side of the Moon as recently as 1959. Why had we not seen it earlier—when Galileo first observed the Moon with his telescope in 1610?

29. Where are neutrino detectors located? Why are neutrinos so difficult to detect?

30. Why do telescopes in space give a better picture of the leftover radiation from the Big Bang?

Applying the Concepts

31. Compare the light-gathering power of the Thirty Meter Telescope with that of the dark-adapted human eye (aperture 8 mm) and with that of one of the 10-meter Keck telescopes.

32. Study the photograph of light entering and leaving a block of refractive material in Figure 6.2b. Use a protractor to measure the angles of the green light as it enters the block and as it leaves the block. How are these angles related?

33. Many amateur astronomers start out with a 4-inch (aperture) telescope and then graduate to a 16-inch telescope. By what factor does the light-gathering power of the telescope increase with this upgrade? How much fainter are the faintest stars that can be seen in the larger telescope?

34. The resolution of the human eye is about 1.5 arcmin. What would the aperture of a radio telescope (observing at 21 cm) have to be to have this resolution? Even though the atmosphere is transparent at radio wavelengths, humans do not see light in the radio range. Using your calculations and logic, explain why.

35. Assume that you have a telescope with an aperture of 1 meter. Compare the telescope's theoretical resolution when you are observing in the near-infrared region of the spectrum ($\lambda = 1{,}000$ nm) with that when you are observing in the violet region of the spectrum ($\lambda = 400$ nm).

36. Assume that the maximum aperture of the human eye, D, is approximately 8 mm and the average wavelength of visible light, λ, is 5.5×10^{-4} mm.
    a. Calculate the diffraction limit of the human eye in visible light.
    b. How does the diffraction limit compare with the actual resolution of 1–2 arcmin (60–120 arcsec)?
    c. To what do you attribute the difference?

37. The diameter of the full Moon in the focal plane of an average amateur's telescope (focal length 1.5 meters) is 13.8 mm. How big would the Moon be in the focal plane of a very large astronomical telescope (focal length 250 meters)?

38. One of the earliest astronomical CCDs had 160,000 pixels, each recording 8 bits (256 levels of brightness). A new generation of astronomical CCDs may contain a billion pixels, each recording 15 bits (32,768 levels of brightness). Compare the number of bits of data that each of these two CCD types produces in a single image.

39. Consider a CCD with a quantum efficiency of 80 percent and a photographic plate with a quantum efficiency of 1 percent. If an exposure time of 1 hour is required to photograph a celestial object with a given telescope, how much observing time would be saved by substituting a CCD for the photographic plate?

40. The VLBA uses an array of radio telescopes ranging across 8,000 km of Earth's surface from the Virgin Islands to Hawaii.
    a. Calculate the angular resolution of the array when radio astronomers are observing interstellar water molecules at a microwave wavelength of 1.35 cm.
    b. How does this resolution compare with the angular resolution of two large optical telescopes separated by 100 meters and operating as an interferometer at a visible wavelength of 550 nm?

41. When operational, the SVLBI may have a baseline of 100,000 km. What will be the angular resolution when studying interstellar molecules emitting at a wavelength of 17 mm from a distant galaxy?

42. The *Mars Reconnaissance Orbiter* (*MRO*) flies at an average altitude of 280 km above the martian surface. If its cameras have an angular resolution of 0.2 arcsec, what is the size of the smallest objects that the *MRO* can detect on the martian surface?

43. *Voyager 1* is now about 125 astronomical units (AU) from Earth, continuing to record its environment as it approaches the limits of our Solar System.
    a. How far away is *Voyager 1*, in kilometers?
    b. How long does it take observational data to come back to us from *Voyager 1*?
    c. How does *Voyager 1*'s distance from Earth compare with that of the nearest star (other than the Sun)?

44. Gravitational waves travel at the speed of light. Their speed, wavelength, and frequency are related as $c = \lambda \times f$. If we were to observe a gravitational wave from a distant cosmic event with a frequency of 10 hertz (Hz), what would be the wavelength of the gravitational wave?

45. Compute the peak of the blackbody spectrum with a temperature of 2.73 K. What region of the spectrum is this?

USING THE WEB

46. A webcast for the International Year of Astronomy 2009 called "Around the World in 80 Telescopes" can be accessed at http://eso.org/public/events/special-evt/100ha.html. The 80 telescopes are situated all over, including Antarctica and space. Pick two of the telescopes and watch the videos. Do you think these videos are effective for public outreach for the observatory in question or for astronomy in general? For each telescope you choose, answer the following questions: Does the telescope observe in the Northern Hemisphere or the Southern Hemisphere? What wavelengths does the telescope observe? What are some of the key science projects at the telescope?

47. Most major observatories have their own websites. Use the link in question 46 to find a master list of telescopes, and click on a telescope name to link to an observatory website (or run a search on names from Tables 6.1 and 6.2). For the telescope you choose, answer the following questions: (a) What is this telescope's "claim to fame"—is it the largest? at the highest altitude? at the driest location? with the darkest skies? the newest? (b) Does the observatory website have news releases? What is a recent discovery from this telescope?

48. Go to the website for the International Dark Sky Association (http://www.darksky.org/). Click on "Night Sky Conservation" and then "Do you live under light pollution?" Is your location dark? From the menu on the left, is there a "dark sky park" near you? What are the ecological arguments against too much light at night?

49. What is the current status of the James Webb Space Telescope (http://jwst.nasa.gov)? How will this telescope be different from the Hubble Space Telescope? What are some of the instruments for the JWST and its planned projects? What is the current estimated cost of the JWST?

50. Pick a mission from Appendix 5, go to its website, and see what's new. For the mission you choose, answer the following questions: Is the spacecraft still active? Is it sending images? What new science is coming from this mission?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

EXPLORATION

Geometric Optics and Lenses

digital.wwnorton.com/astro5

Visit the Student Site at the Digital Landing Page, and open the "Geometric Optics and Lenses" animation in Chapter 6. Read through the animation until you reach the optics simulation, pictured in **Figure 6.31**. The simulator shows a converging lens and a pencil. Rays come from the pencil on the left of the converging lens, pass through the lens, and make an image to the right of the lens. The view that would be seen by an observer at the position of the eye is shown in the circle at upper right. Initially, when the pencil is at position 2.3 and the eye is at position 2.0, the pencil is out of focus and blurry.

1 Is the eraser at the top or the bottom of the actual pencil? (This becomes important later.)

Using the red slider in the upper left of the window, try moving the pencil to the right. Pause when the observer's eye sees a recognizable pencil (even if it's still blurry).

2 Does the eye see the pencil right side up or upside down?

3 This is somewhat analogous to the view through a telescope. The objects are very far from the lenses, and the observer sees things upside down in the telescope. If an object in your field of view is at the top of the field and you want it in the center, which way should you move the telescope: up or down?

Now return the pencil to position 2.3. Use the red slider in the lower right of the window to move the eye closer to the lens (to the left).

4 At what distance does the image of the pencil first become crisp and clear?

5 Is the pencil right side up or upside down?

6 In practice at the telescope, we do not move the observer back (away from the eyepiece) to bring the image into focus. Why not?

7 Instead of moving the observer, we use a focusing knob to move the lens in the eyepiece, which brings the image into focus. Imagine that you are looking through the eyepiece of a telescope and the image is blurry. You turn the focusing knob and things get blurrier! What should you try next?

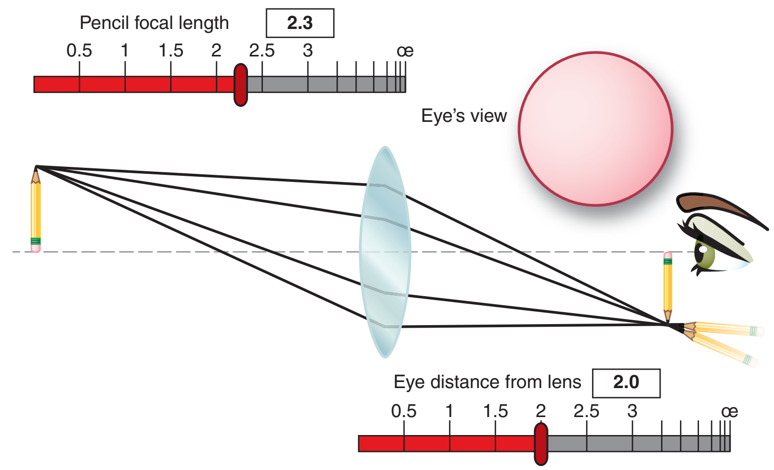


Figure 6.31 Use this simulation to change the position of the object of the eye to explore what will be seen for various configurations.

8 Now imagine that you get the image focused just right, so it is crisp and sharp. The next person to use the telescope wears glasses and insists that the image is blurry. But when you look through the telescope again, the image is still crisp. Explain why your experiences differ.

Step through the animation to the next picture. Carefully study the two telescopes shown and the path the light takes through them.

9 Which telescope has a longer focal length: the top one or the bottom one?

10 Which telescope produces an image with the red and the blue stars more separated: the top one or the bottom one?

11 A longer focal length is an advantage in one sense, but it's not the entire story. What are some disadvantages of a telescope with a very long focal length?

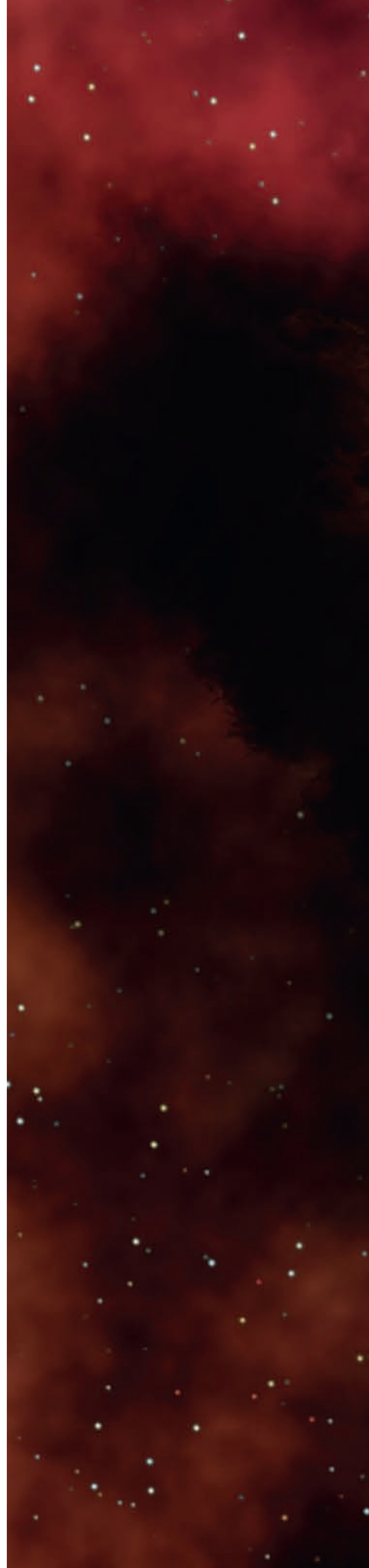
7 The Birth and Evolution of Planetary Systems

The planetary system containing Earth—our Solar System—is a by-product of the birth of the Sun. But the physical processes that shaped the formation of the Solar System are not unique to it. The same processes have formed numerous multiplanet systems. In this chapter, we will examine how planetary systems are born and evolve.

LEARNING GOALS

By the conclusion of this chapter, you should be able to:

- **LG 1** Describe how our understanding of planetary system formation developed from the work of both planetary and stellar scientists.
- **LG 2** Discuss the role of gravity and angular momentum in explaining why planets orbit the Sun in a plane and why they revolve in the same direction that the Sun rotates.
- **LG 3** Explain how temperature at different locations in the protoplanetary disk affects the composition of planets, moons, and other bodies.
- **LG 4** Discuss the processes that resulted in the formation of planets and other objects in our Solar System.
- **LG 5** List how astronomers find planets around other stars, and explain how we know that planetary systems around other stars are common.



From clouds of gas and dust, planetary systems are born. ▶▶▶

How was our Solar System born?

7.1 Planetary Systems Form around a Star

Earth is part of a collection of **planets**—large, round bodies that orbit a star in individual orbits. Astronomers call a system of planets surrounding a star a **planetary system**. The Solar System, shown in **Figure 7.1**, is the planetary system that includes Earth, other planets, and the Sun. It also includes moons that orbit planets and small bodies that occupy particular regions of the Solar System; for example, in the asteroid belt or in the Kuiper Belt. Our Solar System is a tiny part of our galaxy, which is a tiny part of the universe. Review Figure 1.3 in Chapter 1 to remind yourself of the size scales involved. Light takes about 4 hours to travel to Earth from Neptune, the outermost planet in the Solar System, but light from the most distant galaxies takes nearly *14 billion years* to reach Earth.

Until the latter part of the 20th century, the origin of the Solar System remained speculative. Over the past century, with the aid of spectroscopy, astronomers have determined that the Sun is a typical star, one of hundreds of billions in its galaxy, the Milky Way, and that the Milky Way is a typical galaxy, one of hundreds of billions in the universe. In the past few decades, stellar astronomers studying the formation of stars and planetary scientists analyzing clues about the history of the Solar System have found themselves arriving at the same picture of the early Solar System—but from two very different directions. This unified understanding provides the foundation for the way astronomers now think about the Sun and the myriad objects that orbit it. In this section, we will look at how the work of stellar and planetary scientists converged to inform our understanding of planetary system formation.

The Nebular Hypothesis

The first plausible theory for the formation of the Solar System, the **nebular hypothesis**, was proposed in 1734 by the German philosopher Immanuel Kant (1724–1804) and conceived independently a few years later by the French astronomer Pierre-Simon Laplace (1749–1827). Kant and Laplace argued that a rotating cloud of interstellar gas, or **nebula** (Latin for "cloud"), gradually collapsed and flattened to form a disk with the Sun at its center. Surrounding the Sun were rings of material from which the planets formed. This configuration would explain why the planets orbit the Sun in the same direction in the same plane. The nebular hypothesis remained popular throughout the 19th century, and these basic principles of the hypothesis are still retained today.

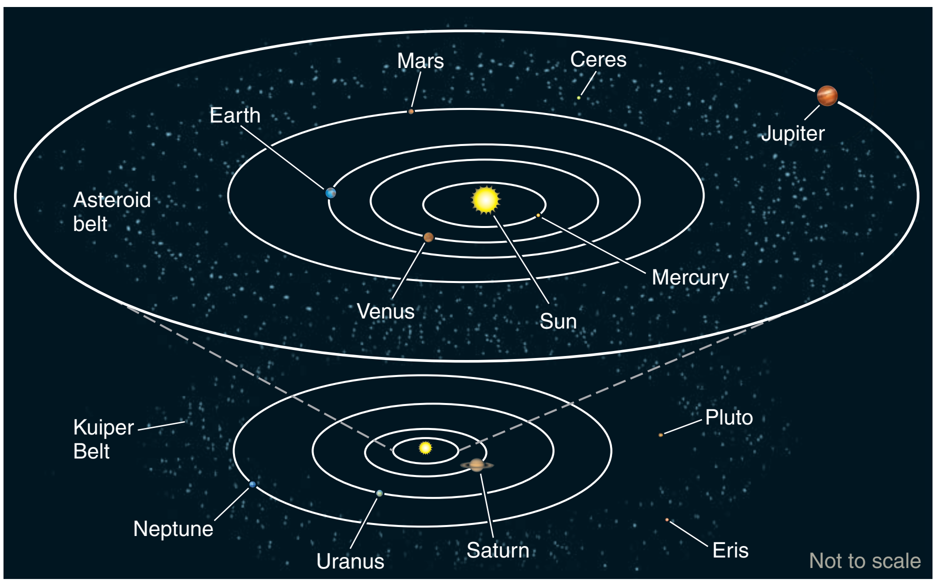


Figure 7.1 Our Solar System includes planets, moons, and other small bodies. Sizes and distances are not to scale in this sketch.

Our modern theory of planetary system formation calculates under what conditions clouds of interstellar gas collapse under the force of their own self-gravity to form stars. Recall from Chapter 4 that self-gravity is the gravitational attraction between the parts of an object such as a planet or star that pulls all the parts toward the object's center. This inward force is opposed by either structural strength (in the case of

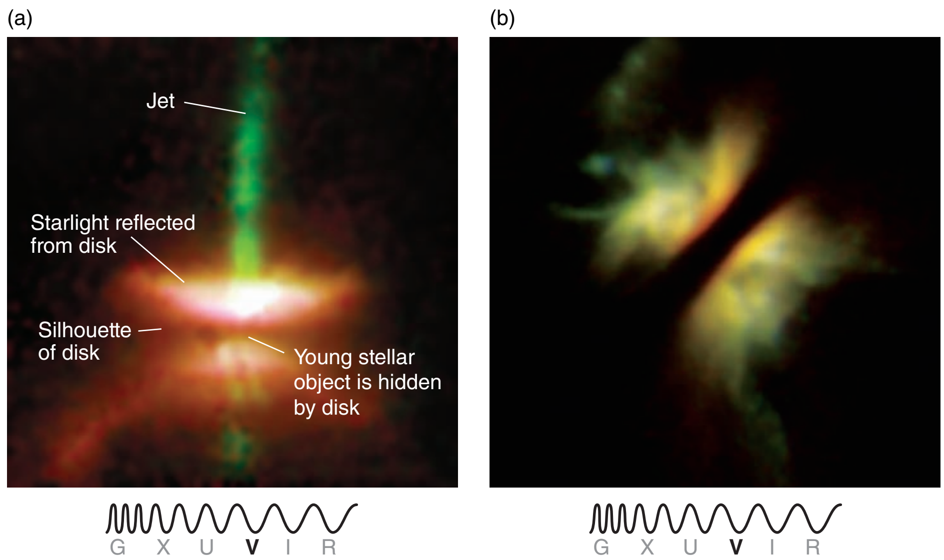


Figure 7.2 Hubble Space Telescope images show disks around newly formed stars. (a) The dark band is the silhouette of the disk seen more or less edge-on. Bright regions are dust illuminated by starlight. Some disk material may be expelled in a direction perpendicular to the plane of the disk in the form of violent jets. (b) In this image, the disk is seen in silhouette. Planets may be forming or have already formed in this disk.

rocks that make up terrestrial planets) or the outward force resulting from gas pressure within a star. If the outward force is less than self-gravity, the object contracts; if it is greater, the object expands. In a stable object, the inward and outward forces are balanced.

In support of the nebular hypothesis, disks of gas and dust have been observed surrounding young stellar objects (**Figure 7.2**). From this observational evidence, stellar astronomers have shown that, much like a spinning ball of pizza dough spreads out to form a flat crust, the cloud that produces a star—the Sun, for example—collapses first into a rotating disk. Material in the disk eventually suffers one of three fates: it travels inward onto the forming star at its center, it remains in the disk itself to form planets and other objects, or it is ejected back into interstellar space.

▶II **AstroTour:** Solar System Formation

Planetary Scientists and the Convergence of Evidence

While astronomers were working to understand star formation, other groups of scientists with very different backgrounds were piecing together the history of the Solar System. Planetary scientists, geochemists, and geologists looking at the current structure of the Solar System inferred what some of its early characteristics must have been. The orbits of all the planets lie very close to a single plane, so the early Solar System must have been flat. Additionally, all the planets orbit the Sun in the same direction, so the material from which the planets formed must have been orbiting the Sun in the same direction as well.

To find out more, scientists study samples of the very early Solar System. Rocks that fall to Earth from space, known as **meteorites**, include pieces of material that are left over from the Solar System's youth. Many meteorites, such as the one in **Figure 7.3**, resemble a piece of concrete in which pebbles and sand are mixed with a much finer filler, suggesting that the larger bodies in the Solar System must have grown from the aggregation of smaller bodies. This chain of thought suggests an early Solar System in which the young Sun was surrounded by a flattened

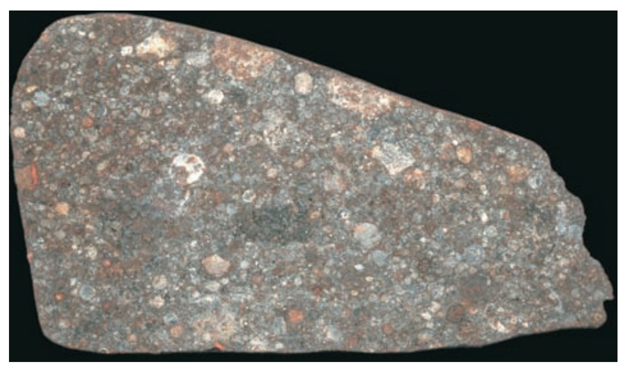
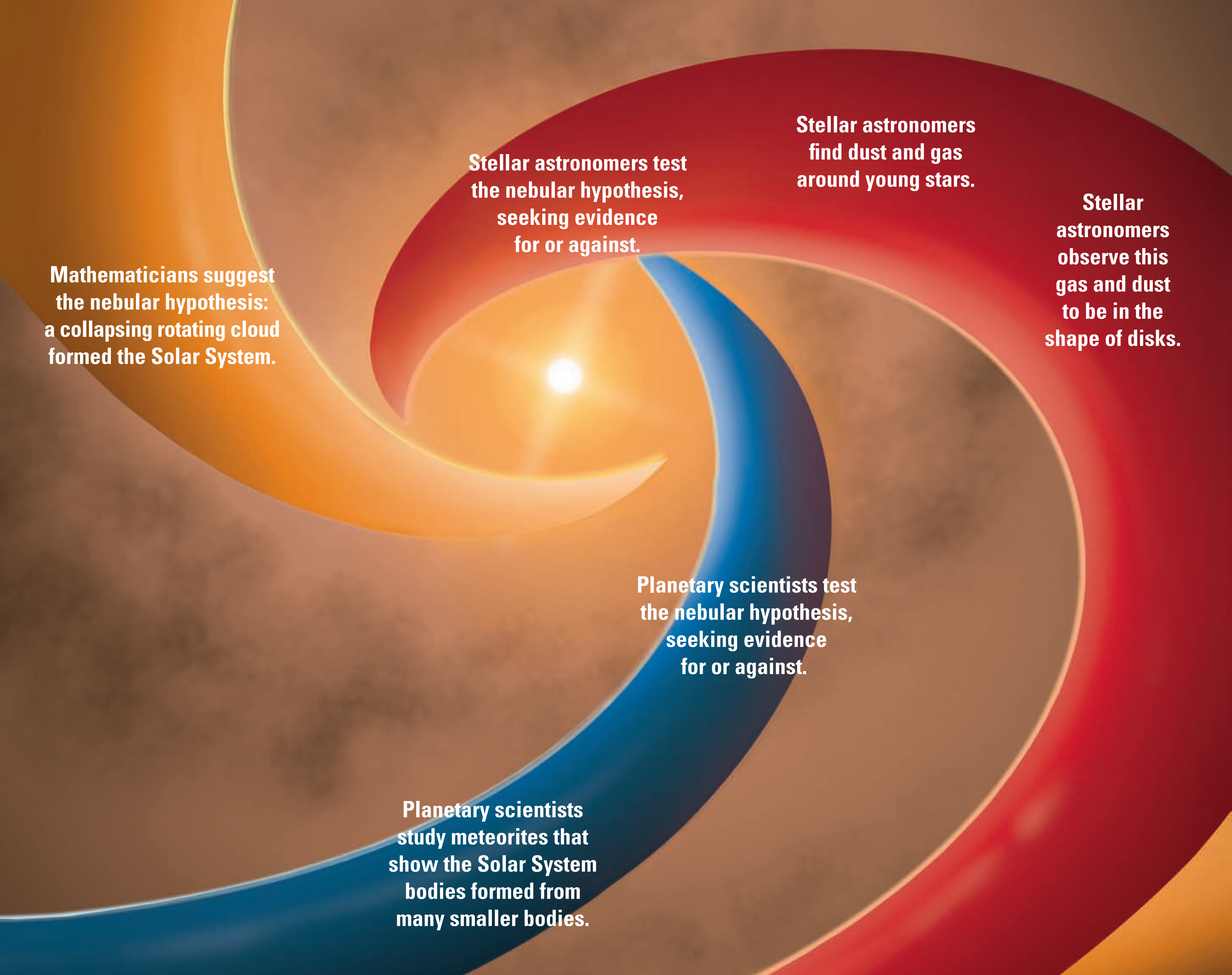


Figure 7.3 Meteorites are the surviving pieces of Solar System fragments that land on the surfaces of planets. This meteorite formed from many smaller components that stuck together.

Process of Science

CONVERGING LINES OF INQUIRY

Astronomers asked: Why is the Solar System a disk, with all planets orbiting in the same direction?



Beginning from the same fundamental observations about the shape of the Solar System, theorists, planetary scientists, and stellar astronomers converge in the nebular theory that stars and planets form together from a collapsing cloud of gas and dust.

disk of both gaseous and solid material. Our Solar System formed from this swirling disk of gas and dust.

As astronomers and planetary scientists compared notes, they realized they had arrived at the same picture of the early Solar System from two completely different directions. The rotating disk from which the planets formed was the remains of the disk that had accompanied the formation of the Sun. Earth, along with all the other orbiting bodies that make up the Solar System, formed from the remnants of an *interstellar cloud* that collapsed to form the local star, the Sun. The connection between the formation of stars and the origin and subsequent evolution of the Solar System is one of the cornerstones of both astronomy and planetary science—a central theme of our understanding of our Solar System (**Process of Science Figure**).

CHECK YOUR UNDERSTANDING 7.1

Which of the following pieces of evidence supports the nebular hypothesis? (Choose all that apply.) (a) Planets orbit the Sun in the same direction. (b) The Solar System is relatively flat. (c) Earth has a large Moon. (d) We observe disks of gas and dust around other stars.

7.2 The Solar System Began with a Disk

Now that we've noted the general idea that planets formed in a disk around young stars, let's look at some of the specifics. **Figure 7.4** illustrates the young Solar System as it appeared roughly 5 billion years ago. At that time, the Sun was still a **protostar**—a large ball of gas but not yet hot enough in its center to be a star. As the cloud of interstellar gas collapsed to form the protostar, its gravitational energy was converted into heat energy and radiation. Surrounding the protostellar Sun was a flat, orbiting disk of gas and dust. Each bit of the material in this thin disk orbited the Sun according to the same laws of motion and gravitation that govern the orbits of the planets. The disk around the Sun, like the disks that astronomers see today surrounding protostars elsewhere in our galaxy, is called a **protoplanetary disk**. The disk probably contained less than 1 percent of the mass of the star forming at its center, but this amount was more than enough to account for the bodies that make up the Solar System today.

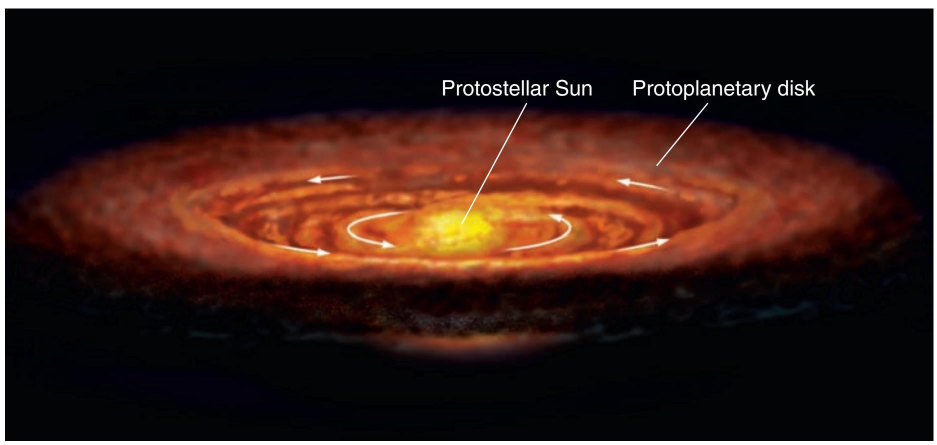


Figure 7.4 Think of the young Sun as being surrounded by a flat, rotating disk of gas and dust that was flared at its outer edge.

The Collapsing Cloud and Angular Momentum

The Solar System formed from a protoplanetary disk, and similar disks are seen around newly formed stars. *Angular momentum* causes these disks to form. **Angular momentum** is a conserved property of a revolving or rotating system with a value that depends on both the velocity and distribution of the system's mass. The angular momentum of an isolated object is always conserved; that is, it remains unchanged unless acted on by an external force. You have likely seen

Figure 7.5 A figure-skater relies on the principle of conservation of angular momentum to change the speed with which she spins.

Astronomy in Action: Angular Momentum

a figure-skater spinning on the ice like the one shown in **Figure 7.5**. Like any other rotating object, the spinning ice-skater has some amount of angular momentum. Unless an external force acts on her, such as the ice pushing on her skates, she will always have the same amount of angular momentum.

The amount of angular momentum depends on three factors:

1. How fast the object is rotating. The faster an object is rotating, the more angular momentum it has.
2. The mass of the object. If a bowling ball and a basketball are spinning at the same speed, the bowling ball has more angular momentum because it has more mass.
3. How the mass of the object is distributed relative to the spin axis; that is, how far the object is from the spin axis, or how spread out the object is. For an object of a given mass and rate of rotation, the more spread out it is, the more angular momentum it has. A spread-out object that is rotating slowly might have the same angular momentum as a compact object rotating rapidly.

Both an ice-skater and a collapsing interstellar cloud are affected by **conservation of angular momentum**: the angular momentum must remain the same in the absence of an external force. In order for angular momentum to be conserved, a change in one of the above quantities (the rate of spin, mass, or distribution of mass) must be accompanied by a change of another quantity. For example, an ice-skater can control how rapidly she spins by pulling in or extending her arms or legs. As she pulls in her arms to become more compact, she decreases her distribution of mass and must spin faster to maintain the same angular momentum. When her arms are held tightly in front of her and one leg is wrapped around the other, the skater's spin becomes a blur. She finishes with a flourish by throwing her arms and leg out—an action that abruptly slows her spin by spreading out her mass. Despite the changes in her spin, the skater's angular momentum remains constant throughout the entire maneuver. Similarly—as shown in **Figure 7.6**—the cloud that formed our Sun rotated faster and faster as it collapsed, just as the ice-skater speeds up when she pulls in her arms.

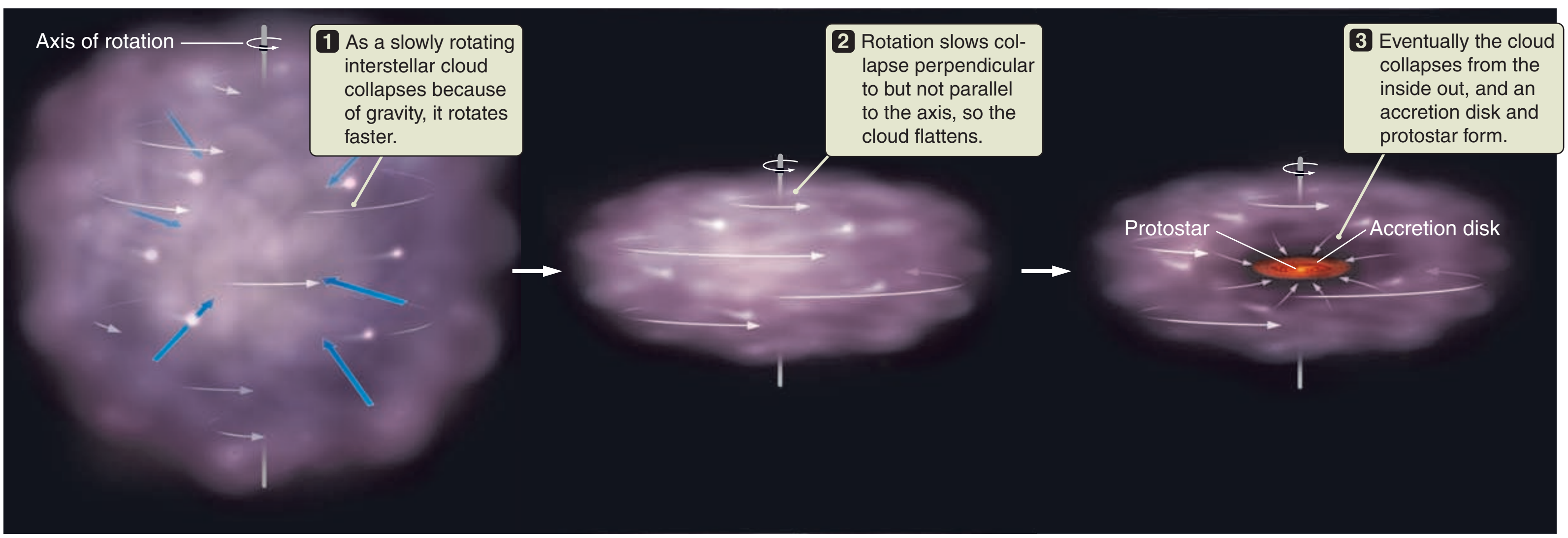


Figure 7.6 A rotating interstellar cloud collapses in a direction parallel to its axis of rotation, thus forming an accretion disk.

However, this description presents a puzzle. Suppose the Sun formed from a typical cloud—one that was about a light-year across and was rotating so slowly that it took a million years to complete one rotation. By the time such a cloud collapsed to the size of the Sun today, it would have been spinning so fast that one rotation would occur every 0.6 second. This is more than 3 million times faster than our Sun actually spins. At this rate of rotation, the Sun would tear itself apart. It appears that angular momentum was not conserved in the actual formation of the Sun—but that can't be right, because angular momentum must be conserved. We must be missing something. Where did the angular momentum go?

The Formation of an Accretion Disk

To understand how angular momentum is conserved in disk formation, we must think in three dimensions. Imagine that the ice-skater bends her knees, compressing herself downward instead of bringing her arms toward her body. As she does this, she again makes herself less spread out, but her rate of spin does not change because no part of her body has become any closer to the axis of spin. Similarly, as shown in Figure 7.6, a clump of a molecular cloud can flatten out without speeding up by collapsing parallel to its axis of rotation. Instead of collapsing into a ball, the interstellar cloud flattens into a disk. As the cloud collapses, its self-gravity increases, and the inner parts begin to fall freely inward, raining down on the growing object at the center. The outer portions of the cloud lose the support of the collapsed inner portion, and they start falling inward, too. As this material makes its final inward plunge, it lands on a thin, rotating disk that forms from the accretion of material around a massive object, called an **accretion disk**. The formation of accretion disks is common in the universe.

A visual analogy might be helpful for understanding how interstellar material collects on the accretion disk. Imagine a huge traffic circle, or roundabout, with multiple entrances but with all exits blocked by incoming traffic, as shown in **Figure 7.7a**. As traffic flows into the traffic circle, it has nowhere else to go, resulting in a continual, growing line of traffic driving around and around in an increasingly crowded circle. Eventually, as more and more cars try to pack in, the traffic piles up. This situation is roughly analogous to an accretion disk, shown in Figure 7.7b. Of course, traffic in a roundabout moves on a flat surface, whereas the accretion disk around a protostar forms from material coming in from all directions in three-dimensional space.

As material falls onto the disk, its motion perpendicular to the disk stops abruptly, but its mass motion *parallel* to the surface of the disk adds to the disk's total angular momentum. In this way, the angular momentum of the infalling material is transferred to the accretion disk. The rotating accretion disk has a radius of hundreds of astronomical units and is thousands of times greater than the radius of the star that will eventually form at its center. Therefore, most of the angular momentum in the original interstellar cloud ends up in the accretion disk rather than in the central protostar (see **Working It Out 7.1** for an example of the relevant calculation).

Now we can explain why the Sun does not have the same angular momentum that was present in the original clump of cloud. The radius of a rotating accretion disk is thousands of times greater than the radius of the star that will form at its center. Much of the angular momentum in the original interstellar clump is conserved in its accretion disk rather than in its central protostar.

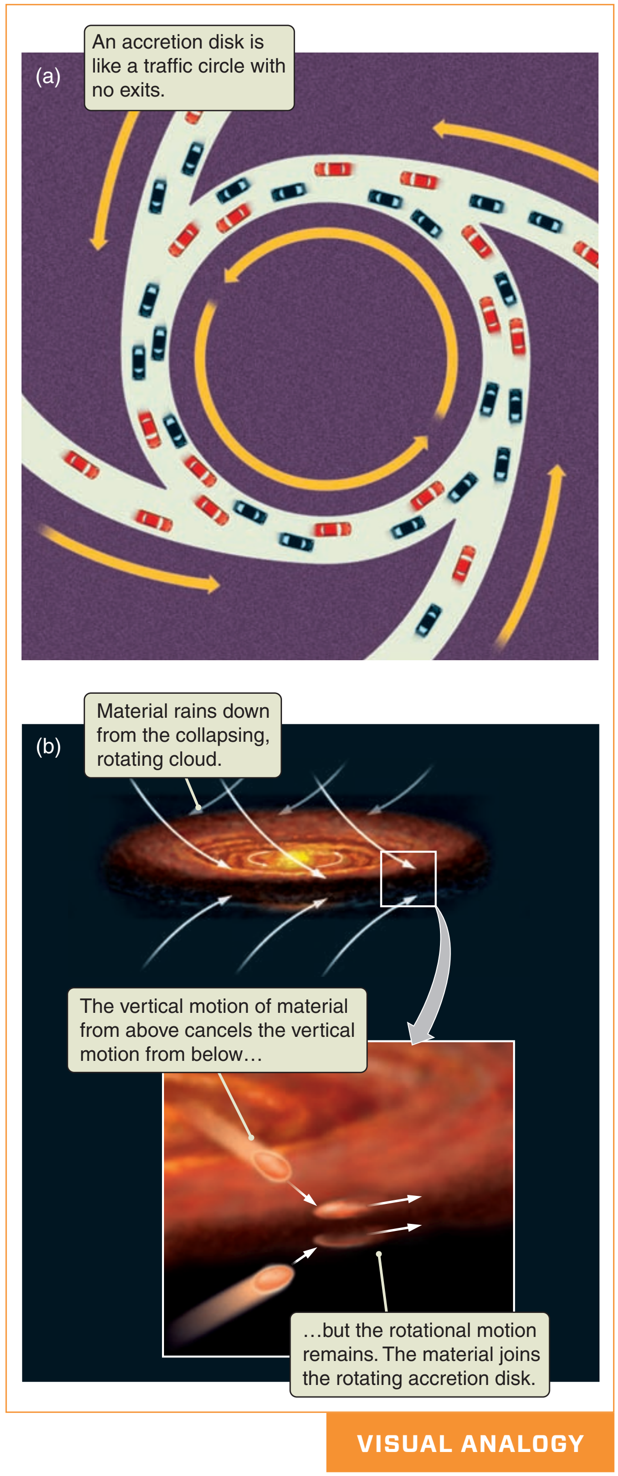


Figure 7.7 (a) Traffic piles up in a traffic circle with entrances but no exits. (b) Similarly, gas from a rotating cloud falls inward from opposite sides, piling up onto a rotating disk.

▶II **AstroTour:** Traffic Circle Analogy

7.1 Working It Out Angular Momentum

In its simplest form, the angular momentum of a system is given by

$$L = m \times v \times r$$

where m is the mass, v is the speed at which the mass is moving, and r represents how spread out the mass is.

As an example, we can apply this relationship to the angular momentum of Jupiter in its orbit about the Sun. The angular momentum from one body orbiting another is called *orbital* angular momentum, L_{orbital}. The mass (m) of Jupiter is 1.90×10^{27} kilograms (kg), the speed of Jupiter in orbit (v) is 1.31×10^4 meters per second (m/s), and the radius of Jupiter's orbit (r) is 7.79×10^{11} meters. Putting all this together gives

$$L_{\mathrm{orbital}} = (1.90 \times 10^{27}\ \mathrm{kg}) \times (1.31 \times 10^4\ \mathrm{m/s}) \times (7.79 \times 10^{11}\ \mathrm{m})$$

$$L_{\mathrm{orbital}} = 1.94 \times 10^{43}\ \mathrm{kg\ m^2/s}$$

Calculating the *spin* angular momentum of a spinning object, such as a skater, a planet, a star, or an interstellar cloud, is more complicated. Here, we must add up the individual angular momenta of *every tiny mass element* within the object. In the case of a uniform sphere, the spin angular momentum is

$$L_{\mathrm{spin}} = \frac{4\pi m R^2}{5P}$$

where R is the radius of the sphere, and P is the rotation period of its spin.

Let's compare Jupiter's orbital angular momentum with the Sun's spin angular momentum to investigate the distribution of angular momentum in the Solar System. Appendix 2 provides the Sun's radius (6.96×10^8 meters), mass (1.99×10^{30} kg), and rotation period (24.5 days = 2.12×10^6 seconds). Assuming that the Sun is a uniform sphere, the spin angular momentum of the Sun is

$$L_{\mathrm{spin}} = \frac{4 \times \pi \times (1.99 \times 10^{30}\ \mathrm{kg}) \times (6.96 \times 10^8\ \mathrm{m})^2}{5 \times (2.12 \times 10^6\ \mathrm{s})}$$

$$L_{\mathrm{spin}} = 1.14 \times 10^{42}\ \mathrm{kg\ m^2/s}$$

Jupiter's orbital angular momentum is about 17 times greater than the spin angular momentum of the Sun. Most of the angular momentum of the Solar System now resides in the orbits of its major planets.

For a collapsing sphere to conserve spin angular momentum, its rotation period P must be proportional to R^2. Like with the skater, when a sphere decreases in radius, its rotation period decreases; that is, it spins faster.

Most of the matter that lands on the accretion disk either becomes part of the star or is ejected back into interstellar space, sometimes in the form of jets or other outflows, as seen in Figure 7.2a. Material swirling in the bipolar jets carries angular momentum away from the accretion disk in the general direction of the poles of the rotation axis. However, a small amount of material is left behind in the disk. It is the objects in this leftover disk—the dregs of the process of star formation—that form planets and other objects that orbit the star. Look again at Figure 7.2 showing images of edge-on accretion disks around young stars. The dark bands are the shadows of the edge-on disks, the top and the bottom of which are illuminated by light from the forming star. Our Sun and Solar System formed from a protostar and disk much like those in these pictures.

Formation of Large Objects

The chain of events that connects the accretion disk around a young star to a planetary system such as the Solar System begins with random motions of the gas within the protoplanetary disk. As shown in **Figure 7.8**, these motions push the smaller grains of solid material back and forth past larger grains, and as this happens, the smaller grains stick to the larger grains. The "sticking" process among smaller grains is due to the same static electricity that causes dust and hair to cling to plastic surfaces. Starting out at only a few microns (μm) across—about the size of particles in smoke—the slightly larger bits of dust grow to the size of pebbles and then to clumps the size of boulders, which are not as easily pushed around by gas. When clumps grow to about 100 meters across, the objects are so few and far between that they collide less frequently, and their growth rate slows down but does not stop. Within a protoplanetary disk, the larger dust grains become larger at the expense of the smaller grains.

For two large clumps to stick together rather than explode into many small pieces, they must bump into each other very gently: collision speeds must be about 0.1 m/s or less for colliding boulders to stick together. Your stride is probably about a meter, so to walk as slowly as the collision speed of 0.1 m/s, you would take one step every 10 seconds. The process is not a uniform movement toward larger and larger bodies. Violent collisions do occur in an accretion disk, and larger clumps break back into smaller pieces. But over a long period, large bodies do form.

Objects continue to grow by "sweeping up" smaller objects that get in their way. These objects can eventually measure up to a couple hundred meters across. As the clumps reach the size of about a kilometer, they are massive enough that their gravity begins to pull on nearby bodies, as shown in **Figure 7.9**. These bodies of rock and ice, 100 meters or more in diameter, are known as **planetesimals** ("tiny planets") and eventually combine with each other to form planets. The growth of planetesimals is not fed only by chance collisions with other objects: a planetesimal's gravity can now pull in and capture small objects outside its direct path. The growth of planetesimals speeds up, and larger planetesimals quickly consume most of the remaining bodies in the vicinity of their orbits to become small planets.

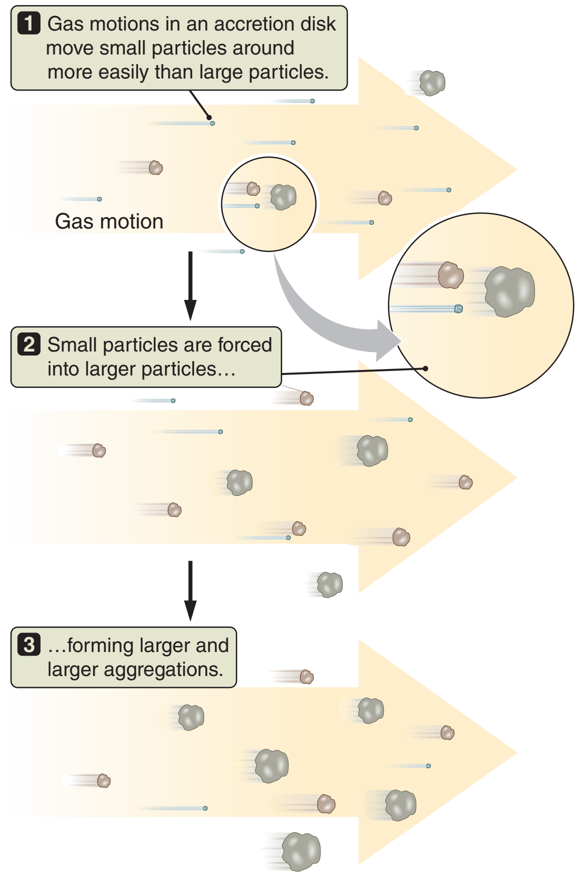


Figure 7.8 Motions of gas in a protoplanetary disk blow smaller particles of dust into larger particles, making the larger particles larger still. This process continues, eventually creating objects many meters in size.

CHECK YOUR UNDERSTANDING 7.2

Where does the majority of the angular momentum of the original cloud go? (a) into the orbital angular momentum of planets; (b) into the star; (c) into the spin of the planets; (d) lost along the jets from the star

7.3 The Inner Disk and Outer Disk Formed at Different Temperatures

In the Solar System, the inner planets are small and mostly rocky, while the outer planets are very large and mostly gaseous. This distinct difference between the inner and the outer Solar System can be explained by how the local disk environment affects the formation process. In this section, we will examine these differences.

Energy in the Disk

The accretion disks surrounding young stars form from interstellar material that may have a temperature of only a few kelvins, but the disks themselves reach temperatures of hundreds of kelvins or more. Astronomers want to understand what heats up the disk around a forming star so that we can calculate how hot these disks get.

Imagine dumping a box of marbles from the top of a tall ladder onto a rough, hard floor below. The marbles fall, picking up speed as they go. Even though the falling marbles are speeding up, they are all speeding up *together*. If you were riding on one of the marbles, the other marbles would not appear to you to be moving very much; it would be the rest of the room that was whizzing

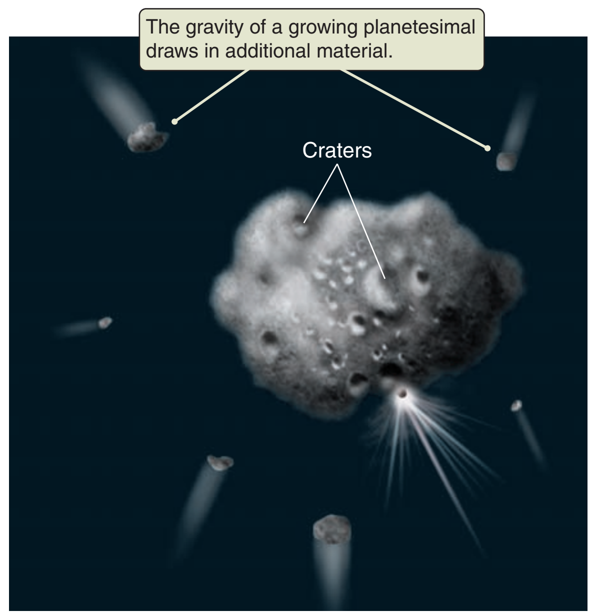


Figure 7.9 The gravity of a planetesimal is strong enough to attract surrounding material, which causes the planetesimal to grow more rapidly.

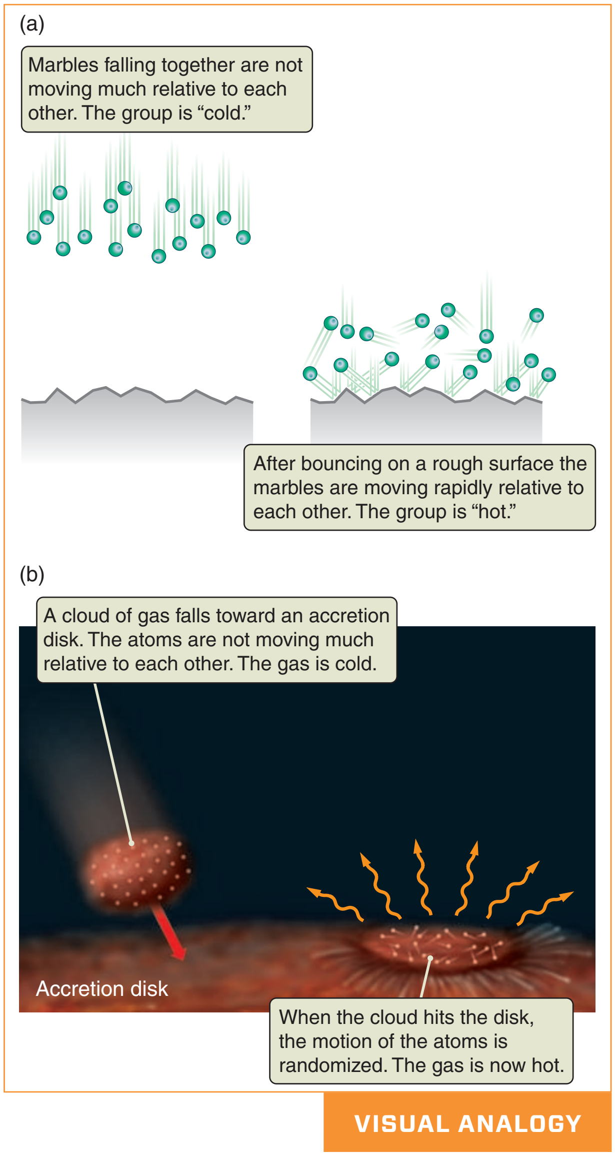


Figure 7.10 (a) Marbles dropped as a group fall together until they hit a rough floor, at which point their motions become randomized. (b) Similarly, atoms in a gas fall together until they hit the accretion disk, at which point their motions become randomized, raising the temperature of the gas.

by (**Figure 7.10a**). The atoms and molecules in the gas falling toward the protostar are like these marbles. They are picking up speed as they fall as a group toward the protostar, but the gas is still cold because the random thermal velocities of atoms and molecules with respect to each other are still low. Now imagine what happens when the marbles hit the rough floor. They bounce every which way. They are still moving rapidly, but they are no longer moving together. A change has taken place from the ordered motion of marbles falling together to the random motions of marbles traveling in all directions.

Like the falling marble, the atoms and molecules in the gas falling toward the central star scatter in the same fashion when they encounter the uneven gravitational field of the dusty accretion disk. As shown in Figure 7.10b, they are no longer moving as a group, but their random thermal velocities are now very large. The gas is now hot. Similarly, material from the collapsing interstellar cloud falls inward toward the protostar, but because of its angular momentum it misses the protostar and instead falls onto the disk. When this material reaches the disk, its infalling motion comes to an abrupt halt, and the velocity that the atoms and molecules in the gas had before hitting the disk is suddenly converted into random *thermal* velocities instead. The cold gas that was falling toward the disk heats up when it lands on the disk.

Another way to think about why the gas falling on the disk makes the disk hot is to apply another conservation law. The law of **conservation of energy** states that unless energy is added to or taken away from a system from the outside, the total amount of energy in the system must remain constant. But the form the energy takes can change. Imagine you are working against gravity by lifting a heavy object; for example, a brick. It takes energy to lift the brick, and the law of conservation of energy states that energy is never lost. Where does that energy go? The energy is stored and changed into a form called **gravitational potential energy**. If you drop the brick it falls, and as it falls it speeds up. The gravitational potential energy that was stored is converted to energy of motion, which is called **kinetic energy**. When the brick hits the floor, it stops suddenly. The brick loses its energy of motion, so what form does this energy take now?

If the brick cracks, part of the energy goes into breaking the chemical bonds that hold it together. Some of the energy is converted into the sound the brick makes when it hits the floor. Some goes into heating and distorting the floor. But much of the energy is converted into thermal energy. The atoms and molecules that make up the brick are moving about within the brick a bit faster than they were before the brick hit, so the brick and its surroundings, including the floor, grow a tiny bit warmer. Similarly, as gas falls toward the disk surrounding a protostar, gravitational potential energy is converted first to kinetic energy, causing the gas to pick up speed. When the gas hits the disk and stops suddenly, that kinetic energy is turned into thermal energy.

Similarly, material falling onto the accretion disk around a forming star causes the disk to heat up. The amount of heating depends on *where* the material hits the disk. Material hitting the inner part of the disk (the *inner disk*) has fallen farther and picked up greater speed within the gravitational field of the forming star than has material hitting the disk farther out. Like a brick dropped from a tall building, material striking the inner disk is moving quite rapidly when it hits, so it heats the inner disk to high temperatures. In contrast, material falling onto the outer part of the disk (the *outer disk*) is moving much more slowly, like a brick dropped from just a foot or so above the ground. So the temperature at the outermost parts of the disk is not much higher than that of the original interstellar cloud. Stated another way, material falling onto the inner disk converts more gravitational potential energy into thermal energy than does material falling onto the outer disk.

The energy released as material falls onto the disk is not the only source of thermal energy in the disk. Even before the nuclear reactions that will one day power the new star have ignited, conversion of gravitational energy into thermal energy drives the temperature at the surface of the protostar to several thousand kelvins, and it also drives the luminosity of the huge ball of glowing gas to many times the luminosity of the present-day Sun. For the same reasons that Mercury is hot while Pluto is not (see Chapter 5), the radiation streaming outward from the protostar at the center of the disk drives the temperature in the inner parts of the disk even higher, increasing the difference in temperature between the inner and outer parts of the disk.

The Compositions of Planets

Temperature affects whether or not a material exists in a solid form. On a hot summer day, ice melts and water quickly evaporates; on a cold winter night, water in your breath freezes into tiny ice crystals. Some materials remain solid even at higher temperatures. These include metals and rocky materials, such as iron, **silicates**—which are minerals containing silicon and oxygen—and carbon. Substances that are capable of withstanding high temperatures without melting or being vaporized are called **refractory materials**. Other materials, such as water, ammonia, and methane, remain in a solid form only if their temperature is very low. These materials, which become gases at moderate temperatures, are called **volatile materials** (or *volatiles* for short). Astronomers generally call the solid form of any volatile material an **ice**.

Differences in temperature from place to place within the protoplanetary disk have a significant effect on the makeup of the dust grains in the disk. As **Figure 7.11** illustrates, in the hottest parts of the disk—closest to the protostar—only the most refractory substances can exist in solid form. In the inner disk, dust grains are composed almost entirely of refractory materials. Some substances can survive in solid form somewhat farther out, including some hardier volatiles, such as water ice and certain chemical compounds that are **organic**, meaning that they contain carbon. These solids add to the materials that make up dust grains. In the coldest, outermost parts of the accretion disk, far from the central protostar, highly volatile components such as methane, ammonia, and carbon monoxide ices and other organic molecules survive only in solid form. The different composition of dust grains within the disk determines the composition of the planetesimals formed from the dust. Planets that form closer to the central star tend to be made up mostly of refractory materials such as rock and metals. Planets that form farther from the central star contain refractory materials, but they also contain large quantities of ices and organic materials.

In the Solar System, the inner planets are composed of rocky material surrounding metallic cores of iron and nickel. Objects in the outer Solar System, including moons, giant planets, and comets, are composed largely of ices of various types. But not all planetary systems are so neatly organized as our Solar System. When planets around other stars were first discovered, they appeared to be very different, with large planets close in to their respective stars. Astronomers now think that **chaotic** encounters, in which a small change in the initial state of a system can lead to a large change in the final state of the system, may change the organization of planetary compositions. In a process called **planet migration**, the

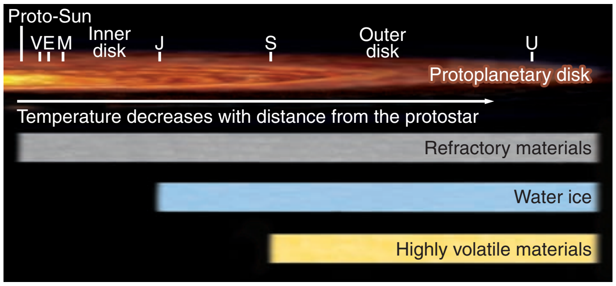


Figure 7.11 Differences in temperature within a protoplanetary disk determine the composition of dust grains that then evolve into planetesimals and planets. The colored bars show that refractory materials are found throughout the disk, while water ice is found only outside Jupiter's orbit, and highly volatile materials are found only outside Saturn's orbit. Shown here are the proto-Sun (PS) and the orbits of Venus (V), Earth (E), Mars (M), Jupiter (J), Saturn (S), and Uranus (U).

force of gravity from all of the nearby objects can move some planets so that they end up far from the place of their birth. For example, in our Solar System, Uranus and Neptune originally may have formed nearer to the orbits of Jupiter and Saturn, but were then driven outward to their current locations by gravitational encounters with Jupiter and Saturn. A planet can also migrate when it gives up some of its orbital angular momentum to the disk material that surrounds it. Such a loss of angular momentum causes the planet slowly to spiral inward toward the central star. Thus, the order of planets in a system can change over time.

Formation of an Atmosphere

Once a solid planet has formed, it may continue growing by capturing gas from the protoplanetary disk. To do so, it must act quickly. Young stars and protostars emit fast-moving particles and intense radiation that can quickly disperse the gaseous remains of the accretion disk. Gaseous planets such as Jupiter probably have only about 10 million years or so to form and to grab whatever gas they can. Because of their strong gravitational fields, more massive young planets can capture more of the hydrogen and helium gas that makes up the bulk of the disk. What follows is much like the formation of a star and protoplanetary disk, but on a smaller scale. Just as happens in the accretion disk around the star, gas from a mini accretion disk moves inward and falls onto the planet.

The gas that is captured by a planet at the time of its formation is called the planet's **primary atmosphere**. The primary atmosphere of a large planet can be more massive than the solid body, as in the case of Jupiter. Some of the solid material in the mini accretion disk might stay behind to coalesce into larger bodies in much the same way that particles of dust in the protoplanetary disk came together to form planets. The result is a mini "solar system"—a group of moons that orbit about the planet.

A less massive planet may also capture some gas from the protoplanetary disk, only to lose it later. The gravity of small planets may be too weak to hold low-mass gases such as hydrogen or helium. Even if a small planet is able to gather some hydrogen and helium from its surroundings, this primary atmosphere will not last long. In the inner solar system, the temperatures are higher, so the hydrogen and helium atoms are moving faster than in the outer solar system and will escape from a small planet. The atmosphere that remains around a small planet like Earth is a **secondary atmosphere**, which forms later in the life of a planet. Volcanism is one important source of a secondary atmosphere because it releases heavier and thus slower-moving gases such as carbon dioxide, water vapor, and other gases from the planet's interior. In addition, volatile-rich comets that formed in the outer parts of the disk continue to fall inward toward the new star long after its planets have formed, and they sometimes collide with planets. **Comets** are icy planetesimals that survive planetary accretion. They may provide a significant source of water, organic compounds, and other volatile materials on planets close to the central star.

CHECK YOUR UNDERSTANDING 7.3

In our Solar System, the inner planets are rocky because: (a) the original cloud had more rocky material near the center; (b) warm temperatures in the inner disk caused the inner planetesimals to be formed of only rocky material; (c) the inner disk filled a smaller volume so it was denser; (d) the hydrogen and helium atoms were too low mass to remain in the inner disk.

7.4 The Formation of Our Solar System

We have seen that nearly 5 billion years ago, the Sun was still a protostar surrounded by a protoplanetary disk of gas and dust. During the next few hundred thousand years, much of the dust in the disk had collected into planetesimals—clumps of rock and metal near the emerging Sun and aggregates of rock, metal, ice, and organic materials farther from the Sun. In this section, we will look at the formation of the different types of planets in our own Solar System.

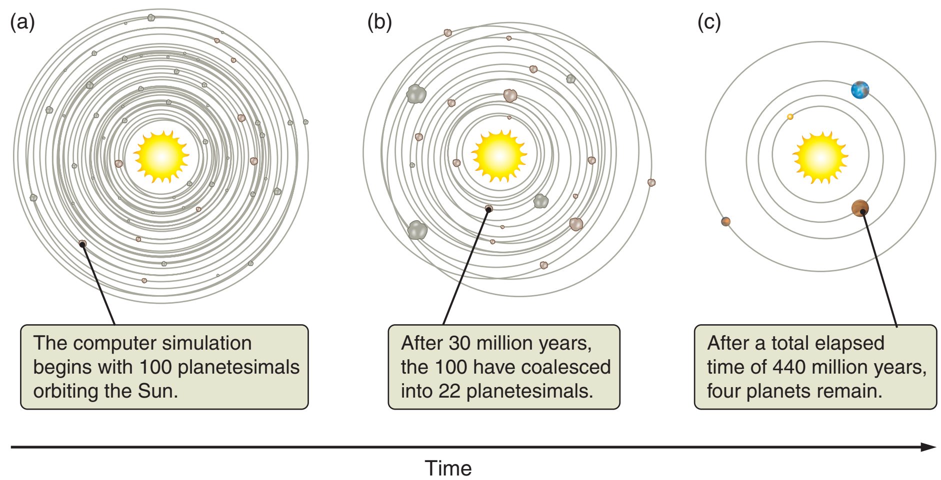


Figure 7.12 Computer models simulate how material in the protoplanetary disk became clumped into the planets over time. Only a few planets remain at the end.

The Terrestrial Planets

Within the inner 5 astronomical units (AU) of the disk, several rock and metal planetesimals quickly grew in size to become the dominant masses in their orbits. With their ever-strengthening gravitational fields, they either captured most of the remaining planetesimals or ejected them from the inner part of the disk. **Figure 7.12** shows some results from a computer simulation of how this might have happened. The dominant planetesimals became planet-sized bodies with masses ranging between 5 percent and 100 percent of Earth's mass. These dominant planetesimals evolved into the **terrestrial planets**, which are planets that are Earth-like, or rocky. Today, the surviving terrestrial planets are Mercury, Venus, Earth, and Mars. Earth's Moon is often grouped with these terrestrial planets because of its similar physical and geological properties, even though it is not a planet itself and formed in a different way. One or two other planets or large moons may have formed in the young Solar System but were later destroyed.

For several hundred million years after the formation of the four surviving terrestrial planets, leftover pieces of debris still in orbit around the Sun continued to rain down on the surfaces of these planets. Today, we can still see the scars of these early impacts on the cratered surfaces of all the terrestrial planets (**Figure 7.13**). This rain of debris continues even today, but at a much lower rate.

Before the proto-Sun became a true star, gas in the inner part of the protoplanetary disk was still plentiful. During this early period the two larger terrestrial planets, Earth and Venus, may have held on to weak primary atmospheres of hydrogen and helium, but these thin atmospheres were soon lost to space. The terrestrial planets did not develop thick atmospheres until the formation of the secondary atmospheres that now surround Venus, Earth, and Mars. Mercury's proximity to the Sun and the Moon's small mass prevented these bodies from retaining significant secondary atmospheres.

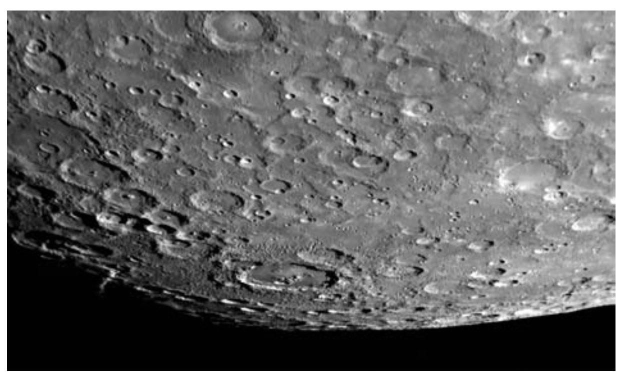


Figure 7.13 Large impact craters on Mercury (and on other solid bodies throughout the Solar System) record the final days of the Solar System's youth, when planets and planetesimals grew as smaller planetesimals rained down on their surfaces.

The Giant Planets

Beyond 5 AU from the Sun, in a much colder part of the accretion disk, planetesimals combined to form a number of bodies with masses about 5–20 times that of Earth. These planet-sized objects formed from planetesimals containing volatile ices and organic compounds in addition to rock and metal. In a process astronomers call *core accretion–gas capture*, mini accretion disks formed around these planetary cores, capturing massive amounts of hydrogen and helium and funneling this material onto the planets. Four such massive bodies became the cores of the **giant planets**—Jupiter, Saturn, Uranus, and Neptune. These giant planets are many times the mass of any terrestrial planet.

Jupiter's massive solid core captured and retained the most gas—roughly 300 times the mass of Earth (300 M_{Earth}). The other outer planetary cores captured less hydrogen and helium, perhaps because their cores were less massive or because there was less gas available to them. Saturn ended up with less than 100 M_{Earth} of gas, and Uranus and Neptune were able to grab less than twenty Earth masses worth of gas.

The core accretion model indicates that it could take up to 10 million years for a Jupiter-like planet to accumulate. Some planetary scientists do not think that our protoplanetary disk could have survived long enough to form gas giants such as Jupiter through the general process of core accretion. All the gas may have dispersed in roughly half that time, cutting off Jupiter's supply of hydrogen and helium. An alternative explanation is a process called *disk instability*, in which the protoplanetary disk suddenly and quickly fragments into massive clumps equivalent to those of a large planet. It is possible that both core accretion and disk instability played a role in the formation of our own and other planetary systems.

During the formation of the planets, gravitational energy was converted into thermal energy as the individual atoms and molecules moved faster. This conversion warmed the gas surrounding the cores of the giant planets. Proto-Jupiter and proto-Saturn probably became so hot that they actually glowed a deep red color, similar to the heating element on an electric stove. Their internal temperatures may have been even higher.

Some of the material remaining in the mini accretion disks surrounding the giant planets combined into small bodies, which became moons. A **moon** is any natural satellite in orbit about a planet or asteroid. The composition of the moons that formed around the giant planets followed the same trend as that of the planets that formed around the Sun: the innermost moons formed under the hottest conditions and therefore contained the smallest amounts of volatile material. For example, the closest of Jupiter's many moons may have experienced high temperatures from nearby Jupiter glowing so intensely that it would have evaporated most of the volatile substances in the inner part of its mini accretion disk.

Remaining Planetesimals

Not all planetesimals in the disk went on to become planets. For example, dwarf planets orbit the Sun but have not cleared other, smaller bodies from their orbits. Ceres and Pluto, which are shown in Figure 7.1, are dwarf planets. More dwarf planets, along with a large number of smaller bodies, are found in the Kuiper Belt, beyond Pluto's orbit. Asteroids are small bodies found interior to Jupiter's orbit; most are located in the main asteroid belt between Mars and Jupiter. Jupiter's gravity kept the region between Jupiter and Mars so stirred up that most planetesimals there never formed a large planet.

Planetesimals persist to this day in the outermost part of the Solar System as well. Formed in a deep freeze, these objects have retained most of the highly volatile materials found in the grains present at the formation of the accretion disk. Unlike the crowded inner part of the disk, the outermost parts of the disk had planetesimals that were too sparsely distributed for large planets to grow. Icy planetesimals in the outer Solar System that survived planetary accretion remain today as **comet nuclei**. The frozen, distant dwarf planets Pluto and Eris are especially large examples of these residents of the outer Solar System.

Many Solar System objects show evidence of cataclysmic impacts that reshaped worlds, suggesting that the early Solar System must have been a remarkably violent and chaotic place. The dramatic difference in the terrain of the northern and southern hemispheres on Mars, for example, has been interpreted as the result of one or more colossal collisions. The leading theory for the origin of our Moon is that it resulted from the collision of an object with Earth. Mercury has a crater on its surface from an impact so devastating that it caused the crust to buckle on the opposite side of the planet. In the outer Solar System, one of Saturn's moons, Mimas, has a crater roughly one-third the diameter of the moon itself. Uranus suffered one or more collisions that were violent enough literally to knock the planet on its side. Today, as a result, its equatorial plane is tilted at almost a right angle to its orbital plane. We will see other examples in subsequent chapters.

CHECK YOUR UNDERSTANDING 7.4

Suppose that astronomers found a rocky, terrestrial planet beyond the orbit of Neptune. What is the most likely explanation for its origin? (a) It formed close to the Sun and migrated outward. (b) It formed in that location and was not disturbed by migration. (c) It formed later in the Sun's history than other planets. (d) It is a captured planet that formed around another star.

7.5 Planetary Systems Are Common

When astronomers turn their telescopes to young nearby stars, they see disks of the same type from which the Solar System formed. As illustrated in **Figure 7.14**, when the light from the central star is blocked, evidence of the planetary disk is observed. The physical processes that led to the formation of the Solar System should be commonplace wherever new stars are being born. Compared to stars, however, planets are small and dim objects. They shine primarily by reflection and therefore are millions to billions of times fainter than their host stars. Thus, they were difficult to identify until advances in telescope detector technology enabled astronomers to discover them in the 1990s through indirect methods. In 1995, astronomers announced the first confirmed **extrasolar planet**, also called an **exoplanet**—a planet orbiting around a star other than the Sun. Today, the number of known extrasolar planets has grown to the thousands, and new discoveries are occurring almost daily.

The discovery of extrasolar planets raised the question of what we mean by the term *planet*. The full International Astronomical Union (IAU) definitions for planets and dwarf planets within the Solar System are provided in Appendix 9. The IAU defines an extrasolar planet as an object that orbits a star and has a mass less than 13 Jupiter masses (13 M_{Jup}). Objects more massive than 13 M_{Jup} but less massive than 0.08 solar masses (0.8 M_{Sun}; about 80 M_{Jup}) are **brown dwarfs**. Objects more massive than 0.08 M_{Sun} are defined as stars. **Figure 7.15** compares the diameters of these different objects.

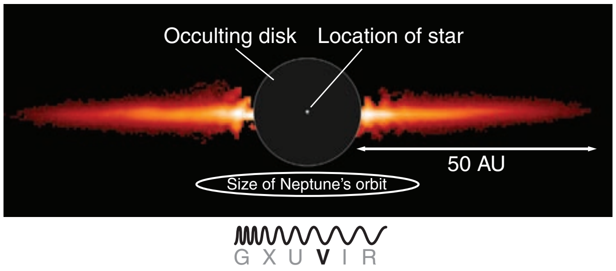


Figure 7.14 An edge-on circumstellar dust disk is seen extending outward to 60 AU from the young (12-million-year-old) star AU Microscopii. The star itself, whose brilliance would otherwise overpower the circumstellar disk, is hidden behind an occulting disk (opaque mask) placed in the telescope's focal plane. Its position is represented by the dot.

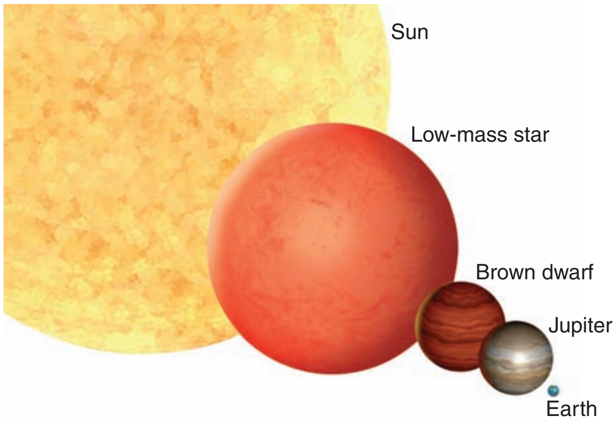


Figure 7.15 A comparison of the diameters of the Sun, a low-mass star, a brown dwarf, Jupiter, and Earth.

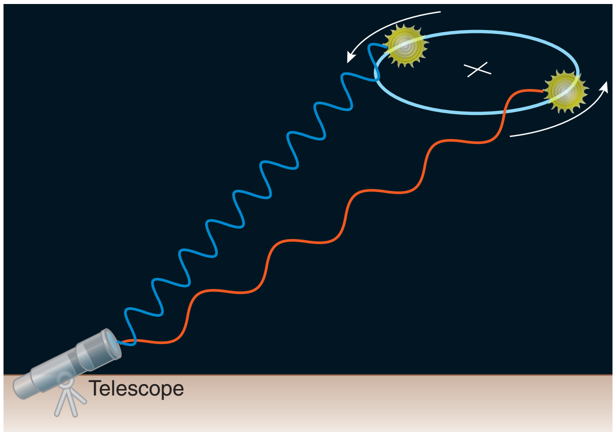


Figure 7.16 Doppler shifts observed in the spectrum of a star are due to the wobble of the star caused by its planet.

Nebraska Simulation: Influence of Planets on the Sun

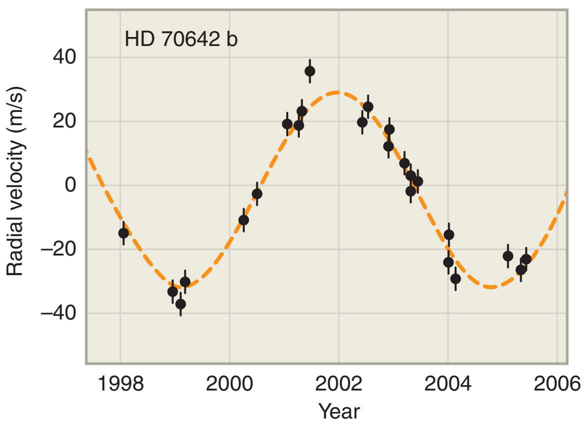


Figure 7.17 Radial velocity data for a star with a planet. A positive number is motion away from the observer; a negative number is motion toward the observer. The plot repeats as the planet completes another orbit around the star.

Nebraska Simulation: Radial Velocity Graph

Astronomy in Action: Doppler Shift

The Search for Extrasolar Planets

Currently, more than 100 projects are focused on searching for extrasolar planets from the ground and from space. The first planets were discovered indirectly, by observing their gravitational tug on the central star. As technology has improved, other methods have become more productive. Astronomers now have direct images of planets orbiting stars and have also been able to take spectra of planets to observe the composition of their atmospheres. Almost certainly, between the time we write this and the time you read it, there will be new discoveries. The field is advancing extremely quickly. We will now look at each discovery method.

The Radial Velocity Method As a planet orbits a star, the planet's gravity tugs the star around ever so slightly. This motion toward or away from us, its radial velocity, creates an observable Doppler shift in the spectrum of the star. **Figure 7.16** illustrates this method. When the star is moving toward us (negative radial velocity), the light is blueshifted; when the star is moving away from us (positive radial velocity), the light is redshifted. This pattern of radial velocity repeats over time. After detecting this wobble (**Figure 7.17**), astronomers can infer the planet's mass and its distance from the star.

We can see how this works by using the Solar System as an example. Jupiter's mass is greater than the mass of all the other planets, asteroids, and comets combined, so this is the planet most likely to be detected. Both the Sun and Jupiter orbit a common center of gravity (sometimes called center of mass; this is the location where the effect of one mass balances the other) that lies just outside the surface of the Sun, as shown in **Figure 7.18**. Alien astronomers would find that the Sun's radial velocity varies by ±12 m/s, with a period equal to Jupiter's orbital period of 11.86 years. From this information, the astronomers would rightly conclude that the Sun has at least one planet with a mass comparable to Jupiter's but, without greater precision, would be unaware of the other less massive major planets. If the alien astronomers could improve the sensitivity of their instruments to measure radial velocities as small as 2.7 m/s, Saturn would be detectable, and if the precision of their spectrograph extended to radial velocities as small as 0.09 m/s, Earth would be detectable.

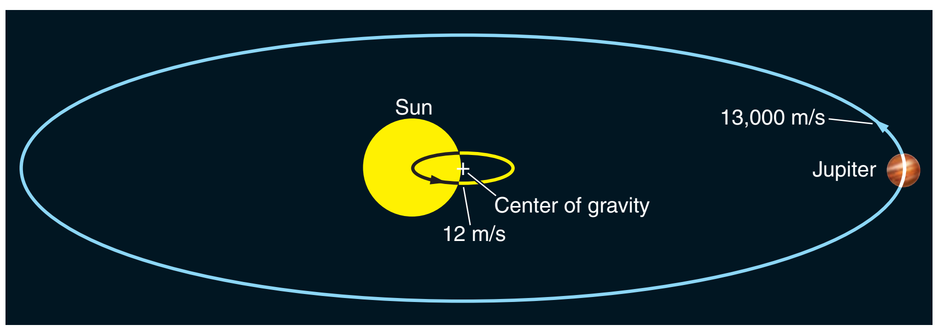


Figure 7.18 The Sun and Jupiter orbit around a common center of gravity, which lies just outside the Sun's surface. Spectroscopic measurements made by an extrasolar astronomer would reveal the Sun's radial velocity varying by ±12 m/s over 11.86 years, which is Jupiter's orbital period. Jupiter travels around its orbit at a speed of 13,000 m/s. (The orbit is shown in perspective and is not actually very elliptical.)

7.2 Working It Out Estimating the Size of the Orbit of a Planet

In the spectroscopic radial velocity method, the star is moving about its center of mass, and its spectral lines are Doppler-shifted accordingly. Recall from Figure 7.18 that the alien astronomer looking toward the Solar System would observe a shift in the wavelengths of the Sun's spectral lines—caused by the presence of Jupiter—of about 12 m/s.

Figure 7.17 showed the radial velocity data for a star with a planet discovered by this method. How do astronomers use this method to estimate the distance (A) of the planet from the star? Recall from Chapter 4 that Newton generalized Kepler's law relating the period of an object's orbit to the orbital semimajor axis:

$$P^2 = \frac{4\pi^2}{G} \times \frac{A^3}{M}$$

where A is the semimajor axis of the orbit, P is its period, and M is the combined mass of the two objects. To find A, we rearrange the equation as follows:

$$A^3 = \frac{G}{4\pi^2} \times M \times P^2$$

From the graph of radial velocity observations in Figure 7.17, we can determine that the period of the orbit is 5.7 years. There are 3.16×10^7 seconds in a year, so

$$P = 5.7\text{ yr} \times (3.16 \times 10^7\text{ s/yr})$$

$$P = 1.8 \times 10^8\text{ s}$$

The mass of the star is much greater than the mass of the planet, so the combined masses of the star and the planet can be approximated as the mass of the star, which in this case is about equal to the mass of the Sun, 2×10^{30} kg. (Stellar masses can be estimated from their spectra.) The gravitational constant $G = 6.67 \times 10^{-20}\text{ km}^3/(\text{kg s}^2)$. Putting in the numbers gives

$$A^3 = \frac{6.67 \times 10^{-20}\dfrac{\text{km}^3}{\text{kg s}^2}}{4\pi^2} \times (2 \times 10^{30}\text{ kg}) \times (1.8 \times 10^8\text{ s})^2$$

$$A^3 = 1.1 \times 10^{26}\text{ km}^3$$

Taking the cube root of $1.1 \times 10^{26}\text{ km}^3$ solves for A, which is equal to 4.8×10^8 km. To get a better feel for this number, we might put it into astronomical units (where 1 AU $= 1.5 \times 10^8$ km). The semimajor axis of the orbit of this planet is given by

$$A = \frac{4.8 \times 10^8\text{ km}}{1.5 \times 10^8\text{ km/AU}} = 3.2\text{ AU}$$

This planet is more than 3 times farther from its star than Earth is from the Sun.

Nebraska Simulation: Exoplanet Radial Velocity Simulator

Current technology limits the precision of radial velocity instruments to about 0.3 m/s, but to date it has been the most successful ground-based approach to finding extrasolar planets. This technique enables astronomers to detect giant planets around solar-type stars, but not yet to find planets with masses similar to Earth's. Finding the signal of the Doppler shift in the noise of the observation requires the star to be quite bright in our sky. So this method is limited to nearby stars, within about 160 light-years from Earth. **Working It Out 7.2** provides additional explanation of the spectroscopic radial velocity method.

Nebraska Simulation: Exoplanet Transit Simulator

The Transit Method Another technique for finding extrasolar planets is the **transit method**, in which we observe the effect of a planet passing in front of its parent star. From Earth it is sometimes possible to see the inner planets Mercury and Venus transit, or pass in front of, the Sun. An alien located somewhere in the plane of Earth's orbit would see Earth pass in front of the Sun and could infer the existence of Earth by detecting the 0.009 percent drop in the Sun's brightness during the transit. Similarly, for astronomers on Earth to observe a planet passing in front of a star, Earth must lie nearly in the orbital plane of that planet. When an extrasolar planet passes in front of its parent star, the light from the star diminishes by a tiny amount, as seen in **Figure 7.19**. Whereas the radial velocity method gives us the mass of the planet and its orbital distance from a star, the transit method provides the size of a planet. **Working It Out 7.3** demonstrates how the radii are estimated.

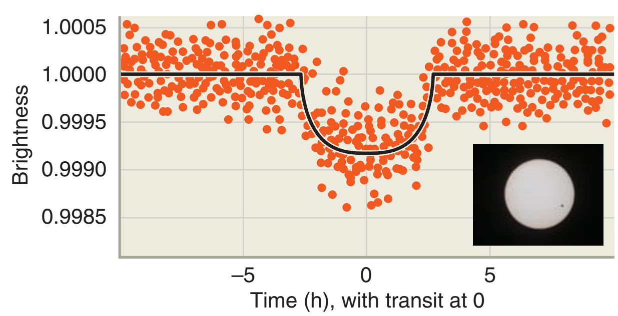


Figure 7.19 The data show the light curve for Kepler-11c. The inset photograph shows Venus passing in front of the Sun in June 2012, similar to this transit of Kepler-11c.

7.3 Working It Out Estimating the Radius of an Extrasolar Planet

The masses of extrasolar planets can often be estimated using Kepler's laws and the conservation of angular momentum. When planets are detected by the transit method, astronomers can estimate the radius of an extrasolar planet. In this method, astronomers look for planets that eclipse their stars and observe how much the star's light decreases during this eclipse (see Figure 7.19). In the Solar System when Venus or Mercury transits the Sun, a black circular disk is visible on the face of the circular Sun. During the transit, the amount of light from the transited star is reduced by the area of the circular disk of the planet divided by the area of the circular disk of the star:

$$\text{Percentage reduction in light} = \frac{\text{Area of disk of planet}}{\text{Area of disk of star}}$$

$$= \frac{\pi R^2_{\text{planet}}}{\pi R^2_{\text{star}}} = \frac{R^2_{\text{planet}}}{R^2_{\text{star}}}$$

Then, to solve for the radius of the planet, astronomers need an estimate of the radius of the star and a measurement of the percentage reduction in light during the transit. The radius of a star is estimated from the surface temperature and the luminosity of the star.

Let's consider an example. Kepler-11 is a system of at least six planets that transit a star. The radius of the star, R_{star}, is estimated to be 1.1 times the radius of the Sun, or $1.1 \times (7.0 \times 10^5\ \text{km}) = 7.7 \times 10^5\ \text{km}$. The light from planet Kepler-11c is observed to decrease by 0.077 percent, or 0.00077 (see Figure 7.19). What is Kepler-11c's size?

$$0.00077 = \frac{R^2_{\text{Kepler-11c}}}{R^2_{\text{star}}} = \frac{R^2_{\text{Kepler-11c}}}{(7.7 \times 10^5\ \text{km})^2}$$

$$R^2_{\text{Kepler-11c}} = 4.5 \times 10^8\ \text{km}^2$$

$$R_{\text{Kepler-11c}} = 2.1 \times 10^4\ \text{km}$$

Dividing Kepler-11c's radius by the radius of Earth (6,400 km) shows that the planet Kepler-11c has a radius of 3.3 R_{Earth}.

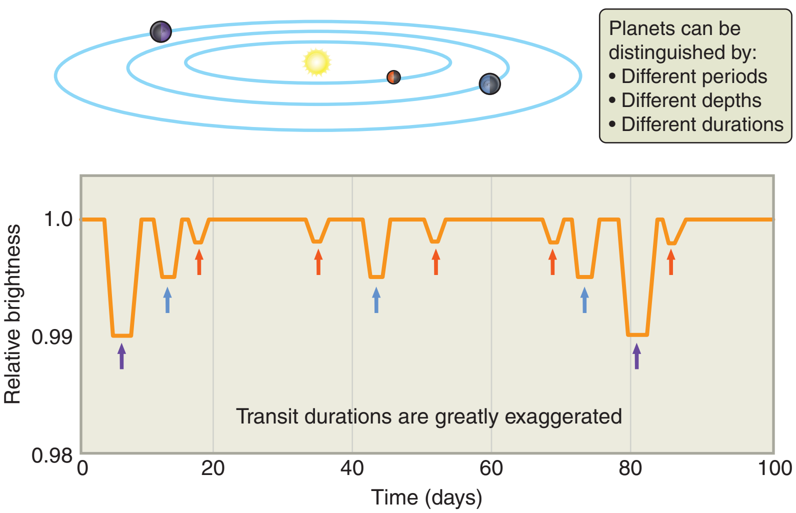


Figure 7.20 Multiple planets can be detected by multiple transits with different brightness changes. The arrows point to the changes in the total light as the three planets transit the star.

More than a thousand extrasolar planets have been detected from ground-based and space telescopes using the transit method. Current ground-based technology limits the sensitivity of the transit method to about 0.1 percent of a star's brightness. Amateur astronomers have confirmed the existence of several extrasolar planets by observing transits using charge-coupled device (CCD) cameras mounted on telescopes with apertures as small as 20 centimeters (cm). Telescopes in space improve the sensitivity because smaller dips in brightness can be measured. The small French COROT telescope (27 cm) discovered 32 planets during its 6 years of operation (2007–2013). NASA's 0.95-meter Kepler telescope has discovered many planets and has found thousands more candidates that are being investigated further. **Figure 7.20** illustrates how multiplanet systems are identified with this method: if one planet is found, then observations of the variations in timing of the transit can indicate that there are other planets orbiting the same star.

Microlensing The gravitational field of an unseen planet can act like a lens, bending the light from a distant star in such a way that it causes the star to brighten temporarily while the planet is passing in front of it. Because the effect is small, it is usually called microlensing. Like the radial velocity method, microlensing provides an estimate of the mass of the planet. To date, several dozen extrasolar planets have been found with this technique.

The Astrometric Method Planets may also be detected by astrometry—precisely measuring the position of a star in the sky. If the system is viewed from "above," the star moves in a mini-orbit as the planet pulls it around. This motion is generally tiny and therefore very difficult to measure. However, for systems viewed from above the plane of the planet's orbit, none of the prior methods will work because the planet neither passes in front of the star nor causes a shift in its speed along the line of sight. Space missions such as the Gaia observatory, launched in 2013 by the European Space Agency, is conducting observations of this kind.

Direct Imaging Direct imaging means taking a picture of the planet directly. This technique is conceptually straightforward but is technically difficult because it involves searching for a relatively faint planet in the overpowering glare of a bright star—a challenge far more difficult than looking for a star in a clear, bright daytime sky. Even when an object is detected by direct imaging, an astronomer must still determine whether the observed object is actually a planet. Suppose we detect a faint object near a bright star. Could it be a more distant star that just happens to be in the line of sight? Future observations could tell if the object shares the bright star's motion through space. But it could also be a brown dwarf rather than a true planet. An astronomer would need to make further observations to determine the object's mass.

Some planets have been discovered by this method with large ground-based telescopes operating in the infrared region of the spectrum using adaptive optics. **Figure 7.21** is an infrared image of Beta Pictoris b. The first visible-light discovery was made from space while the Hubble Space Telescope was observing Fomalhaut, a bright naked-eye star only 25 light-years away. The planet Fomalhaut b is shown in **Figure 7.22**. It has a mass no more than 3 times that of Jupiter and orbits within a dusty debris ring about 17 billion km from the central star. A related form of direct observation involves separating the spectrum of a planet from the spectrum of its star to obtain information about the planet directly. Large ground-based telescopes have been able to obtain spectra of the atmospheres of some extrasolar planets and have found, for example, carbon monoxide and water in these atmospheres.

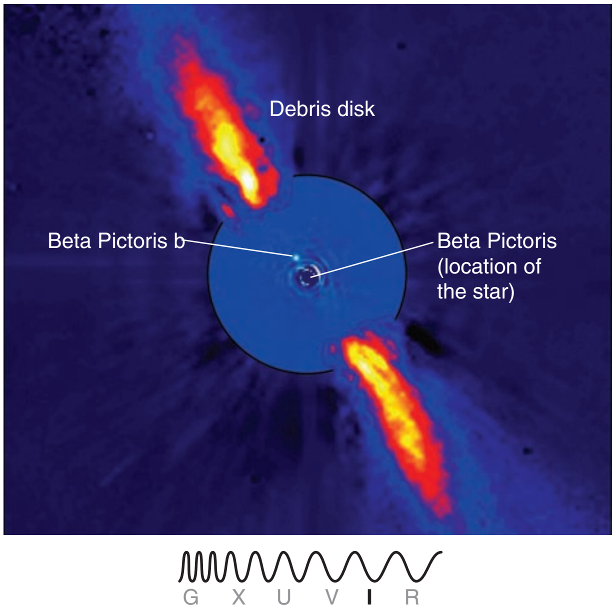


Figure 7.21 Beta Pictoris b is seen orbiting within a dusty debris disk that surrounds the bright naked-eye star Beta Pictoris. The planet's estimated mass is 8 times that of Jupiter. The star is hidden behind an opaque mask, and the planet appears through a semitransparent mask used to subdue the brightness of the dusty disk.

The Discovery of Extrasolar Planets

Searches for extrasolar planets have been remarkably successful. Between the discovery of the first (in 1995) and this writing, nearly 2,000 more have been confirmed, and thousands more candidates are under investigation. As the number of observed systems with single and multiple planets increases, astronomers can compare them with those of the Solar System, and they have found more variation than they expected. The field is changing so fast that the most up-to-date information can only be found online or through mobile applications such as the Kepler App.

The first discoveries included many **hot Jupiters**, which are Jupiter-sized planets orbiting solar-type stars in circular or highly eccentric orbits that bring them closer to their parent stars than Mercury is to our own Sun. These planets were among the first to be detected because they are relatively easy targets for the spectroscopic radial velocity method. The large mass of a nearby hot Jupiter tugs the star very hard, creating large radial velocity variations in the star. In addition, these large planets orbiting close to their parent stars are more likely to pass in front of the star periodically and reveal themselves via the transit method. Therefore, these hot Jupiter systems are easier to find than smaller, more distant planets. Astronomers realized that these hot Jupiter systems are not representative of most planetary systems; they were just easier to find. Scientists call this bias a *selection effect*.

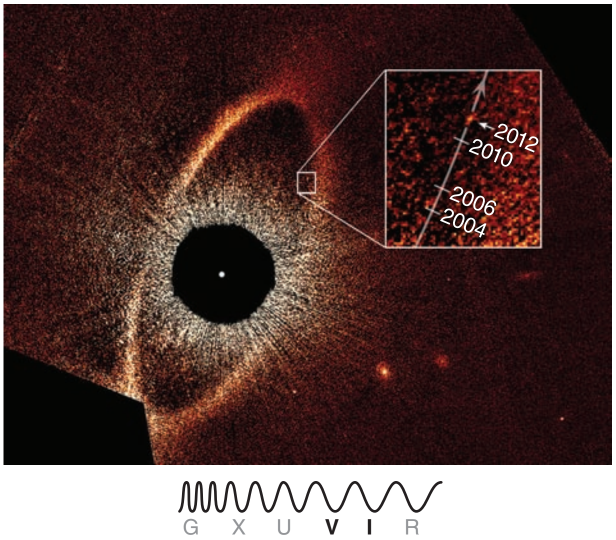


Figure 7.22 A Hubble Space Telescope image of Fomalhaut b, seen here moving in its orbit around Fomalhaut, a nearby star easily visible to the naked eye. The parent star, hidden by an obscuring mask, is about a billion times brighter than the planet, which is located within a dusty debris ring that surrounds the star.

Astronomers were surprised by the hot Jupiters because, according to the planetary system formation theory available at the time (based only on the Solar System), these giant, volatile-rich planets should not have been able to form so close to their parent stars. The expectation was that Jupiter-type planets should form in the more distant, cooler regions of the protoplanetary disk, where the volatiles that make up much of their composition are able to survive. So astronomers suggested that perhaps hot Jupiters formed much farther away from their parent stars and subsequently migrated inward to a closer orbit. The mechanism by which a planet could migrate over such a distance must involve an interaction with gas or planetesimals in which orbital angular momentum is somehow transferred from the planet to its surroundings, allowing it to spiral inward.

Many of the new planets being discovered by Kepler are mini-Neptunes (gaseous planets with masses of 2–10 M_{Earth}) or super-Earths (rocky planets more massive than Earth), but each month brings an announcement of the discovery of smaller planets. Planets with longer orbital periods, and therefore larger orbits, can be discovered only when the observations have gone on long enough to observe more than one complete orbit. Some of the extrasolar planets have highly elliptical orbits compared with those in the Solar System. Planets have been found with orbits that are highly tilted compared with the plane of the rotation of their star, and some planets move in orbits whose direction is opposite that of their star's rotation. Multiple-planet systems have been observed in which the larger mini-Neptunes alternate with smaller super-Earths. The multiple-planet systems that have been found by the transit method reside in flat systems like our own, offering further evidence that the planets formed in a flat protoplanetary disk around a young star. But the current hypothesis to explain the Solar System's inner, small rocky planets and outer, large gaseous planets may not be applicable in these other planetary systems.

In addition, some planets detected by microlensing seem to be wandering freely through the Milky Way. These planets may have been ejected from their solar systems after their formation and are no longer in gravitationally bound orbits around their stars. The frequent new discoveries requiring revisions of existing theories make extrasolar planets one of the most exciting topics in astronomy today.

CHECK YOUR UNDERSTANDING 7.5

Suppose you hear of the discovery of an Earth-mass planet around a star. This planet was most likely discovered through the ______ method. (a) Doppler spectroscopy; (b) direct imaging; (c) transit; (d) astrometric

Origins

Kepler's Search for Earth-Sized Planets

The discovery of planetary systems, many different from the Solar System, shows us that the formation of planets frequently, and perhaps always, accompanies the formation of stars. The implications of this conclusion are profound. Planets are a common byproduct of star formation. In a galaxy of 200 billion stars and a universe of hundreds of billions of galaxies, how many planets (and also moons) might exist? And with all of these planets in the universe, how many might have suitable conditions for the particular category of chemical reactions that we refer to as "life"? (We will return to this point in Chapter 24.)

The Kepler Mission was developed by NASA to find Earth-sized and larger planets in orbit about a variety of stars. Kepler is a 1-meter telescope with 42 CCD detectors and is designed to observe approximately 150,000 stars in 100 square degrees of sky and look for planetary transits. To confirm a planetary detection, the transits need to be observed three times with repeatable changes in brightness, duration of transit times, and computed orbital period. Kepler can detect a dip in the brightness of a star of 0.01 percent—which is sensitive enough to detect an Earth-sized planet. Kepler identified the first Earth-sized planets in 2011. Stars with transiting planets detected by Kepler are also observed spectroscopically to obtain radial velocity measurements that can lead to an estimate of a planet's mass. If a planet's radius and mass are known, the planet's density (mass per volume) can be estimated, too. From the density, astronomers can get a sense of whether the planet is composed primarily of gas, rock, ice, water, or a mixture of some of these.

On Earth, liquid water was essential for the formation and evolution of life. Because life on Earth is the only example of life for which we have evidence, we do not know whether liquid water is a cosmic requirement, but it is a place to start. The primary scientific goal of the Kepler Mission is to look for rocky planets at the right distance from their stars to permit the existence of liquid water, a distance known as the **habitable zone**. If a planet is too close to its star, water will exist only as a vapor; if it is too far, water will be frozen as ice. In the Solar System, Earth is the only planet in the habitable zone. Although announcements of new planets often state whether the planet is in the habitable zone, just being in the zone doesn't guarantee that the planet actually has liquid water—or that the planet is inhabited! An example of an Earth-sized planet in a habitable zone is shown in **Figure 7.23**.

In 2013, Kepler suffered a mechanical failure that stopped observations, but a work-around was approved, and observations resumed in 2014. Kepler has identified thousands of planet candidates, some in the habitable zones of their respective stars. The candidates must be confirmed by follow-up observations of more transits or of radial velocities before they are officially announced as planet detections. Amateur astronomers can access the candidate lists online (at the "Exoplanet Transit Database") and conduct their own observations. Anyone with Internet access can go to planethunters.org, examine some Kepler data, and contribute to the search.

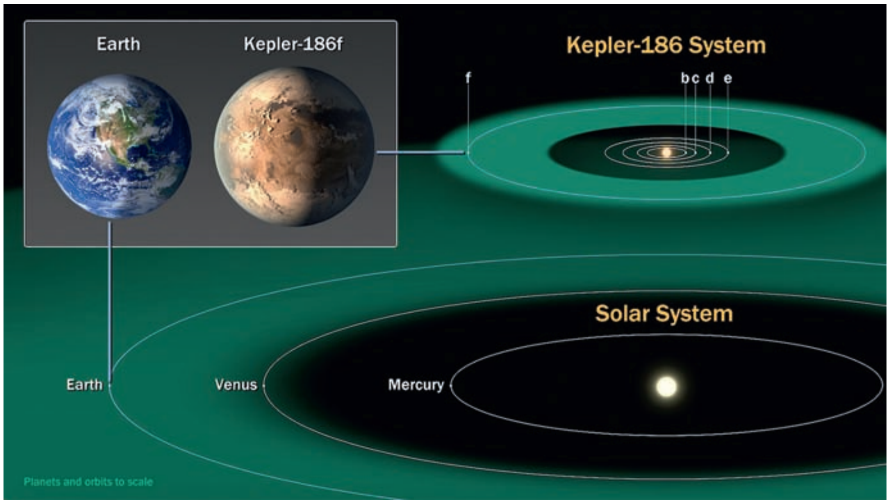


Figure 7.23 An artist's conception of the Kepler-186 system. Located about 500 light-years from Earth, this system has a planet in its habitable zone. The Solar System is shown for comparison.

A system with five planets was observed by NASA's Kepler space telescope.

Earth-Size Planet Found in the "Habitable Zone" of Another Star

By **Science@NASA**

Using NASA's Kepler space telescope, astronomers have discovered the first Earth-size planet orbiting in the "habitable zone" of another star (see Figure 7.23). The planet, named "Kepler-186f," orbits an M dwarf, or red dwarf, a class of stars that makes up 70 percent of the stars in the Milky Way Galaxy. The discovery of Kepler-186f confirms that planets the size of Earth exist in the habitable zone of stars other than our Sun.

The "habitable zone" is defined as the range of distances from a star where liquid water might pool on the surface of an orbiting planet. While planets have previously been found in the habitable zone, the previous finds are all at least 40 percent larger in size than Earth, and understanding their makeup is challenging. Kepler-186f is more reminiscent of Earth.

Kepler-186f orbits its parent M dwarf star once every 130 days and receives one-third the energy that Earth gets from the Sun, placing it nearer the outer edge of the habitable zone. On the surface of Kepler-186f, the brightness of its star at high noon is only as bright as our Sun appears to us about an hour before sunset.

"M dwarfs are the most numerous stars," said Elisa Quintana, research scientist at the SETI Institute at NASA's Ames Research Center in Moffett Field, California, and lead author of the paper published today in the journal *Science*. "The first signs of other life in the galaxy may well come from planets orbiting an M dwarf."

However, "being in the habitable zone does not mean we know this planet is habitable," cautions Thomas Barclay, a research scientist at the Bay Area Environmental Research Institute at Ames, and coauthor of the paper. "The temperature on the planet is strongly dependent on what kind of atmosphere the planet has. Kepler-186f can be thought of as an Earth-cousin rather than an Earth-twin. It has many properties that resemble Earth."

Kepler-186f resides in the Kepler-186 system, about 500 light-years from Earth in the constellation Cygnus. The system is also home to four companion planets: Kepler-186b, Kepler-186c, Kepler-186d, and Kepler-186e, whiz around their sun every four, seven, 13, and 22 days, respectively, making them too hot for life as we know it. These four inner planets all measure less than 1.5 times the size of Earth.

Although the size of Kepler-186f is known, its mass and composition are not. Previous research, however, suggests that a planet the size of Kepler-186f is likely to be rocky.

"The discovery of Kepler-186f is a significant step toward finding worlds like our planet Earth," said Paul Hertz, NASA's Astrophysics Division director at the agency's headquarters in Washington.

The next steps in the search for distant life include looking for true Earth-twins—Earth-size planets orbiting within the habitable zone of a Sun-like star—and measuring their chemical compositions. The Kepler space telescope, which simultaneously and continuously measured the brightness of more than 150,000 stars, is NASA's first mission capable of detecting Earth-size planets around stars like our Sun.

Looking ahead, Hertz said, "future NASA missions, like the Transiting Exoplanet Survey Satellite and the James Webb Space Telescope, will discover the nearest rocky exoplanets and determine their composition and atmospheric conditions, continuing humankind's quest to find truly Earth-like worlds."

ARTICLES QUESTIONS

1. This NASA press release was picked up by business and international news feeds. Why do you think coverage of this discovery was so widespread?
2. The planet is closer to its star than Earth is to the Sun yet receives much less energy. What does that imply about the temperature of the star?
3. Why is the mass of this planet not yet known? What method will be used to find its mass?
4. How will astronomers estimate the planet's composition?
5. Why is this planet called a "cousin" of Earth?

Summary

Stars and their planetary systems form from collapsing interstellar clouds of gas and dust, following the laws of gravity and conservation of angular momentum. Conservation of angular momentum produces an accretion disk around a protostar that often fragments to form multiple planets, as well as smaller objects such as asteroids and dwarf planets, through the gradual accumulation of material into larger and larger objects. There are multiple methods for finding planets around other stars, and these planets are now thought to be very common. This field of study is evolving very quickly as technology advances.

LG 1 **Describe how our understanding of planetary system formation developed from the work of both planetary and stellar scientists.** Planets are a common by-product of star formation, and many stars are surrounded by planetary systems. Gravity pulls clumps of gas and dust together, causing them to shrink and heat up. Angular momentum must be conserved, leading to both a spinning central star and an accretion disk that rotates and revolves in the same direction as the central star. Solar System meteorites show that larger objects build up from smaller objects.

LG 2 **Discuss the role of gravity and angular momentum in explaining why planets orbit the Sun in a plane and why they revolve in the same direction that the Sun rotates.** As particles orbit the forming star, the cloud of dust and gas flattens into a plane. Conservation of angular momentum determines both the speed and the direction of the revolution of the objects in the forming system. Dust grains in the protoplanetary disk first stick together because of collisions and static electricity. As these objects grow, they eventually have enough mass to attract other objects gravitationally. Once this occurs, they begin emptying the space around them. Collisions of planetesimals lead to the formation of planets.

LG 3 **Explain how temperature at different locations in the protoplanetary disk affects the composition of planets, moons, and other bodies.** Near the central protostar, the temperature is higher. This forces volatile elements, such as water, to evaporate and leave the inner part of the disk. Planets in the inner part of the disk will have fewer volatiles than those in the outer part of the disk. The gas that is captured by a planet at the time of its formation is the planet's primary atmosphere. Less massive planets lose their primary atmospheres and then form secondary atmospheres.

LG 4 **Discuss the processes that resulted in the formation of planets and other objects in our Solar System.** In the current model of the formation of the Solar System, solid terrestrial planets formed in the inner disk, where temperatures were high, and giant gaseous planets formed in the outer disk, where temperatures were low. Dwarf planets such as Pluto formed in the asteroid belt and in the region beyond the orbit of Neptune. Asteroids and comet nuclei remain today as leftover debris.

LG 5 **List how astronomers find planets around other stars, and explain how we know that planetary systems around other stars are common.** Astronomers find planets around other stars using a variety of methods: the radial velocity method, the transit method, microlensing, astrometry, and direct imaging. As technology has improved, the number and variety of known extrasolar planets has increased dramatically, with thousands of planets and planet candidates discovered orbiting other stars near the Sun within the Milky Way Galaxy in just the past few years.

? UNANSWERED QUESTIONS

- How typical is the Solar System? Only within the past few years have astronomers found other systems containing four or more planets, and so far the observed distributions of large and small planets in these multiplanet systems have looked different from those of the Solar System. Computer simulations of planetary system formation suggest that a system with an orbital stability and a planetary distribution like those of the Solar System may develop only rarely. Improved supercomputers can run more complex simulations, which can be compared with the observations to understand better how solar systems are configured.
- How Earth-like must a planet be before scientists declare it to be "another Earth"? An editorial in the science journal *Nature* cautioned that scientists should define "Earth-like" in advance—before multiple discoveries of planets "similar" to Earth are announced and a media frenzy ensues. Must a planet be of similar size and mass, be located in the habitable zone, and have spectroscopic evidence of liquid water before we call it "Earth 2.0"?

Questions and Problems

Test Your Understanding

1. Place the following events in the order that corresponds to the formation of a planetary system.
   a. Gravity collapses a cloud of interstellar gas.
   b. A rotating disk forms.
   c. Small bodies collide to form larger bodies.
   d. A stellar wind "turns on" and sweeps away gas and dust.
   e. Primary atmospheres form.
   f. Primary atmospheres are lost.
   g. Secondary atmospheres form.
   h. Dust grains stick together by static electricity.

2. If the radius of an object's orbit is halved, and angular momentum is conserved, what must happen to the object's speed?
   a. It must be halved.
   b. It must stay the same.
   c. It must be doubled.
   d. It must be squared.

3. Unlike the giant planets, the terrestrial planets formed when
   a. the inner Solar System was richer in heavy elements than the outer Solar System.
   b. the inner Solar System was hotter than the outer Solar System.
   c. the outer Solar System took up more volume than the inner Solar System, so there was more material to form planets.
   d. the inner Solar System was moving faster than the outer Solar System.

4. The terrestrial planets and the giant planets have different compositions because
   a. the giant planets are much larger.
   b. the terrestrial planets formed closer to the Sun.
   c. the giant planets are made mostly of solids.
   d. the terrestrial planets have few moons.

5. The spectroscopic radial velocity method preferentially detects
   a. large planets close to the central star.
   b. small planets close to the central star.
   c. large planets far from the central star.
   d. small planets far from the central star.
   e. the method detects all of these equally well

6. The concept of disk instability was developed to solve the problem that
   a. Jupiter-like planets migrate after formation.
   b. there was not enough gas in the Solar System to form Jupiter.
   c. the early solar nebula likely dispersed too soon to form Jupiter.
   d. Jupiter consists mostly of volatiles.

7. Because angular momentum is conserved, an ice-skater who throws her arms out will
   a. rotate more slowly.
   b. rotate more quickly.
   c. rotate at the same rate.
   d. stop rotating entirely.

8. Clumps grow into planetesimals by
   a. gravitationally pulling in other clumps.
   b. colliding with other clumps.
   c. attracting other clumps with opposite charge.
   d. conserving angular momentum.

9. The transit method preferentially detects
   a. large planets close to the central star.
   b. small planets close to the central star.
   c. large planets far from the central star.
   d. small planets far from the central star.
   e. the method detects all of these equally well

10. If the radius of a spherical object is halved, what must happen to the period so that the spin angular momentum is conserved?
    a. It must be divided by 4.
    b. It must be halved.
    c. It must stay the same.
    d. It must double.
    e. It must be multiplied by 4.

11. The amount of angular momentum in an object does *not* depend on
    a. its radius.
    b. its mass.
    c. its rotation speed.
    d. its temperature.

12. The planets in the inner part of the Solar System are made primarily of refractory materials; the planets in the outer Solar System are made primarily of volatiles. The difference occurred because
    a. refractory materials are heavier than volatiles, so they sank farther into the nebula.
    b. there were no volatiles in the inner part of the accretion disk.
    c. the volatiles on the inner planets were lost soon after the planet formed.
    d. the outer Solar System has gained more volatiles from space since formation.

13. If scientists want to find out about the composition of the early Solar System, the best objects to study are
    a. the terrestrial planets.
    b. the giant planets.
    c. the Sun.
    d. asteroids and comets.

14. The direction of revolution in the plane of the Solar System was determined by
    a. the plane of the galaxy in which the Solar System sits.
    b. the direction of the gravitational force within the original cloud.
    c. the direction of rotation of the original cloud.
    d. the amount of material in the original cloud.

15. A planet in the "habitable zone"
    a. is close to the central star.
    b. is far from the central star.
    c. is the same distance from its star as Earth is from the Sun.
    d. is at a distance where liquid water can exist on the surface.

Thinking about the Concepts

16. What is the source of the material that now makes up the Sun and the rest of the Solar System?
17. Describe the different ways by which stellar astronomers and planetary scientists each came to the same conclusion about how planetary systems form.
18. What is a protoplanetary disk? What are two reasons that the inner part of the disk is hotter than the outer part?
19. Physicists describe certain properties, such as angular momentum and energy, as being *conserved*. What does this mean? Do conservation laws imply that an individual object can never lose or gain angular momentum or energy? Explain your reasoning.
20. The Process of Science Figure in this chapter makes the point that different areas of science must agree with one another. Suppose that a handful of new exoplanets are discovered that appear not to have formed from the collapse of a stellar nebula (for example, the planetary orbits might be in random orientations). What will scientists do with this new information?
21. How does the law of conservation of angular momentum control a figure-skater's rate of spin?
22. What is an accretion disk?
23. Describe the process by which tiny grains of dust grow to become massive planets.
24. Look under your bed, the refrigerator, or any similar place for dust bunnies. Once you find them, blow one toward another. Watch carefully and describe what happens as they meet. What happens if you repeat this action with additional dust bunnies? Will these dust bunnies ever have enough gravity to begin pulling themselves together? If they were in space instead of on the floor, might that happen? What force prevents their mutual gravity from drawing them together into a "bunny-tesimal" under your bed?
25. Why do we find rocky material everywhere in the Solar System but large amounts of volatile material only in the outer regions?
26. Why were the four giant planets able to collect massive gaseous atmospheres, whereas the terrestrial planets could not? Explain the source of the secondary atmospheres surrounding the terrestrial planets.
27. Describe four methods that astronomers use to search for extrasolar planets. What are the limitations of each method; that is, what circumstances are necessary to detect a planet by each method?
28. Why is it so difficult for astronomers to obtain an image of an extrasolar planet?
29. Many of the first exoplanets that astronomers found orbiting other stars are giant planets with Jupiter-like masses and with orbits located very close to their parent stars. Explain why these characteristics are a selection effect of the discovery method.
30. How does Kepler find Earth-like planets, and what do astronomers mean by "Earth-like"?

Applying the Concepts

31. Study Figure 7.17. What is the maximum radial velocity of HD 70642b in meters per second? Convert this number to miles per hour (mph). How does this compare to the speed at which Earth orbits the Sun (67,000 mph)?
32. Use Appendix 4 to answer the following:
    a. What is the total mass of all the planets in the Solar System, expressed in Earth masses (M_{Earth})?
    b. What fraction of this total planetary mass is Jupiter?
    c. What fraction does Earth represent?
33. Compare Earth's orbital angular momentum with its spin angular momentum using the following values: $m = 5.97 \times 10^{24}$ kg, $v = 29.8$ kilometers per second (km/s), $r = 1$ AU, $R = 6{,}378$ km, and $P = 1$ day. Assume Earth to be a uniform body. What fraction does each component (orbital and spin) contribute to Earth's total angular momentum? Refer to Working It Out 7.1.
34. Venus has a radius 0.949 times that of Earth and a mass 0.815 times that of Earth. Its rotation period is 243 days. What is the ratio of Venus's spin angular momentum to that of Earth? Assume that Venus and Earth are uniform spheres.
35. Jupiter has a mass equal to 318 times Earth's mass, an orbital radius of 5.2 AU, and an orbital velocity of 13.1 km/s. Earth's orbital velocity is 29.8 km/s. What is the ratio of Jupiter's orbital angular momentum to that of Earth?
36. In the text, we give an example of an interstellar cloud having a diameter of 10^{13} km and a rotation period of 10^6 years collapsing to a sphere the size of the Sun (1.4×10^6 km in diameter). We point out that if all the cloud's angular momentum went into that sphere, the sphere would have a rotation period of only 0.6 second. Do the calculation to confirm this result.
37. The asteroid Vesta has a diameter of 530 km and a mass of 2.7×10^{20} kg.
    a. Calculate the density (mass/volume) of Vesta.
    b. The density of water is 1,000 kg/m^3, and that of rock is about 2,500 kg/m^3. What does this difference tell you about the composition of this primitive body?
38. Study Figure 7.20.
    a. Recalling Kepler's Laws, put the three planets in order, from fastest to slowest.
    b. Compare the duration of the transits. Why does the outermost planet have the longest duration?
39. The best current technology can measure radial velocities of about 0.3 m/s. Suppose you are observing a spectral line with a wavelength of 575 nanometers (nm). How large a shift in wavelength would a radial velocity of 0.3 m/s produce?
40. Earth tugs the Sun around as it orbits, but it has a much smaller effect (only 0.09 m/s) than that of any known extrasolar planet. How large a shift in wavelength does this effect cause in the Sun's spectrum at 500 nm?
41. If an alien astronomer observed a plot of the light curve as Jupiter passed in front of the Sun, by how much would the Sun's brightness drop during the transit?

42. A planet has been found to orbit a 1-M_{Sun} in 200 days.
    a. What is the orbital radius of this extrasolar planet?
    b. Compare its orbit with that of the planets around our own Sun. What environmental conditions must this planet experience?
43. One of the planets orbiting the star Kepler-11 with an orbital radius of radius 1.1 solar radii, or R_{Sun} has a radius of 4.5 Earth radii (R_{Earth}). By how much does the brightness of Kepler-11 decrease when this planet transits the star?
44. Kepler detected a planet with a diameter of 1.7 Earth (D_{Earth}).
    a. How much larger is the volume of this planet than Earth's?
    b. Assume that the density of the planet is the same as Earth's. How much more massive is this planet than Earth?
45. The planet COROT-11b was discovered using the transit method, and astronomers have followed up with radial velocity measurements, so both its size (radius 1.43 R_{Jup}) and its mass (2.33 M_{Jup}) are known. The density provides a clue about whether the object is gaseous or rocky.
    a. What is the mass of this planet in kilograms?
    b. What is the planet's radius in meters?
    c. What is the planet's volume?
    d. What is the planet's density? How does this density compare to the density of water (1,000 kg/m^3)? Is the planet likely to be rocky or gaseous?

USING THE WEB

46. Go to the "Extrasolar Planets Global Searches" Web page (http://exoplanet.eu/searches.php) of the Extrasolar Planets Encyclopedia. Click on one ongoing project under "Ground" and one ongoing project under "Space." What method is used to detect planets in each case? Has the selected project found any planets, and if so, what type are they? Now click on one of the future projects. When will the one you chose be ready to begin? What will be the method of detection?
47. Using the exoplanet catalogs:
    a. Go to the "Catalog" Web page (http://exoplanet.eu/catalog) of the Extrasolar Planets Encyclopedia and set to "All Planets detected." Look for a star that has multiple planets. Make a graph showing the distances of the planets from that star, and note the masses and sizes of the planets. Put the Solar System planets on the same axis. How does this extrasolar planet system compare with the Solar System?
    b. Go to the "Exoplanets Data Explorer" website (http://exoplanets.org) and click on "Table." This website lists planets that have detailed orbital data published in scientific journals, and it may have a smaller total count than the website in part (a). Pick a planet that was discovered this year or last, as specified in the "First Reference" column. What is the planet's minimum mass? What is its semimajor axis and the period of its orbit? What is the eccentricity of its orbit? Click on the star name in the first column to get more information. Is there a radial velocity curve for this planet? Was it observed in transit, and if so, what is the planet's radius and density? Is it more like Jupiter or more like Earth?
48. Space missions:
    a. Go to the website for the Kepler Mission (http://kepler.nasa.gov). How many confirmed planets has Kepler discovered? Mouse over "confirmed planets": How many planet candidates are there? What kinds of follow-up observations are being done to verify whether the candidates are planets? What is new?
    b. Search for the latest version of the "Kepler Orrery," an animation that shows multiplanet systems discovered by Kepler. Do most of these systems look like our own?
    c. Go to the website for the European Space Agency (ESA) mission Gaia (http://sci.esa.int/gaia). This mission was launched in 2013. Click on the "Exoplanets" link on the left-hand side. What method(s) will *GAIA* use to look for planets? What are the science goals? Have some planets been found?
49. Citizen science projects:
    a. Go to the "PlanetHunters" website at http://planethunters.org. PlanetHunters is part of the Zooniverse, a citizen science project that invites individuals to participate in a major science project using their own computers. To participate in this or any of the other Zooniverse projects mentioned in later chapters, you will need to sign up for an account. Read through the sections under "About," including the FAQ. What are some of the advantages to crowdsourcing Kepler data analysis? Back on the PlanetHunters home page, click on "Tutorial" and watch the "Introduction" and "Tutorial Video." When you're ready to try looking for planets, click on "Classify" and begin. Save a copy of your stars for your homework.
    b. Go to the "Disk Detective" website at http://www.diskdetective.org/, another Zooniverse project for which you will need to make an account as in part (a). In this project, you will look at observations of young stars to see if there is evidence for a planetary disk. Under "Menu," read "Science" and "About," and then "Classify." Work through an example, and then classify a few images.
50. Go to the "Super Planet Crash" Web page (http://www.stefanom.org/spc/ or http://apod.nasa.gov/apod/ap150112.html). Read "Help" to see the rules. First build a system like ours with four Earth-sized planets in the inner 2 AU—is this stable? What happens if you add in super-Earths or "ice giants"? Build up a few completely different planetary systems and see what happens. What types of situations cause instability in the inner 2 AU of these systems?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

digital.wwnorton.com/astro5

Visit the Student Site at the Digital Landing Page, and open the Exoplanet Radial Velocity Simulator in Chapter 7. This applet has a number of different panels that allow you to experiment with the variables that are important for measurement of radial velocities. First, in the window labeled “Visualization Controls,” check the box to show multiple views. Compare the views shown in panels 1–3 with the colored arrows in the last panel to see where an observer would stand to see the view shown. Start the animation (in the “Animation Controls” panel), and allow it to run while you watch the planet orbit its star from each of the views shown. Stop the animation, and in the “Presets” panel, select “Option A” and then click “set.”

1 Is Earth’s view of this system most nearly like the “side view” or most nearly like the “orbit view”?

2 Is the orbit of this planet circular or elongated?

3 Study the radial velocity graph in the upper right panel. The blue curve shows the radial velocity of the star over a full period. What is the maximum radial velocity of the star?

4 The horizontal axis of the graph shows the “phase,” or fraction of the period. A phase of 0.5 is halfway through a period. The vertical red line indicates the phase shown in views in the upper left panel. Start the animation to see how the red line sweeps across the graph as the planet orbits the star. The period of this planet is 365 days. How many days pass between the minimum radial velocity and the maximum radial velocity?

5 When the planet moves away from Earth, the star moves toward Earth. The sign of the radial velocity tells the direction of the motion (toward or away). Is the radial velocity of the star positive or negative at this time in the orbit? If you could graph the radial velocity of the planet at this point in the orbit, would it be positive or negative?

In the “Presets” window, select “Option B” and then click “set.”

6 What has changed about the orbit of the planet as shown in the views in the upper left panel?

7 When is the planet moving fastest: when it is close to the star or when it is far from the star?

8 When is the star moving fastest: when the planet is close to it or when the planet is far away?

9 Explain how an astronomer would determine, from a radial velocity graph of the star’s motion, whether the orbit of the planet was in a circular or elongated orbit.

10 Study the “Earth view” panel at the top of the window. Would this planet be a good candidate for a transit observation? Why or why not?

In the “System Orientation” panel, change the inclination to 0.0.

11 Now is Earth’s view of this system most nearly like the “side view” or most nearly like the “orbit view”?

12 How does the radial velocity of the star change as the planet orbits?

13 Click the box that says “show simulated measurements,” and change the “noise” to 1.0 m/s. The gray dots are simulated data, and the blue line is the theoretical curve. Use the slider bar to change the inclination. What happens to the radial velocity as the inclination increases? (Hint: Pay attention to the vertical axis as you move the slider, not just the blue line.)

14 What is the smallest inclination for which you would find the data convincing? That is, what is the smallest inclination for which the theoretical curve is in good agreement with the data?

8 The Terrestrial Planets and Earth's Moon

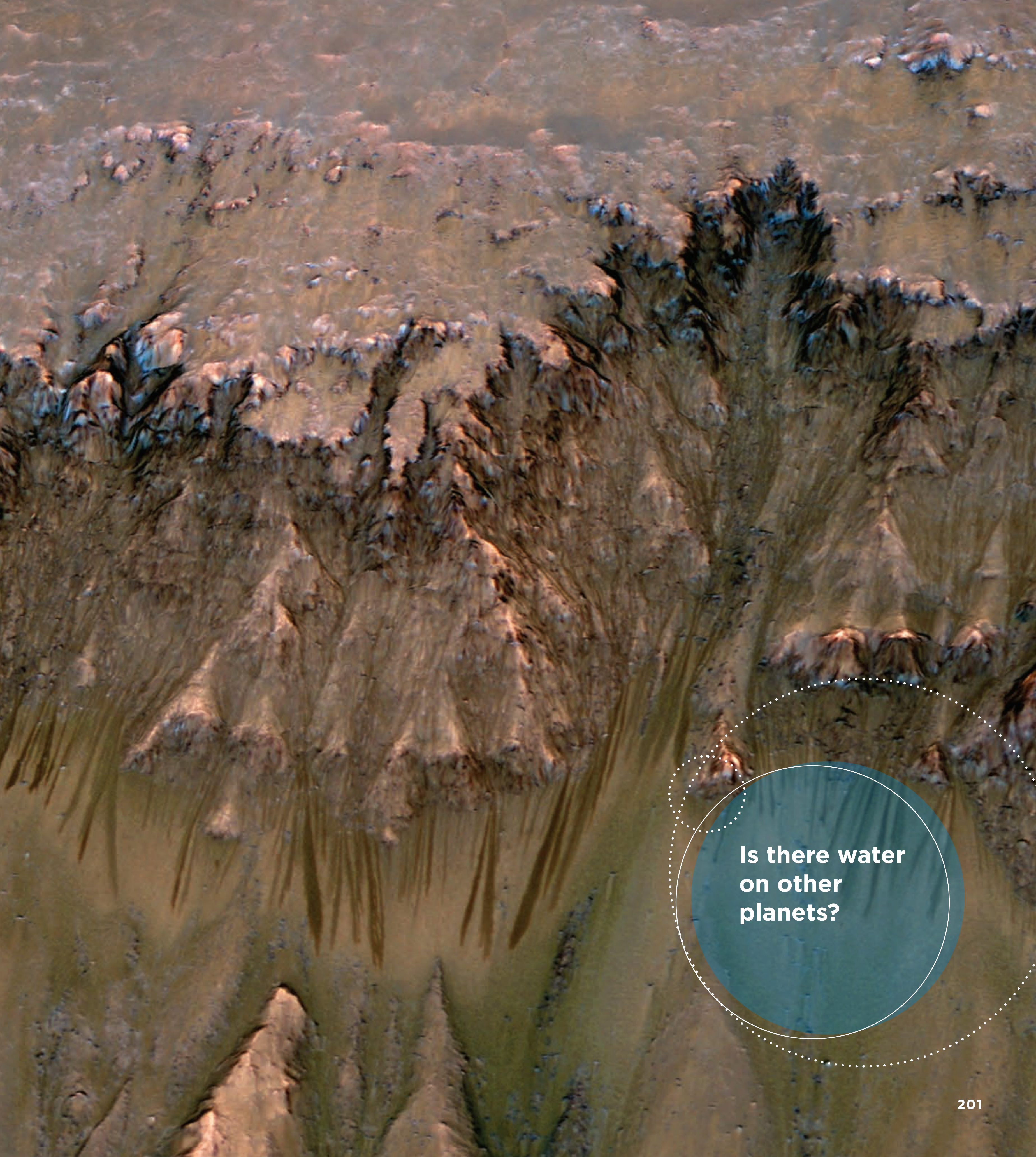
The objects that formed in the inner part of the protoplanetary disk around the Sun are relatively small, rocky worlds, one of which is Earth. A comparison of these worlds reveals the forces that shape a planet. The past six decades have been an exciting time for exploration of and discovery about Earth and the other planets in the Solar System. Robotic probes have visited every planet, and astronauts walked on the surface of the Moon. In addition to discoveries from new space missions and telescopes, improved analytical techniques applied to the rocks and soil brought back from the Moon more than 40 years ago have led to some surprising new results. The information from these missions has revolutionized the understanding of the Solar System, offering insights into the current state of each of the neighboring planets and clues about their histories.

LEARNING GOALS

By the conclusion of this chapter, you should be able to look at an image of a planet and identify which geological features occurred early in the history of that world and which occurred late. You should also be able to:

- **LG 1** Describe how impacts have affected the evolution of the terrestrial planets.
- **LG 2** Explain how radiometric dating is used to measure the ages of rocks and terrestrial planetary surfaces.
- **LG 3** Explain how scientists use both theory and observation to determine the structure of terrestrial planetary interiors.
- **LG 4** Describe tectonism and volcanism and the forms they take on different terrestrial planets.
- **LG 5** Summarize the knowledge of water on the terrestrial planets.

Mars Reconnaissance Orbiter image of Newton Crater on Mars. The dark streaks may be indications of flowing water. ▶▶▶



Is there water on other planets?

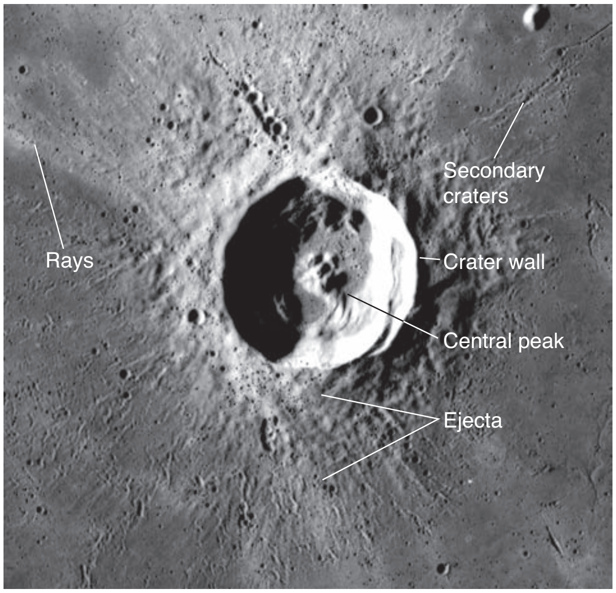


Figure 8.1 A lunar crater showing the crater wall and central peak surrounded by ejected material (*ejecta*), rays, and secondary craters—all typical features associated with impact craters.

8.1 Impacts Help Shape the Evolution of the Planets

Four principal geological processes constantly reshape the planets: *impact cratering, tectonism, volcanism,* and *erosion*. Some geological processes originate in a planet's interior, and other processes are external. The relative importance of each of these processes to each planet varies. Planetary scientists can learn about the evolutionary history of the Solar System by comparing these geological processes on the terrestrial planets and the Moon. In this section, we will examine **impact cratering**, which occurs when large collisions by other Solar System objects leave distinctive scars in the outer layer of a planet.

Comparative Planetology

The four innermost planets in the Solar System are Mercury, Venus, Earth, and Mars, collectively known as the *terrestrial planets*. Although the Moon is Earth's lone natural satellite, we include it in this chapter because of its close similarity to the terrestrial planets.

When comparing planets, we first compare the basic physical characteristics, such as distance from the Sun, size and density, and gravitational pull at the surface. These characteristics reveal what a planet is made of, what its surface temperature is likely to be, and how well it can hold an atmosphere (planetary atmospheres will be discussed in Chapter 9). By comparing the different planets, scientists can sort out the vast quantity of information returned by space probes. The correct explanation for a particular aspect of one planet must be consistent with what is known about the other planets. For example, an analysis of why the Moon is covered with craters must allow for the fact that preserved craters are rare on Earth. An explanation for why Venus has such a massive atmosphere should point to reasons that Earth and Mars do not. Such comparisons are key to an approach called **comparative planetology**. Some of the basic physical properties of the terrestrial planets are compared in **Table 8.1**.

TABLE 8.1 Comparison of Physical Properties of the Terrestrial Planets and the Moon

	Mercury	Venus	Earth	Mars	Moon
Orbital radius	0.387 AU	0.723 AU	1.000 AU	1.524 AU	384,000 km
Orbital period	0.241 yr	0.615 yr	1.000 yr	1.881 yr	27.32 days
Orbital velocity (km/s)	47.9	35.0	29.8	24.1	1.02
Mass (M_{Earth} = 1)	0.055	0.815	1.000	0.107	0.012
Equatorial diameter (km)	4,880	12,104	12,756	6,794	3,476
Equatorial diameter (D_{Earth} = 1)	0.383	0.949	1.000	0.533	0.272
Density (water = 1)	5.43	5.24	5.52	3.93	3.34
Sidereal rotation period*	58.65^d	243.02^d	23^h56^m	24^h37^m	27.32^d
Obliquity (degrees)†	0.04	177.36	23.45	25.19	6.68
Surface gravity (m/s²)	3.70	8.87	9.78	3.71	1.62
Escape velocity (km/s)	4.25	10.36	11.18	5.03	2.38

*The superscript letters *d*, *h*, and *m* stand for days, hours, and minutes of time, respectively.
†An obliquity greater than 90° indicates that the planet rotates in a retrograde, or backward, direction.

Impacts and Craters

Of the four geological processes, impact cratering causes the most concentrated and sudden release of energy. Planets and other objects orbit the Sun at very high speeds. For example, as seen in Table 8.1, Earth orbits the Sun at an average speed of around 30 kilometers per second (km/s), equivalent to 67,000 miles per hour (mph). Collisions between orbiting bodies can release huge amounts of energy and produce craters like the one in **Figure 8.1**. **Figure 8.2** shows the process

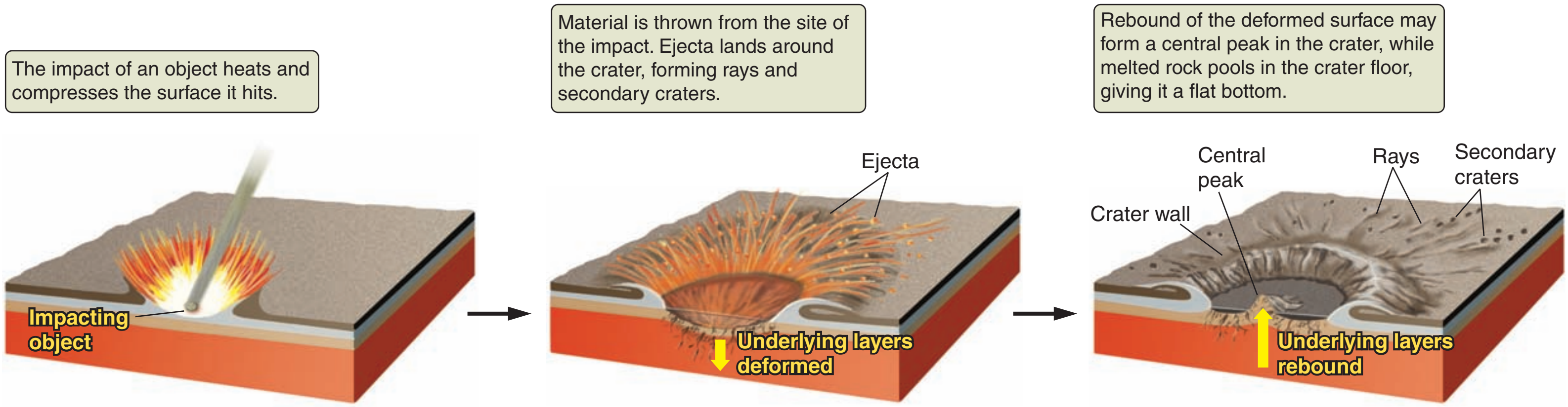


Figure 8.2 Stages in the formation of an impact crater.

of impact cratering. When an object hits a planet, its kinetic energy heats and compresses the surface that it strikes and throws material far from the resulting impact crater. Sometimes, material thrown from the crater, called **ejecta**, falls back to the surface of the planet with enough energy to cause **secondary craters**. The rebound of heated and compressed material can also lead to the formation of a central peak or a ring of mountains on the crater floor as shown in the lunar crater in Figure 8.1. These processes are similar to what happens when a drop lands in milk, as shown in **Figure 8.3**.

The energy of an impact can be great enough to melt or even vaporize rock. The floors of some craters are the cooled surfaces of melted rock that flowed as lava. The energy released in an impact can also lead to the formation of new minerals. Because some minerals form only during an impact, they are evidence of ancient impacts on Earth's surface. The space rocks that cause these impacts are defined by three closely related terms: **meteoroids** are small (less than 100 meters in diameter) cometary or asteroid fragments in space. A meteoroid that enters and burns up in a planetary atmosphere is called a **meteor**. Any meteoroids that survive to hit the ground are known as **meteorites**.

One of the best-preserved impact structures on Earth is Meteor Crater in Arizona. This impact occurred about 50,000 years ago. From the crater's size and shape and from the remaining pieces of the impacting body, we know that the nickel-iron asteroid fragment was about 50 meters across, had a mass of about 300 million kilograms (kg), and was traveling at 13 km/s relative to Earth, when it hit Earth's upper atmosphere. Approximately half of the original mass was vaporized in the atmosphere before the remainder hit the ground. This collision released about 300 times as much total energy as the first atom bomb. At only 1.2 km in diameter, Meteor Crater is

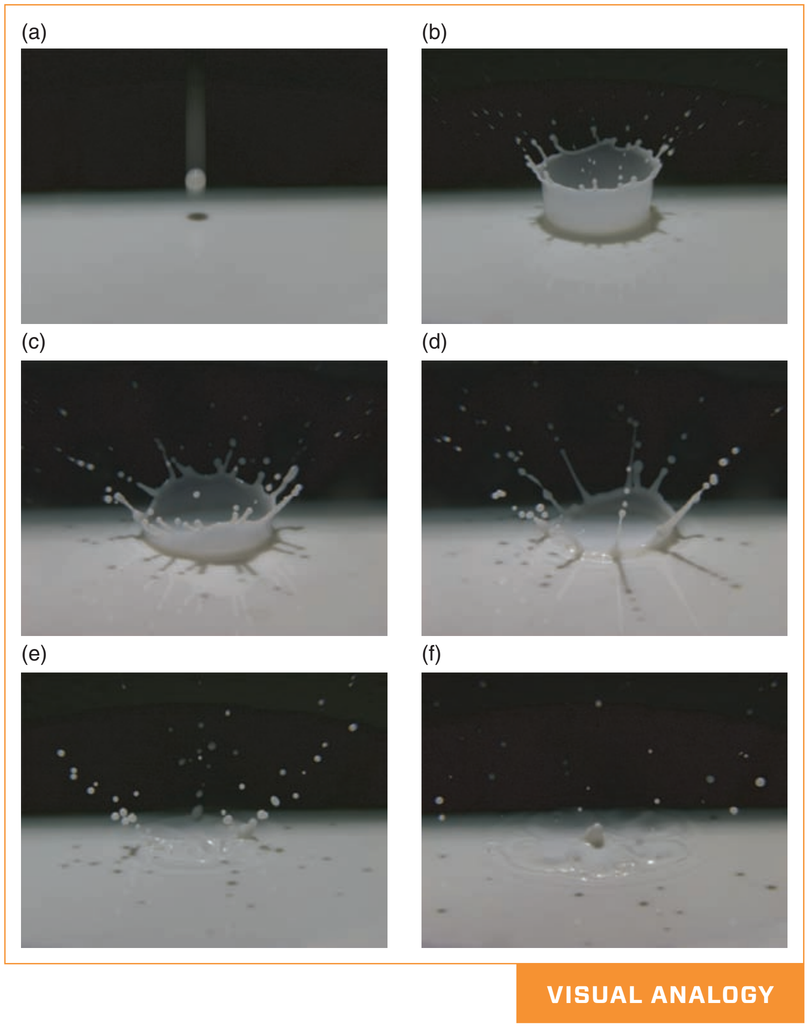


Figure 8.3 A drop (a) hitting a pool of milk illustrates the formation of features in an impact crater, including crater walls (b, c), secondary craters (d, e), and a central peak (f).

Figure 8.4 Meteor Crater (also known as Barringer Crater), located in northern Arizona, is an impact crater 1.2 km in diameter that formed some 50,000 years ago by a nickel-iron meteoroid's collision with Earth.

tiny compared to impact craters seen on the Moon or ancient impact scars on Earth (**Figure 8.4**).

Impact craters cover the surfaces of Mercury, Mars, and the Moon. For example, the Moon has millions of craters of all different sizes, one on top of another as seen outlined by yellow circles in **Figure 8.5**. Nearly all of these craters are the result of impacts. On Earth and Venus, by comparison, most impact craters have been destroyed. Fewer than 200 impact craters have been identified on Earth, and about 1,000 have been found on Venus. Earth's crater shortage is primarily due to two processes we will discuss later in the chapter—plate tectonics in Earth's ocean basins and erosion on land. On Venus, lava flows have destroyed most of the craters.

The atmospheres of Earth and Venus provide another explanation for their low number of small craters. The surfaces of the Moon and Mercury are directly exposed to bombardment from space, whereas the surfaces of Earth and Venus are partly protected by their atmospheres. Rock samples from the Moon show craters smaller than a pinhead, formed by micrometeoroids. In contrast, most meteoroids smaller than 100 meters in diameter that enter Earth's atmosphere are either burned up or broken up by friction before they reach the surface. Small meteorites found on the ground on Earth are probably pieces of much larger bodies that broke apart on entering the atmosphere. With an atmosphere far thicker than that of Earth, Venus is even better protected.

Planetary scientists can tell a lot about the surface of a planet by studying its craters because the characteristics of a crater depend on the properties of the planetary surface. An impact in a deep ocean on Earth might create an impressive wave but leave no lasting crater. In contrast, an impact scar formed in an ancient rocky area can be preserved for billions of years. For example, craters on the Moon's pristine surface are often surrounded by strings of smaller secondary craters formed from material thrown out by the impact, like those shown in Figure 8.2.

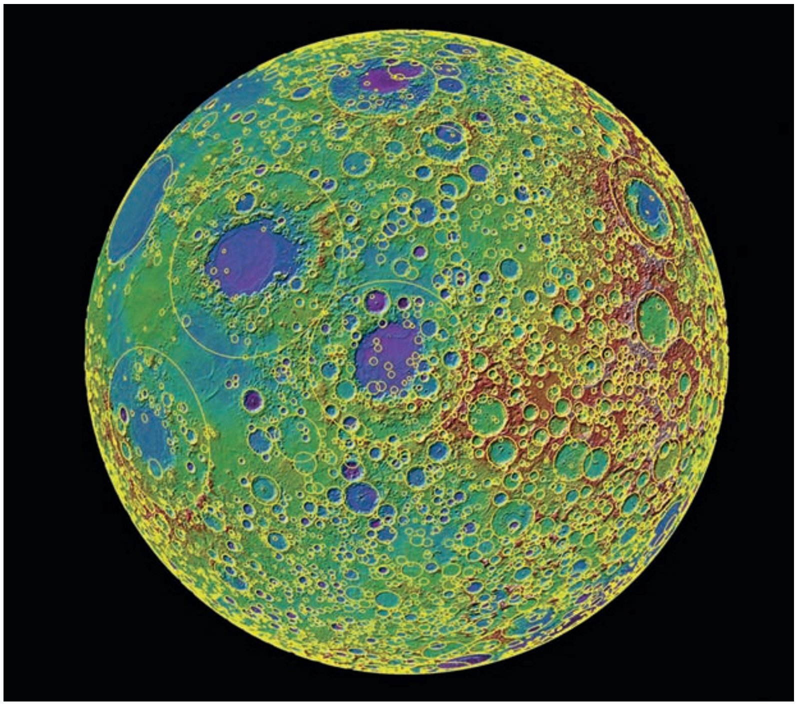


Figure 8.5 *Lunar Reconnaissance Orbiter* false-color image of craters on the Moon.

Some craters on Mars have a very different appearance. They are surrounded by structures that look much like the pattern you might see if you threw a rock into mud (**Figure 8.6**). The flows appear to indicate that the martian surface rocks contained water or ice at the time of the impact. At the time these craters formed, there may have been liquid water on the surface of Mars. Features resembling canyons and dry riverbeds are further evidence of this hypothesis. Not all martian craters have this feature, so the water or ice must have been concentrated in only some areas, and these icy locations might have changed with time.

Another explanation for the appearance of these craters is that the impact heated the surface enough to liquefy temporarily the frozen water in the ground. Today, the surface of Mars is dry in some regions and frozen in others, which suggests that water once on the surface has evaporated, or soaked into the ground, much like water frozen in the ground in Earth's polar regions. The energy released by an impact would have melted this ice, turning the surface material into a slurry with a consistency much like wet concrete. When thrown from the crater by the force of the impact, this slurry would hit the surrounding terrain and slide across the surface, forming the mudlike craters we see today.

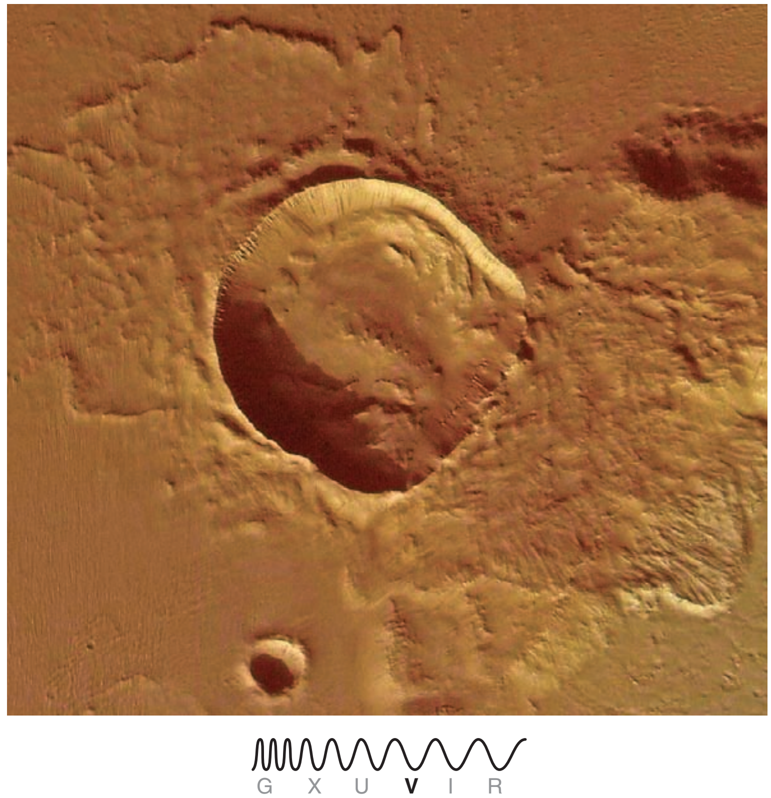


Figure 8.6 Some craters on Mars look like those formed by rocks thrown into mud, suggesting that material ejected from the crater contained large amounts of water. This crater is about 20 km across.

Giant Impacts Reshape Planets

Because many planetesimals were roaming around the early Solar System, every young planet experienced heavy bombardment early in its history. The last major bombardment is called *the late heavy bombardment*, and it took place from 4.2 billion to 3.8 billion years ago. Observations of uneven thicknesses of the crusts of inner planets have led to theories that some or all of the terrestrial planets were disrupted by at least one giant impact—a collision with an object the size of a large asteroid. A giant impact with Mercury could have removed some of the lighter material of its outside layer, leaving behind an overall denser planet. A giant impact with Venus may have led to its retrograde (backward) rotation. A giant impact probably explains the large differences between the northern and southern hemispheres of Mars. The southern highlands have a thicker crust and formed early in martian history. The northern lowlands have a thinner and younger crust and may have formed when there was melting after the impact. Early giant impacts on Mars also may be responsible for its loss of a magnetic field. Impacts with smaller icy comets from the outer parts of the Solar System brought water, atmospheric gases, and possibly organic molecules to the inner planets. As we'll discuss at the end of this chapter, an impact with Earth about 65 million years ago might have been a crucial event that paved the way for the evolution of *Homo sapiens*.

Although there are several different theories about how the Moon formed, a leading theory involves a giant impact. According to this impact theory, about 4.5 billion years ago, a Mars-sized protoplanet collided with Earth, blasting off and vaporizing parts of Earth's outer layers. The debris from the impact condensed into orbit around Earth and evolved into the Moon. This theory accounts for the similarities in composition between the Moon and Earth's outer layers. It also explains the lower amounts of volatiles on the Moon: during the vaporization stage of the collision, most gases were lost to space, leaving primarily the nonvolatiles to condense as the Moon. Earth, in contrast, was large enough to keep more of its volatiles, which continued to be released from its interior after the collision. Because of the stronger gravity of Earth, these gases were retained as part of Earth's atmosphere. If this account of the Moon's formation is correct, scientists expect to observe chemical evidence of material from the colliding protoplanet that was incorporated into the Moon's composition along with material from Earth. Currently, there is debate about whether chemical evidence of the colliding object has been found (**Process of Science Figure**).

AstroTour: Processes That Shape the Planets

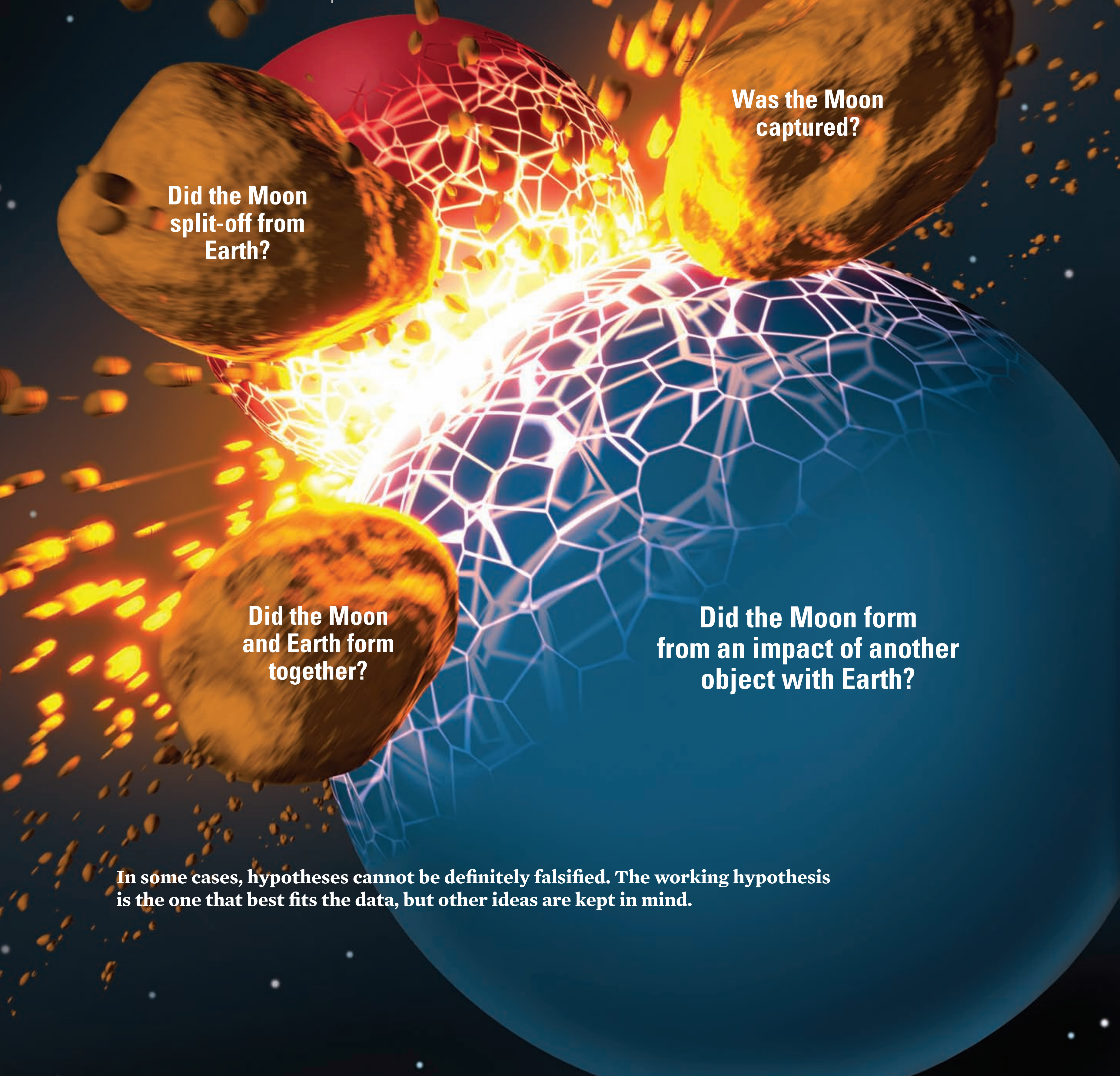
CHECK YOUR UNDERSTANDING 8.1

Geologists can find the relative age of impact craters on a world because: (a) the ones on top must be older; (b) the ones on top must be younger; (c) the larger ones must be older; (d) the larger ones must be younger.

Process of Science

CERTAINTY IS SOMETIMES OUT OF REACH

There are several hypotheses for how the Moon formed. One of these fits the data better than the others, but none have been absolutely ruled out.



In some cases, hypotheses cannot be definitely falsified. The working hypothesis is the one that best fits the data, but other ideas are kept in mind.

8.2 Radioactive Dating Tells Us the Age of the Moon and the Solar System

The number of visible craters on a planet is determined by the rate at which those craters are destroyed. Geological activity on Earth, Mars, and Venus erased most evidence of early impacts. By contrast, the Moon's surface still preserves the scars of craters dating from about 4 billion years ago. The lunar surface has remained essentially unchanged for more than a billion years because the Moon has no atmosphere or surface water and a cold, geologically dead interior. Mercury also has well-preserved craters, although recent evidence from the *Messenger* mission shows tilted crater floors that are higher on one side than the other—evidence that internal forces lifted the floors unevenly after the craters formed.

Planetary scientists use this cratering record to estimate the ages and geological histories of planetary surfaces: extensive cratering means an older planetary surface that remains relatively unchanged because of minimal geological activity. The amount of cratering can be used as a clock to measure the relative ages of surfaces. But to determine the exact age of a surface based on the number of craters, we need to know how fast the clock runs. In other words, we need to "calibrate the cratering clock."

To assign real dates to these different layers, scientists use a technique called radiometric dating. A geologist can find the age of a rock by measuring the relative amounts of a radioactive element, known as a **radioisotope**, and the decay products it turns into. An isotope is an atom with the same number of protons but a different number of neutrons as other atoms of the same chemical element. The radioactive element is known as the **parent element**, and the decay products are called **daughter products**. Chemical analysis of a rock containing radioactive elements immediately after its formation would reveal the presence of the radioactive parents, but the daughter products of the radioactive decay would be absent because they would not have formed yet. As radioactive atoms decay over time, however, the amount of parent elements decreases and the amount of daughter products builds up. Chemical analysis reveals both the remaining radioactive parent atoms and the daughter products trapped within the structure of the mineral.

The time interval over which a radioactive isotope decays to half its original amount is called its **half-life**. With every half-life that passes, the remaining amount of the radioisotope decreases by a factor of 2. For example, after 3 half-lives the remaining amount of a parent radioisotope will be $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$ of its original amount. This is illustrated in **Figure 8.7**. At formation, there is 100 percent of the radioactive parent isotope (in red) and no daughter isotope (in blue). After 1 half-life has passed, half of the parent isotope has decayed, and there are equal numbers of parent and daughter. After another half-life has passed, the sample is now only $\frac{1}{4}$ parent and $\frac{3}{4}$ daughter isotopes, and so on. By comparing the percentages of parent and daughter isotopes in a mineral, one can figure out how many half-lives have passed, and thus the age of the mineral. Some numerical examples are discussed in **Working It Out 8.1**.

The age of the Solar System is estimated from radioactive dating of meteorites found on Earth that are 4.5 billion to 4.6 billion years old. Earth may be as young as 4.4 billion years old. The age of the Moon comes from radioactive dating of lunar rocks. Between 1969 and 1976, *Apollo* astronauts and Soviet unmanned probes visited the Moon and brought back samples taken from nine different locations on

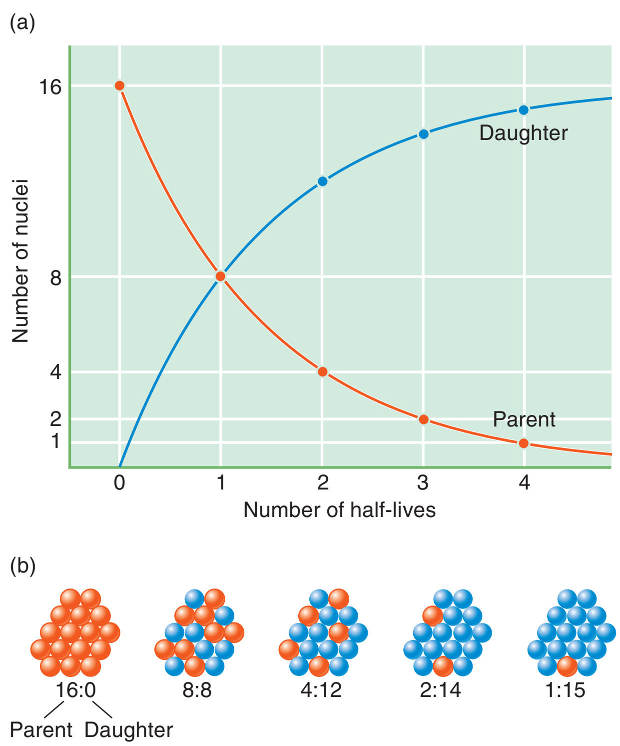


Figure 8.7 The concept of half-life. A parent population of 16 radioactive nuclei decays over a number of half-lives. This information can be presented (a) graphically or (b) as a collections of particles.

8.1 Working It Out Computing the Ages of Rocks

With every half-life that passes, the remaining amount will decrease by a factor of 2. If we express the number of half-lives more generally as n, then we can translate this relationship into math:

$$\frac{P_F}{P_O} = \left(\frac{1}{2}\right)^n$$

where P_O and P_F are the original and final amounts, respectively, of a parent radioisotope; and n is the number of half-lives that have gone by, which equals the time interval of decay (its age) divided by the half-life of the isotope.

For example, the most abundant isotope of the element uranium (uranium-238, or ^{238}U—the parent) decays through a series of intermediate daughters to an isotope of the element lead (lead-206, or ^{206}Pb—its final daughter). The half-life of ^{238}U is 4.5 billion years. This means that in 4.5 billion years, a sample that originally contained the uranium isotope (the parent) but no lead (its final daughter) would be found instead to contain equal amounts of uranium and lead. If we were to find a mineral with such composition, we would know that half the uranium atoms had turned to lead and that the mineral formed 4.5 billion years ago.

Let's look at another example, this time with a different isotope of uranium (^{235}U) that decays to a different lead isotope (^{207}Pb) with a half-life of 700 million years. Suppose that a lunar mineral brought back by astronauts has 15 times as much ^{207}Pb (the daughter product) as ^{235}U (the parent radioisotope). This means that 15/16 of the parent radioisotope (^{235}U) has decayed to the daughter product (^{207}Pb), leaving only 1/16 of the parent remaining in the mineral sample. Noting that 1/16 is $(1/2)^4$, we see that 4 half-lives have elapsed since the mineral was formed, and that this lunar sample is therefore 4×700 million years $= 2.8$ billion years old.

Because the measured quantity of the isotope is not always a neat power of 2 like this, it's worthwhile to look at how we would solve the equation mathematically. We do this by taking the logarithm on both sides:

$$\log_{10}\frac{P_F}{P_O} = \log_{10}\left(\frac{1}{2}\right)^n$$

$$\log_{10}\frac{P_F}{P_O} = n\log_{10}\frac{1}{2}$$

$$\log_{10}\frac{P_F}{P_O} = -0.3n$$

Putting this back into words, we can write this relationship as

$$\log_{10}\left(\frac{\text{Actual measured quantity of isotope}}{\text{Original quantity of isotope}}\right) = -0.3 \times \frac{\text{Time it has been decaying (age)}}{\text{Half-life}}$$

Solving for age,

$$\text{Age} = -3.3 \times \text{Half-life} \times \log_{10}\left(\frac{\text{Actual measured quantity of isotope}}{\text{Original quantity of isotope}}\right)$$

(Most calculators have a button called "log" or "$\log_{10}$" for calculating such numbers.)

In the second example introduced earlier, ^{235}U decays to ^{207}Pb with a half-life of 700 million years. The lunar mineral is measured to have 15 times as much lead as uranium, so the mineral currently contains only 1/16 of the original quantity of uranium:

$$\text{Age of mineral} = -3.3 \times (700 \times 10^6\ \text{yr}) \times \log_{10}\left(\frac{1}{16}\right) = 2.8 \times 10^9\ \text{yr}$$

The mineral is 2.8 billion years old.

the lunar surface. By measuring relative amounts of various radioactive elements and the elements into which they decay, scientists were able to assign ages to these different lunar regions. The oldest, most heavily cratered regions on the Moon date back to about 4.4 billion years ago, whereas most of the smoother parts of the lunar surface are typically 3.1 billion to 3.9 billion years old. This suggests the Moon formed after Earth, and the heavy cratering suggests there was heavy bombardment at that time. As you can see in **Figure 8.8**, almost all of the major cratering in the Solar System took place within its first billion years.

CHECK YOUR UNDERSTANDING 8.2

If radioactive element A decays into radioactive element B with a half-life of 20 seconds, then after 40 seconds: (a) none of element A will remain; (b) none of element B will remain; (c) half of element A will remain; (d) one-quarter of element A will remain.

8.3 The Surface of a Terrestrial Planet Is Affected by Processes in the Interior

While impact cratering is driven by forces external to a planet, two other important processes, tectonism and volcanism, are determined by conditions in the interior of the planet. To understand these processes, we must understand the structure and composition of the interiors of planets. But how do we know what the interiors of planets are like? On Earth, the deepest holes ever drilled are about 12 km deep; tiny when compared to Earth's radius of 6,378 km. It is impossible to drill down into Earth's core to observe Earth's interior structure directly. Scientists have determined a lot about the interior of Earth but less about the interiors of the other terrestrial planets.

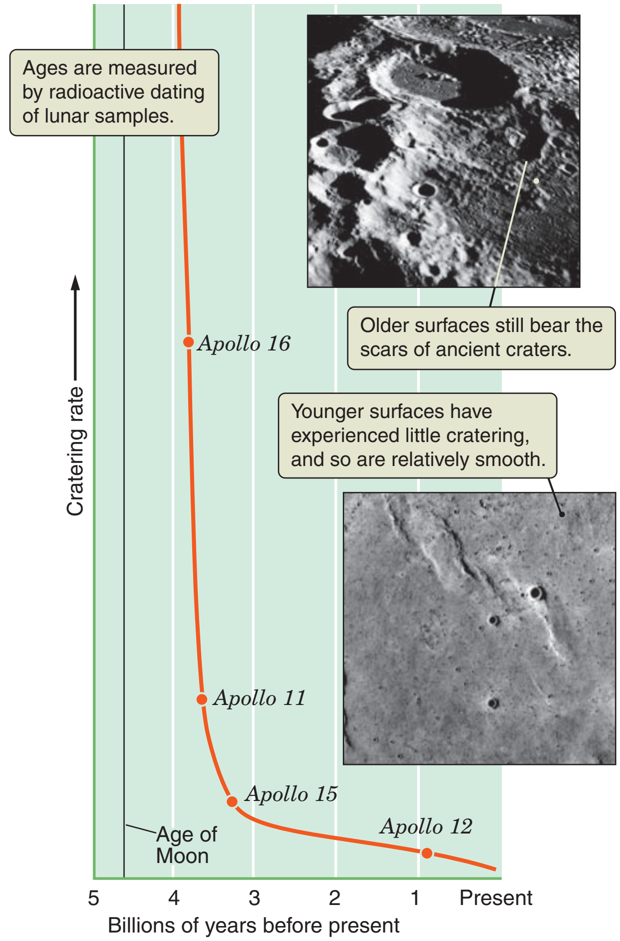


Figure 8.8 Radiometric dating of lunar samples returned from specific sites by *Apollo* astronauts was used to determine how the cratering rate has changed over time. Cratering records can then be used to establish the age of other parts of the lunar surface.

Probing the Interior of Earth

The composition of Earth's interior can be determined in two different ways. In one approach, Kepler's or Newton's laws are used to find the mass of Earth; for example, from applying Kepler's third law to a satellite orbiting Earth. Dividing the mass by the volume of Earth gives an average density of 5,500 kilograms per cubic meter (kg/m^3), or 5.5 times the density of water. But rocky surface material averages only 2,900 kg/m^3. Because the density of the whole planet is greater than the density of the surface, the interior must contain material denser than surface rocks. Another approach to determine the composition of Earth's interior comes from studies of meteorites. Because meteorites are left over from a time when the Solar System was young and Earth was forming from similar materials, the overall composition of Earth should resemble the composition of meteorite material. This material includes minerals with large amounts of iron, which has a density of nearly 8,000 kg/m^3. From these considerations, planetary scientists can determine the composition of Earth's interior.

The most important source of information about the structure of Earth's interior comes from monitoring the vibrations from earthquakes. When an earthquake occurs, vibrations spread out through and across the planet as **seismic waves**. There are different classes of seismic waves—those that travel across the surface of a planet and those that travel through a planet. **Surface waves** travel across the surface of a planet, much like waves on the ocean. If conditions are right, surface waves from earthquakes can be seen rolling across the countryside like ripples on water. These waves are responsible for much of the heaving of Earth's surface during an earthquake, causing damage such as the buckling of roadways.

The other types of seismic waves travel *through* Earth, probing the interior of the planet, at a higher speed than surface waves travel. **Primary waves** (P waves) are a type of **longitudinal wave** resulting from alternating compression and decompression of a material. Imagine a stretched-out spring, as illustrated in **Figure 8.9a**. A quick push along its length will make a longitudinal wave. P waves distort the material they travel through, much as compression waves do when they move along the length of a spring. **Secondary waves** (S waves) are a type of **transverse wave** resulting from the sideways motion of material (Figure 8.9b).

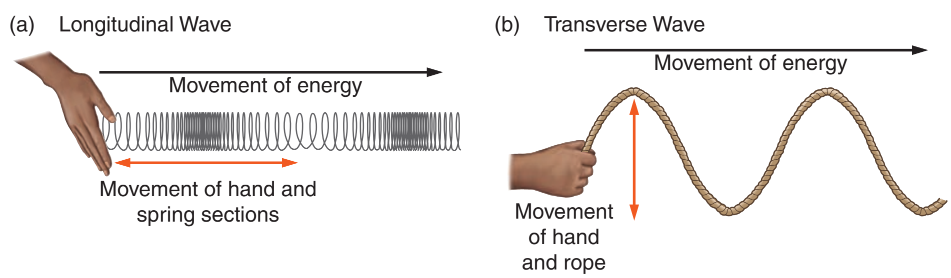


Figure 8.9 (a) A longitudinal wave involves oscillations along the direction of travel of the wave. (b) A transverse wave involves oscillations that are perpendicular to the direction in which the wave travels. Primary seismic waves are longitudinal; secondary seismic waves are transverse.

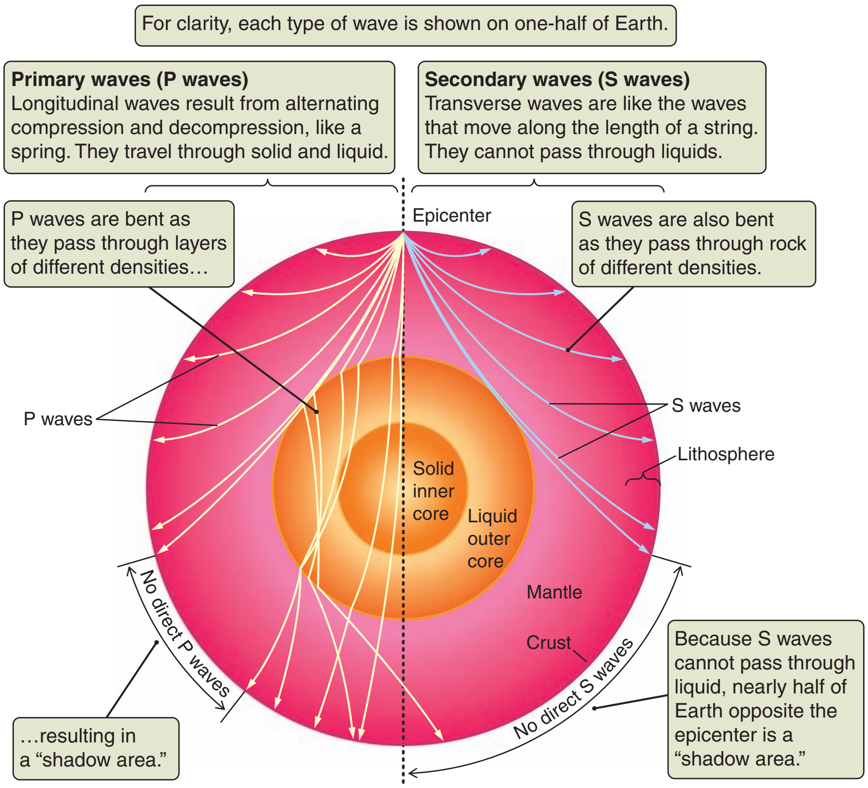


Figure 8.10 Primary and secondary seismic waves move through the interior of Earth in distinctive ways. Measurements of when and where different types of seismic waves arrive after an earthquake enable scientists to test predictions from detailed models of Earth's interior. Note the "shadow areas" caused by the refraction of primary waves (yellow) at the outer boundary of the liquid outer core and the inability of secondary waves (blue) to pass through the liquid outer core.

The progress of seismic waves through Earth's interior depends on the characteristics of the material through which they are moving. Primary waves (white) can travel through either solids or liquid, but secondary waves (blue) cannot travel through liquids, as shown in **Figure 8.10**. Seismic waves travel at different speeds, depending on the density and composition of the rocks they encounter. As a result, seismic waves moving through rocks of varying densities or composition are bent in much the same way that waves of light are bent when they enter or leave glass. Their speed provides additional information about Earth's interior. The refraction of primary waves at the outer edge of Earth's liquid outer core and the inability of secondary waves to penetrate the liquid outer core create "shadows" of the liquid core on the side of Earth opposite an earthquake's epicenter, as shown in Figure 8.10. Much of scientists' knowledge of Earth's liquid outer core is due to studies of these waves.

Scientists use instruments called seismometers to measure the distinctive patterns of seismic waves. For more than 100 years, thousands of seismometers scattered around the globe have measured the vibrations from countless earthquakes and other seismic events, such as volcanic eruptions and nuclear explosions. A single seismometer can record ground motion at only one place on Earth, but when combined with the recordings of many other seismometers placed all over Earth, scientists can use the data to get a comprehensive picture of the planet's interior.

Building a Model of Earth's Interior

Geologists use the laws of physics and the properties of materials and how these behave at different temperatures and pressures to model the structure of Earth's interior. The pressure at any point in Earth's interior must be just high enough that the outward forces balance the inward force of the weight of all the material above that point. If the outward pressure at some point within a planet were *less* than the weight per unit area of the overlying material, then that material would fall inward, crushing what was underneath it. If the pressure at some point within a planet were *greater* than the weight per unit area of the overlying material, then the material would expand and push outward, lifting the overlying material. The situation is stable only when the weight of matter above is just balanced by the pressure within the whole interior of the planet. The balance between pressure and weight is known as **hydrostatic equilibrium**, and it is important to the structure of planetary interiors, planetary atmospheres, and the structure and evolution of stars.

From consideration of hydrostatic equilibrium and seismic wave measurements, scientists construct a layered model of Earth's interior. They then test their model by comparing its predictions of how seismic waves would propagate through Earth with actual observations of seismic waves from real earthquakes. The extent to which the predictions agree with observations indicates both strengths and weaknesses of the model. Geologists adjust the model—always remaining consistent with the known physical properties of materials—until a good match is found between prediction and observation.

This is the method geologists used to arrive at the current picture of the interior of Earth shown in Figure 8.10. The innermost region of Earth's interior consists of a **core**. Earth's solid inner core is at a temperature of about 6000 K and is primarily composed of iron, nickel, and other dense metals. The liquid outer core is cooler, at about 4000 K, and is composed of liquid metals. Outside of the outer core is Earth's **mantle**, a rocky shell made of solid, medium-density materials such as silicates. Covering the mantle, the **crust** is a thin, hard layer of lower-density materials that is chemically distinct from the interior.

The cross sections in **Figure 8.11** show the interior structures of each of the terrestrial planets and the Earth's Moon. As you can see, Earth's interior is not uniform. The materials have been separated by density, a process known as **differentiation**. When rocks of different types are mixed together, they tend to stay mixed. Once this rock melts, however, the denser materials sink to the center and the less dense materials float toward the surface. Today, little of Earth's interior is molten, but the differentiated structure shows that Earth was once much hotter, and its interior was liquid throughout. The cores of all the terrestrial planets and the core of the Moon were once molten. When planetary scientists reanalyzed 8 years of data from seismometers left on the Moon by the *Apollo* astronauts using new, improved methods, they found that the Moon has a solid inner core, a liquid outer core, and a partially melted layer between the core and the mantle.

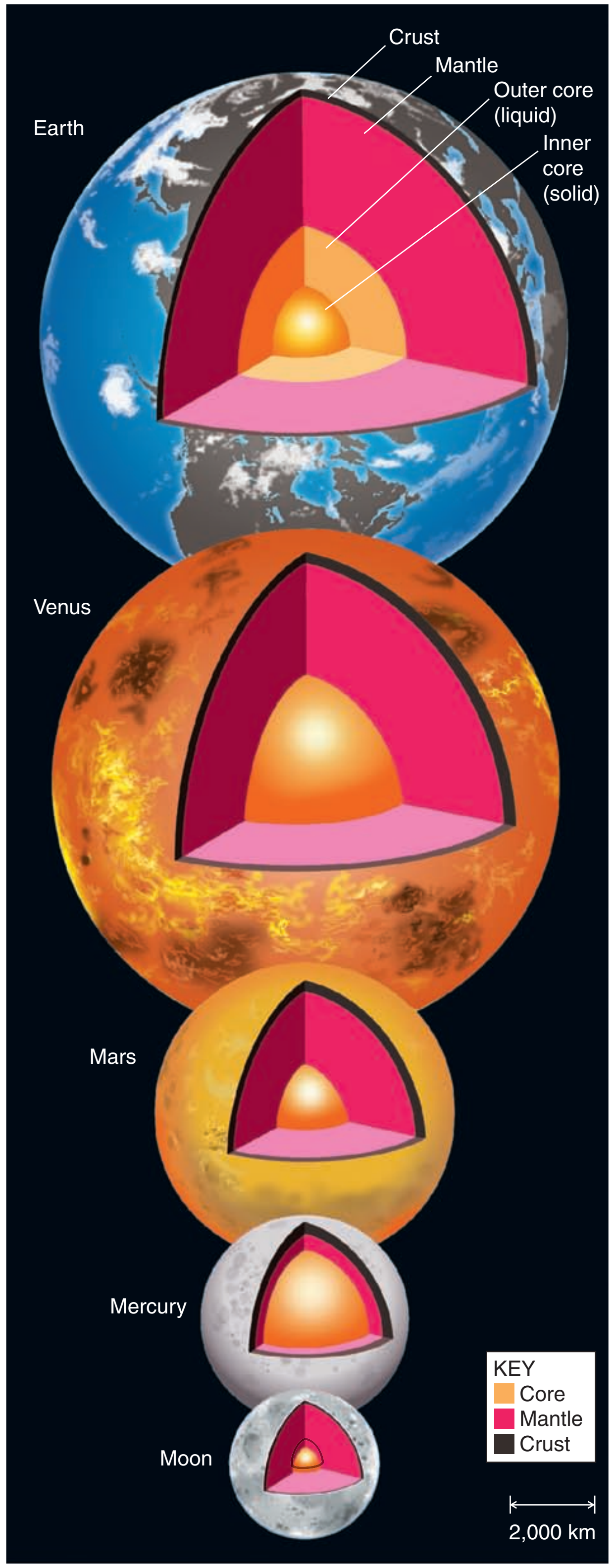


Figure 8.11 A comparison of the interiors of the terrestrial planets and Earth's Moon. Some fractions of the cores of Mercury, Venus, the Moon, and Mars are probably liquid.

The Evolution of Planetary Interiors

The balance between energy received and energy produced and emitted governs the temperature within a planet. The interiors of planets evolve as their temperatures change over time. Factors that influence how the temperature changes include the size of the planet, the composition of the material, and heating from various sources. Here, we are concerned with thermal energy—the kinetic energy of particles within a substance that determines the temperature. In general, the interior of a planet cools down over time as heat is emitted from the surface. Because it takes time for heat to travel through rock, the deeper we go within a planet, the higher the temperature. This is similar to the effect of taking a hot pie out of the oven. Over time, the pie radiates heat from the surface and cools down, but the filling takes much longer to cool than the crust.

Planets lose thermal energy from their surfaces primarily through radiation. Recall from Chapter 5 that when objects radiate energy, the hotter they are, the more energy they radiate. The type of energy radiated (infrared, optical, ultraviolet, and so forth) depends on the temperature of the object. The rate at which a planet cools depends on its size. A larger planet has a larger volume of matter and more thermal energy trapped inside. Thermal energy has to escape through the planet's surface, so the planet's surface area determines the rate at which energy is lost. Smaller planets have more surface area in comparison with their small volumes, so they cool off faster, whereas larger planets have a smaller surface area to volume ratio and cool off more slowly (**Working It Out 8.2**). Because geological activity is powered by heat, smaller objects become geologically inactive sooner. Major geological activity ended on Mercury and the Moon first, but the larger terrestrial planets—Venus, Earth, and Mars—continued to have geological activity.

Some of the thermal energy in the interior of Earth is left over from when Earth formed. The tremendous energy of collisions and the energy from

8.2 Working It Out How Planets Cool Off

If we assumed that all the terrestrial planets formed with the same percentage of radioactive materials in their bulk composition and that these radioactive materials are their sole source of internal thermal energy, then a planet's volume would determine the total amount of the thermal energy–producing material it contains. The energy-producing volume of a spherical planet is proportional to the cube of the planet's radius (volume $= \frac{4}{3} \times \pi R^3$).

A planet loses its internal energy by radiating it away at its surface, so a planet's cooling surface area determines the rate at which it can get rid of its thermal energy. The cooling surface area of the planet is proportional to only the square of the radius (surface area $= 4\pi R^2$). The ratio of the two—the energy-producing volume divided by the surface area through which thermal energy can escape—is given by

$$\frac{\text{Amount of energy to lose}}{\text{Surface area of energy escape}} = \frac{\text{Volume}}{\text{Surface area}} = \frac{\frac{\cancel{4}}{3} \times \cancel{\pi} R^{\cancel{3}}}{\cancel{4}\cancel{\pi}\cancel{R^2}} = \frac{R}{3}$$

A planet's ability to transfer internal energy from its hot core to its cooling surface also depends on some of its own internal properties. Nevertheless, all things being equal, planets with larger radii retain their internal energy longer than smaller planets do. For example, Mars has a radius about half that of Earth, so it has been losing its internal thermal energy to space about twice as fast as Earth has. This is one reason that Mars is less geologically active than Earth.

short-lived radioactive elements melted the planet, leading to the differentiated structure. As the surface of Earth radiated energy into space, it cooled rapidly. A solid crust formed above a molten interior. Because a solid crust does not conduct thermal energy well, it helped to retain the remaining heat. Over a long time, energy from the interior of the planet continued to leak through the crust and radiate into space. As a result, the interior of the planet slowly cooled, and the mantle and the inner core solidified.

If the thermal energy from Earth's formation were the only source of heating in Earth's interior, Earth would have long ago solidified completely. Most of the rest of the thermal energy in Earth's interior comes from long-lived radioactive elements trapped in the mantle. As these radioactive elements decay, they release energy, which heats the planet's interior. Today, the temperature of Earth's interior is determined by dynamic equilibrium between the radioactive heating of the interior and the loss of energy to space. As the radioactive elements decay, the amount of thermal energy generated declines, and Earth's interior cools as it ages. A small amount of additional heating of Earth's interior is friction generated by tidal effects of the Moon and Sun.

Although temperature plays an important role in a planet's interior structure, whether a material is solid or liquid also depends on pressure. Higher pressure forces atoms and molecules closer together and makes the material more likely to become a solid. Toward the center of Earth, the effects of temperature and pressure oppose each other: the higher temperatures make it more likely that material will melt, but the higher pressure favors a solid form. In the outer core of Earth, the high temperature wins, allowing the material to exist in a molten state. At the center of Earth, even though the temperature is higher, the pressure is so great that the inner core of Earth is solid.

CHECK YOUR UNDERSTANDING 8.3

Differentiation refers to materials that are separated based on their: (a) weight; (b) mass; (c) volume; (d) density.

Magnetic Fields

A magnetic field is created by moving charges and exerts a force on magnetically reactive objects, such as iron and on charged particles. A navigation compass is a familiar example on Earth. A compass needle lines up with Earth's magnetic field and points "north" and "south," as shown in **Figure 8.12a**. In the north, a compass needle points to a location in the Arctic Ocean off the coast of northern Canada, near to but not at the geographic North Pole (about which Earth spins). In the south, a compass needle points to a location off the coast of Antarctica, 2,800 km from the geographic South Pole. Earth behaves as if it contained a giant bar magnet that was slightly tilted with respect to the planet's rotation axis and had its two endpoints near the two magnetic poles, as shown in Figure 8.12b. Earth also has a **magnetosphere**, which is the region surrounding a planet that is filled with relatively intense magnetic fields and charged particles.

Earth's magnetic field is not actually due to a bar magnet buried within the planet. A magnetic field is the result of moving electric charges. Earth's magnetic field is created by the combination of Earth's rotation about its axis and a liquid, electrically conducting, circulating outer core. From this combination, Earth converts mechanical energy into magnetic energy. The magnetic field of a planet is an important probe into its internal structure.

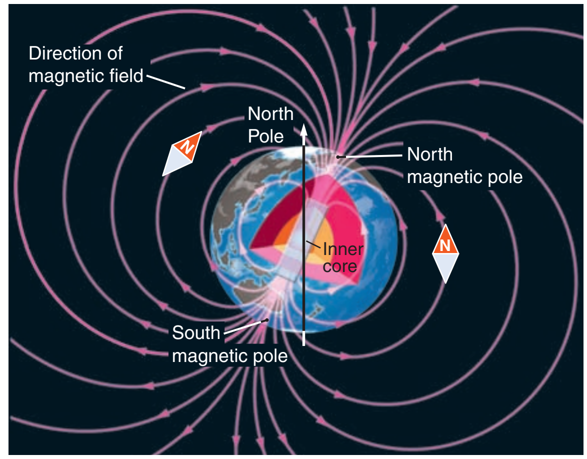
Earth's magnetic field is constantly changing. At the moment, the north magnetic pole is traveling several tens of kilometers per year toward the northwest. If this rate and direction continue, the north magnetic pole could be in Siberia before the end of the century. The magnetic pole tends to wander, constantly changing direction as a result of changes in the core.

The geological record shows that much more dramatic changes in the magnetic field have occurred over the history of our planet. When a magnet made of material such as iron gets hot enough, it loses its magnetization. As the material cools, it again becomes magnetized by any magnetic field surrounding it. Thus, iron-bearing minerals record the direction of Earth's magnetic field at the time that they cooled. In this way, a memory of that magnetic field becomes "frozen" into the material. For example, lava extruded from a volcano carries a record of Earth's magnetic field at the moment the lava cooled. By using radiometric techniques to date these materials, geologists obtain a record of how Earth's magnetic field has changed over time. Although Earth's magnetic field has probably existed for at least 3.5 billion years, the north and south magnetic poles switch from time to time. On average, these reversals in Earth's magnetic field take place about every half-million years.

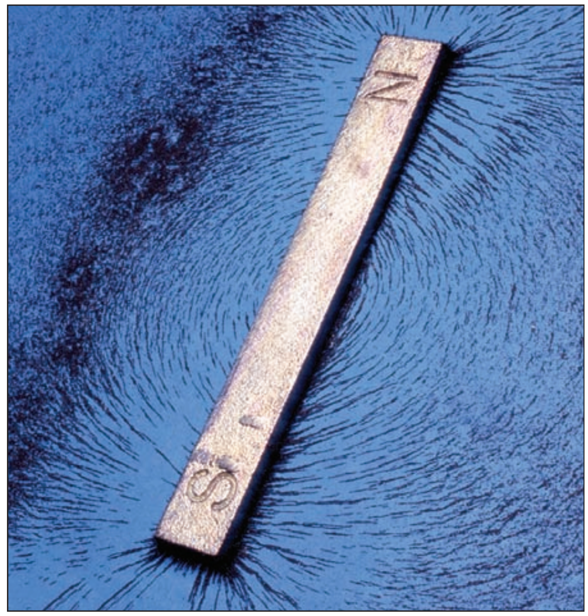
The general idea of how Earth's magnetic field (and those of other planets) originates is called the dynamo theory. In general, magnetic fields result from electric currents, which are moving electric charges. Earth's magnetic field is thought to be a side effect of three factors: Earth's rotation about its axis; an electrically conducting, liquid outer core; and fluid motions within the outer core. This model has been tested with computer simulations, which also produce the pole reversals. The theory suggests that any rotating planet will have a magnetic field if it has an internal heat source.

During the *Apollo* program, astronauts measured the Moon's local magnetic fields, and small satellites have searched for global magnetism. The Moon has a very weak field, possibly none at all, because the Moon is very small and therefore has a solid (not liquid and rotating) inner core. The Moon also has a very small core. However, remnant magnetism is preserved in lunar rocks from an earlier

(a)



(b)



VISUAL ANALOGY

Figure 8.12 (a) Earth's magnetic field can be visualized as though it were a giant bar magnet tilted relative to Earth's axis of rotation. Compass needles line up along magnetic-field lines and point toward Earth's north magnetic pole. (b) Iron filings sprinkled around a bar magnet help us visualize such a magnetic field.

time when the lunar surface and rocks solidified. Recent analysis of the oldest of the lunar rocks brought back on *Apollo 17* suggests that 4.2 billion years ago, the Moon had a liquid core with a generated magnetic field that lasted at least a few million years. Because the Moon has solidified, it no longer generates a global magnetic field, so what is detected is the "fossil" remains of its early field. Data from India's *Chandrayaan-1* spacecraft suggest that the Moon has a very weak and localized magnetosphere.

Other than Earth, Mercury is the only terrestrial planet with a significant global magnetic field today—although its field is only about 1 percent as strong as Earth's. Slow rotation and a large iron core, parts of which are molten and circulating, cause Mercury's magnetic field. Because the field is so weak, Mercury's magnetosphere is small, meeting the solar wind about 1,700 km above its surface. At this boundary, twisted bundles of magnetic fields transfer magnetic energy from the planet to space.

Planetary scientists expected that Venus would have a magnetic field because its mass and distance from the Sun imply an iron-rich core and partly molten interior like Earth's. Its lack of a magnetic field might be attributed to its extremely slow rotation (see Table 8.1), but this explanation is still uncertain. Or perhaps Venus's magnetic field is temporarily dormant—a condition that Earth is believed to have experienced at times of magnetic field reversals.

Mars has a weak magnetic field, presumably frozen in place early in its history. The magnetic signature occurs only in the ancient crustal rocks, showing that early in the history of Mars, some sort of an internally generated magnetic field must have existed. Geologically younger rocks lack this residual magnetism, so the planet's original magnetic field has long since disappeared. The lack of a strong magnetic field today on Mars might be the result of its small core. Or Mars might have lost its ability to generate a magnetic field after a series of giant impacts early in the planet's history, which could have heated the mantle of Mars enough to reduce the flow of heat out of the core to the mantle. The oldest large impact basins on Mars appear to be magnetized; newer ones are not.

CHECK YOUR UNDERSTANDING 8.4

The dynamo theory says that a planet will have a strong magnetic field if it has: (a) fast rotation and a solid core; (b) slow rotation and a liquid core; (c) fast rotation and a liquid core; (d) slow rotation and a solid core; (e) fast rotation and a gaseous core.

8.4 Planetary Surfaces Evolve through Tectonism

Figure 8.13 Tectonic processes fold and warp Earth's crust, as seen in these rocks along a roadside in Israel.

Now that we have looked at planetary interiors, we can connect the interior conditions to the processes that shape the surface. The crust and part of the upper mantle form the **lithosphere** of a planet. **Tectonism**, the deformation of a planet's lithosphere, warps, twists, and shifts the lithosphere to form visible surface features. If you have driven through mountainous or hilly terrain, you may have seen places like the one shown in **Figure 8.13**, where the roadway has been cut through rock. The exposed layers tell the story of Earth through the vast expanse of geological time. In this section, we will look at tectonic processes that create these layers and play an important part in shaping the surface of a planet.

AstroTour: Continental Drift

The Theory of Plate Tectonics

Early in the 20th century, some scientists recognized that Earth's continents could be fit together like pieces of a giant jigsaw puzzle. In addition, the layers in the rock and the fossil records they hold on the east coast of South America match those on the west coast of Africa. Based on this evidence, Alfred Wegener (1880–1930) proposed a hypothesis that the continents were originally joined in one large landmass that broke apart as the continents began to "drift" away from each other over millions of years. This hypothesis was further developed into the theory known today as **plate tectonics**. Geologists now recognize that Earth's outer shell is composed of a number of relatively brittle segments, or **lithospheric plates**. There are about seven major plates and about a half dozen smaller plates floating on top of the mantle. The motion of these plates is constantly changing the surface of Earth.

Originally, the idea of plate tectonics was met with great skepticism among geologists because they could not imagine a mechanism that could move such huge landmasses. In the late 1950s and early 1960s, however, studies of the ocean floor provided compelling evidence for plate tectonics. These surveys showed surprising characteristics in bands of basalt—a type of rock formed from cooled lava—that were found on both sides of the ocean rifts. Ocean floor rifts such as the Mid-Atlantic Ridge are **spreading centers**. As **Figure 8.14** shows, hot material in these rifts rises toward Earth's surface, becoming new ocean floor. When this hot material cools, it becomes magnetized along the direction of Earth's magnetic field, thus recording the direction of Earth's magnetic field at that time. Greater distance from the rift indicates the ocean floor is older and formed at an earlier time. Combined with radiometric dates for the rocks, this magnetic record proved that the spreading of the seafloor and the motions of the plates have continued over long geological time spans.

Precise surveying techniques and global positioning systems (GPSs) can now determine locations on Earth to within a few centimeters. These measurements confirm that Earth's lithosphere is moving. Some areas are being pulled apart by more than 15 centimeters (cm) each year. Over millions of years, such motions add up. Over 10 million years—a short time by geological standards—15 cm/yr becomes 1,500 km, and maps definitely need to be redrawn.

The theory of plate tectonics is perhaps the greatest advance in 20th century geology. Plate tectonics is responsible for a wide variety of geological features on our planet, including the continental drift that Wegener hypothesized.

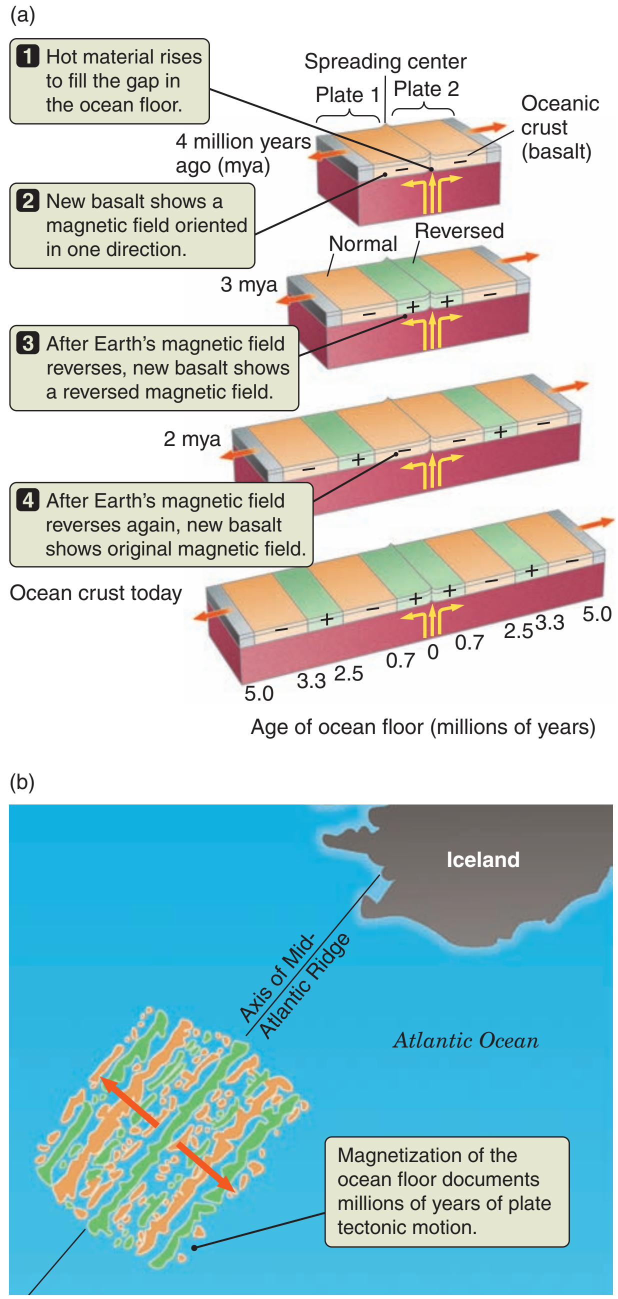


Figure 8.14 (a) New seafloor is formed at a spreading center, the cooling rock becomes magnetized, and is then carried away by tectonic motions. (b) Maps like this one of banded magnetic structure in the seafloor near Iceland provide support for the theory of plate tectonics.

The Role of Convection

The movement of lithospheric plates requires immense forces. These forces are the result of thermal energy escaping from the interior of Earth. The transport of thermal energy by the movement of packets of gas or liquid is known as

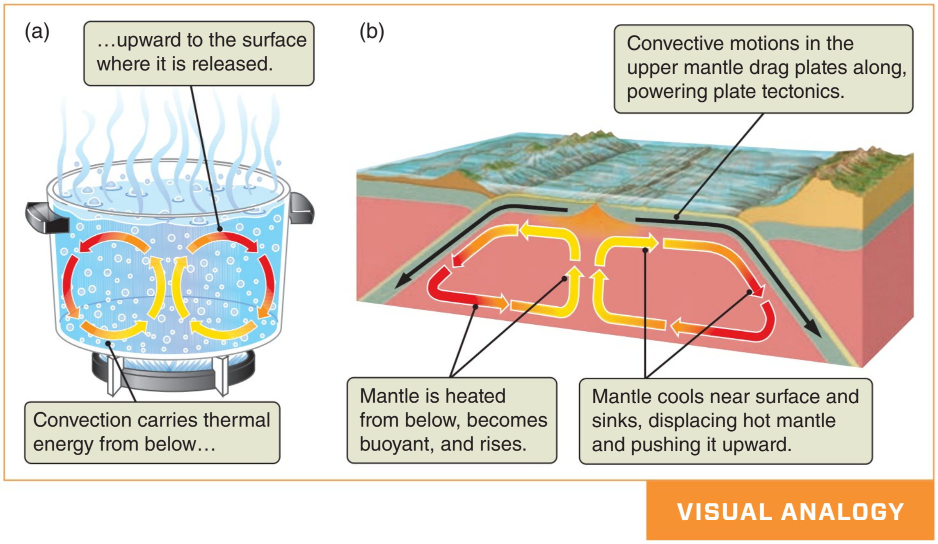


Figure 8.15 (a) Convection occurs when a fluid is heated from below. (b) Convection in Earth's mantle drives plate tectonics.

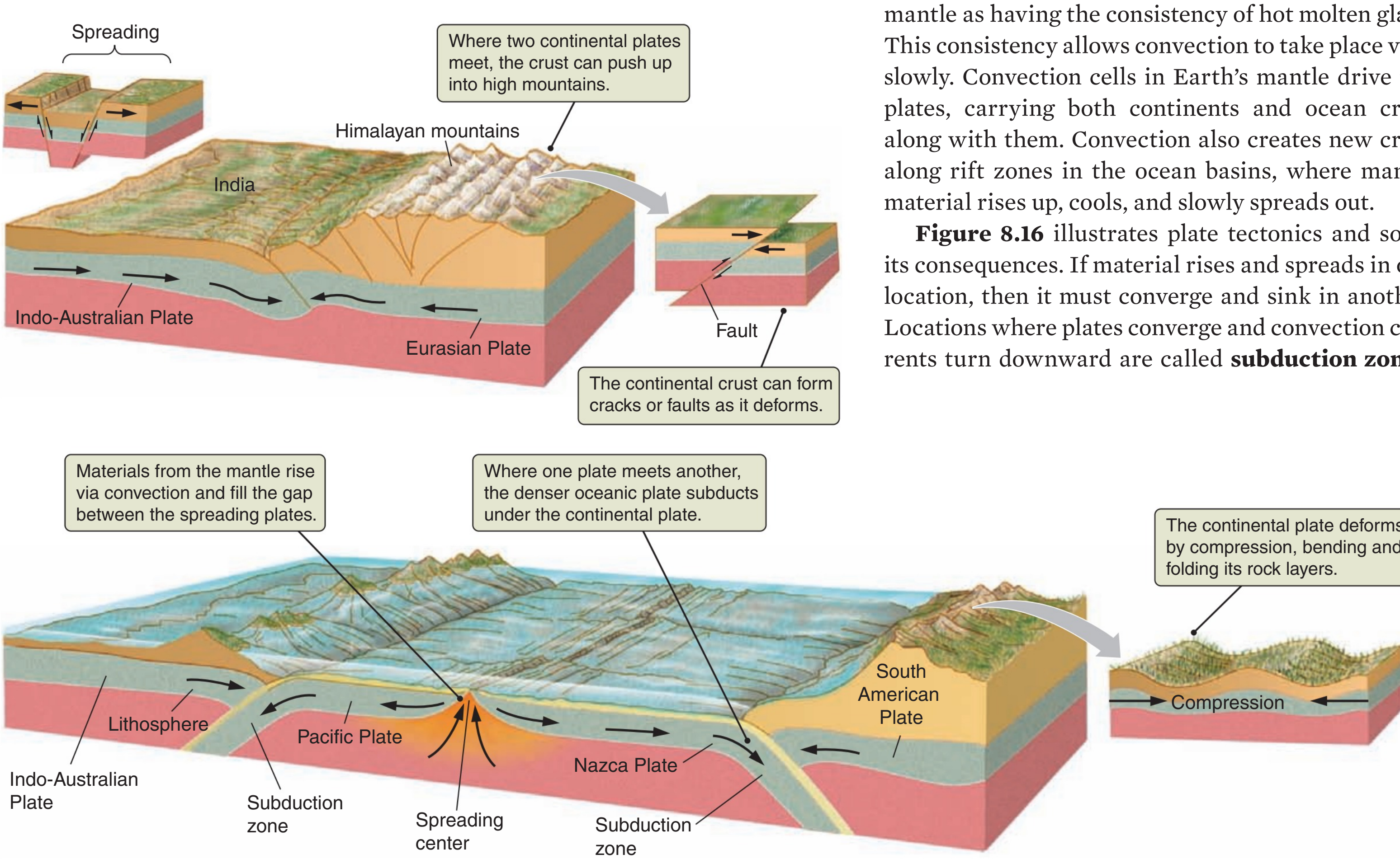


Figure 8.16 Divergence and collision of tectonic plates create a wide variety of geological features.

convection. **Figure 8.15a** illustrates the process. If you have ever watched water in a heated pot on a stovetop, you have observed convection. Thermal energy from the stove warms water at the bottom of the pot. The warm water expands slightly, becoming less dense than the cooler water above it, and the cooler water with higher density sinks, displacing the warmer water upward. When the lower-density water reaches the surface, it gives up part of its energy to the air and cools; as the water cools, it then becomes denser and sinks back toward the bottom of the pot. Water rises in some locations and sinks in others, forming convection cells. As we will see in later chapters, convection also plays an important role in planetary atmospheres and in the structure of the Sun and stars.

Figure 8.15b shows how convection works in Earth's mantle. Radioactive decay provides the heat source to drive convection in Earth's mantle. We know the mantle is not molten because secondary seismic waves would not be able to travel through it, but the mantle is somewhat mobile. Think of the mantle as having the consistency of hot molten glass. This consistency allows convection to take place very slowly. Convection cells in Earth's mantle drive the plates, carrying both continents and ocean crust along with them. Convection also creates new crust along rift zones in the ocean basins, where mantle material rises up, cools, and slowly spreads out.

Figure 8.16 illustrates plate tectonics and some its consequences. If material rises and spreads in one location, then it must converge and sink in another. Locations where plates converge and convection currents turn downward are called **subduction zones**.

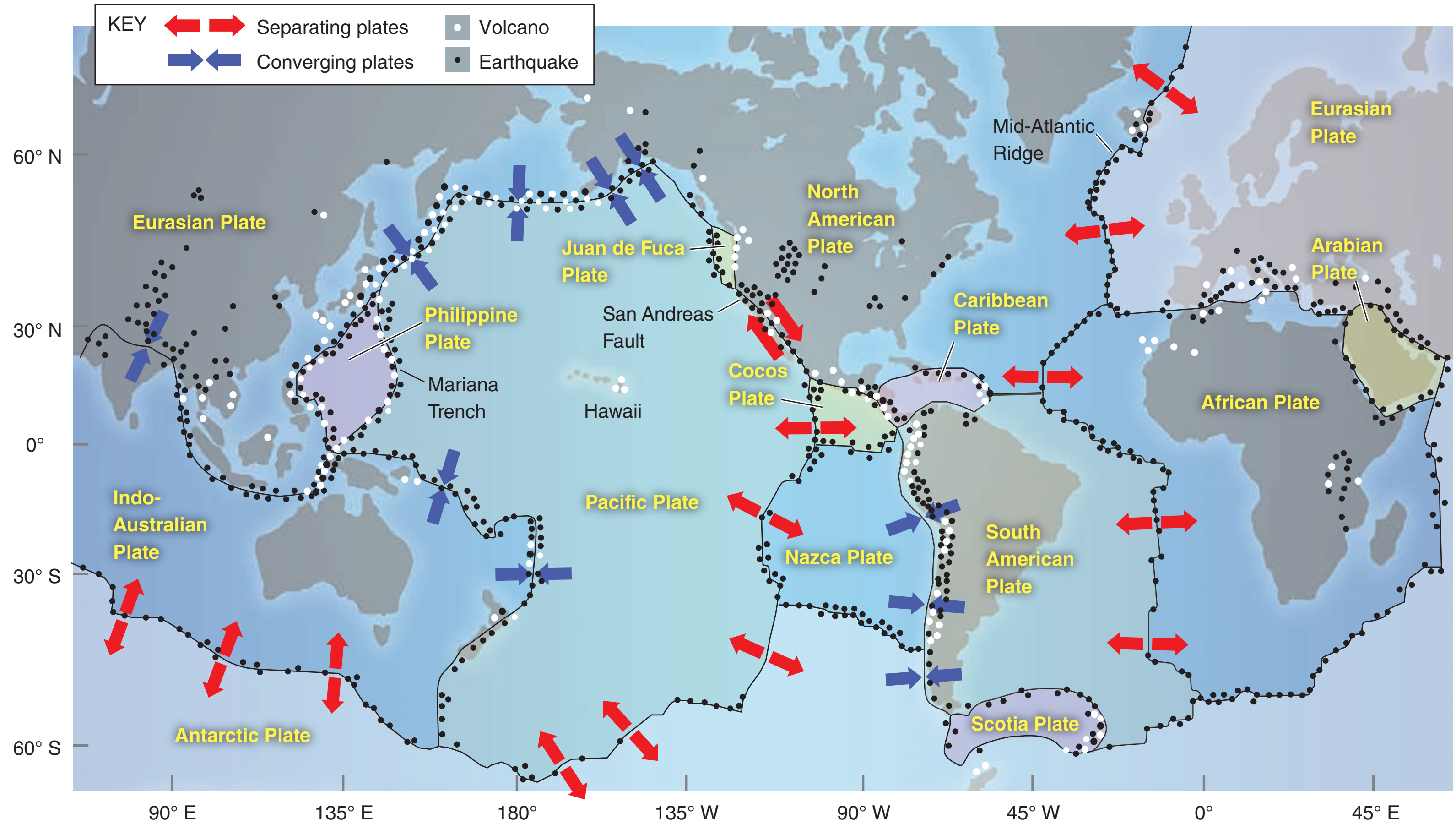


Figure 8.17 Major earthquakes and volcanic activity are often concentrated along the boundaries of Earth's principal tectonic plates.

In a subduction zone, one plate slides beneath the other, and convection drags the submerged lithospheric material back down into the mantle. The Mariana Trench—the deepest part (11 km) of Earth's ocean floor—is such a subduction zone. Much of the ocean floor lies between spreading centers and subduction zones, and so the ocean floor is the youngest portion of Earth's crust. In fact, the *oldest* seafloor rocks are less than 200 million years old.

In some places, the plates are not sinking but colliding and, consequently, shoved upward. The highest mountains on Earth, the Himalayas, grow a half-meter per century as the Indo-Australian subcontinental plate collides with the Eurasian Plate. In other places, plates meet at oblique angles and slide along past each other. One such place is the San Andreas Fault in California, where the Pacific Plate slides past the North American Plate. A **fault** is a fracture in a planet's crust along which material can slide.

Locations where plates meet tend to be very active geologically. One of the best ways to see the outline of Earth's plates is to look at a map of where earthquakes and volcanism occur, such as the map in **Figure 8.17**. Where plates meet, enormous stresses build up. Earthquakes occur when a portion of the boundary between two plates suddenly slips, relieving the stress. Volcanoes are created when friction between plates melts rock, which is then pushed up through cracks to the surface. Earth also has numerous **hot spots**, where hot deep-mantle material rises, releasing thermal energy. As plates shift, some parts move more rapidly

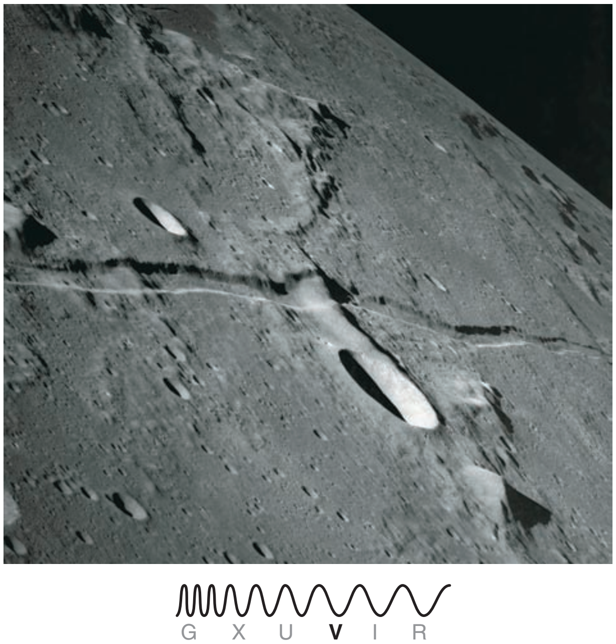


Figure 8.18 This *Apollo 10* photograph shows Rima Ariadaeus, a 2-km-wide valley between two tectonic faults on the Moon.

than others, causing the plates to stretch, buckle, or fracture. These effects are seen on the surface as folded and faulted rocks. Mountain chains are common near converging plate boundaries, where plates buckle and break.

Tectonism on Other Planets

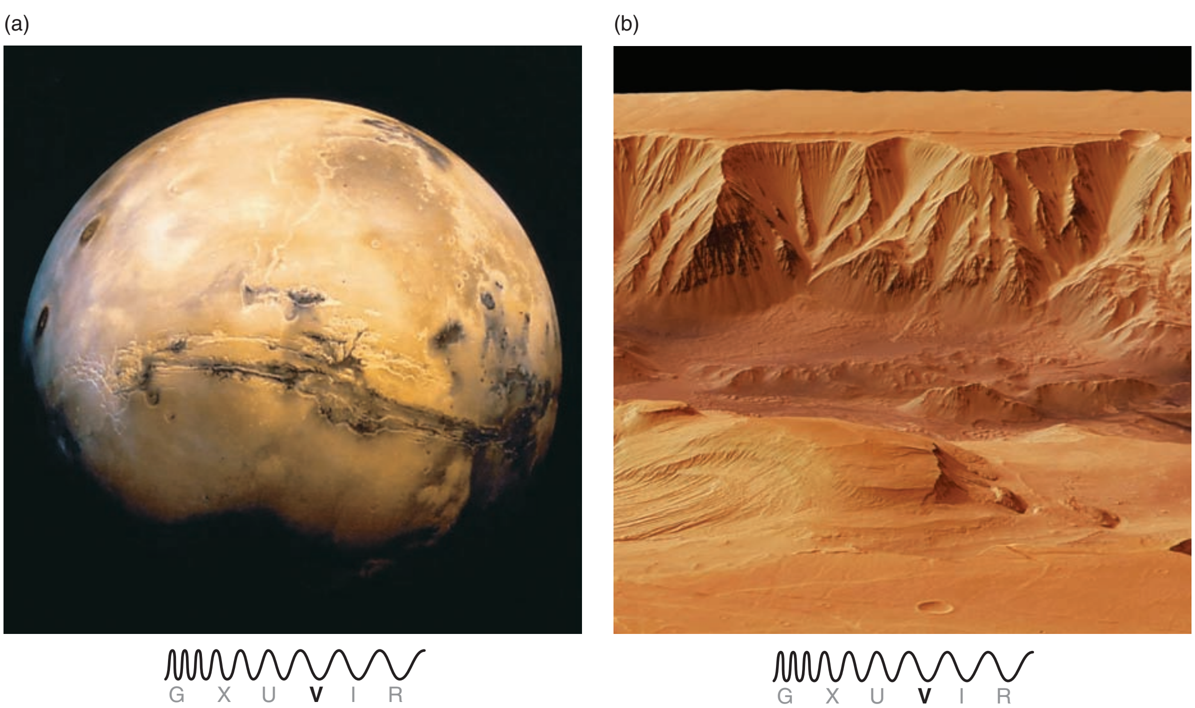
We have observed plate tectonics only on Earth. However, all of the terrestrial planets and some moons show evidence of tectonic disruptions. Fractures have cut the crust of the Moon in many areas, leaving fault valleys such as the one pictured in **Figure 8.18**. Many of these features are the result of large impacts that cracked and distorted the lunar crust.

Mercury has fractures and faults similar to those on the Moon. In addition, numerous cliffs on Mercury are hundreds of kilometers long. These appear to be the result of the shrinking of Mercury; recent observations by *Messenger* suggest that the planet has shrunk by about 10–14 km across. Like the other terrestrial planets, Mercury was once molten. As it shrank, Mercury's crust cracked and buckled in much the same way that a grape skin wrinkles as it shrinks to become a raisin.

Possibly the most impressive tectonic feature in the Solar System is Valles Marineris on Mars (**Figure 8.19**). Stretching nearly 4,000 km, and nearly 4 times as deep as the Grand Canyon, this canyon system is as long as the distance between San Francisco and New York. Valles Marineris includes a series of massive cracks in the crust of Mars that formed as local forces, perhaps related to mantle convection, pushed the crust upward from below. The surface could not be equally supported by the interior everywhere, and unsupported segments fell in. Once formed, the cracks were eroded by wind, water, and landslides, resulting in the structure we see today. Other parts of Mars have faults similar to those on the Moon, but cliffs as high and long as those seen on Mercury are absent.

The mass of Venus is only 20 percent less than that of Earth, and its radius is just 5 percent smaller than Earth's, leading to a surface gravity 90 percent that

Figure 8.19 (a) A mosaic of *Viking Orbiter* images shows Valles Marineris, the major tectonic feature on Mars, stretching across the center of the image from left to right. This canyon system is more than 4,000 km long. The dark spots on the left are huge shield volcanoes. (b) This close-up perspective view of the canyon wall was photographed by the European Space Agency's *Mars Express* orbiting spacecraft.



of Earth. Because of the similarities between the two planets, many scientists predicted that Venus might also show evidence of plate tectonics. The NASA *Magellan* mission orbited Venus from 1990 to 1994, and *Magellan* mapped nearly the entire surface of Venus, providing the first high-resolution radar views of the planet's surface (**Figure 8.20**).

The European Space Agency's (ESA's) *Venus Express*, in orbit from 2006 to 2014, mapped Venus in the infrared, which can penetrate through the clouds to enable a view of the surface. The impact craters on Venus seem to be evenly distributed, suggesting that the surface is all about the same age, about a billion years. Venus is mostly covered with smooth lava, but there are two highland regions: Ishtar Terra in the north and Aphrodite Terra in the south. The highland rocks are less smooth and older than those on the rest of Venus and may be similar to granite rocks on Earth. Because granite results from plate tectonics and water, the data hint at the possibility that these highlands on Venus are ancient continents, created by volcanic activity, on a planet with oceans.

Because of the similarities between Venus and Earth, the interior of Venus should be very much like the interior of Earth, and convection should be occurring in its mantle. On Earth, mantle convection and plate tectonism release the most thermal energy from the interior. By contrast, on Venus, hot spots may be the principal way that thermal energy escapes from the planet's interior. Circular fractures called coronae on the surface of Venus, ranging from a few hundred kilometers to more than 2,500 km across, may be the result of upwelling plumes of hot mantle that have fractured Venus's lithosphere. Alternatively, energy may build up in the interior until large chunks of the lithosphere melt and overturn, releasing an enormous amount of energy. Then, the surface cools and solidifies. It is uncertain why Venus and Earth are so different with regard to plate tectonics.

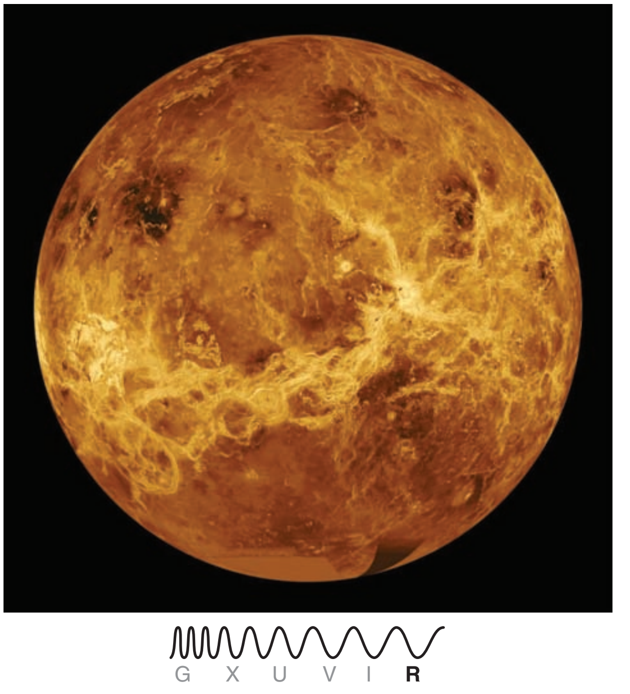


Figure 8.20 The atmosphere of Venus blocks our view of the surface in visible light. This false-color view of Venus is a radar image made by the *Magellan* spacecraft. Bright yellow and white areas are mostly fractures and ridges in the crust. Some circular features seen in the image may be regions of mantle upwelling, or *hot spots*. Most of the surface is formed by lava flows, shown in orange.

CHECK YOUR UNDERSTANDING 8.5

On which of the following does plate tectonics occur now? (Select all that apply.) (a) Mercury; (b) Venus; (c) Earth; (d) the Moon; (e) Mars

8.5 Volcanism Signifies a Geologically Active Planet

You are probably familiar with the image of a volcano spewing molten rock onto the surface of Earth. This molten rock, known as **magma**, originates deep in the crust and in the upper mantle, where sources of thermal energy combine. These sources include rising convection cells in the mantle, heating by friction from movement in the crust, and concentrations of radioactive elements. In this section, we will look at the occurrence of volcanic activity on a planet or moon, which is called **volcanism**. Volcanism not only shapes planetary surfaces but also is a key indicator of a geologically active planet.

Terrestrial Volcanism Is Related to Tectonism

Volcanoes are usually located along plate boundaries and over hot spots. Maps of geological activity such as the one in Figure 8.17 leave little doubt that most terrestrial volcanism is linked to the same forces responsible for plate motions. A tremendous amount of friction is generated as plates slide under each other. This

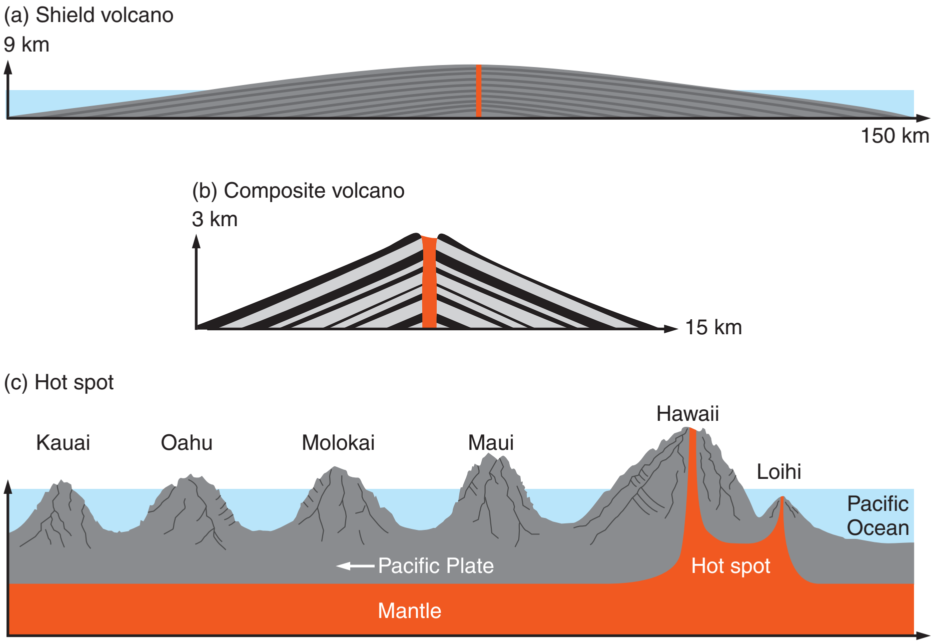


Figure 8.21 Magma reaching Earth's surface commonly forms (a) shield volcanoes, such as Mauna Loa, which have gently sloped sides built up by fluid lava flows; and (b) composite volcanoes, such as Vesuvius, which have steeply symmetric sides built up by viscous lava flows. (c) Hot spots are convective plumes of lava that can form a successive series of volcanoes as the plate above them slides by.

friction raises the temperature of rock toward its melting point.

Material at the base of a lithospheric plate is under a great deal of pressure because of the weight of the plate pushing down on it. This pressure increases the melting temperature of the material, forcing it to remain solid even at high temperature. As this material is forced up through the crust, its pressure drops, and therefore the material's melting temperature drops too. Material that was solid at the base of a plate becomes molten as it nears the surface. Places where convection carries hot mantle material toward the surface are frequent sites of eruptions. Iceland, which is one of the most volcanically active regions in the world, sits astride one such spreading center—the Mid-Atlantic Ridge (see Figure 8.17). In recent years, volcano eruptions in Iceland have led to travel disruptions for thousands as the airborne volcanic ash made it unsafe for airplanes to fly near the eruption.

Once lava reaches the surface of Earth, it can form many types of structures. Flows often form vast sheets, especially if the eruptions come from long fractures called fissures. If very fluid lava flows from a single *point source*, it spreads out over the surrounding terrain or ocean floor, forming a **shield volcano**, shown in **Figure 8.21a**. A **composite volcano** forms when thick lava flows alternating with explosively generated rock deposits build a steep-sided structure, shown in Figure 8.21b.

Terrestrial volcanism also occurs where convective plumes rise toward the surface in the interiors of lithospheric plates, creating local hot spots. Volcanism over hot spots works much like volcanism elsewhere at a spreading center, except that the convective upwelling occurs at a single spot rather than along the edge of a plate. These hot spots force mantle and lithospheric material toward the surface, where the material emerges as liquid lava.

Earth has numerous hot spots, including the regions around Yellowstone Park and the Hawaiian Islands (Figure 8.21c). The Hawaiian Islands are a chain of shield volcanoes that formed as the lithospheric plate moved across a hot spot. Volcanoes erupt over a hot spot, building an island. The island ceases to grow as the plate motion carries the island away from the hot spot. Meanwhile, a new island grows over the hot spot. Today, the Hawaiian hot spot is located off the southeast coast of the Big Island of Hawaii, where it continues to power the active volcanoes. On top of the hot spot, the newest Hawaiian island, Loihi, is forming. Loihi is already a massive shield volcano, rising more than 3 km above the ocean floor. Loihi will eventually break the surface of the ocean and merge with the Big Island of Hawaii—but not for another 100,000 years.

▶II **AstroTour:** Hot Spot Creating a Chain of Islands

Volcanism in the Solar System

The Moon Although Earth is the only planet on which plate tectonics is an important process, evidence of volcanism is found throughout the Solar System, including several moons of the outer planets. Some of the first observers to use telescopes to view the Moon noted dark areas that looked like bodies of water—thus they were named **maria** (singular: *mare*), Latin for "seas." Early photographs showed flowlike features in the dark regions of the Moon. We now know that the maria are actually vast, hardened lava flows, similar to volcanic rocks known as basalts on Earth. Because the maria contain relatively few craters, these volcanic flows must have occurred after the period of heavy bombardment ceased.

Many of the rock samples that the *Apollo* astronauts brought back from the lunar maria were found to contain gas bubbles typical of volcanic materials (**Figure 8.22**). The lava that flowed across the lunar surface must have been relatively fluid. This fluidity, due partly to the lava's chemical composition, explains why lunar basalts form vast sheets that fill low-lying areas such as impact basins (**Figure 8.23**). It also partly explains the Moon's lack of classic volcanoes: the lava was too fluid to pile up, like motor oil poured from a container spreading out.

The lunar rock samples also showed that most of the lunar lava flows are older than 3 billion years. Samples from the heavily cratered terrain of the Moon also originated from magma, indicating that the young Moon went through a molten stage. These rocks cooled from a "magma ocean" and are more than 4 billion years old, preserving the early history of the Solar System. Most of the sources of heating and volcanic activity on the Moon must have shut down some 3 billion years ago—unlike on Earth, where volcanism continues. This conclusion is consistent with the idea that smaller objects and planets cool more efficiently and thus are less active than larger planets.

Only in a few limited areas of the Moon are younger lavas thought to exist; most of these have not been sampled directly. The *Lunar Reconnaissance Orbiter* observed volcanic cones that were likely built up from volcanic rocks erupting from the surface. These volcanic rocks are far different from the mare basalt rocks and contain silica and thorium. These domes could have been formed as recently as 800 million years ago, which would make them the result of the most recent volcanic activity found on the Moon.

Figure 8.22 This rock sample from the Moon, collected by the *Apollo 15* astronauts from a lunar lava flow, shows gas bubbles typical of gas-rich volcanic materials. The rock is about 6 × 12 cm.

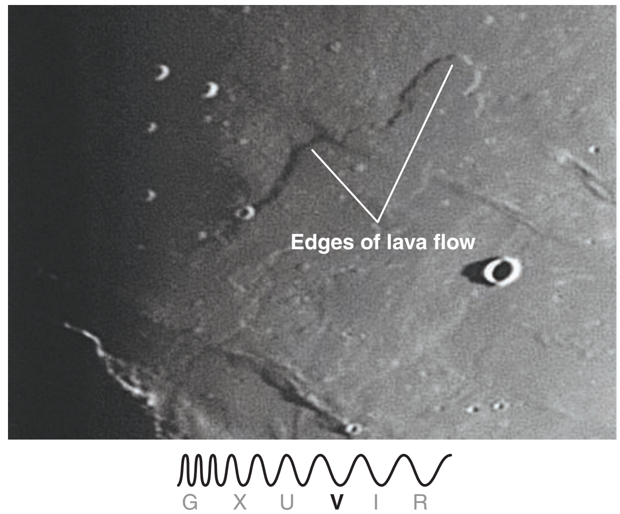


Figure 8.23 The lava flowing across the surface of Mare Imbrium on the Moon must have been extremely fluid to spread out for hundreds of kilometers in sheets that are only tens of meters thick.

Mercury Mercury also shows evidence of past volcanism. The *Mariner 10* and *Messenger* missions revealed smooth plains on Mercury similar in appearance to the lunar maria. These sparsely cratered plains are the youngest areas on Mercury and, like those on the Moon, are almost certainly volcanic in origin, created when fluid lavas flowed into and filled huge impact basins. Many of the volcanic plains on Mercury are also associated with impact scars. The volcanic activity that created the plains likely ceased 3.8 billion years ago, possibly from the shrinking of the planet as it cooled. The ending of the late heavy bombardment might also have been a factor. High-resolution imaging by *Messenger* has also identified a number of volcanoes. Vents that could be from explosive volcanism have been found around the large, old impact basin Caloris (**Figure 8.24**) and may be as young as 1 billion to 2 billion years old.

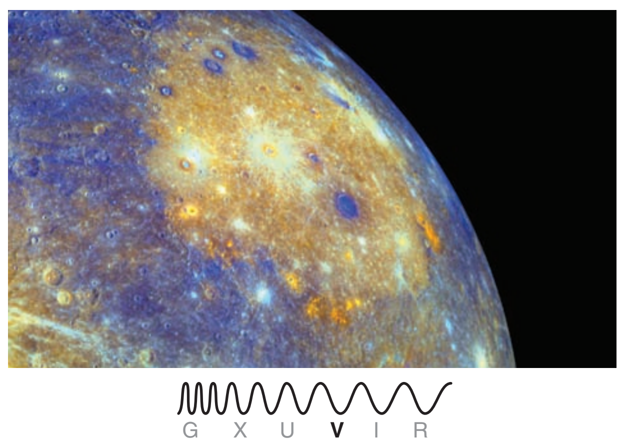


Figure 8.24 The Caloris Basin on Mercury (yellow) is one of the largest impact basins in the Solar System, with a span of about 1,500 km. The orange regions may be volcanic vents. The false color is enhanced to show more detail.

Mars Mars has also been volcanically active. More than half the surface of Mars is covered with volcanic rocks. Lavas covered huge regions of Mars, flooding the older, cratered terrain. Most of the vents or long cracks that created these flows are buried under the lava that poured forth from them. Among the most impressive features on Mars are its enormous shield volcanoes. These volcanoes are the largest mountains in the Solar System. Olympus Mons,

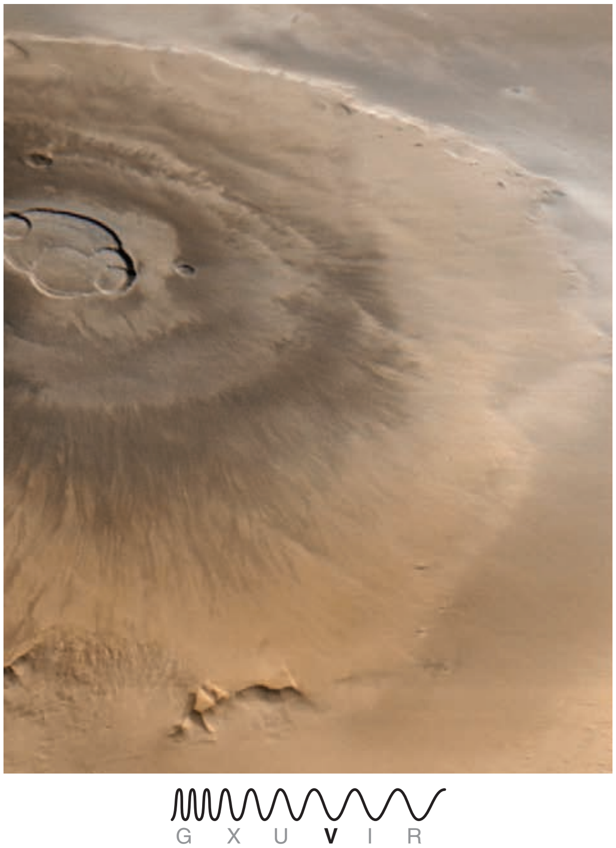


Figure 8.25 The largest known volcano in the Solar System, Olympus Mons is a 27-km-high shield-type volcano on Mars, similar to but much larger than Hawaii's Mauna Loa. This partial view of Olympus Mons was taken by the *Mars Global Surveyor*.

standing 27 km high at its peak and 550 km wide at its base (**Figure 8.25**), would tower over Earth's largest mountains. Olympus Mons and its neighbors grew as the result of hundreds of thousands of individual eruptions. In the absence of plate tectonics on Mars, its volcanoes have remained over their hot spots for billions of years, growing ever taller and broader in the lower surface gravity with each successive eruption.

Lava flows and other volcanic landforms span nearly the entire history of Mars, estimated to extend from the formation of crust some 4.4 billion years ago to geologically recent times and to cover more than half of the red planet's surface. Although some "fresh-appearing" lava flows have been identified on Mars, until rock samples are radiometrically dated we will not know the age of these latest eruptions. Mars could, in principle, experience eruptions today.

Venus Of the terrestrial planets, Venus has the most volcanoes. Radar images reveal a wide variety of volcanic landforms. These include highly fluid flood lavas covering thousands of square kilometers, shield volcanoes approaching those of Mars in terms of size and complexity, and lava channels thousands of kilometers long. These lavas must have been extremely hot and fluid to flow for such long distances. Some of the volcanic eruptions on Venus are thought to have been associated with deformation of Venus's lithosphere above hot spots such as the circular features mentioned earlier.

Lavas on Venus are basalts, much like the lavas on Earth, the Moon, Mars, and possibly Mercury. The *Venus Express* spacecraft imaged three of the nine Hawaii-like hot spots in infrared wavelengths. Each hot spot has several volcanoes, with altitudes of 500–1,200 meters above the nearby plains. It was found that some of the volcanic regions were radiating heat more efficiently than the regions nearby. This suggests that these volcanic regions have younger material and that volcanic activity had taken place within the past 2.5 million years, and perhaps as recently as a few thousand years ago. As we'll describe in the next chapter, Venus has some of the volcanic gas sulfur dioxide in its atmosphere, so Venus may still be cooling its interior through volcanic activity.

A geological timescale for Venus has not yet been devised, but from its relative lack of impact craters, most of the surface is considered to be less than 1 billion years old, and some of it may be much more recent. When volcanism began on Venus and how much active volcanism exists today remain unanswered questions.

CHECK YOUR UNDERSTANDING 8.6

Which is *not* a reason for the large size of volcanoes on Mars compared to Earth's smaller volcanoes? (a) absence of plate tectonics; (b) distance from the Sun; (c) lower surface gravity than Earth's; (d) many repeated eruptions

8.6 The Geological Evidence for Water

Today, Earth is the only planet in the Solar System where the temperature and atmospheric conditions allow extensive liquid surface water to exist. The other inner planets do not have extensive liquid surface water, but there is evidence for water ice in deep craters or in the polar regions and for water below the surface in permafrost, subsurface glaciers, or possibly as liquid in the core.

Life, as we know it on Earth, requires water as a solvent and as a delivery mechanism for essential chemistry. Because of this, the search for water is central to the search for life in the Solar System. Additionally, if humans are ever going to live on another terrestrial planet, they will need a source of water. In this section, we will look at how water modifies the surface of a planet and then discuss the search for water in the Solar System.

Water and Erosion

Tectonism, volcanism, and impact cratering affect Earth's surface by creating variations in the height of the surface. **Erosion** is the wearing away of a planet's surface by mechanical action. The term *erosion* covers a wide variety of processes. Erosion by running water, but also by wind and by the actions of living organisms, wears down hills, mountains, and craters; the resulting debris fills in valleys, lakes, and canyons. If erosion were the only geological process operating, it would eventually smooth out the surface of the planet completely. Because Earth is a geologically and biologically active world, however, its surface is an ever-changing battleground between processes that build up topography and those that tear it down.

Weathering is the first step in the process of erosion. During weathering, rocks are broken into smaller pieces and may be chemically altered. For example, rocks on Earth are physically weathered along shorelines, where the pounding waves break them into beach sand. Other weathering processes include chemical reactions, such as when oxygen in the air combines with iron in rocks to form a type of rust. One of the most efficient forms of weathering is caused by water: liquid water runs into crevices and then freezes. As the water freezes, it expands and shatters the rock.

After weathering, the resulting debris can be carried away by flowing water, glacial ice, or blowing wind and deposited in other areas as sediment. Where material is eroded, we can see features such as river valleys, wind-sculpted hills, or mountains carved by glaciers. Where eroded material is deposited, we see features such as river deltas, sand dunes, or piles of rock at the bases of mountains and cliffs. Erosion is most efficient on planets with water and wind. On Earth, where water and wind are prevalent, most impact craters on land are worn down and filled in.

Even though the Moon and Mercury have almost no atmosphere and no running water, a type of slow erosion is still at work. Radiation from the Sun and from deep space slowly decomposes some types of minerals, effectively weathering the rock. Such effects are only a few millimeters deep at most. Impacts of micrometeoroids also chip away at rocks. In addition, landslides can occur wherever gravity and differences in elevation are present. Although water enhances landslide activity, landslides are also seen on dry bodies like Mercury and the Moon.

As we will discuss in the next chapter, Earth, Mars, and Venus have atmospheres, and all three planets show the effects of windstorms. Images of Mars and Venus returned by spacecraft landers show surfaces that have been subjected to the forces of wind. Sand dunes are common on Earth and Mars (**Figure 8.26**), and some have been identified on Venus. Orbiting spacecraft have also found wind-eroded hills and surface patterns called wind streaks. These surface patterns appear, disappear, and change in response to winds blowing sediments around hills, craters, and cliffs. They serve as local weather vanes, telling plane-

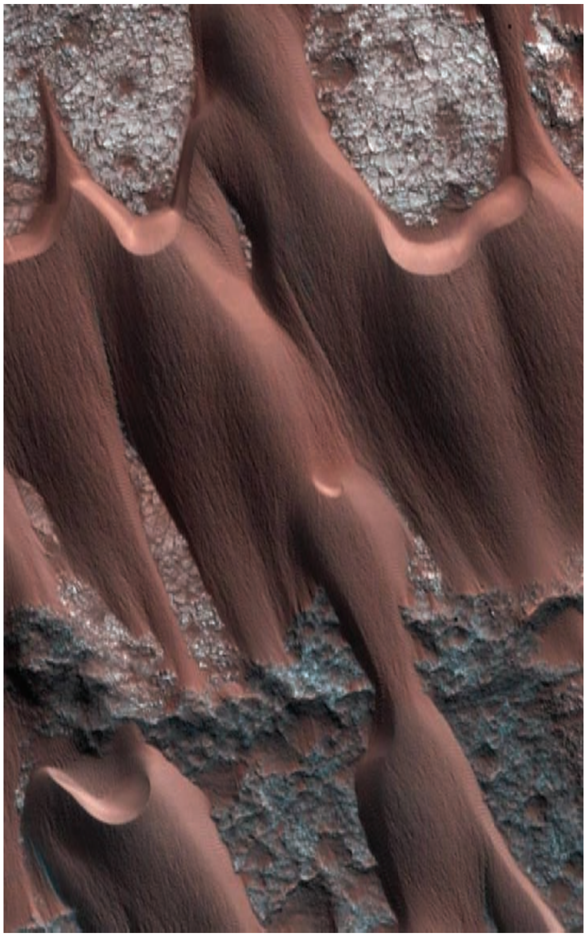


Figure 8.26 A *Mars Reconnaissance Orbiter* image of the Nili Patera dune field on Mars. The dunes change over months because of winds on Mars.

tary scientists about the direction of local prevailing surface winds. Planet-encompassing dust storms have been seen on Mars.

The Search for Water in the Solar System

A priority of recent planetary exploration missions is the search for water on the terrestrial planets and the Moon. Some of the evidence for past water comes from the geological processes discussed earlier in the chapter. Water was brought in by impacts in the early Solar System, and it is affected by geological and atmospheric activity on a planet. The search for water includes examination of images of the terrain obtained by flybys, orbiters, and landers. For the Moon, the search has included reanalyzing 40-year-old lunar rocks and soil brought back to Earth in the *Apollo* missions and crashing spacecraft into the surface in order to analyze the debris that is kicked up.

Mars The search for water on Mars goes back almost a century and a half. Even small telescopes show polar ice caps, which change with the martian seasons. In 1877, Italian astronomer Giovanni Schiaparelli (1835–1910) observed what appeared to be linear features on Mars and dubbed them *canali* ("channels" in Italian). Unfortunately, some other observers, including the American observer of Mars, Percival Lowell (1855–1916), incorrectly translated Schiaparelli's *canali* as "canals," implying that they were artificially constructed by intelligent life, rather than naturally formed by geology. Lowell strongly advocated the theory that these "canals" were built to move water around a drying planet Mars. Other observers of the time disputed this idea, arguing that these were optical illusions seen in telescopes. Larger telescopes and astrophotographs did not show canals, astronomical spectroscopy did not find water vapor, and this idea of artificial canals went out of favor after Lowell died.

Scientists debate about how recently there has been significant liquid water flow on the surface of Mars. The geological evidence suggests that at one time, water flowed across the surface of Mars in vast quantities. Canyons and huge, dry riverbeds attest to tremendous floods that poured across the martian surface. In addition, many regions on Mars show small networks of valleys that probably were carved by flowing water (**Figure 8.27**). Large deposits of subsurface ice have been detected under the surface. Mars may have contained oceans at one time, including one ocean that might have covered a third of the planet's surface.

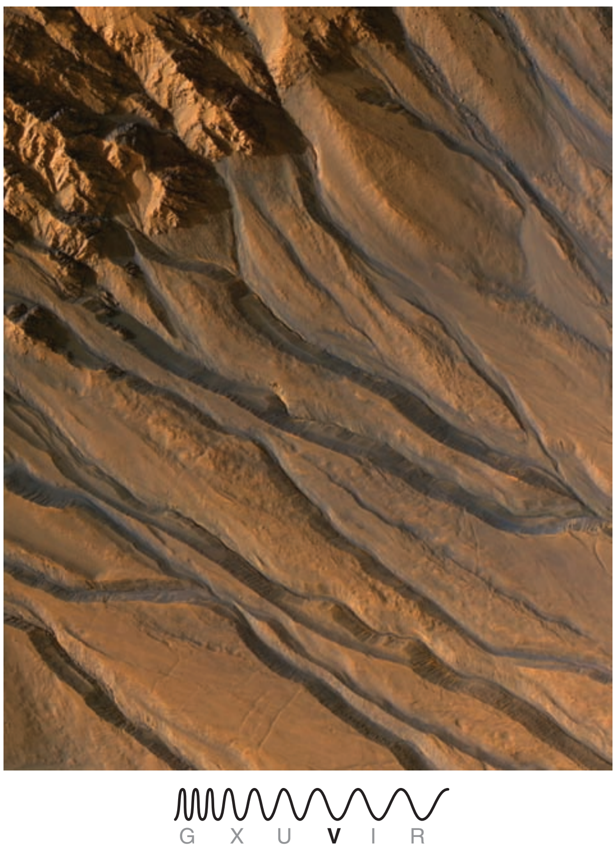


Figure 8.27 A photograph of gully channels in a crater on Mars taken by the *Mars Reconnaissance Orbiter.* The gullies coming from the rocky cliffs near the crater's rim (out of the image, to the upper left) show meandering and braided patterns similar to those of water-carved channels on Earth.

In 2004, NASA sent two instrument-equipped roving vehicles, *Opportunity* and *Spirit*, to search for evidence of water on Mars. *Opportunity* landed inside a crater. For the first time, martian rocks were available for study in the original order in which they had been laid down. Previously, the only rocks that landers and rovers had come across were those that had been dislodged from their original settings by either impacts or river floods. The layered rocks at the *Opportunity* site revealed that they had once been soaked in or transported by water. The form of the layers was typical of layered sandy deposits laid down by gentle currents of water. Magnified images of the rocks showed "blueberries," small, bluish spheres a few millimeters across that probably formed in place among the layered rocks. Analysis of the spheres revealed abundant hematite, an iron-rich mineral that forms in the presence of water.

Observations by ESA's *Mars Express* and NASA's *Mars Odyssey* and *Mars Reconnaissance Orbiter* have shown the hematite signature and the presence of sulfur-rich compounds in a vast area surrounding the *Opportunity* landing site. These observations suggest the existence of an ancient martian sea larger than the combined area of the Great Lakes and as much as 500 meters deep.

In August 2012, NASA's Mars rover *Curiosity* landed in Gale Crater, a large (150 km) crater just south of the equator of Mars. *Curiosity* found evidence of a stream that flowed at a rate of about 1 meter per second and was as much as 2 feet deep. The streambed is identified by water-worn gravel (**Figure 8.28**). The rover, which is about the size of a car, includes cameras, a drill, and an instrument to measure chemical composition. When the rover drilled into a rock, it found sulfur, nitrogen, hydrogen, oxygen, phosphorus, and carbon, together with clay minerals that formed in a water-rich environment that was not very salty. Taken together, these pieces of evidence indicate that Mars may have had conditions suitable to support Earth-like microbial life in the distant past.

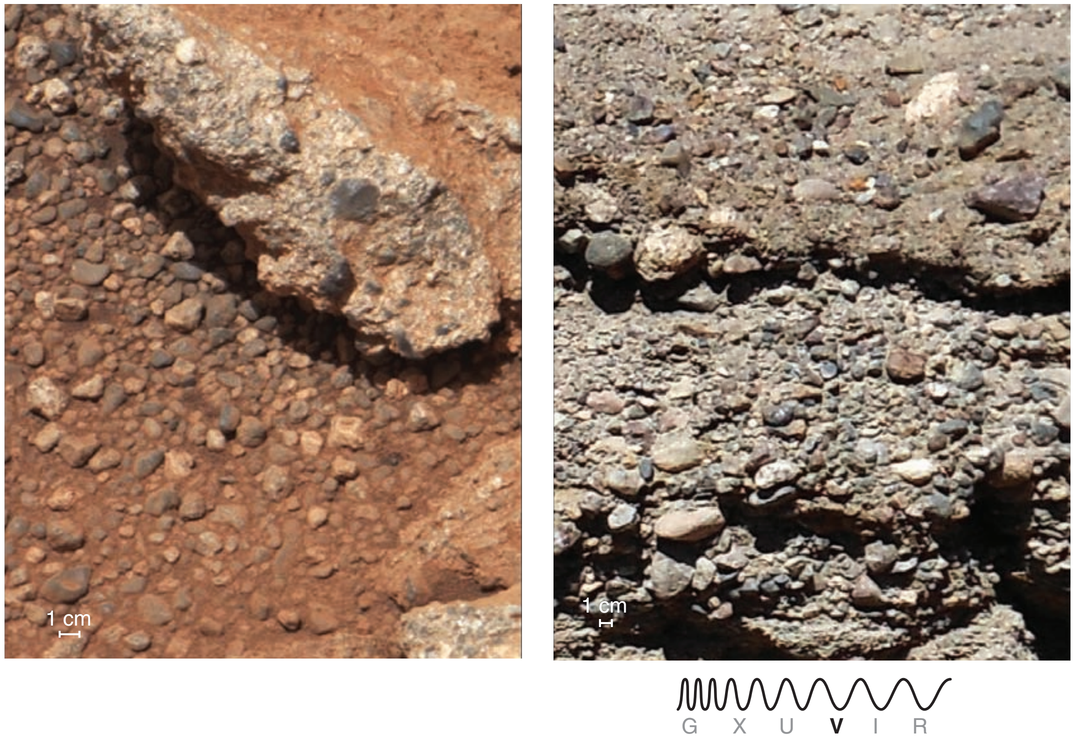


Figure 8.28 This image compares a photograph taken by NASA's *Curiosity* rover (left) with a photograph of a streambed on Earth (right). The Mars image shows water-worn gravel embedded in sand, sure evidence of an ancient streambed.

Where did the water go? Some escaped into the thin atmosphere of Mars, and some is locked up as ice in the polar regions, just as the ice caps on Earth hold much of its water. Unlike Earth's polar caps of frozen water, those on Mars are a mixture of frozen carbon dioxide and frozen water. Water must be hiding elsewhere on Mars. Small amounts of water can be found on the surface, and in 2008 NASA's *Phoenix* lander found water ice just a centimeter or so beneath surface soils at high northern latitudes (**Figure 8.29**). However, most of the water on Mars appears to be trapped well below the surface. Radar imaging by *Mars Express* and the *Mars Reconnaissance Orbiter* (*MRO*) indicates huge quantities of subsurface water ice, not only in the polar areas as expected but also at lower latitudes under craters. In addition, *MRO* images suggest that there might be seasonal salt water that flows on the surface far from the poles. Salt water freezes at a lower temperature, so some sites could be warm enough to have temporary liquid salt water. Another location for liquid water may be in martian volcanoes.

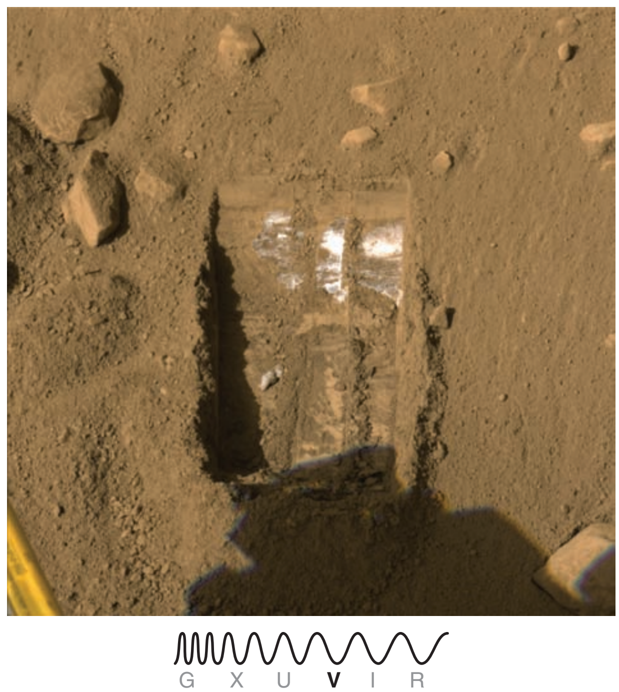


Figure 8.29 Water ice appears a few centimeters below the surface in this trench dug by a robotic arm on the *Phoenix* lander. The trench measures about 20 × 30 cm.

Venus Evidence for liquid water on Venus comes primarily from water vapor in its atmosphere, but there are some geological indications of past water, such as color differences between the highland and lowland regions. As noted earlier, on Earth such a difference indicates the presence of granite, which requires water for its formation. We will return to the subject of what happened to the water on Venus and Mars in the next chapter, when we discuss their atmospheres.

The Moon Infrared measurements of the Moon by the U.S. *Clementine* mission in 1994 returned information supporting the possibility of ice at the lunar poles. In 1998, NASA's *Lunar Prospector* observations suggested subsurface water ice in the polar regions. When its primary mission was completed, NASA crashed *Lunar Prospector* into a crater near the Moon's south pole while ground-based telescopes searched for evidence of water vapor above the impact site, but none was seen. Since 2007, several new missions have been sent to the Moon, including Japan's *Kaguya*, India's *Chandrayaan-1*, and NASA's *Lunar Reconnaissance Orbiter* (*LRO*) and its companion *Lunar Crater Observation and Sensing Satellite* (*LCROSS*).

In 2009, NASA crashed the *LCROSS* launch vehicle into the Cabeus Crater at the lunar south pole, which sent up dust and vapor that was analyzed by the *LCROSS* and *LRO* spacecraft. More than 5 percent of the resulting plume was water, which makes this part of the Moon wetter than many Earth deserts. Other volatiles were also detected. Measurements of hydrogen by the *LRO* suggest that there is a fair amount of buried water ice in the cold southern polar region.

These space observations of lunar ice sent planetary scientists back to the collections of lunar rocks and soil returned to Earth decades ago by the *Apollo* mission astronauts. New analysis of volcanic glass beads in lunar soil suggests that the interior of the Moon may have a much larger amount of volatiles than previously believed. Reanalysis of the *Apollo* lunar rocks also found evidence of water. One way to distinguish whether water on the Moon originated from its interior or from impacts is to look at the ratio of water molecules composed of regular hydrogen (with one proton) and oxygen to water molecules composed of oxygen, hydrogen, and an isotope of hydrogen called deuterium (hydrogen with one proton and one neutron). The ratio is higher in the water in lunar rocks than in the water on Earth. Water that originated in comets or in meteorites rich in water has a different ratio. Alternatively protons from the solar wind or from high-energy cosmic rays in space could have combined with oxygen on the lunar surface, yielding a different ratio. A recent study suggests that the Moon's water came from the solar wind.

These results on lunar water are preliminary. There is still considerable debate among scientists about exactly how much water ice exists on the lunar surface and how much liquid water is in the interior, how the Moon acquired this water, and how the presence and origin of water affect the current theories of lunar formation. Several countries—and some private companies—are considering proposals to send robotic spacecraft to the Moon to collect additional lunar material and bring it back to Earth for analysis.

Mercury Water ice has also been detected in the polar regions of Mercury. Some deep craters in the polar regions of Mercury have floors that are in perpetual shadow, and thus receive no sunlight. Temperatures in these permanently shadowed areas remain very cold, below 180 K. For many years, planetary scientists had speculated that ice could be found in these polar craters, and there was a possible detection by radar in the early 1990s. The *Messenger* spacecraft, which orbited Mercury from 2011–2015, found deposits of ice at craters at the planet's north pole. Other frozen volatiles were also seen in the polar craters. The icy areas have sharp boundaries, which indicates they are relatively recent, either from comet impacts or from some ongoing process on the planet.

CHECK YOUR UNDERSTANDING 8.7

Which of the following worlds show evidence of the current presence of liquid or frozen water? (Choose all that apply.) (a) Mercury; (b) Venus; (c) Earth; (d) the Moon; (e) Mars

Origins

The Death of the Dinosaurs

When large impacts happen on Earth, they can have far-reaching consequences for Earth's climate and for terrestrial life. One of the biggest and most significant impacts happened at the end of the Cretaceous Period, which lasted from 146 million years ago to 65 million years ago. At the end of the Cretaceous Period, more than 50 percent of all living species, including the dinosaurs, became extinct. This mass extinction is marked in Earth's fossil record by the Cretaceous-Tertiary boundary, or *K-T boundary* (the *K* comes from *Kreide*, German for "Cretaceous"). Fossils of dinosaurs and other now-extinct life-forms are found in older layers below the K-T boundary. Fossils in the newer rocks above the K-T boundary lack more than half of all previous species but contain a record of many other newly evolving species. Big winners in the new order were the mammals—distant ancestors of humans—that moved into ecological niches vacated by extinct species.

Figure 8.30 This artist's rendition depicts an asteroid or comet, perhaps 10 km across, striking Earth 65 million years ago in what is now the Yucatán Peninsula in Mexico. The lasting effects of the impact might have killed off most forms of terrestrial life, including the dinosaurs.

How do scientists know that an impact was involved? The K-T boundary is marked in the fossil record in many areas by a layer of clay. Studies at more than 100 locations around the world have found that this layer contains large amounts of the element iridium, as well as traces of soot. Iridium is very rare in Earth's crust but is common in meteorites. The soot at the K-T boundary possibly indicates that widespread fires burned the world over. The thickness of the layer of clay at the K-T boundary and the concentration of iridium increases toward what is today the Yucatán Peninsula in Mexico. Although the original crater has largely been erased by erosion, geophysical surveys and rocks from drill holes in this area show a deeply deformed subsurface rock structure, similar to that seen at known impact sites. These results provide compelling evidence that 65 million years ago, an asteroid about 10 km in diameter struck the area, throwing great clouds of red-hot dust and other debris into the atmosphere (**Figure 8.30**) and possibly igniting a worldwide conflagration. The energy of the impact is estimated to have been more than that released by 5 billion nuclear bombs.

An impact of this energy clearly would have had a devastating effect on terrestrial life. In addition to the possible firestorm ignited by the impact, computer models suggest there would have been earthquakes and tsunamis. Dust from the collision and soot from the firestorms thrown into Earth's upper atmosphere would have remained there for years, blocking out sunlight and plunging Earth into decades of a cold and dark "impact winter." Recent measurements of ancient microbes in ocean sediments suggest that Earth may have cooled by 7°C. The firestorms, temperature changes, and decreased food supplies could have led to a mass starvation that would have been especially hard on large animals such as the dinosaurs.

Not all paleontologists believe that this mass extinction was the result of an impact; some think volcanic activity was important as well. However, the evidence is compelling that a great impact did occur at the end of the Cretaceous Period. Life on our planet has had its course altered by sudden and cataclysmic events when asteroids and comets have slammed into Earth. It seems very possible that we owe our existence to the luck of our remote ancestors—small rodent-like mammals—that could live amid the destruction after such an impact 65 million years ago.

READING ASTRONOMY NEWS

ARTICLES QUESTIONS

Scientists report that the Moon may have had volcanic activity more recently than expected.

Did Volcanoes Erupt on the Moon while Dinosaurs Roamed Earth?

By **AMINA KHAN, Los Angeles Times**

Ever looked up into the night sky and seen the ancient face of the "man on the Moon"? Well, turns out he may have had some recent work done.

Scientists thought the Moon has been cold and dead for roughly a billion years. But strange small features on the surface discovered by NASA's *Lunar Reconnaissance Orbiter* reveal that there could have been volcanic activity during the time of the dinosaurs. That's practically just last week, by geological timescales.

The findings, described in the journal *Nature Geoscience*, could force researchers to reconsider established theories on the Moon's evolution.

The large dark patches on the lunar surface that give shape to the Moon's "face" are called *maria*, and they're thought to be the remains of volcanic activity on the Moon that started 3.5 billion years ago. Scientists thought the Moon cooled quickly, and this period of volcanism ended abruptly, around a billion years back.

There were some anomalies—for example a strange feature called Ina, imaged from orbit by *Apollo 15* astronauts in 1971, that seemed to be very young. But Ina was thought to be an exception, and it wasn't clear what its existence meant.

Now, using the NASA orbiter, a team led by Arizona State University scientists picked out 70 of these strange features—round, smooth areas, surrounded by rough, choppy terrain. They're called "irregular mare patches," and they're too small to be distinguished with the naked eye from Earth. Though they range in size from 328 feet to 3.1 miles, the average is 1,591 feet, or 0.3 miles (**Figure 8.31**).

Since the scientists have no way to bring this rock back to the lab to study, they relied on a commonly used method to date these strange features. Essentially, the more craters that pock their surfaces, the older they are (because older features have had more time to be smashed by space debris). These crater counts have been calibrated using the laboratory-measured ages of Moon rock samples brought back by *Apollo* astronauts.

The researchers found that scores of these features were less than 100 million years old—which would put them in range of the Cretaceous Period on Earth, which was the dinosaurs' heyday. Some were even younger—Ina could be 33 million years old and another patch, Sosigenes, could be just 18 million years old.

That means there could have been regular volcanic activity all around the Moon in very recent times—not like the dramatic volcanism that produced the enormous *maria*, but still significant and widespread. It also means that the Moon cooled more gradually than scientists thought, and that we may not really understand how much heat still remains inside of it. Theories about the Moon's thermal evolution might need a serious rethink.

The best way to know for sure? Return to the lunar surface and bring back rock samples that can be analyzed in the lab, the authors say. (The last time that happened was in the 1970s.)

"Sample return will be required for radiometric age dating to confirm the relatively young ages implied by remote sensing observations," the study authors wrote.

Figure 8.31 This feature on the lunar surface, called Maskelyne, is one of many newly-discovered young volcanic deposits on the moon. These "irregular mare patches" are thought to be remnants of small eruptions that occurred just a few tens of millions of years ago.

ARTICLES QUESTIONS

1. Why did scientists expect that the Moon cooled quickly?
2. Why are the features called "maria" distributed in patches?
3. What was the evidence that indicated volcanic activity ended a billion years ago?
4. Why would bringing a sample back to Earth yield a more accurate age estimate for more recent volcanic activity?
5. Do a search for "Moon volcanic activity." Are there any new findings about either more recent or billion-year-old volcanic activity?

Summary

The terrestrial planets in the Solar System are Mercury, Venus, Earth, and Mars, all of which have evidence of past or present water. The Moon is usually included in discussions of the terrestrial worlds because it is similar to them in many ways. Comparative planetology is the key to understanding the planets. Four geological processes—impacts, volcanism, tectonism, and erosion—are responsible for topography on the terrestrial planets. Active volcanism and tectonics are the results of a "living" planetary interior: one that is still hot inside. Over time, the interiors cool, and tectonics and volcanism weaken. On Earth, radioactive decay and tidal effects from the Moon contribute to heat in the interior. Erosion is a surface phenomenon that results from weathering by wind or water. Surface features on the terrestrial planets, such as tectonic plates, volcanoes, mountain ranges, or canyons, are the result of the interplay between these four processes. Evolution on Earth may have been affected by impacts, such as the impact of an asteroid 65 million years ago that might have led to the death of the dinosaurs.

LG 1 **Describe how impacts have affected the evolution of the terrestrial planets.** Impact cratering is the result of a direct interaction of an astronomical object with the surface of a planet. The layering of craters gives their relative ages, with more recent craters found superimposed on older ones. Crater densities can be used to find the relative ages of regions on a surface; more heavily cratered regions are older than less cratered ones. Planets protected by atmospheres, like Earth and Venus, have fewer small impact craters. The Moon was probably created when a Mars-sized protoplanet collided with Earth.

LG 2 **Explain how radiometric dating is used to measure the ages of rocks and planetary surfaces.** Radioactive isotopes found in rocks can be used to measure their age. The oldest rocks measured, from the Moon and from meteorites, give the age of the Solar System of 4.5 billion to 4.6 billion years.

LG 3 **Explain how scientists use both theory and observation to determine the structure of planetary interiors.** Models of Earth's interior are used to predict how seismic waves should propagate through the interior, and these predictions are compared to observations of seismic waves. The interiors of other planets are modeled using physical principles, along with observational data on their magnetic fields. Earth has a strong magnetic field, but Venus and Mars do not. The cause for this difference between the terrestrial planets is uncertain.

LG 4 **Describe tectonism and volcanism and the forms they take on different planets.** Tectonism folds, twists, and cracks the outer surface of a planet. Plate tectonics is unique to Earth, although other types of tectonic disruptions are observed on the other terrestrial planets, such as cracking and buckling on the surface. Smooth areas on the Moon and Mercury are ancient lava flows. While Venus has the most volcanoes, the largest mountains in the Solar System are volcanoes on Mars. Earth's surface is still changing as volcanic hot-spot activity forms new members of island chains.

LG 5 **Summarize the knowledge of water on the terrestrial planets.** Geological features observed in orbiting and surface missions to Mars suggest there once was liquid water on the surface. Mars today has large amounts of subsurface water ice. Venus might have had liquid oceans early in its history. Space mission data indicate that water ice exists near the poles of the Moon and Mercury. This search for water is important to both the search for extraterrestrial life and the possibilities of human colonization of space.

? UNANSWERED QUESTIONS

- Why is Venus so different from Earth? These two planets of similar size, mass, and composition are very different geologically, with respect to magnetic fields, plate tectonics, and recent activity, and it is not yet known why. In addition, how did Venus end up rotating in the direction opposite that of its revolution around the Sun? Did it form with a different orbit or rotation? Was it the result of an impact early in its history? Did it change very slowly over time because of tidal effects from other planets?
- Will humans someday "live off the land" on the Moon? Recent space missions have provided evidence that there is some water ice on the Moon. If there is water on the Moon, that would certainly make living there more practical than if water had to be brought from Earth or synthesized from hydrogen and oxygen extracted from the lunar soil. Scientists and engineers have been studying several methods to see whether oxygen can be extracted from lunar rocks to make breathable air for people. Others have looked at using lunar rock as a building material; for example, to make concrete. But the most valuable material on the Moon might turn out to be an isotope of helium, helium-3 (^3He, which is helium with two protons and one neutron). On Earth, this isotope exists only as a by-product of nuclear weapons, but there may be up to a million tons of it on the Moon. Some scientists and engineers think that helium-3 could be used in a "clean" type of nuclear energy. This helium-3 could be brought back from the Moon for use on Earth or possibly even used in a power plant on the Moon to create energy for a lunar colony.

Questions and Problems

Test Your Understanding

1. __________, __________, and __________ build up structures on the terrestrial planets, while __________ tears them down.
   a. impacts, erosion, volcanism; tectonism
   b. impacts, tectonism, volcanism; erosion
   c. tectonism, volcanism, erosion; impacts
   d. tectonism, impacts, erosion; volcanism
2. Geologists can determine the relative age of features on a planet because
   a. the ones on top must be older.
   b. the ones on top must be younger.
   c. the larger ones must be older.
   d. the larger ones must be younger.
3. Scientists can learn about the interiors of the terrestrial planets from
   a. seismic waves.
   b. satellite observations of gravitational fields.
   c. physical arguments about cooling.
   d. satellite observations of magnetic fields.
   e. all of the above
4. Earth's interior is heated by
   a. angular momentum and gravity.
   b. radioactive decay and gravity.
   c. radioactive decay and tidal effects.
   d. angular momentum and tidal effects.
   e. gravity and tidal effects.
5. If a radioactive element has a half-life of 10,000 years, what fraction of it is left in a rock after 40,000 years?
   a. 1/2
   b. 1/4
   c. 1/8
   d. 1/16
   e. 1/32
6. Lava flows on the Moon and Mercury created large, smooth plains. We don't see similar features on Earth because
   a. Earth has less lava.
   b. Earth had fewer large impacts in the past.
   c. Earth has plate tectonics that recycle the surface.
   d. Earth is large compared to the size of these plains, so they are not as noticeable.
   e. Earth rotates much faster than either of these other worlds.
7. Scientists know the history of Earth's magnetic field because
   a. the magnetic field hasn't changed since Earth formed.
   b. they see today's changes and project backward in time.
   c. the magnetic field becomes frozen into rocks, and plate tectonics spreads those rocks apart.
   d. they compare the magnetic fields on other planets to Earth's.
8. Suppose an earthquake occurs on an imaginary planet. Scientists on the other side of the planet detect primary waves but not secondary waves after the quake. This suggests that
   a. part of the planet's interior is liquid.
   b. all of the planet's interior is solid.
   c. the planet has an iron core.
   d. the planet's interior consists entirely of rocky materials.
   e. the planet's mantle is liquid.
9. Geologists can determine the actual age of features on a planet by
   a. radiometric dating of rocks retrieved from the planet.
   b. comparing cratering rates on one planet to those on another.
   c. assuming that all features on a planetary surface are the same age.
   d. both a and b
   e. both b and c
10. Impacts on the terrestrial planets and the Moon
    a. are more common than they used to be.
    b. have occurred at approximately the same rate since the Solar System formed.
    c. are less common than they used to be.
    d. periodically become more common and then less common.
    e. never occur anymore.
11. Earth has fewer craters than Venus. Why?
    a. Earth's atmosphere protects better than Venus's.
    b. Earth is a smaller target than Venus.
    c. Earth is closer to the asteroid belt.
    d. Earth's surface experiences more erosion.
12. Scientists propose an early period of heavy bombardment in the Solar System because
    a. the Moon is heavily cratered.
    b. all the craters on the Moon are old.
    c. the smooth part of the Moon is nearly as old as the heavily cratered part.
    d. all the craters on the Moon are young.
13. Scientists know that Earth was once completely molten because
    a. the surface is smooth.
    b. the interior layers are denser.
    c. the chemical composition indicates this.
    d. volcanoes exist today.
14. What is the main reason that Earth's interior is liquid today?
    a. tidal force of the Moon on Earth
    b. seismic waves that travel through Earth's interior
    c. decay of radioactive elements
    d. convective motions in the mantle
    e. pressure on the core from Earth's outer layers
15. Mars has a diameter that is approximately half that of Earth. If the interiors of these planets are heated by radioactive decays, how does the heating rate of the interior of Mars compare to that of Earth?
    a. The heating rate of Mars is 0.125 times that of Earth.
    b. The heating rate of Mars is 8 times that of Earth.
    c. The heating rate of Mars is 0.5 times that of Earth.
    d. The heating rate of Mars is 4 times that of Earth.
    e. The heating rates are about the same.

Thinking about the Concepts

16. In discussing the terrestrial planets, why do we include Earth's Moon?
17. Can all rocks be dated with radiometric methods? Explain.
18. Explain how scientists know that rock layers at the bottom of the Grand Canyon are older than those found on the rim.
19. Describe the sources of heating that are responsible for generating Earth's magma.
20. Explain why the Moon's core is cooler than Earth's.
21. Explain the difference between longitudinal waves and transverse waves.
22. How do we know that Earth's core includes a liquid zone?
23. Study the Process of Science Figure. What evidence makes the impactor theory the currently preferred favorite explanation for the origin of the Moon? What evidence remains to be found to rule out the competing theories?
24. Compare and contrast tectonism on Venus, Earth, and Mercury.
25. Explain plate tectonics and identify the only planet on which this process has been observed.
26. Volcanoes have been found on all of the terrestrial planets. Where are the largest volcanoes in the inner Solar System?
27. Explain the criteria you would apply to images (assume adequate resolution) in order to distinguish between a crater formed by an impact and one formed by a volcanic eruption.
28. What are the primary reasons that the surfaces of Venus, Earth, and Mars have been determined to be younger than those of Mercury and the Moon?
29. Explain some of the geological evidence suggesting that Mars once had liquid water on its surface.
30. What evidence supports the theory suggesting that a mass extinction occurred as a consequence of an enormous impact on Earth 65 million years ago?

Applying the Concepts

31. Study Figure 8.8.
    a. How has the cratering rate changed over time? Has it fallen off gradually or abruptly?
    b. At present, what is the cratering rate compared to that about 4 billion years ago?
    c. Explain why this falloff in cratering rate fits nicely in the theory of planet formation.
32. Study Figure 8.7. Are the vertical and horizontal axes linear or logarithmic? After how many half-lives will the number of parent isotopes equal the number of daughter isotopes? Is this result unique to this example? Why or why not?
33. Study Figure 8.7. The destruction of the parent isotope is an example of exponential decay. Is the growth of the daughter isotope an example of exponential growth? How can you tell?
34. Compare Figures 8.18 and 8.23. Which of these regions is older? How do you know?
35. Assume that Earth and Mars are perfect spheres with radii of 6,371 km and 3,390 km, respectively.
    a. Calculate the surface area of Earth.
    b. Calculate the surface area of Mars.
    c. If 0.72 (72 percent) of Earth's surface is covered with water, compare the amount of Earth's land area to the total surface area of Mars.
36. Compare the kinetic energy ($= \frac{1}{2}mv^2$) of a 1-gram piece of ice (about half the mass of a dime) entering Earth's atmosphere at a speed of 50 km/s to that of a 2-metric-ton SUV (mass $= 2 \times 10^3$ kg) speeding down the highway at 90 km/h.
37. The object that created Arizona's Meteor Crater was estimated to have a radius of 25 meters and a mass of 300 million kg. Calculate the density of the impacting object, and explain what that may tell you about its composition.
38. Using the information in Table 8.1 and Working It Out 8.2, determine the relative rates of internal energy loss experienced by Earth and the Moon.
39. Earth's mean radius is 6,371 km, and its mass is 6.0×10^{24} kg. The Moon's mean radius is 1,738 km, and its mass is 7.2×10^{22} kg.
    a. Calculate Earth's average density. Show your work; do not look this value up.
    b. The average density of Earth's crust is 2,600 kg/m^3. What does this value tell you about Earth's interior?
    c. Compute the Moon's average density. Show your work.
    d. Compare the average densities of the Moon, Earth, and Earth's crust. What do these values tell you about the Moon's composition compared to that of Earth and of Earth's crust?
40. Suppose you find a piece of ancient pottery and find that the glaze contains radium, a radioactive element that decays to radon and has a half-life of 1,620 years. There could not have been any radon in the glaze when the pottery was being fired, but now it contains three atoms of radon for each atom of radium. How old is the pottery?
41. Archaeological samples are often dated by radiocarbon dating. The half-life of carbon-14 is 5,700 years.
    a. After how many half-lives will the sample have only 1/64 as much carbon-14 as it originally contained?
    b. How much time will have passed?
    c. If the daughter product of carbon-14 is present in the sample when it forms (even before any radioactive decay happens), you cannot assume that every daughter you see is the result of carbon-14 decay. If you did make this assumption, would you overestimate or underestimate the age of a sample?
42. Different radioisotopes have different half-lives. For example, the half-life of carbon-14 is 5,700 years, the half-life of uranium-235 is 704 million years, the half-life of potassium-40 is 1.3 billion years, and the half-life of rubidium-87 is 49 billion years.
    a. Why wouldn't you use an isotope with a half-life similar to that of carbon-14 to determine the age of the Solar System?
    b. The age of the universe is approximately 14 billion years. Does that mean that no rubidium-87 has decayed yet?

43. Assume that the east coast of South America and the west coast of Africa are separated by an average distance of 4,500 km. Assume also that GPS measurements indicate that these continents are now moving apart at a rate of 3.75 cm/yr. If this rate has been constant over geological time, how long ago were these two continents joined together as part of a supercontinent?

44. Shield volcanoes are shaped something like flattened cones. The volume of a cone is equal to the area of its base multiplied by one-third of its height. The largest volcano on Mars, Olympus Mons, is 27 km high and has a base diameter of 550 km. Compare its volume with that of Earth's largest volcano, Mauna Loa, which is 9 km high and has a base diameter of 120 km.

45. Using the data in Table 8.1, compare the surface gravity on Mars with that on Earth. How does this help explain why the volcanoes on Mars can grow so high?

USING THE WEB

46. Go to the U.S. Geological Survey's "Earthquake" website (http://earthquake.usgs.gov/earthquakes/map). Set "Zoom" to "World," set the "Settings" icon in the upper right to "Seven Days, Magnitude 2.5+," and look at the earthquakes for the past week. Were there any really large ones? Compare the map of recent earthquakes with Figure 8.17 in the text. Are any of the quakes in surprising locations? Where was the most recent one? Now change the "Zoom" to the United States (or to "Your location") and change the settings to "30 days, Magnitude 2.5+." Has there been seismic activity, and if so where?

47. Use Google Earth to explore the Moon, Mercury, and Mars.
    a. View all sides of the Moon. Does one hemisphere look more heavily cratered than others, and if so, why?
    b. View the planet Mercury. In what ways is Mercury similar to and in what ways different from the Moon? (You might need to get the Mercury KMZ file: http://messenger.jhuapl.edu/the_mission/google.html.)
    c. View all sides of the planet Mars. What differences can you see between the northern and southern hemispheres?

48. Citizen science:
    a. Go to the website for "Moon Zoo" (http://moonzoo.org), a project that lets everyone participate in the analysis of images from NASA's *Lunar Reconnaissance Orbiter*. Read through the FAQ, then click on "Tutorials" and select "How to Take Part." (You will need to create an account if you haven't already done so for another Zooniverse project.) In this project you count craters on the Moon, noting where there are boulders, classifying some of these features, and looking for hardware left over from exploration missions.
    b. Go to the website for Cosmoquest (http://cosmoquest.org) and click on "Mercury Mappers." You will need to create an account for the Cosmoquest projects. Click on the circled question mark under the blue check box, and read the FAQ and watch the tutorial. What is the goal of this project? Where did the data come from? Classify some images.
    c. Go to the website for Cosmoquest (http://cosmoquest.org) and click on "Moon Mappers." As in part (b), you will need an account. Click on the circled question mark under the blue check box and read the FAQ and watch the four tutorials. What are some of the basic features? How does the angle of the sunlight and the direction of illumination affect what you see? Now classify a few craters.

49. Space missions:
    a. Go to the website for NASA's *Messenger* mission to Mercury (http://messenger.jhuapl.edu). Click on "Gallery" and then "Science Images," and look at a few of the pictures. Are the color images using real or false colors? Click on "News Center." Describe a result.
    b. Go to the website for the *Mars Science Laboratory Curiosity* (http://mars.jpl.nasa.gov/msl), which landed in 2012. What are the latest science results?
    c. The Google Lunar X Prize (http://googlelunarxprize.org) goes to the first privately funded team to send a robot to the Moon. The winning robot must travel some distance on the Moon's surface and send back pictures. On the website, click on "Teams" and read about a few that are still competing. What kind of people and companies are on the team? What is their plan to go to the Moon? Aside from this prize, why do they want to go to the Moon: what commercial opportunities on the Moon do they anticipate?

50. Video:
    a. Watch one of the available documentaries about the *Apollo* missions to the Moon (for example, *In the Shadow of the Moon*, 2008). Why did the United States decide to send astronauts to the Moon? Why did the *Apollo* program end? Are there current plans to send people to the Moon?
    b. The first science fiction film was the short *Voyage to the Moon* (Georges Méliès, 1902). A version with an English narration can be viewed at https://archive.org/details/Levoyagedanslalune. A restored digitized and colorized version was released in 2011 and can be found at http://vimeo.com/39275260. Where do the "Selenians" live on the Moon? In this first cinematic depiction of contact with life from outside of Earth, what do the human astronomers do to the Selenians? Contrast what the astronomers in the film find on the Moon with what the *Apollo* astronauts actually saw.

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EXPLORATION Exponential Behavior

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Knowledge of the exponential function is critical to understanding life in modern times because this function shows up in many contexts, from economics to population studies to climate change.

Radioactive decay exhibits exponential decay, where the amount of a radioactive material that remains after an elapsed time is proportional to the amount that was present at the beginning of the time period. In this Exploration, you will use a small (1.69-ounce) bag of plain M&M's to investigate this behavior.

This size bag of M&M's contains approximately 56 pieces of candy. Each piece has an *M* stamped on one side. Thus, there are two ways for each piece to fall when dropped: *M* side up or *M* side down. This is much like what happens to a radioactive nucleus: for any given period of time, either it decays or it doesn't.

Rather than acquiring 10 bags of M&M's, with all the mess that would make, you will use the same bag 10 times, and then add your results together. This approach makes the sample large enough that the exponential behavior becomes apparent.

Step 1 For the first trial, shake all the M&M's into your hands and then pour them onto the table.

Step 2 Count how many land *M* side up, and record that number in the provided table under Trial 1, Time Step 1.

Step 3 Set the *M*-side-up candies to one side.

Step 4 Repeat steps 1–3 for time steps 2, 3, 4, and so on, until the last candy lands *M* side up.

Step 5 Repeat steps 1–4 for 9 more trials (making a total of 10 trials).

Step 6 Add together the results of the trials for each time step, and record them in the Sum column of the table.

Step 7 It's very difficult to make sense of numbers in tabular form like this, so plot the results on a graph with the sum on the *y*-axis and the time step on the *x*-axis.

Time Step	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Sum
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											

1 Study your graph. At first, does the number of M&M's landing *M* side up decrease slowly or quickly? In later time steps (such as 8 or 9), does the number decrease slowly or quickly?

2 Generalize your answer to question 1 to the behavior of radioactive sources. Does the radioactivity fall off slowly or quickly at the beginning of an observation? How about at later times?

3 As time goes by, what happens to the number of M&M's that remain? What happens to the number of M&M's in the pile that is set aside?

4 Generalize your answer to question 3 to the behavior of radioactive sources. What happens to the number of radioactive isotopes over time? What happens to the number of daughter products?

5 Imagine that you walk into a room and observe another student performing this experiment. She pours the M&M's onto the table and counts 10 candies that landed *M* side up. About how many time steps have passed since this student started the experiment?

6 Apply your answer to question 5 to the behavior of radioactive sources. When scientists study radioactive sources, they generally study the ratio of the number of radioactive isotopes to the number of daughter products. Explain how this method, while different from what you did in step 5, contains the same information about the amount of time that has passed.

9 Atmospheres of the Terrestrial Planets

Earth's atmosphere surrounds its inhabitants like an ocean of air. It is evident in the blueness of the sky and in the breezes in the air. Without Earth's atmosphere, there would be neither clouds nor oceans. Without an atmosphere, Earth would look something like the Moon, and life would not exist on our planet. Among the five terrestrial bodies that we discussed in Chapter 8, only Venus and Earth have dense atmospheres. Mars has a very low-density atmosphere, and the atmospheres of Mercury and the Moon are so sparse that they can hardly be detected. To understand the origins of the atmospheres of Venus, Earth, and Mars, how they have changed over time, how they compare to one another, and how they are likely to evolve in the future requires us to look back nearly 5 billion years to a time when the planets were just completing their growth.

LEARNING GOALS

In this chapter, we will compare the atmospheres of the terrestrial planets. By the conclusion of this chapter, you should be able to:

LG 1 **Identify the processes that cause primary and secondary atmospheres to be formed, retained, and lost.**

LG 2 **Compare the strength of the greenhouse effect and differences in the atmospheres of Earth, Venus, and Mars.**

LG 3 **Describe the layers of the atmospheres on Earth, Venus, and Mars, and explain how Earth's atmosphere has been reshaped by the presence of life.**

LG 4 **Compare the atmospheres of Venus and Mars with the atmosphere of Earth.**

LG 5 **Describe how comparative planetology contributes to a better understanding of the changes in Earth's climate.**

Earth from space. ▶▶▶

Why can you breathe only on Earth?

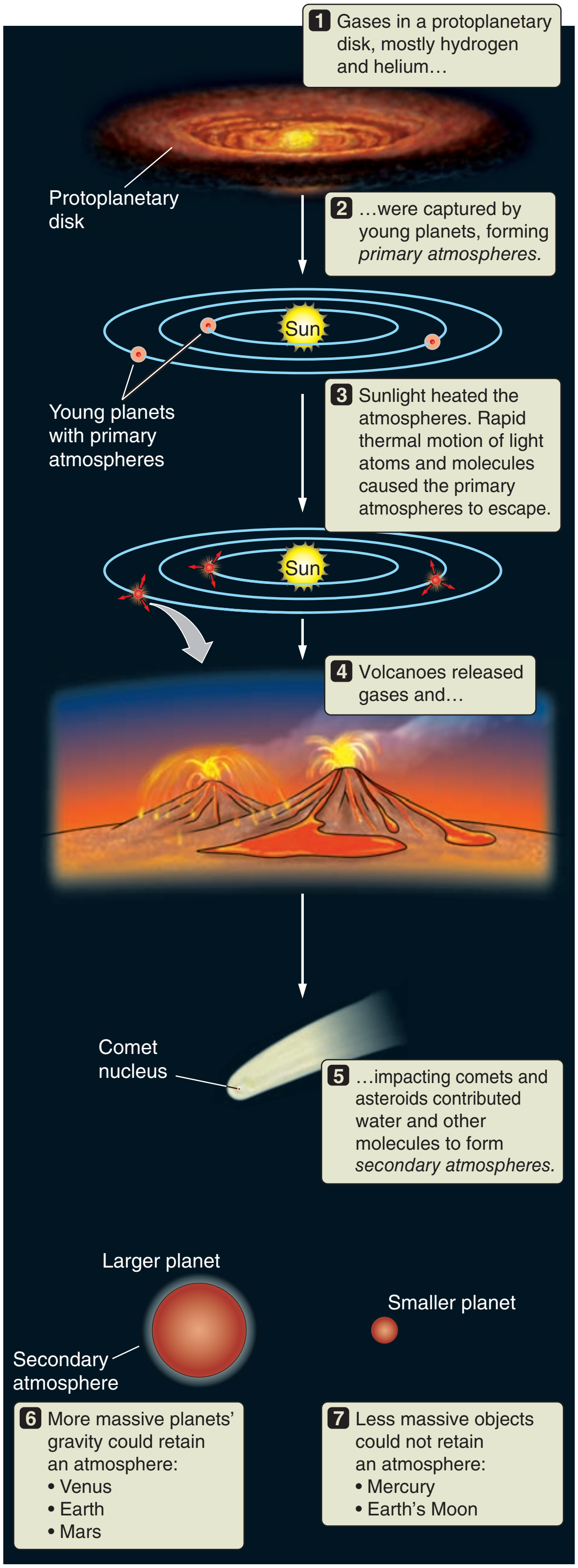


Figure 9.1 Planetary atmospheres form and evolve in phases.

9.1 Atmospheres Change over Time

An atmosphere is a layer of gas that sits above the surface of a solid body such as a terrestrial planet. A blanket of atmosphere warms and sustains Earth's temperate climate. On Venus, by contrast, a thick, carbon dioxide atmosphere pushes the planet's surface temperature very high. A thin atmosphere leaves the surface of Mars unprotected and frozen. Mercury and the Moon have essentially no atmosphere. Why should some of the terrestrial planets have dense atmospheres while others have little or none? In this section, we will look at the formation of planetary atmospheres.

Formation and Loss of Primary Atmospheres

Planetary atmospheres formed in phases, which are shown in **Figure 9.1**. At the time of formation, the young planets were initially enveloped by the remaining hydrogen and helium that filled the protoplanetary disk surrounding the Sun, and they captured some of this surrounding gas. Gas capture continued until soon after formation of the planets when the gaseous disk dissipated and the supply of gas ran out. The gaseous atmosphere collected by a newly formed planet is called its primary atmosphere. This primary atmosphere was lost from the terrestrial planets as these lightweight atoms and molecules escaped from the planet's gravity. To understand this, we must consider how particles move within a planetary atmosphere.

In Chapter 7, you saw that the terrestrial planets are less massive than the giant planets and therefore have weaker gravitational attraction. These planets lack the ability to hold light gases such as hydrogen and helium. Giant impacts by large planetesimals early in the history of the Solar System may have blasted away some of their primary atmospheres. When the supply of gas in the protoplanetary disk ran out, the primary atmospheres of the terrestrial planets began leaking back into space. How can gas molecules escape from a planet? Recall from Chapter 4 that any object—from a molecule to a spacecraft—can escape a planet if the object reaches a speed greater than the escape velocity and is pointed in the right direction. Intense radiation from the Sun—which is the primary source of thermal, or kinetic, energy in the atmospheres of the terrestrial planets—raises the temperature and thus the speed of atmospheric molecules enough for some to escape.

Let's look more closely at how molecules move within a planetary atmosphere. Imagine a large box that contains air. In thermal equilibrium, each type of molecule in the box, from the lightest to the most massive, will have the same average kinetic energy. Because the kinetic energy of a molecule (or any object) is determined by its mass and its speed, if each type has the same average energy, then the lightest molecules must be moving faster than the more massive ones. This average kinetic energy of the gas molecules is directly proportional to the temperature of the gas. So for a gas at a given temperature, if each type of molecule has the same average energy, then the less massive molecules must be moving faster than the more massive ones. For example, in a mixture of hydrogen and oxygen at room temperature, hydrogen molecules will be rushing around the box at about 2,000 meters per second (m/s) on average, while the much more massive oxygen molecules will be moving at a slower 500 m/s. Remember, though, that these are the average speeds. A few of the molecules will always be moving much faster or slower than average.

Deep within a planet's atmosphere, fast molecules near the ground will almost certainly collide with other molecules before the fast molecules have a chance to escape. Higher regions of the atmosphere contain fewer molecules. Therefore, fast molecules in the upper atmosphere are less likely to collide with other molecules and have a better chance of escaping as long as they are heading more or less upward. At a given temperature, lighter molecules such as hydrogen and helium move faster and are more quickly lost to space than more massive molecules such as nitrogen or carbon dioxide.

Solar heating caused the molecules to move quickly on the young terrestrial planets. In addition, small planets, like the terrestrial planets, have only a weak gravitational grasp. These conditions caused the terrestrial planets to lose the hydrogen and helium they had acquired as a primary atmosphere. This process was likely assisted by collisions with other planetesimals. Because the giant planets were farther from the Sun, they were far more massive and also cooler: stronger gravity and lower temperatures enabled them to retain nearly all of their massive primary atmospheres.

▶II **AstroTour:** Atmospheres: Formation and Escape

The Formation of Secondary Atmospheres

Although their primary atmospheres were lost, some of the terrestrial planets do have an atmosphere today, known as a secondary atmosphere. Where did this secondary atmosphere come from? Accretion, volcanism, and impacts are responsible for the atmospheres of Earth, Venus, and Mars today. During the planetary accretion process, minerals containing water, carbon dioxide, and other volatile matter collected in the planetary interiors. Later, as an interior heated up, these gases were released from the minerals that had held them. Volcanism then brought the gases to the surface, where they accumulated and created a secondary atmosphere, as shown in step 4 of Figure 9.1.

Impacts by comets and asteroids were another important source of gases. Huge numbers of comets formed in the outer parts of the Solar System and were therefore rich in volatiles. As the giant planets of the outer Solar System grew to maturity or migrated their orbits, their gravitational perturbations stirred up the comets and asteroids that orbited relatively nearby. Many of these icy bodies were flung outward by the giant planets to join other existing planetesimals in the Kuiper Belt, 30–50 astronomical units (AU) from the Sun. Other bodies joined the part of the Solar System known as the Oort Cloud, a spherical cloud of icy planetesimals that surrounds the Sun at a distance ranging from the Kuiper Belt to about 50,000 AU from the Sun—nearly one-quarter of the way to the nearest star. Other comets were scattered into the inner parts of the Solar System. Upon impact with the terrestrial planets, these objects brought ices such as water, carbon monoxide, methane, and ammonia. On the terrestrial planets, cometary water mixed with the water that had been released into the atmosphere by volcanism, as shown in step 5 of Figure 9.1. On Earth, and perhaps Mars and Venus as well, most of the water vapor then condensed as rain and flowed into the lower areas to form the earliest oceans.

Sunlight also influenced the composition of secondary atmospheres. Ultraviolet (UV) light from the Sun easily fragments cometary molecules such as ammonia (NH_3) and methane (CH_4). Ammonia, for example, is broken down into hydrogen and nitrogen. When this happens, the lighter hydrogen atoms quickly escape to space, leaving behind the much heavier nitrogen atoms. Pairs of nitrogen atoms then combine to form more massive nitrogen molecules (N_2), and these molecules are even less likely to escape into space. Decomposition of ammonia by sunlight became the primary source of molecular nitrogen in the atmospheres of the terrestrial planets. Molecular nitrogen makes up the bulk of Earth's atmosphere.

Among the terrestrial planets, today only Venus, Earth, and Mars have significant secondary atmospheres. What happened in the case of Mercury and the Moon? Even if these two bodies experienced less volcanism than the other terrestrial planets (see Chapter 8), they would have had the same early bombardment of comet nuclei from the outer Solar System. Some carbon dioxide and water must have accumulated during volcanic eruptions and comet impacts. A secondary atmosphere can be lost through the same processes that cause the loss of a primary atmosphere. Large impacts were less frequent as the Solar System aged, but atmospheric escape continued over the past 4 billion years. In addition, decreases in the magnetic field as Mercury and the Moon cooled might have contributed to atmospheric escape. With a weaker magnetic field, the planet became less protected from the **solar wind**—a constant stream of charged particles from the Sun. The solar wind can accelerate atmospheric particles to escape velocity.

Nebraska Simulation: Gas Retention Simulator

Both the Moon and Mercury have virtually no atmosphere today. Mercury lost nearly its entire secondary atmosphere to space, just as it had previously lost its primary atmosphere. Even molecules as massive as carbon dioxide can escape from a small planet if the temperature is high enough, as it is on Mercury's sunlit side. Furthermore, intense UV radiation from the Sun can break molecules into less massive fragments, which are lost to space even more quickly. Because the distance from the Sun to the Moon is much farther than the distance from the Sun to Mercury, the Moon is much cooler than Mercury, but its mass is so small that molecules easily escaped even at relatively low temperatures. The ability of planets to hold on to their atmospheres is explored further in **Working It Out 9.1**.

CHECK YOUR UNDERSTANDING 9.1

Which are reasons Mercury has so little gas in its atmosphere? (Choose all that apply.) (a) Its mass is small. (b) It has a high temperature. (c) It is close to the Sun. (d) Its escape velocity is low. (e) It has no moons.

9.2 Secondary Atmospheres Evolve

Although Venus, Earth, and Mars most likely started out with atmospheres of similar composition, they ended up being very different from one another. Earth is volcanically active, Venus might still be volcanically active, and Mars has been volcanically active in the recent past. All three planets must have shared the intense cometary showers of the early Solar System. Their similar geological histories suggest that their early secondary atmospheres might also have been quite similar. However, Earth's secondary atmosphere has changed significantly since it formed—the development of life increased the amount of oxygen. Earth's atmosphere is made up primarily of nitrogen and oxygen, with only a trace of carbon dioxide. In contrast, the composition of the atmospheres of Venus and Mars today are nearly identical—mostly carbon dioxide, with much smaller amounts of nitrogen. The atmospheres of these planets differ for two reasons we will explore: planetary mass and the greenhouse effect.

9.1 Working It Out Atmosphere Retention

To estimate a planet's ability to retain its atmosphere, we compare the escape velocity from the planet (which depends on the planet's gravity, determined by the mass and radius) with the average speed of the molecules in a gas (which depends on the temperature of the gas and the mass of the molecules that make up the gas). The escape velocity is defined as

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

and the values of v_{esc}, in kilometers per second (km/s), for the inner planets are given at the bottom of Table 8.1.

We said in Chapter 4 that the temperature, T, of a gas is proportional to the kinetic energy of the particles, $\frac{1}{2}mv^2$. We can rearrange that relationship to solve for v and insert the constants of proportionality to get the average speed of a molecule in a gas:

$$v_{molecule} = \sqrt{\frac{3kT}{m}}$$

where T is the temperature of the gas in kelvins, m is the mass of the molecule in kilograms (kg), and k is the Boltzmann constant. The atomic mass of a molecule is found by adding up the atomic masses of its composite atoms as specified in the periodic table. (Atomic masses of atoms come from the total number of neutrons and protons; the electron weighs little in comparison). Oxygen molecules (O_2), for example, are 16 times as massive as hydrogen molecules (H_2).

If we put in the value of the Boltzmann constant ($k = 1.38 \times 10^{-23}$ joule per kelvin, or J/K) and the mass of the hydrogen atom ($m = 1.67 \times 10^{-27}$ kg), then $v_{molecule}$, in kilometers per second, is given by

$$v_{molecule} = 0.157 \text{ km/s} \times \sqrt{\frac{\text{Temperature of gas}}{\text{Atomic weight of molecule}}}$$

The higher the temperature, the higher the average kinetic energy of the individual molecules, and the faster the average speed of the particles. This difference explains why Earth can hold onto the oxygen in its atmosphere but loses hydrogen to space.

To use our example of hydrogen and oxygen molecules, H_2 has an atomic weight of 2 (1 for each hydrogen atom), and O_2 has an atomic weight of 32 (16 for each oxygen atom, from 8 protons and 8 neutrons). Earth has an average temperature of 288 K. The average speeds of the molecules are thus

$$\text{For } H_2\text{: } v_{molecule} = 0.157\sqrt{\frac{288}{2}} = 1.88 \text{ km/s}$$

$$\text{For } O_2\text{: } v_{molecule} = 0.157\sqrt{\frac{288}{32}} = 0.47 \text{ km/s}$$

Thus, in a gas containing both hydrogen and oxygen molecules, the average hydrogen molecule will be moving 4 times faster than the average oxygen molecule. At any given temperature, the lighter molecules will be moving faster. Not all molecules in a gas are moving at the average speed: some move faster and some slower (**Figure 9.2**). The general rule is that over the age of the Solar System, a planet can keep its atmosphere if, for that type of gas molecule:

$$v_{molecule} \leq \frac{1}{6} v_{esc}$$

The escape velocity from Earth is 11.2 km/s, and one-sixth of this is 1.87 km/s. These numbers explain why Earth has been able to keep its O_2 but not its H_2. A similar analysis shows that on the Moon, with its lower v_{esc} value, both the H_2 and the O_2 molecules escape. On Jupiter, with its much colder temperatures and higher v_{esc} value, both the H_2 and the O_2 molecules are retained.

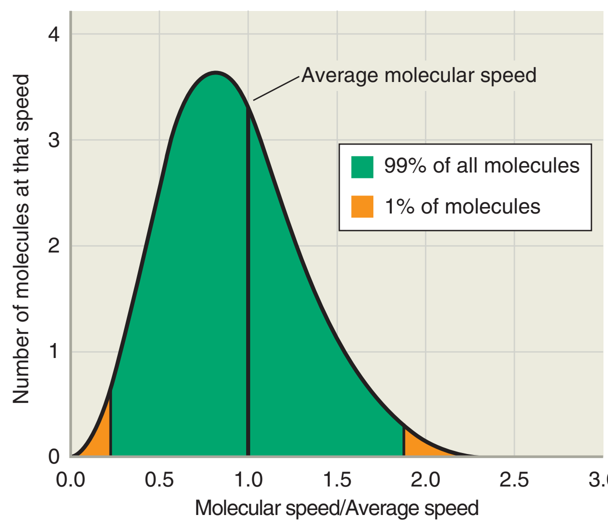


Figure 9.2 This plot shows the distribution of the speeds of molecules in a gas. The shape of the curve and the exact numbers will depend on the temperature of the gas and the masses of the molecules. In all cases, some of the speedier molecules may be able to escape if they are faster than the escape velocity.

TABLE 9.1 Atmospheres of the Terrestrial Planets

Physical Properties and Composition

	PLANET		
	Venus	Earth	Mars
Surface pressure (bars)	92	1.0	0.006
Atmospheric mass (kg)	4.8×10^{20}	5.1×10^{18}	2.5×10^{16}
Surface temperature (K)	740	288	210
Carbon dioxide (%)	96.5	0.039	95.3
Nitrogen (%)	3.5	78.1	2.7
Oxygen (%)	0.00	20.9	0.13
Water (%)	0.002	0.1 to 3	0.02
Argon (%)	0.007	0.93	1.6
Sulfur dioxide (%)	0.015	0.02	0.00

The Effect of Planetary Mass on a Planet's Atmosphere

Table 9.1 shows that the atmospheres of Venus and Mars today are nearly identical in composition. They are both composed mostly of carbon dioxide, with much smaller amounts of nitrogen. Carbon dioxide and water vapor came from volcanic gases; and nitrogen came from decomposed cometary ammonia. However, the total *amount* of atmosphere is very different among the three planets. The atmospheric pressure on the surface of Venus is nearly 100 times greater than Earth's. By contrast, the average surface pressure on Mars is less than a hundredth that on Earth. Venus is nearly 8 times as massive as Mars, so we assume it probably had about 8 times as much carbon within its interior to produce carbon dioxide, the principal secondary-atmosphere component of both planets. Even allowing for the differences in planetary mass, however, Venus today has greater than 2,500 times more atmospheric mass than Mars.

The large difference in atmospheric mass comes from the relative strengths of each planet's surface gravity, which involves both the mass and the radius of a planet. Venus has the gravitational pull necessary to hang on to its atmosphere; Mars has less gravitational attraction to keep its atmosphere (see Working It Out 9.1). Furthermore, when a planet such as Mars began to lose its atmosphere to space, the process began to take on a *runaway* behavior. With a thinner atmosphere, there were fewer slow molecules to keep fast molecules from escaping, and the rate of escape increased. This process in turn led to even less atmosphere and still greater escape rates.

Mars might also have lost atmosphere in a giant impact. In addition, scientists debate how much atmospheric loss arises from the effects of the solar wind on planetary atmospheres, especially in the absence of a planetary magnetic field. All three planets are currently losing some atmosphere to space, even though Earth has a magnetic field and Venus and Mars do not. The extent to which the lack of a magnetic field on Mars played a role in its atmospheric loss is being studied by NASA's *Mars Atmosphere and Volatile EvolutioN* (MAVEN) mission, which arrived at Mars in September 2014.

The Atmospheric Greenhouse Effect

Differences in the present-day masses of the atmospheres of Venus, Earth, and Mars have a large effect on their surface temperatures. Recall from Chapter 5 that the temperature of a planet is determined by a balance between the amount of sunlight being absorbed and the amount of energy being radiated back into space. When we calculated the temperature of a planet by finding the equilibrium between the amount of energy it receives and the amount of energy it radiates, we found that this calculation gives a good result for planets without atmospheres. But Earth is somewhat warmer than expected, and Venus is very much hotter than this simple model predicted. When the predictions of a model fail, the implication is that something was left out of the model. In this case, that something was the *atmospheric greenhouse effect*, which traps solar radiation.

The atmospheric greenhouse effect in planetary atmospheres and the conventional **greenhouse effect** operate in different ways, although the end results are much the same. Planetary atmospheres and the interiors of greenhouses are both heated by trapping the Sun's energy, but here the similarities end. The conventional greenhouse effect is the rise in temperature in a car on a sunny day when you leave the windows closed, or what allows plants to grow in the winter in a greenhouse. Sunlight pours through the glass, heating the interior and raising the internal air temperature. With the windows closed, hot air is trapped, and temperatures can climb as high as 80°C (about 180°F). Heating by solar radiation is most efficient when an enclosure is transparent, which is why the walls and roofs of real greenhouses, which allow plants to grow in the winter, are made mostly of glass.

The atmospheric greenhouse effect is illustrated in **Figure 9.3**. Atmospheric gases freely transmit visible light, allowing the Sun to warm the planet's surface. The warmed surface radiates the energy in the infrared region of the spectrum. Some of the atmospheric gases strongly absorb this infrared radiation and convert it to thermal energy, which is released in random directions. Some of the thermal energy continues into space, but much of it goes back to the ground, which causes a planet's surface temperature to rise. As a result of this radiation, the planet's surface receives thermal energy from both the Sun and the atmosphere. Gases that transmit visible radiation but absorb infrared radiation are known as **greenhouse gases**. Examples of atmospheric greenhouse gases include water vapor, carbon dioxide, methane, and nitrous oxide, as well as industrial chemicals such as halogens. The presence of greenhouse gases in a planet's atmosphere will cause its surface temperature to rise.

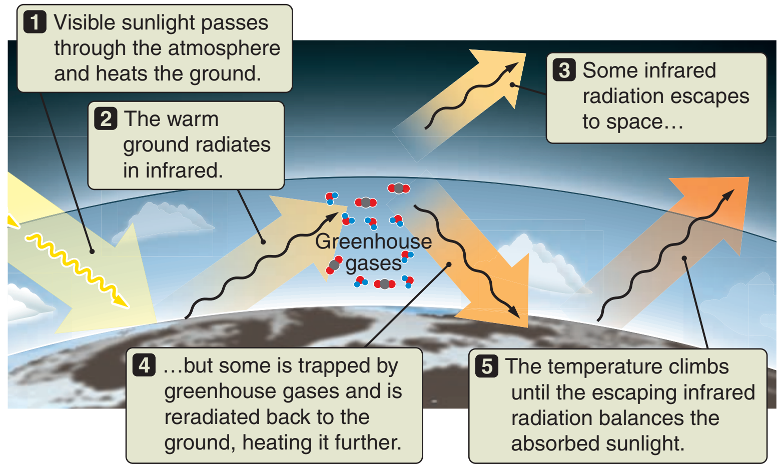


Figure 9.3 In the atmospheric greenhouse effect, greenhouse gases such as water vapor and carbon dioxide trap infrared radiation, increasing a planet's temperature.

This rise in temperature continues until the surface becomes sufficiently hot—and therefore radiates enough energy—that the fraction of infrared radiation leaking out through the atmosphere balances the absorbed sunlight, and equilibrium is reached. Convection also helps maintain equilibrium by transporting thermal energy to the top of the atmosphere, where it can be more easily radiated to space. In short, the temperature rises until an equilibrium between absorbed sunlight and thermal energy radiated away by the planet is reached. If the amount of greenhouse gases increases in the atmosphere, the trapping effect increases, and the temperature at which energy input and output balances also increases. Even though the mechanisms are somewhat different, the conventional greenhouse effect and the atmospheric greenhouse effect produce the same net result: the local environment is heated by trapped solar radiation.

Astronomy in Action: Changing Equilibrium

AstroTour: Greenhouse Effect

Similarities and Differences among the Terrestrial Planets

Let's look more closely at how the atmospheric greenhouse effect operates on Mars, Earth, and Venus. What really matters is the actual number of greenhouse molecules in a planet's atmosphere, not the fraction they represent. For example, even though the atmosphere of Mars is composed almost entirely of carbon dioxide (see Table 9.1)—an effective greenhouse molecule—the atmosphere is very thin and contains relatively few greenhouse molecules compared to the atmospheres of Venus or Earth. As a result, the atmospheric greenhouse effect is relatively weak on Mars and raises the average surface temperature by only about 5 K (9°F). At the other extreme, Venus's massive atmosphere of carbon dioxide and sulfur compounds raises its average surface temperature by more than 400 K, to about 740 K (467°C, or 870°F). At such high temperatures, any remaining water and most carbon dioxide locked up in surface rocks are driven into the atmosphere, further enhancing the atmospheric greenhouse effect.

The atmospheric greenhouse effect on Earth is not as severe as it is on Venus—the average global temperature near Earth's surface is about 288 K (15°C, or 59°F). Temperatures on Earth's surface are about 35 K (63°F) warmer than they would be in the absence of an atmospheric greenhouse effect, mainly because of water vapor and carbon dioxide. Yet this comparatively small difference has been crucial in shaping the Earth we know. Without this greenhouse effect, Earth's average global temperature would be −18°C (0°F), well below the freezing point of water, leaving us with a world of frozen oceans and ice-covered continents.

How has the atmospheric greenhouse effect made the composition of Earth's atmosphere so different from the high-carbon-dioxide atmospheres of Venus and Mars? The answer lies in Earth's location in the Solar System. Earth and Venus have about the same mass, but Venus orbits the Sun somewhat closer than Earth, at 0.7 AU. Volcanism and cometary impacts produced large amounts of carbon dioxide and water vapor to form early secondary atmospheres on both planets. Most of Earth's water quickly rained out of the atmosphere to fill vast ocean basins. But because Venus was closer to the Sun, its surface temperatures were higher than those of Earth. As the Sun itself aged and brightened, Venus got warmer, and most of the rainwater on Venus immediately reevaporated, much as water does in Earth's desert regions. Venus was left with a surface that contained very little liquid water and an atmosphere filled with water vapor. The water vapor caused even higher temperatures, which led to the release of more carbon dioxide from the rocks to the atmosphere. The continuing buildup of both water vapor and carbon dioxide in the atmosphere of Venus led to a runaway atmospheric greenhouse effect that drove up the surface temperature of the planet even more. Ultimately, the surface of Venus became so hot that no liquid water could exist on it.

This early difference between a watery Earth and an arid Venus forever changed the ways that their atmospheres and surfaces evolved. On Earth, water erosion caused by rain and rivers continually exposed fresh minerals, which then reacted chemically with atmospheric carbon dioxide to form solid carbonates. This reaction removed some of the atmospheric carbon dioxide, burying it within Earth's crust as a component of a rock called limestone. Later, the development of life in Earth's oceans accelerated the removal of atmospheric carbon dioxide. Tiny sea creatures built their protective shells of carbonates, and as they died they built up massive beds of limestone on the ocean floors. Water erosion and the chemistry of life tied up all but a trace of Earth's total inventory of carbon dioxide in limestone beds. Earth's particular location in the Solar System seems to have spared it from the runaway atmospheric greenhouse effect. If all the carbon dioxide now in limestone beds had not been locked up by these reactions, Earth's atmosphere would be composed of about 98 percent carbon dioxide, similar to that of Venus or Mars. The atmospheric greenhouse effect would be much stronger, and Earth's temperature would be much higher.

The details of the differences in the amount of water on Venus, Earth, and Mars are not well understood. Geological evidence indicates that liquid water was once plentiful on the surface of Mars. Several of the spacecraft orbiting Mars have found evidence that significant amounts of water still exist on Mars in the form of subsurface ice—far more than the atmospheric abundance indicated in Table 9.1. Earth's liquid and solid water supply is even greater, about 0.02 percent of its total mass. More than 97 percent of Earth's water is in the oceans, which have an average depth of about 4 km. Earth today has 100,000 times more water than Venus.

Some scientists think that Venus once had as much water as Earth—as liquid oceans or as more water vapor than is measured today. As the Sun aged and became brighter, and the planets received more solar energy, water molecules high in the atmosphere of Venus were broken apart into hydrogen and oxygen by solar UV radiation. The low-mass hydrogen atoms were quickly lost to space. Oxygen escaped more slowly, so some eventually migrated downward to the planet's surface, where it was removed from the atmosphere by bonding with minerals on the surface. The *Venus Express* spacecraft has measured hydrogen and some oxygen escaping from the upper levels of Venus's atmosphere in support of this theory.

CHECK YOUR UNDERSTANDING 9.2

The main greenhouse gases in the atmospheres of the terrestrial planets are: (a) oxygen and nitrogen; (b) methane and ammonia; (c) carbon dioxide and water vapor; (d) hydrogen and helium.

9.3 Earth's Atmosphere Has Detailed Structure

Now that we have considered some of the overall processes that have influenced the evolution of the terrestrial planet atmospheres, we will look in depth at each of them. We begin with the composition and structure of Earth's atmosphere, not only because we know it best, but also because it will help us better understand the atmospheres of other worlds.

Life and the Composition of Earth's Atmosphere

Two principal gases make up Earth's atmosphere: about four-fifths is nitrogen (N_2) and one-fifth is oxygen (O_2) (see Table 9.1). There are also many important minor constituents, such as water vapor and carbon dioxide (CO_2), the amounts of which vary depending on global location and season. The composition of Earth's atmosphere is relatively uniform on a global scale, but temperatures can vary widely. Atmospheric temperatures near Earth's surface can range from as high as 60°C (140°F) in the deserts to as low as −90°C (−130°F) in the polar regions. The mean global temperature is about 15°C.

Oxygen Table 9.1 shows that Earth's atmosphere contains abundant amounts of oxygen (O_2) while the atmospheres of other planets do not. Oxygen is a highly reactive gas: it chemically combines with, or oxidizes, almost any material it touches. The rust (iron oxide) that forms on steel is an example. The reddish surface of Mars is coated with oxidized iron-bearing minerals, and this is one reason the martian atmosphere is almost completely free of oxygen. A planet with significant amounts of oxygen in its atmosphere requires a means of replacing oxygen lost through oxidation. On Earth, plants perform this role.

The oxygen concentration in Earth's atmosphere has changed over the history of the planet, as shown in **Figure 9.4**. When Earth's secondary atmosphere first appeared about 4 billion years ago, it had very little oxygen because O_2 is not found in volcanic gases or comets. Studies of ancient sediments show that about 2.8 billion years ago, an ancestral form of cyanobacteria—single-celled organisms that contain chlorophyll, which enables them to obtain energy from

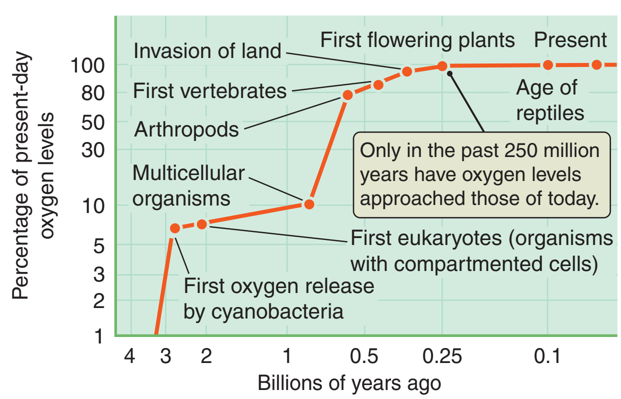


Figure 9.4 The amount of oxygen in Earth's atmosphere has built up over time as a result of plant life on the planet.

sunlight—began releasing oxygen into Earth's atmosphere as a waste product of their metabolism. At first, this biologically generated oxygen combined with exposed metals and minerals in surface rocks and soils and so was removed from the atmosphere as quickly as it formed. Ultimately, the explosive growth of cyanobacteria and then plant life accelerated the production of oxygen, building up atmospheric concentrations that approached today's levels only about 250 million years ago.

All true plants, from tiny green algae to giant redwoods, use the energy of sunlight to build carbon compounds out of carbon dioxide and produce oxygen as a metabolic waste product in a process called photosynthesis. In this way, emerging life dramatically changed the very composition and appearance of Earth's surface—the first of many such widespread modifications imposed on Earth by living organisms. Earth's atmospheric oxygen content is held in a delicate balance primarily by plants. If plant life on the planet were to disappear, so, too, would nearly all of Earth's atmospheric oxygen, and therefore all animal life—including us.

Ozone Ozone (O_3) is another constituent in Earth's atmosphere. Ozone is formed when UV light from the Sun breaks molecular oxygen (O_2) into its individual atoms. These oxygen atoms can then recombine with other oxygen molecules to form ozone (the net reaction is $O_2 + O \rightarrow O_3$). Most of Earth's natural ozone is concentrated in the upper atmosphere at altitudes between 20 and 50 km. There it acts as a very strong absorber of UV sunlight. Without the ozone layer, this radiation would reach all the way to Earth's surface, where it would be lethal to nearly all forms of life. However, ozone in the lower atmosphere occurs primarily as a by-product of power plants, factories, and automobiles. This human-made pollutant is a health hazard, which raises the risk of respiratory and heart problems.

In the mid-1980s, scientists began noticing that the measured amount of ozone in Earth's upper atmosphere had been decreasing seasonally since the 1970s, primarily over the polar latitudes during springtime in both the Northern and Southern hemispheres. They called these depleted regions "ozone holes," although they are more like depressions than real holes in the ozone layer. Ozone depletion is caused by a seasonal buildup of atmospheric halogens—mostly chlorine, fluorine, and bromine—such as those found in industrial refrigerants, especially chlorofluorocarbons (CFCs). Halogens diffuse upward into the stratosphere, where they destroy ozone without themselves being consumed. Such agents are called catalysts—materials that participate in and accelerate chemical reactions but are not themselves modified in the process. Because they are not modified or used up, halogens may remain in Earth's upper atmosphere for decades or even centuries. Even though more of the chemicals originated in the north, the depletions are greater in the Southern Hemisphere because the colder temperatures in the southern polar regions produce a type of cloud that provides a surface on which the ozone-destroying chemical reactions can take place (**Figure 9.5**).

Figure 9.5 Polar stratospheric clouds form in the polar springtime and provide the surface upon which ozone destruction takes place.

Scientists predicted that the continuing removal of ozone from the high atmosphere could cause trouble for terrestrial life as more and more UV radiation reached the ground. Measured increases in the levels of UV radiation appear to be related to increases in skin cancer in humans, and the mutating effects it may have on other life-forms are not yet understood. By the late 1980s, international agreements on phasing out the production of CFCs and other ozone-depleting chemicals were signed, and world consumption has steadily declined. The largest

Southern Hemisphere ozone hole occurred over Antarctica in 2006. The largest Arctic hole to date occurred in 2011, but this may have been due to unusually cold temperatures. Full recovery to 1980 levels is not expected until the late 21st century at the earliest, but scientists are hopeful that the international agreements have solved the problem.

Carbon Dioxide Carbon dioxide (CO_2) is another variable component of Earth's atmosphere. A complex pattern of carbon dioxide *sources* (places where it originates) and *sinks* (places where it goes) determines how much carbon dioxide will be present in the atmosphere at any one time. Plants consume carbon dioxide in great quantities as part of their metabolic process. Coral reefs are colonies of tiny ocean organisms that build their protective shells with carbonates produced from dissolved carbon dioxide. Fires, decaying vegetation, and human burning of fossil fuels all release carbon dioxide back into the atmosphere. This balance between carbon dioxide sources and sinks changes with time. As we'll describe later, the amount of carbon dioxide in the atmosphere has varied historically but has been increasing more rapidly for almost two centuries—since the industrial revolution. This recent increase in carbon dioxide in turn has had a direct effect on global temperature because carbon dioxide is a powerful greenhouse gas.

Water Vapor Water vapor (H_2O) in Earth's atmosphere also affects daily life and is a powerful greenhouse gas. Over the range of temperatures on Earth, the amount of water in the atmosphere varies from time to time and from place to place. In warm, moist climates, water vapor may account for as much as 3 percent of the total atmospheric composition. In cold, arid climates, it may be less than 0.1 percent. The continual process of condensation and evaporation of water involves the exchange of thermal and other forms of energy, making water vapor a major contributor to Earth's weather.

The Layers of Earth's Atmosphere

Earth's atmosphere is a blanket of gas that is several hundred kilometers thick. It has a total mass of approximately 5×10^{18} kg, which is less than one-millionth of Earth's total mass. The weight of Earth's atmosphere creates a force of approximately 100,000 newtons (N) acting on each square meter of the planet's surface, equivalent to about 14.7 pounds pressing on every square inch. This amount of pressure is called a **bar** (from the Greek *baros*, meaning "weight" or "heavy"). Earth's average atmospheric pressure at sea level is approximately 1 bar. A millibar (mb) is one-thousandth of 1 bar and is more commonly used in meteorology and in weather reports. One bar of pressure is equivalent to what you would experience underwater at a depth of 10 meters, or 33 feet. We are largely unaware of Earth's atmospheric pressure because the same pressure exists both inside and outside our bodies, so the force pushing out precisely balances the force pushing in.

Recall from Chapter 8 that the pressure at any point within a planet's interior must be great enough to balance the weight of the overlying layers. The same principle holds true in a planetary atmosphere. The atmospheric pressure on a planet's surface must be great enough to support the weight of the overlying atmosphere. Different forms of matter provide the pressure within a planet's interior and in its atmosphere. In the interior of a solid planet, solid materials exert pressure as they resist being compressed. In a planetary atmosphere, the motions of gas molecules exert sufficient pressure to support the atmosphere.

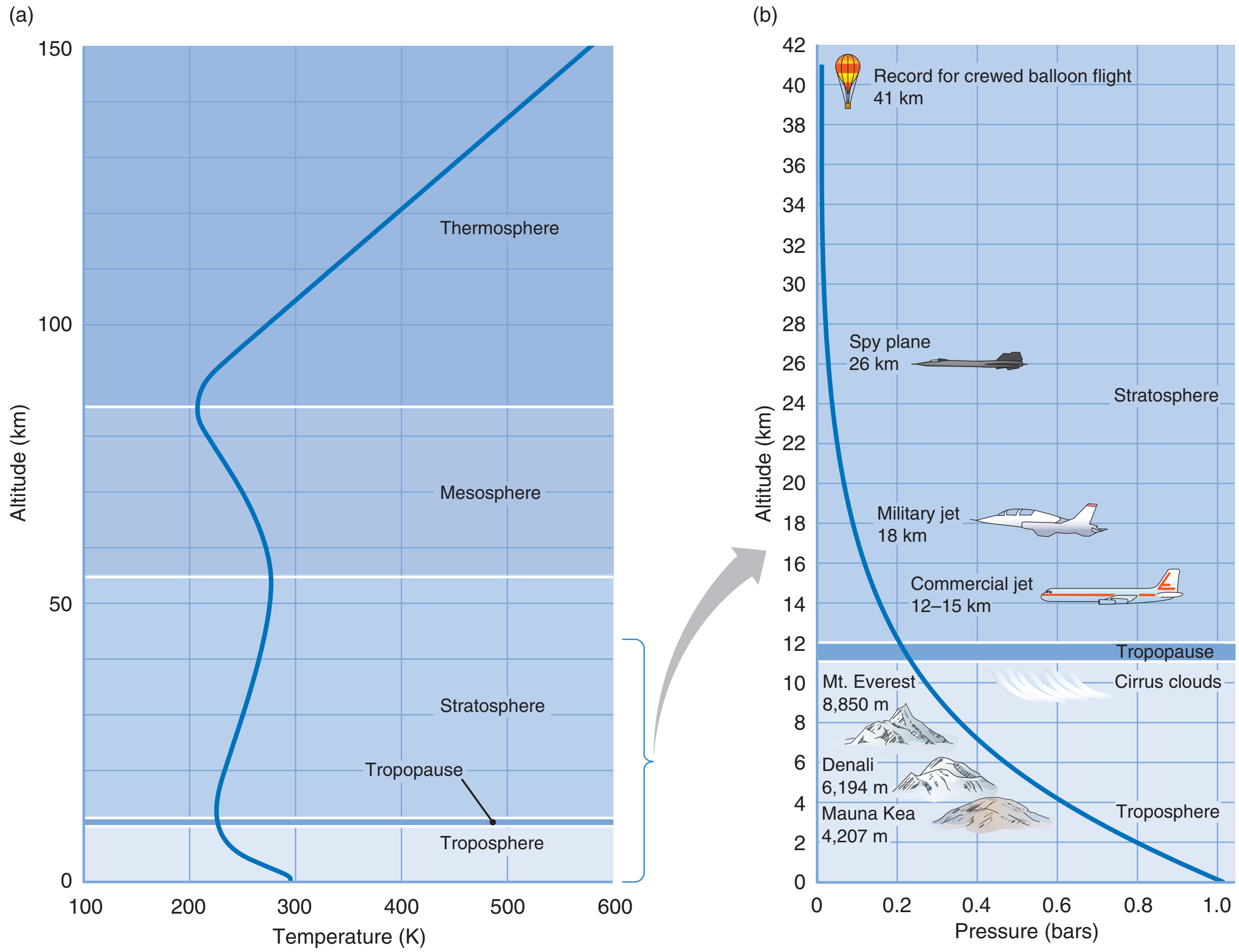


Figure 9.6 These graphs show (a) temperature and (b) pressure plotted for Earth's atmospheric layers as a function of height. Most human activities are confined to the bottom layers of Earth's atmosphere.

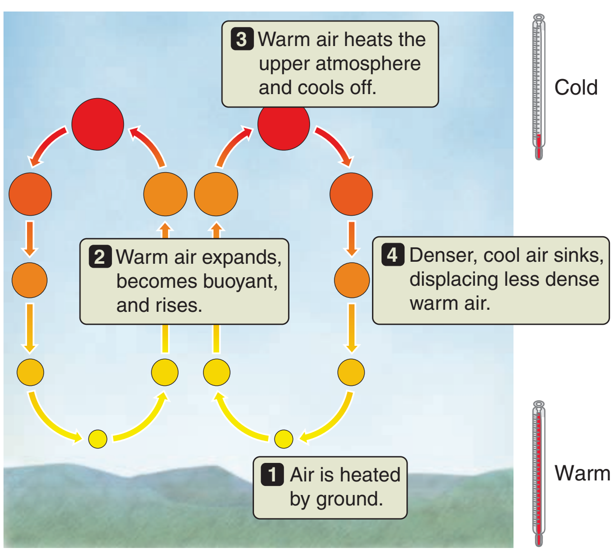


Figure 9.7 Atmospheric convection carries thermal energy from the Sun-heated surface of Earth upward through the atmosphere.

The atmosphere of Earth is made up of several distinct layers, shown in **Figure 9.6**. These layers are distinguished by the changes in temperature and pressure through the atmosphere. The lowest layer, the one in which humans live and breathe, is called the **troposphere**. It contains 90 percent of Earth's atmospheric mass and is the source of all our weather. At Earth's surface, usually called sea level, the troposphere has an average temperature of 15°C (288 K). Within the troposphere, atmospheric pressure, density, and temperature all decrease as altitude increases. For example, at an altitude of 5.5 km (18,000 feet, which is a few thousand feet below the summit of Denali in Alaska), the atmospheric pressure and density are only 50 percent of their sea-level values, and the average temperature has dropped to −20°C (253 K). Still higher, at an altitude of 12 km, where commercial jets cruise, the temperature is −60°C (213 K), and the density and pressure are less than one-fifth what they are at sea level.

The atmosphere is warmer near Earth's surface because the air is closer to the sunlight-heated ground, which warms the air by infrared radiation. The atmosphere is cooler at very high altitudes because there the atmosphere freely radiates its thermal energy into space. In fact, it would get colder with increasing altitude even faster if not for convection. **Figure 9.7** illustrates how convection carries thermal energy upward through Earth's atmosphere. At a given pressure, cold air is denser than warm air. So when cold air encounters warm air, the denser cold air slips under the less dense warm air, pushing the warm air upward. This convection sets up air circulation between the lower and upper levels of the atmosphere and tends to diminish the temperature extremes caused by heating at the bottom and cooling at the top.

Convection also affects the vertical distribution of atmospheric water vapor. The ability of air to hold water in the form of vapor depends very strongly on the air temperature: the warmer the air, the more water vapor it can hold. The amount of water vapor in the air relative to what the air could hold at a particular temperature is called the relative humidity. Air that is saturated with water vapor has a relative humidity of 100 percent. As air is convected upward, it cools, limiting its capacity to hold water vapor. When the air temperature decreases to the point at which the air can no longer hold all its water vapor, water begins to condense to tiny droplets or ice crystals. In large numbers these become visible as clouds. When these droplets combine to form large drops, convective updrafts can no longer support them, and they fall as rain or snow. For this reason, most of the water vapor in Earth's atmosphere stays within 2 km of the surface. At an altitude of 4 km, the Mauna Kea Observatories (see the Chapter 6 opening figure) are higher than approximately one-third of Earth's atmosphere, but they lie above nine-tenths of the atmospheric water vapor. This is important for astronomers who observe in the infrared region of the spectrum, because water vapor strongly absorbs infrared light. The water in the atmosphere is more often visible as condensed water in the form of clouds and ice.

Returning to Figure 9.6, you can see that above the troposphere and extending upward to an altitude of 50 km above sea level is the **stratosphere**. The boundary between the troposphere and stratosphere is called the **tropopause**, the height at which temperature no longer decreases with increasing altitude. This change in atmospheric behavior is caused by heating from absorbed sunlight within the atmospheric layers that lie above the tropopause. The tropopause varies between 10 and 15 km above sea level, depending on latitude, and is highest at the equator. In this region, little convection takes place, because the temperature-altitude relationship reverses at the tropopause, and the temperature begins to increase with altitude. This temperature reversal is caused by the ozone layer, which warms the stratosphere by absorbing UV radiation from the Sun.

The region above the stratosphere is the **mesosphere**, which extends from an altitude of 50 km to about 90 km. In the mesosphere there is no ozone to absorb sunlight, so temperatures once again decrease with altitude. The base of the stratosphere and the upper boundary of the mesosphere are two of the coldest levels in Earth's atmosphere. Higher in Earth's atmosphere, interactions with space begin to be important. The solar wind is a flow of high-energy particles that stream continually from the Sun. At altitudes above 90 km, solar UV radiation and high-energy particles from the solar wind strip electrons from, or **ionize**, atmospheric molecules, causing the temperature once again to increase with altitude. This region, called the **thermosphere**, is the hottest part of the atmosphere. The temperature can reach 1000 K near the top of the thermosphere, at an altitude of 600 km.

The atoms and molecules in the gases within and beyond the thermosphere are ionized by UV photons and high-energy particles from the Sun. This region of ionized atmosphere is called the **ionosphere**, and it overlaps the thermosphere but also extends farther into space. The ionosphere reflects certain frequencies of radio waves back to the ground. For example, the frequencies used by AM radio bounce back and forth between the ionosphere and the surface, enabling radio receivers to pick up stations at great distances from the transmitters. Amateur radio operators are able to communicate with each other around the world by bouncing their signals off the ionosphere.

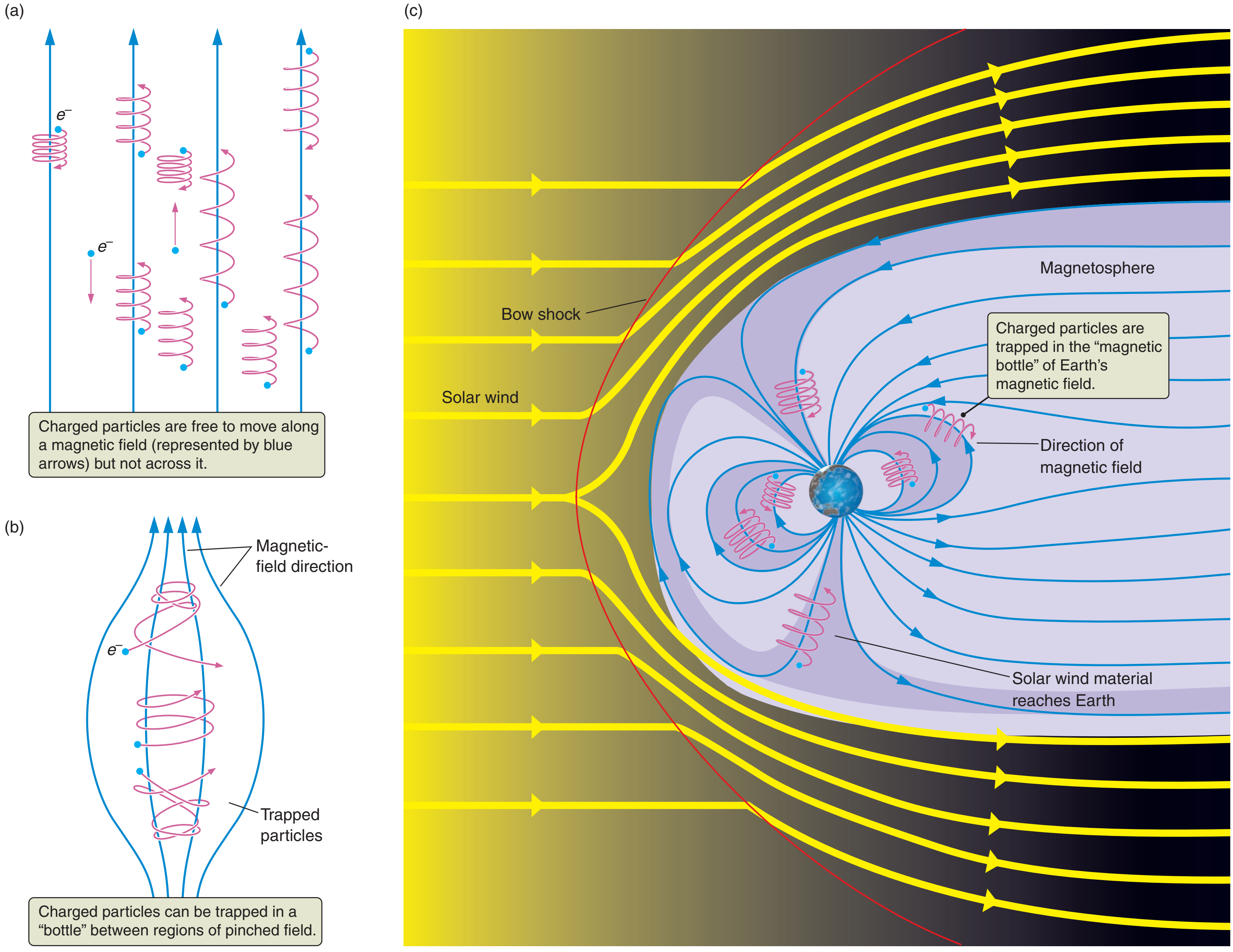
CHECK YOUR UNDERSTANDING 9.3

Rank the layers of the atmosphere in order of height above the surface: (a) stratosphere; (b) thermosphere; (c) troposphere; (d) ionosphere; (e) mesosphere.

Earth's Magnetosphere

Even farther out than the ionosphere is Earth's magnetosphere, which surrounds Earth and its atmosphere. The magnetosphere is a large region filled with electrons, protons, and other charged particles from the Sun that have been captured by the planet's magnetic field. This region has a radius approximately 10 times that of Earth and fills a volume more than 1,000 times as large as the volume of the planet itself. Magnetic fields only affect moving charges. Charged particles are free to move along the direction of the magnetic field but cannot cross magnetic

Figure 9.8 (a) Charged particles, in this case electrons, spiral in a uniform magnetic field. (b) When the field is pinched, charged particles can be trapped in a "magnetic bottle." (c) Earth's magnetic field acts like a bundle of magnetic bottles, trapping particles in Earth's magnetosphere. In all these images, the radius of the helix that the charged particle follows is greatly exaggerated.



field lines. If they try to move across the direction of the field, they experience a force that is perpendicular both to the attempted motion of the particles across the field and to the direction of the magnetic field, as illustrated in **Figure 9.8a**. This force causes them to spiral around the direction of the magnetic field. Charged particles act like beads on a string, free to slide along the direction of the magnetic field but unable to cross it.

If the magnetic field is pinched together at some point, particles moving into the pinch will feel a magnetic force that reflects them back along the direction they came from, creating a sort of "magnetic bottle" that contains the charged particles. If charged particles are located in a region where the field is pinched on both ends, as shown in Figure 9.8b, then they may bounce back and forth many times. Earth's magnetic field is pinched together at the two magnetic poles and spreads out around the planet.

Earth and its magnetic field are immersed in the solar wind. When the charged particles of the solar wind first encounter Earth's magnetic field, the smooth flow is interrupted and their speed suddenly drops—they are diverted by Earth's magnetic field like a river is diverted around a boulder. As they flow past, some of these charged particles become trapped by Earth's magnetic field, where they bounce back and forth between Earth's magnetic poles as illustrated in Figure 9.8c.

An understanding of Earth's magnetosphere is of great practical importance. Regions in the magnetosphere that contain especially strong concentrations of energetic charged particles, called **radiation belts**, can be very damaging to both electronic equipment and astronauts. Yet it is not necessary to leave the surface of the planet to witness the dramatic effects of the magnetosphere. Disturbances in Earth's magnetosphere caused by changes in the solar wind can lead to changes in Earth's magnetic field that are large enough to trip power grids, cause blackouts, and disrupt communications.

Earth's magnetic field also funnels energetic charged particles down into the ionosphere in two rings located around the magnetic poles. These charged particles (mostly electrons) collide with atoms and molecules such as oxygen, nitrogen, and hydrogen in the upper atmosphere, causing them to glow like the gas in a neon sign. Interactions with different atoms cause different colors. These glowing rings, called **auroras**, can be seen from space (**Figure 9.9a**). When viewed from the ground (Figure 9.9b), auroras appear as eerie, shifting curtains of multicolored light. People living far from the equator are often treated to spectacular displays of the aurora borealis ("northern lights") in the Northern Hemisphere or the aurora australis in the Southern Hemisphere. When the solar wind is particularly strong, auroras can be seen at lower latitudes far from their usual zone. Auroras have also been seen on Venus, Mars, all of the giant planets, and some moons.

The general structure we have described here is not limited to Earth's atmosphere. The major vertical structural components—troposphere, tropopause, stratosphere, and ionosphere—also exist in the atmospheres of Venus and Mars, as well as in the atmospheres of Titan and the giant planets. The magnetospheres of the giant planets are among the largest structures in the Solar System.

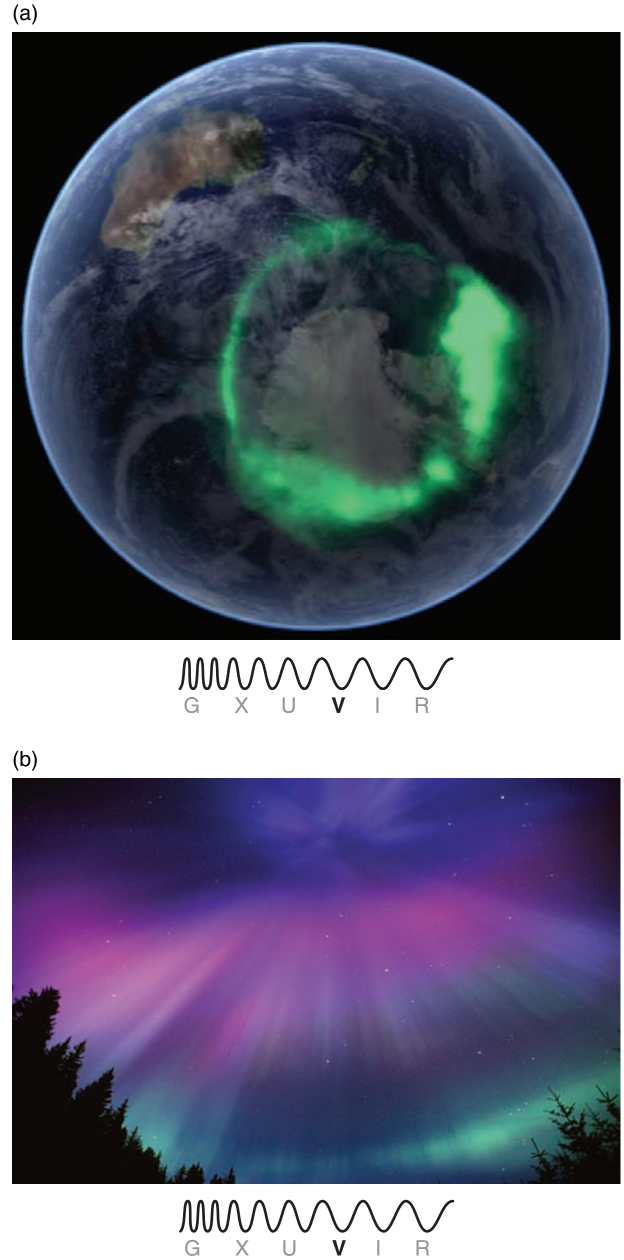


Figure 9.9 Auroras result when particles trapped in Earth's magnetosphere collide with molecules in the upper atmosphere. (a) An auroral ring around Earth's south magnetic pole, as seen from space. (b) Aurora borealis—the "northern lights"—viewed from the ground in Alaska.

Astronomy in Action: Charged Particles and Magnetic Fields

Wind and Weather

Weather is the local day-to-day state of the atmosphere. Local weather is caused by winds and convection. Recall from Chapter 5 that heating a gas increases its

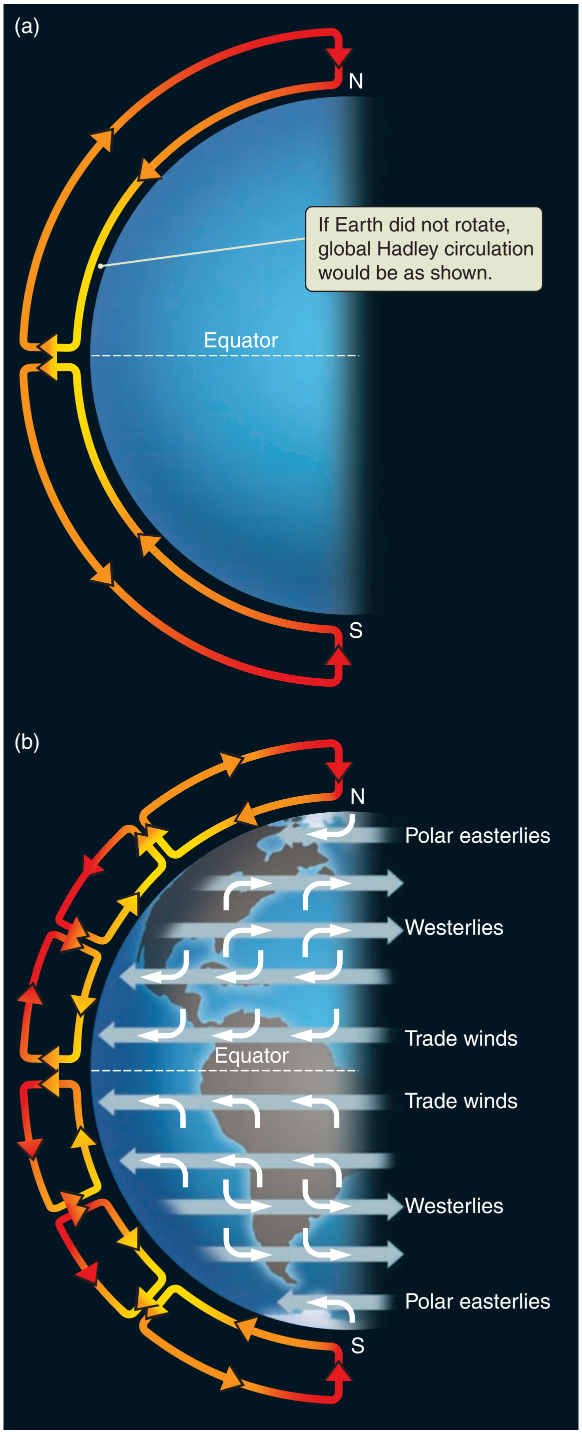


Figure 9.10 (a) Hadley circulation covers an entire hemisphere. (b) On Earth, Hadley circulation breaks up into smaller circulation cells due to the Coriolis effect which diverts the north–south flow into east–west zonal flow.

pressure, which causes it to push into its surroundings. These pressure differences cause winds. Winds are the natural movement of air, both locally and on a global scale, in response to variations in temperature from place to place. The air is usually warmer in the daytime than at night, warmer in the summer than in winter, and warmer at the equator than in the polar regions. Large bodies of water, such as oceans, also affect atmospheric temperatures. The strength of the winds is governed by the size of the temperature difference from place to place.

Recall from Chapter 2 that the effect of Earth's rotation on winds—and on the motion of any object—is called the Coriolis effect (see Figure 2.11). As air in Earth's equatorial regions is heated by the warm surface, convection causes it to rise. The warmed surface air displaces the air above it, which then has nowhere to go but toward the poles. This air becomes cooler and denser as it moves toward the poles, and so it sinks back down through the atmosphere. It displaces the surface polar air, which is forced back toward the equator, completing the circulation. As a result, the equatorial regions remain cooler and the polar regions remain warmer than they otherwise would be. Air moves between the equator and poles of a planet in a pattern known as **Hadley circulation**, which is shown in **Figure 9.10a**.

On Earth, other factors break up the planetwide flow into a series of smaller Hadley cells. Most planets and their atmospheres rotate rapidly, and the Coriolis effect strongly interferes with Hadley circulation by redirecting the horizontal flow, shown in Figure 9.10b. The Coriolis effect creates winds that blow predominantly in an east–west direction and are often confined to relatively narrow bands of latitude. Meteorologists call these **zonal winds**. More rapidly rotating planets have a stronger Coriolis effect and stronger zonal winds. Between the equator and the poles in most planetary atmospheres, the zonal winds alternate between winds blowing from the east toward the west (easterlies) and winds blowing from the west toward the east (westerlies).

In Earth's atmosphere, several bands of alternating zonal winds lie between the equator and each hemisphere's pole. This zonal pattern is called Earth's **global circulation** because its extent is planetwide. The best-known zonal currents are the subtropical trade winds—more or less easterly winds that once carried sailing ships from Europe westward to the Americas—and the midlatitude prevailing westerlies that carried them home again.

Embedded within Earth's global circulation pattern are systems of winds associated with large high-pressure and low-pressure regions. A combination of a low-pressure region and the Coriolis effect produces a circulating pattern called **cyclonic motion** (**Figure 9.11**). Cyclonic motion is associated with stormy weather, including hurricanes. Similarly, high-pressure systems are localized regions where the air pressure is higher than average. We think of these regions of greater-than-average air concentration as "mountains" of air. Owing to the Coriolis effect, high-pressure regions rotate in a direction opposite to that of low-pressure regions. These high-pressure circulating systems experience **anticyclonic motion** and are generally associated with fair weather.

Earth has a water cycle: water from the oceans enters the air and later returns to the oceans. When liquid water in Earth's oceans, lakes, and rivers absorbs enough thermal energy from sunlight, it turns to water vapor. The water vapor carries this thermal energy as it circulates throughout the atmosphere, releasing the energy to its surroundings when the water vapor recondenses. This process powers rainstorms, thunderstorms, hurricanes, and other dramatic weather. For example, a thunderstorm begins when moist air close to the ground is warmed by the Sun and is convected upward, cooling as it gains altitude, until it condenses as rain. With strong solar heating and an adequate supply of moist air, this self-feeding process can grow within minutes to become a violent thunderstorm. Water falls as rain, eventually returning to lakes and oceans, wearing down mountains and eroding the soil as it flows.

Coriolis forces acting on air rushing into regions of low atmospheric pressure create huge circulating systems that result in hurricanes. The conditions must be just right: warm tropical seawater, light winds, and a region of low pressure in which air spirals inward. Warm seawater evaporates; then the moisture-laden air rises and releases energy as it condenses at cooler levels, similar to the process that leads to thunderstorms. Sustained winds near the center of the storm can reach speeds of greater than 300 kilometers per hour (km/h), causing widespread damage and fatalities. Tornadoes are small but violent circulations of air associated with storm systems. Dust devils are similar in structure to tornadoes, but they are generally smaller and less intense and usually occur in fair weather; for example, in the deserts of the American Southwest. Diameters of dust devils range from a few meters to a few dozen meters, with average heights of several hundred meters. The lifetime of a typical tornado or dust devil is brief, limited to a dozen or so minutes.

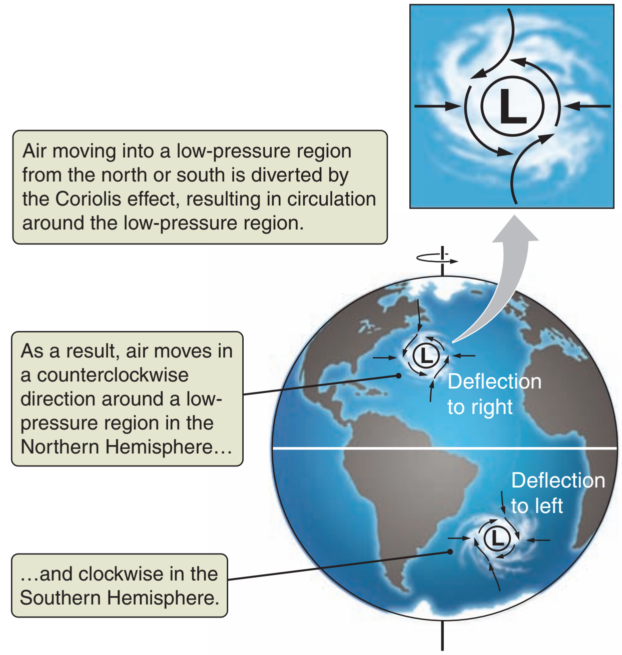


Figure 9.11 As a result of the Coriolis effect, air circulates around regions of low pressure on the rotating Earth.

CHECK YOUR UNDERSTANDING 9.4

All weather and wind on Earth are a result of convection in the: (a) troposphere; (b) stratosphere; (c) mesosphere; (d) ionosphere; (e) thermosphere.

9.4 The Atmospheres of Venus and Mars Differ from Earth's

As shown in Table 9.1, the atmospheres of Venus, Earth, and Mars are very different. The atmosphere of Venus is very hot and dense compared to that of Earth, while the atmosphere of Mars is very cold and thin. The greenhouse effect has turned Venus hellish, with extremely high temperatures and choking amounts of sulfurous gases. Compared to Venus, the surface of Mars is almost hospitable. Understanding why and how these atmospheres are so different helps us understand how Earth's atmosphere may evolve in the future.

Venus

Venus and Earth are similar enough in size and mass that they were once thought of as sister planets. Indeed, when we used the laws of radiation in Chapter 5 to predict temperatures for the two planets, we concluded that they should be very similar. However, spacecraft visits to Venus in the 1960s revealed that the temperature, density, and pressure of Venus's atmosphere were all much higher than for Earth's atmosphere. Ninety-six percent of Venus's massive atmosphere is carbon dioxide, with only 3.5 percent of nitrogen and lesser amounts of other gases. These atmospheric properties are due to the greenhouse effect and the role of carbon dioxide in blocking the infrared radiation typically emitted by a planetary surface. This thick blanket of carbon dioxide effectively traps the infrared radiation, raising the temperature at the surface of the planet to a sizzling 740 K, which is hot enough to melt lead (**Figure 9.12**). The atmospheric pressure at the

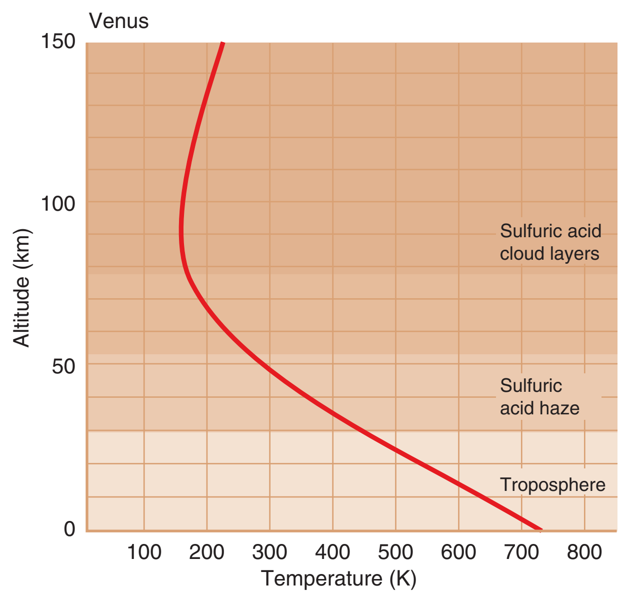


Figure 9.12 The temperature of the atmosphere on Venus primarily drops with increase in altitude, unlike temperatures in Earth's atmosphere, which fall and rise and fall again through the troposphere, stratosphere, and mesosphere, respectively.

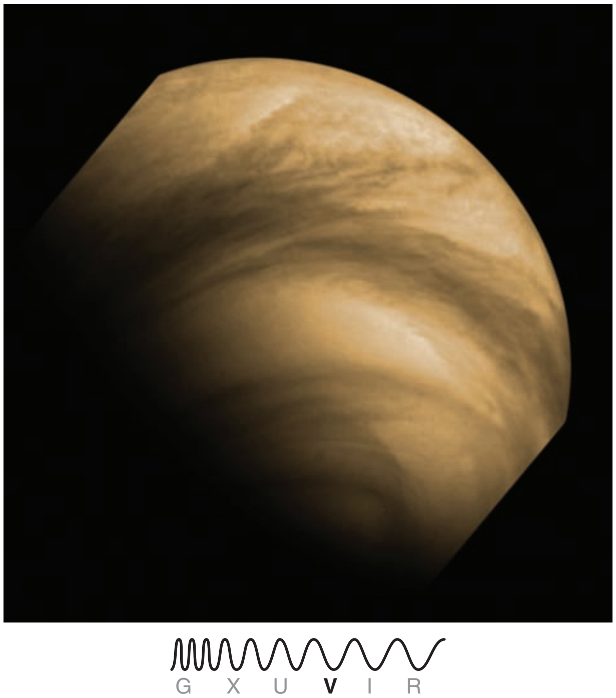


Figure 9.13 This image from *Venus Express* shows the thick clouds obscuring the view of the surface of Venus.

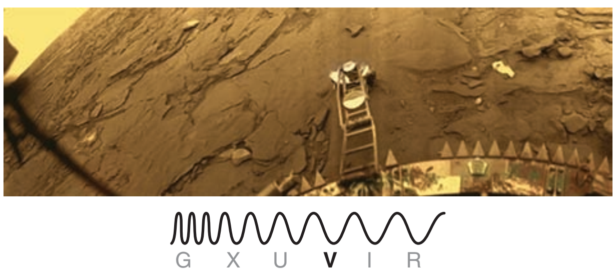


Figure 9.14 This image of Venus is from the 1982 Soviet *Venera 14* mission. The spacecraft is in the foreground. Note the rocky ground and the orange sky.

Figure 9.15 This true-color image of the surface of Mars was taken by the rover *Spirit*. In the absence of dust, the sky's thin atmosphere would appear deep blue. In this image, windblown dust turns the sky pinkish.

surface of Venus is 92 times greater than that at Earth's surface: this is equal to the water pressure at an ocean depth of 900 meters, which is more than enough pressure to crush the hull of a submarine.

As you can see in Figure 9.12, the atmospheric temperature of Venus decreases continuously with altitude throughout the planet's troposphere—similar to Earth, dropping to a low of about 160 K at the tropopause. At an altitude of approximately 50 km, Venus's atmosphere has an average temperature and pressure similar to Earth's atmosphere at sea level. At altitudes between 50 and 80 km, the atmosphere is cool enough for sulfurous oxide vapors to react with water vapor to form dense clouds of concentrated sulfuric acid droplets (H_2SO_4). These dense clouds completely block Earth's view of the surface of Venus, as **Figure 9.13** shows. Large variations in the observed amounts of sulfurous compounds in the high atmosphere of Venus suggest that the sulfur arises from sporadic episodes of volcanic activity. This along with some bright spots seen near a large shield volcano strengthens the possibility that Venus is currently volcanically active.

In the 1960s, radio telescopes and spacecraft with cloud-penetrating radar provided low-resolution views of the surface of Venus. It was not until 1975, when the Soviet Union succeeded in landing cameras there, that scientists got a clear picture of the surface. These images showed fields of rocks 30–40 centimeters (cm) across and basalt-like slabs surrounded by weathered material. A series of Soviet landers in the 1980s revealed similar landscapes (**Figure 9.14**). Radar images taken by the *Magellan* spacecraft in the early 1990s (see Figure 8.20) produced a global map of the surface of Venus. The high atmospheric temperatures on Venus also mean that neither liquid water nor liquid sulfurous compounds can exist on its surface, leaving an extremely dry lower atmosphere with only 0.01 percent water and sulfur dioxide vapor.

Imagine yourself standing on the surface of Venus. Because sunlight cannot easily penetrate the dense clouds above you, noontime on the surface of Venus is no brighter than a very cloudy day on Earth. High temperatures and very light winds keep the lower atmosphere of Venus free of clouds and hazes. The local horizon can be seen clearly, but strong scattering of light by molecules in the dense atmosphere of Venus would greatly soften any view you might have of distant mountains.

Unlike the other Solar System planets, Venus rotates on its axis in a direction opposite to its motion around the Sun. Astronomers call this *retrograde rotation*. Relative to the stars, Venus rotates on its axis once every 243 Earth days. However, a solar day on Venus—the time it takes for the Sun to return to the same place in the sky—is only 117 Earth days. The slow rotation means that Coriolis effects on the atmosphere are small. Global Hadley circulation seldom occurs in planetary atmospheres, because other factors, such as planet rotation, break up the planetwide flow into a series of smaller Hadley cells. However, because of its slow rotation, Venus is an exception and as a result is the only planet with global circulation that is quite close to a classic Hadley pattern (see Figure 9.10a).

The massive atmosphere on Venus is highly efficient in transporting thermal energy around the planet, so the polar regions are only a few degrees cooler than the equatorial regions, and there is almost no temperature difference between day and night. Because Venus's equator is nearly in the plane of the planet's orbit, seasonal effects are quite small, producing only negligible changes in surface temperature. Such small temperature variations also mean that wind speeds near the surface of Venus are quite low, typically about a meter per second, so wind erosion is weak compared to that on Earth and Mars. High in the atmosphere, 70 km up, temperature differences are larger, contributing to super hurricane force winds that reach speeds of 110 m/s (400 km/h), circling the planet in only 4 days. The variation of this high-altitude wind speed with latitude can be seen in the chevron, or V-shaped, cloud patterns.

When the *Pioneer Venus* spacecraft was orbiting Venus during the 1980s, its radio receiver picked up many bursts of lightning static—so many that Venus appears to have a rate of lightning activity comparable to that of Earth. On Venus, as on Earth, lightning is created in the clouds; but Venus's clouds are so high—typically 55 km above the surface of the planet—that the lightning bolts never hit the ground. More recently, *Venus Express* observed magnetic signatures of lightning on Venus.

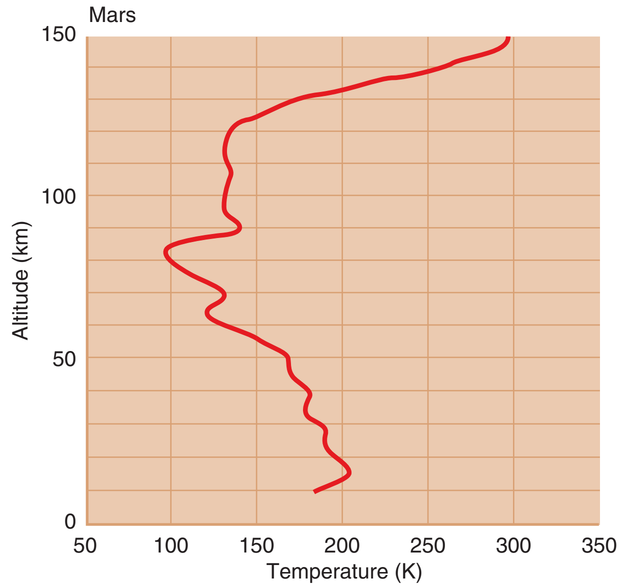


Figure 9.16 The temperature profile of the atmosphere of Mars. Note the differences in temperature and structure between this profile and the profile of the atmosphere of Venus (see Figure 9.12).

Mars

Mars has a stark landscape, colored reddish by the oxidation of iron-bearing surface minerals. The sky is sometimes dark blue but more often a pinkish color caused by windblown dust (**Figure 9.15**). The lower density of the martian atmosphere makes it more responsive than Earth's atmosphere to heating and cooling, so its temperature extremes are greater. The surface near the equator at noontime is a comfortable 20°C—a cool room temperature (68°F) on Earth. However, nighttime temperatures typically drop to a frigid −100°C, and during the polar night the air temperature can reach −150°C—cold enough to freeze carbon dioxide out of the air in the form of a dry-ice frost. The temperature profile of the atmosphere of Mars shown in **Figure 9.16** has a range of only 100 degrees up to about 125 km. Above that. the temperature rises because of absorption of sunlight in the upper atmosphere. The temperature profile of Mars is more similar to that of Earth than that of Venus.

The average atmospheric surface pressure of Mars is equivalent to the pressure at an altitude of 35 km above sea level on Earth, far higher than Earth's highest mountain. There is no "sea level" on Mars because there are no oceans. Surface pressure varies from 11.5 mb in the lowest impact basins of Mars to 0.3 mb at the summit of Olympus Mons. Recall that Earth's pressure at sea level is about 1 bar, so the highest pressure on Mars is only 1.1 percent of Earth's pressure at sea level. Like Earth, Mars has some water vapor in its atmosphere, but its low temperatures condense much of the water vapor out as clouds of ice crystals. Mars can have early-morning ice fog in the lowlands (**Figure 9.17**) and clouds hanging over the mountains.

In the absence of plants, Mars has only a tiny trace of oxygen, which is so important to life on Earth. Like Venus, the atmosphere of Mars is composed almost entirely of carbon dioxide (95 percent) and a lesser amount of nitrogen (2.7 percent). The near absence of oxygen means that Mars has very little ozone. Without ozone, solar UV radiation reaches all the way to the surface. These UV rays could be lethal to any surface life-forms, so any life would either need to develop protective layers or be located away from direct exposure on the surface of the planet; for example, in caves or below the surface.

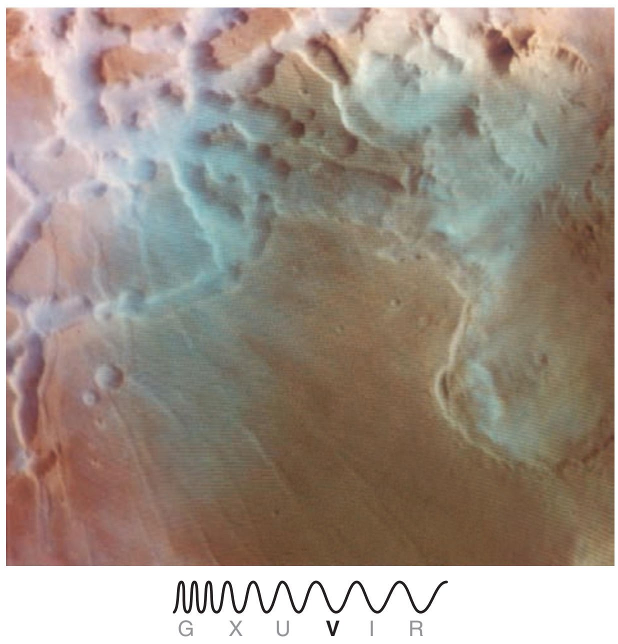


Figure 9.17 This image shows patches of early-morning water vapor fog forming in canyons on Mars.

The tilt of the rotation axis of Mars is similar to Earth's at present, so both planets have similar seasons. But seasonal effects on Mars are larger for two reasons: Mars varies more in its annual orbital distance from the Sun than Earth does, and the low density of the martian atmosphere makes it more responsive to

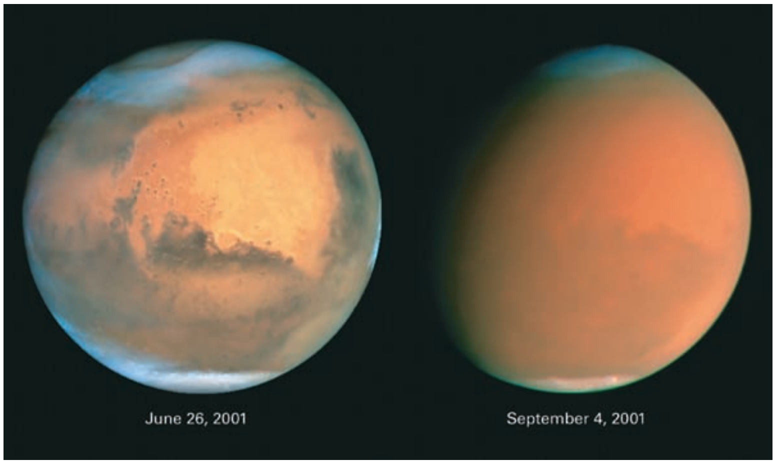


Figure 9.18 Hubble Space Telescope images show the development of a global dust storm that enshrouded Mars in September 2001. The same region of the planet is shown in both images; surface features are obscured by the thick layer of dust.

seasonal change. The large daily, seasonal, and latitudinal surface temperature differences on Mars often create locally strong winds, some estimated to be higher than 100 m/s (360 km/h). High winds can stir up huge quantities of dust and distribute it around the planet's surface. For more than a century, astronomers have watched the seasonal development of springtime dust storms on Mars. The stronger storms spread quickly and can envelop the entire planet in a shroud of dust within a few weeks (**Figure 9.18**). Such large amounts of windblown dust can take many months to settle out of the atmosphere. Seasonal movement of dust from one area to another alternately exposes and covers large areas of dark, rocky surface. This phenomenon led some astronomers of the late 19th and early 20th centuries to believe that they were witnessing the seasonal growth and decay of vegetation on Mars.

The *Viking* landers first noticed dust devils on Mars in 1976. More recently, *Mars Reconnaissance Orbiter* spotted a large number of dust devils, visible because of the shadows they cast on the martian surface. **Figure 9.19** shows a 20-km-high, 70-m-wide dust devil. Most martian dust devils leave dark meandering trails behind them where they have lifted bright surface dust, revealing the dark surface rock that lies beneath the dust. Dust devils on Mars—typically higher, wider, and stronger than dust devils on Earth—reach heights of up to 8 km and have diameters ranging from a few dozen to a few hundred meters.

Mars likely had a more massive secondary atmosphere in the distant past. As discussed in Chapter 8, geological evidence strongly suggests that liquid water once flowed across its surface. But the low incidence (possibly cessation) of volcanism and the planet's low gravity, and perhaps the decrease of its magnetic field, was responsible for the loss of much of this earlier atmosphere. Scientists have not yet reached a consensus on how massive the martian atmosphere was in the past.

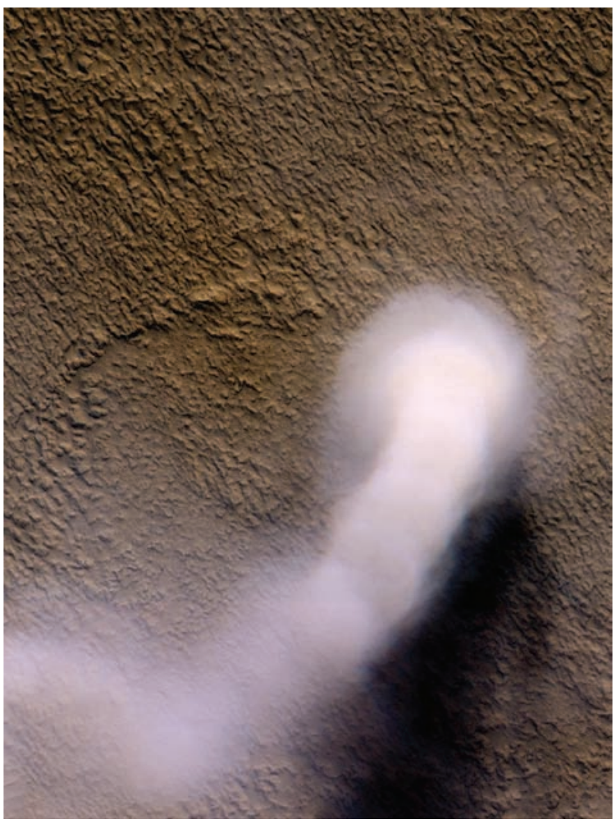


Figure 9.19 This dust devil on Mars was imaged by the *Mars Reconnaissance Orbiter.*

Mercury and the Moon

The ultrathin atmospheres of Mercury and the Moon are known as **exospheres**, and they are less than a million-billionth (10^{-15}) as dense as Earth's atmosphere. The recent NASA *Lunar Atmosphere and Dust Environment Explorer* (*LADEE*) mission found helium, argon, and dust in the Moon's exosphere. Other atoms, such as sodium, calcium, and even water-related ions, were seen in Mercury's exosphere by the *Messenger* spacecraft, and they may have been blasted loose from Mercury's surface by the solar wind or micrometeoroids. The exospheres of Mercury and the Moon probably vary somewhat with the strength of the solar wind and the atoms of hydrogen and helium they capture from it. Exospheres have no effect on local surface temperatures, but astronomers study their interactions with the solar wind.

Mercury and Venus are too hot for people to visit or live on their surfaces. If people ever create settlements on the Moon or Mars, they will need to take along or find local materials to produce a pressurized environment with oxygen to breathe and to construct protection from solar radiation.

CHECK YOUR UNDERSTANDING 9.5

Rank, from greatest to smallest, the seasonal variations on the following planets: (a) Mercury; (b) Venus; (c) Earth; (d) Mars

9.5 Greenhouse Gases Affect Global Climates

Climate is the *average* state of an atmosphere, including temperature, humidity, winds, and so on. Climate describes the planet as a whole. This is an important distinction from weather, which is the state of an atmosphere at any given time and place. The study of climate change on Earth and Mars is not new to the 21st century. Nineteenth-century scientists found evidence of past ice ages and knew that Earth's climate had been very different at earlier times in its history. Observations of changes in the martian ice caps led to speculation about whether Mars also had ice ages in its history. In this section, we will look at the natural factors that can cause climates to change on planets, and then we will examine the additional factors that affect Earth.

Factors That Can Cause Climate Change on a Planet

Scientists study the astronomical, geological, and, on Earth, biological mechanisms controlling climate on the planets. Astronomical mechanisms that influence changes in planetary temperature include changes in the Sun's energy output, which has increased slowly as the Sun ages, and possibly changes in the galactic environment as the Sun travels in its orbit around the center of the Milky Way. Scientists have suggested that sporadic bursts of gamma rays or cosmic rays (fast-moving protons) from distant exploding stars could interact with planetary atmospheres. These mechanisms would affect *all* of the planets in the Solar System at the same time.

Other astronomical mechanisms relevant to climate change and specific to each planet are the Milankovitch cycles, named for geophysicist Milutin Milanković (1879–1958). For example, a planet's energy balance can be affected by periodic changes in its orbital eccentricity, or its precession, or the tilt of its rotational axis. Recall from Working It Out 5.4 that numerous factors affect a planet's energy balance and therefore its temperature. If a planet's orbit becomes more eccentric, the amount of energy it receives from the Sun will vary more over its year. If the tilt of a planet increases, its seasons will become more extreme, and its temperature variation during the year will increase. The precession cycle affects which hemisphere is pointed to the Sun at different times of the elliptical orbit, so that one hemisphere may have longer winters and the other longer summers.

The tilt (obliquity) of Earth's axis varies from 22.1° to 24.5°, and Earth's relatively large Moon keeps that tilt from changing more than this. In contrast, the moons of Mars are small, and the gravitational influence of Jupiter is a greater factor on Mars. The tilt of Mars is thought to vary from 13° to 40°, or possibly even more. Given the precession of Mars and its more eccentric orbit, which creates differences in season length between its northern and southern hemispheres, Mars may have had very large swings in its climate throughout its history as the obliquity changed.

Another set of factors that can affect climate is the geological activity of a planet. Volcanic eruptions can produce dust, aerosol particles, clouds, or hazes that block sunlight over the entire globe and lower the temperature. Impacts by large objects can kick up sunlight-blocking particles. Tectonic activity can also affect climate. For example, on Earth the shifting of the plates has led to different configurations of the oceans and the shifting continents, affecting global atmospheric and oceanic circulatory patterns. The albedo of a planet can increase if there are more clouds and ice or decrease if ice melts or is covered by volcanic ash. Changes may also arise from variations in carbon cycles. On Earth, long-term interactions of the oceans, the land, and the atmosphere can affect the levels of greenhouse gases such as carbon dioxide and water vapor.

A third set of mechanisms that trigger climate changes is biological. Recall from Section 9.3 that over billions of years on Earth, photosynthesis by bacteria and later by plants removed carbon dioxide from the atmosphere and replaced it with oxygen. Biological (and geological) activity on Earth can produce methane, a strong greenhouse gas. Certain microorganisms produce methane as a metabolic by-product. For example, those bubbles you see rising to the surface of a stagnant pond—swamp gas—contain biologically produced methane. Methane is also emitted from the guts of grain-fed livestock (and, in the past, from some of the large dinosaurs) as well as from termites. Another biological effect on climate could come from phytoplankton. If the oceans get more solar energy and warm up from one of the astronomical mechanisms, then the phytoplankton in the ocean may grow faster, leading to more aerosol release and more cloud formation, which increases albedo. Finally, human activities are triggering some major changes, as discussed in the next subsection.

In short, many factors affect the temperature of a planet. Earth's climate is the most complicated of those of the terrestrial planets because Earth is the most geologically and biologically active. How do scientists sort out all of these factors? They use the scientific method. Scientists create mathematical models to simulate the general circulation and energy balance of a planet, incorporating all of the appropriate factors. The goal is to create a global climate model that reproduces the empirical data from observations of a planet. Once the model correctly predicts past and present climate, then it can be used to predict future climate. The first simple climate models for Earth were run on the earliest computers in the 1950s and 1960s. One set of models developed at NASA's Goddard Institute for Space Studies in the 1970s was a spinoff of a program originally designed for the study of Venus. The insights from comparative planetology are very important for producing better models that will aid in scientific predictions of climate change on Earth.

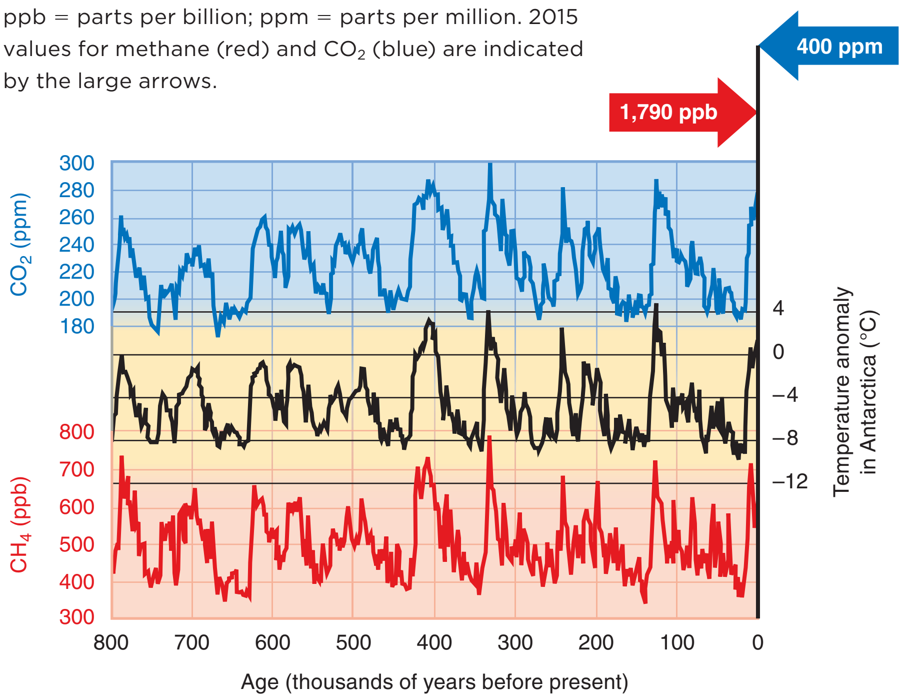


Figure 9.20 This graph shows global variations in carbon dioxide (CO_2), temperature, and methane (CH_4) concentrations over the past 800,000 years of Earth's history. Notice the multiple *y*-axes on this graph. The axis on the right relates to the temperature data (black); the axes on the left relates to the CO_2 (blue) and CH_4 (red) data. These data sets have been plotted on the same graph to make the similarities and differences easier to see. The low points correspond to ice ages. ppb = parts per billion; ppm = parts per million. 2015 values for methane (red) and CO_2 (blue) are indicated by the large arrows.

Climate Change on Earth

Paleoclimatology is the study of changes in Earth's climate throughout its history. Earth's atmosphere is so sensitive to even small temperature changes that it takes a drop of only a few degrees in the mean global temperature to plunge the planet's climate into an ice age. Scientists use evidence from geology and paleontology such as sediments, ice sheets, rocks, tree rings, coral, shells, and fossils to get data on Earth's past climate. They have found that Earth's climate has lengthy temperature cycles, some lasting hundreds of thousands of years and some tens of thousands of years. As you can see in the middle plot in **Figure 9.20**, there have been periods of colder temperatures on Earth, known as ice ages. These oscillations in the mean global temperature are far smaller than typical geographic or seasonal temperature variations.

Periodic Milankovitch cycle changes in Earth's orbit correspond to some temperature cycles. As shown in **Figure 9.21**, Earth's tilt varies in cycles of 41,000 years; the eccentricity of Earth's orbit varies with two cycles of about 100,000 and 413,000 years, respectively; and the time of the year when Earth is closest to the Sun varies in cycles of about 21,000 years. Global climate models using these Milankovitch cycles have successfully replicated much of the observed paleoclimatology data. Temperature changes that are not periodic may have been triggered internally by volcanic eruptions or long-term interactions between Earth's oceans and its atmosphere or by other factors mentioned already.

If Earth's climate has been changing naturally for most of its history, then why are scientists especially concerned about the current trend in global climate? Figure 9.20 shows the carbon dioxide levels, methane levels, and temperature of Earth's atmosphere over the past 800,000 years, obtained from measuring deep ice-cores in the polar regions. Notice that these three factors are correlated. When one rises, so do the others. These data show the naturally occurring ranges since before the existence of the first humans. The temperature difference between ice ages and interglacial periods is only 10°C–15°C. Note that these changes are gradual, occurring over tens of thousands of years.

Two major changes have taken place on Earth during the past 150 years. First, the industrial revolution led to an increase in the production of greenhouse gases, especially from the burning of fossil fuels, which releases carbon dioxide into the atmosphere. In 1896, Svante Arrhenius (1859–1927), a Nobel Prize–winning chemist, produced calculations showing that CO_2 released from burning fossil fuels could increase the greenhouse effect and raise Earth's surface temperature. The second change has been the rapid growth in human population. When populations increase, people burn forests to clear land for agriculture and industry, removing photosynthesizing plants, increasing CO_2 emissions, and locally changing Earth's albedo. A higher population means more agricultural soil that releases nitrous oxide, more livestock that releases methane, and more people who release carbon dioxide by burning fossil fuels. The data in **Figure 9.22** show that concentrations of these greenhouse gases in the atmosphere have been increasing since

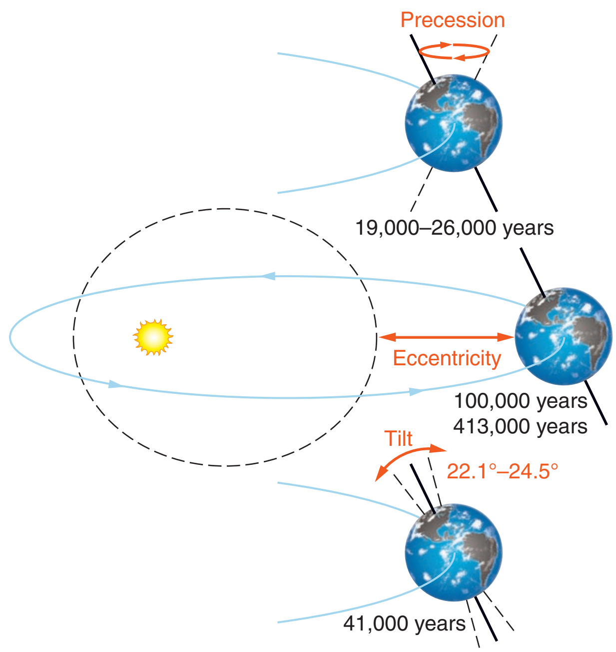


Figure 9.21 An illustration of the Milankovitch cycles for Earth. The precession of Earth and the rotation of its elliptical orbit combine to a cyclic variation of about 21,000 years; its eccentricity varies with two cycles of about 100,000 and 413,000 years, and its tilt varies in cycles of 41,000 years. (Not to scale.)

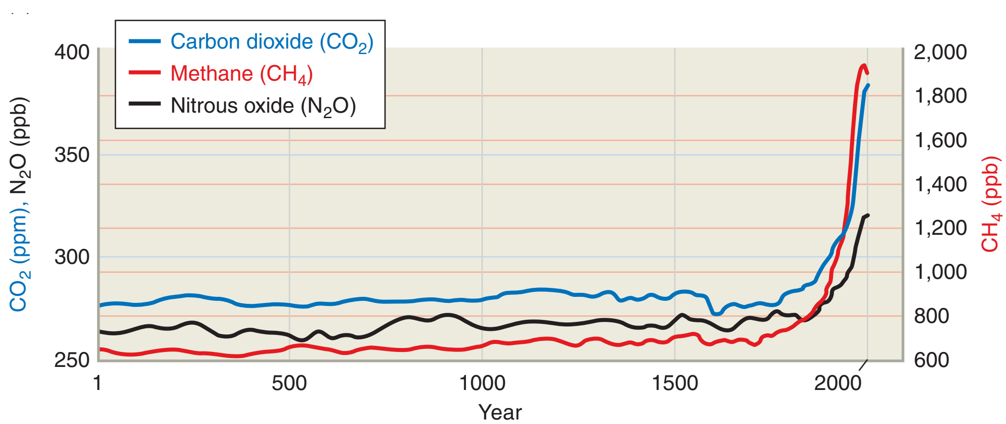


Figure 9.22 Concentrations of greenhouse gases from the year 1 to 2005, showing the increases beginning at the time of industrialization.

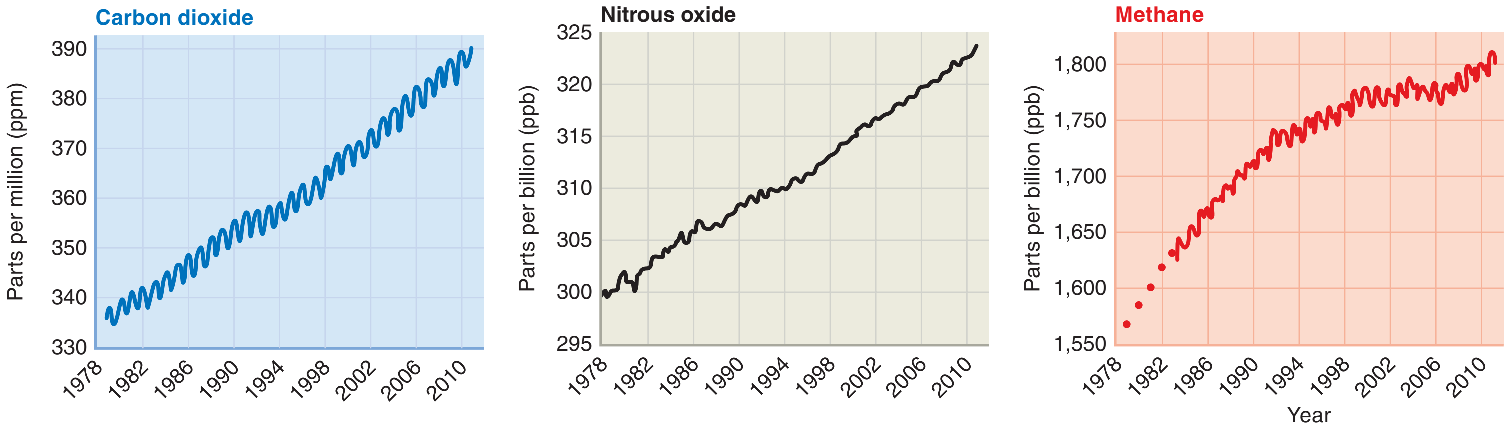
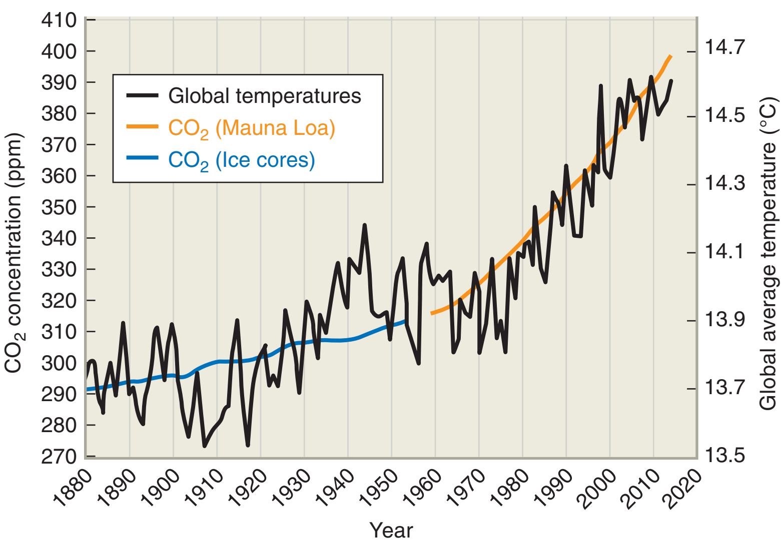


Figure 9.23 The National Oceanic and Atmospheric Administration (NOAA) plots of global average amounts of the major greenhouse gases. CO_2 reached 400 ppm in some months in 2014 and 2015.

Figure 9.24 Earth's global average temperature and CO_2 concentrations since 1880. This graph shows that global temperatures are climbing along with concentrations of carbon dioxide. Annual variations in atmospheric CO_2 can be attributed to seasonal variations in plant life and fossil fuel use, while the overall steady climb is due to human activities.



the industrial revolution. The CO_2 level has risen and is higher than any of the levels seen in Figure 9.20. **Figures 9.23** and **9.24** show that there has been a steady increase in nitrous oxide, methane, and the mean global temperature.

The vast majority of climatologists accept the computer models indicating that this trend represents the beginning of a long-term change in temperature caused by the buildup of human-produced greenhouse gases. This anthropogenic (human-caused) change is happening much faster than the changes seen in Figure 9.20. Even an average increase of a few degrees can greatly affect Earth. The planet's atmosphere is a delicately balanced mechanism. Earth's climate is a complex, chaotic system within which tiny changes can produce enormous and often unexpected results. To add to the complexity, Earth's climate is intimately tied to ocean temperatures and currents. Ocean currents are critical in transporting energy from one part of Earth to another, and it is uncertain how increased temperatures may affect those systems. Warmer oceans evaporate, leading to wetter air, which can mean more intense summer and winter storms (including more snow). We see examples of this connection in the periodic El Niño and La Niña conditions, small shifts in ocean temperature that cause much larger global changes in air temperature and rainfall. The **Process of Science Figure** discusses how scientists think about complex issues like this.

Changes in climate affect where plants and animals can live, and thus dates and locations of breeding, migration, hibernation, and so on. Agricultural growing seasons and pollination are also affected, as is the availability of freshwater. The melting of mountain glaciers and polar sea ice from the increase in temperature is already being observed. Melted ice from Greenland and Antarctica will raise the level of the oceans—a serious problem for the large numbers of people who live in coastal or low-lying regions. A warmer Arctic can lead to a higher release of methane from the permafrost. Less ice and snow can decrease Earth's albedo, allowing more sunlight to reach the surface, although albedo may be increased by an increase in cloud cover, caused by more water in the atmosphere.

The processes are so complex that it is still not possible to predict accurately all of the long-term outcomes of small changes that humans are now making to the composition of Earth's atmosphere and to Earth's albedo. In a real sense, we are *experimenting* with Earth. We are asking the question, What happens to Earth's climate if we steadily increase the number of greenhouse molecules in its atmosphere? We do not yet know the full answer, but we are already seeing some of the consequences.

Process of Science

THINKING ABOUT COMPLEXITY

Climate change is an example of a complex scientific issue. When confronted with complex science, there are several questions you should ask.

What is the quality of the evidence?

How many studies have been done?

How many kinds of studies have been done?

Does the basic physics make sense?

Is it logical?

If this claim were not true, what else would that imply?

Is the explanation natural or supernatural?

If this scientific claim were true, what else would that imply?

Is the claim falsifiable?

If I hold this in my head as if it were true, what would convince me it was false?

If I hold this in my head as if it were false, what would convince me it was true?

Scientific issues become remarkably complex when they relate to policy decisions with a broad reach. Keeping an open mind in such cases means thinking carefully about the quality of the evidence, as well as what data would make you change your mind. If your mind cannot be changed, you are not participating in science.

CHECK YOUR UNDERSTANDING 9.6

Over the past 800,000 years, ice-core data indicate which of the following are correlated? (Choose all that apply.) (a) temperature; (b) CO_2 levels; (c) methane levels; (d) the size of the ozone hole

Origins

Our Special Planet

We might ask the question, Why are we here on Earth, instead of elsewhere in the Solar System? In Chapter 7, we defined the habitable zone of a planetary system as the distance from its star where a planet could have a surface temperature such that large amounts of water could exist in liquid form. In this chapter, you have learned that the temperature of a planet can depend on more than just distance from the star, and it can change over time because of numerous factors, such as the planet's ability to hold on to its atmosphere, the atmospheric greenhouse effect, and orbital variations. Mercury and the Moon were too small to hold on to either their primary or their secondary atmospheres, leaving them as airless rocks. Venus, Earth, and Mars all had some liquid water at one time: early in the history of the Solar System all three might have been classified as habitable. Their atmospheres were likely similar then, too, before the atmosphere of Mars escaped, the atmosphere of Venus was heated by the greenhouse effect, and the atmosphere of Earth was oxygenated. It is even possible that primitive life developed on Venus and Mars at the same time it developed on Earth, about a billion years after the Solar System formed.

Ultimately, the three planets evolved differently, and currently only Earth has the liquid water that is vital for our biology. Venus receives more energy from the Sun and was slightly warmer than the young Earth. The young Venus might have been too hot for liquid water to form oceans or any liquid water might have quickly evaporated. Because Venus had a lot of water vapor in its atmos-phere and lacked a liquid ocean to store carbon dioxide, the greenhouse effect created a thicker atmosphere. This thicker atmosphere fed back to a stronger greenhouse effect, which created an even thicker atmosphere. With this resulting runaway greenhouse effect, Venus became just too hot: the evaporated water molecules broke apart, the hydrogen escaped to space, and any water cycle was completely destroyed. It is possible that primitive bacteria lingered in water vapor in the clouds on Venus, but life did not evolve into anything more complex.

Mars is smaller and less massive than Venus or Earth, so it has a weaker gravity. It has a larger orbit than Venus and Earth, and so receives less energy from the Sun. Over time, much of its atmosphere escaped and was not replaced by volcanic emissions, and the atmospheric pressure became too low to maintain liquid water. But whereas Venus was too hot, when Mars was young it was too cold. Back then it had a thicker atmosphere and liquid rain. Images of the surface of Mars show flood basins indicating huge rivers. Liquid water on the surface of Mars was too effective at scrubbing the planet's atmosphere of carbon dioxide. The process that prevented Earth from becoming a Venus-like hothouse continued further on Mars, and the temperature fell until the water froze. There are hints of subsurface water on Mars, and perhaps some form of martian bacteria will be found beneath the ground.

Thus, our Solar System contains astronomical evidence of how the greenhouse effect can influence planetary atmospheres, including Earth's. Planetary scientists view these different planets as a cautionary tale, showing the results of varied "doses" of greenhouse gases. Only Earth stayed "just right" and was able to retain the liquid oceans in which more complex life evolved. We owe our lives to the blanket of atmosphere that covers the planet. The study of the Solar System reveals that Earth is maintained by the most delicate of balances. Over billions of years, life has shaped Earth's atmosphere, and today, through the activities of humans, life is reshaping the planet's atmosphere once again. Human civilization is very young compared to Earth, and it has been brief compared to the cycles of climate on the planet. The past 10,000 years have been a relatively stable period of Earth's climate: many argue that this stability is what enabled agriculture and civilization to develop. It is uncertain what will happen to agriculture, civilization, or the planet itself if the climate undergoes fast, intense changes. The other planets in the Solar System are not places where billions of people from our planet can live. Earth is the only planet suitable for human life.

ARTICLES QUESTIONS

Planetary scientists conclude that Mars had more liquid water than expected.

Mars Once Had an Entire Ocean—and then Lost It, Scientists Say

By **AMINA KHAN, Los Angeles Times**

Dry, dusty Mars once had an ocean that held as much water as the Arctic Ocean and covered a larger share of the red planet's surface than the Atlantic Ocean does on Earth, according to a surprising new study.

The findings, described online in the journal *Science*, examined the patterns in the martian atmosphere to try to understand how much water it has lost in the last few billion years—and finds that the planet may have been wetter and for longer than scientists may have thought.

As the scientists examined their surprising findings, "the story started to make sense," said lead author Geronimo Villanueva, a planetary scientist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Researchers have gone back and forth on whether Mars held enough water for long enough to have given microbial life a sporting chance to emerge on the red planet. NASA's *Curiosity* rover has tasted the air and found that the martian atmosphere may have been stripped so long ago that there was a slim chance for life; but studies of rocks that the rover has drilled in Gale Crater have revealed signs of a series of lakes that lasted for many millions of years.

To get at this question, an international team of researchers used ground-based telescopes to study the composition of the traces of water in the atmosphere over almost six Earth years (which are roughly three Mars years). Thus, they were able to map the atmospheres, and witness seasonal and microclimate changes over the entire planet.

They specifically looked at two isotopes of water left in the atmosphere: regular water, made of an oxygen and two hydrogens, and semi-heavy water, where one of the hydrogens has an extra neutron in its nucleus. Regular water, which is lighter, tends to rise up and escape the atmosphere at a faster rate, while the heavier water stays put. So over time, the share of heavy water grows—and the greater the share of heavy water today, the more water must have been lost over time.

The scientists took a particular interest in the atmosphere near the polar regions, because much of the red planet's water is stored in its polar ice caps. Based on their calculations, the scientists found that the share of heavy water in the atmosphere near the polar areas was about 7 times as high as in the water on Earth. At one point, the water reserves must have been about 6.5 times larger than the reserves mostly stored in the martian polar ice caps today. An early Mars would have held about 20 million cubic kilometers (4.8 million cubic miles) of water.

Where did all this water lie? While it probably could have covered the entire planet with a 450-foot-deep layer, it was probably mostly contained on the low-lying northern plains, and in some places could have gone about a mile deep.

"If you drop all that water on the planet, it will accumulate in the northern part of the planet," Villanueva said. "So that's [where] we think it formed an ocean."

NASA's MAVEN spacecraft is studying what remains of Mars' now-thin atmosphere to see if scientists can learn how much of it escaped—data that will be of great use to planetary scientists looking to solve the mystery of the Martian water. The European Space Agency's first ExoMars mission is also scheduled to arrive at Mars in 2016.

"In the next five years we're going to probably change our perception of what Mars was in the past," Villanueva said.

ARTICLES QUESTIONS

1. Sketch the heavy water molecule described in the article. How much more massive is it than a "regular" water molecule?
2. Explain why regular water escapes faster than heavy water.
3. Why did the scientists want to study the atmosphere over the polar regions of Mars?
4. Why did Mars lose its ocean of water?
5. Do a news search for "Mars water." What are the most recent discoveries? What is the evidence being reported, and when was the water thought to have existed? What was different on Mars at that time so that it was able to have liquid water?

Summary

Earth's atmosphere is thick enough to warm the surface to life-sustaining temperatures, but not so thick that Earth becomes overheated. Earth, Venus, and Mars all have significant atmospheres that are different from the original atmospheres they captured when they formed. These atmospheres are complex, both in chemical composition and in physical characteristics such as temperature and pressure. The climates of Earth, Venus, and Mars are all determined by their individual atmospheres. Venus, Earth, and Mars are warmer than they would be from solar illumination alone. The atmospheres of Earth, Venus, and Mars have different chemical compositions. These, in turn, lead to dramatic differences in temperature and pressure. Life has altered Earth's atmosphere several times, most notably in the distant past from an increase in the amount of oxygen in the atmosphere and in modern times from an increase in greenhouse gases. Mars and Venus might have been habitable early in the history of the Solar System, but now only Earth has liquid water.

LG 1 **Identify the processes that cause primary and secondary atmospheres to be formed, retained, and lost.** Planetary atmospheres evolve over time. The primary atmospheres consisted mainly of hydrogen and helium captured from the protoplanetary disk. The terrestrial planets lost their primary atmospheres soon after the planets formed. Secondary atmospheres were created by volcanic gases and from volatiles brought in by impacting comets and asteroids. Planetary bodies must have sufficient mass to hold on to their atmospheres.

LG 2 **Compare the strength of the greenhouse effect and differences in the atmospheres of Earth, Venus, and Mars.** Naturally occurring greenhouse gases exist on Venus, Earth, and Mars, which increase the average surface temperature of each planet. The amount by which these greenhouse gases raise the temperature of a planet depends on the number of greenhouse gas molecules in the atmosphere. The differences in global temperatures among these planets can be explained in part by their distances from the Sun. However, the different compositions and densities of their atmospheres is a far more significant factor in global temperature. The atmospheric greenhouse effect keeps Earth from freezing, but it turns the atmosphere of Venus into an inferno.

LG 3 **Describe the layers of the atmospheres on Earth, Venus, and Mars, and explain how Earth's atmosphere has been reshaped by the presence of life.** The atmospheres of Venus, Earth, and Mars have different temperatures, pressures, and compositions. Earth's atmosphere, in particular, has many layers. The layers are determined by the variations in temperature and absorption of solar radiation vertically throughout the atmosphere. Temperature and pressure decrease with altitude in the tropospheres of Venus, Earth, and Mars. Earth's magnetosphere shields the planet from the solar wind. The oxygen levels in Earth's atmosphere have been enhanced through photosynthesis by bacteria and then by plants. Increased oxygen allowed for the development of more advanced forms of life.

LG 4 **Compare the atmospheres of Venus and Mars with the atmosphere of Earth.** Venus has a massive, hot atmosphere of carbon dioxide and sulfur compounds. It has surprisingly fast winds for a slowly rotating planet. Mars has a thin, cold, carbon dioxide atmosphere that may have been much thicker in the past. Earth's atmosphere is thicker than Mars', but thinner than Venus', and is composed primarily of nitrogen.

LG 5 **Describe how comparative planetology contributes to a better understanding of the changes in Earth's climate.** Astronomical, geological, and biological processes can lead to large changes in the climate of planets. The study of climate on the terrestrial planets expands scientists' knowledge of Earth's past, present, and future conditions. Large variations in global temperature over the past 800,000 years correlate strongly with the number of greenhouse molecules in the atmosphere. The current level of greenhouse gases in Earth's atmosphere is higher than any seen during this period and correlates with a subsequent rise in temperature.

? UNANSWERED QUESTIONS

- What is the role of magnetic fields in helping a planet retain its atmosphere? In the absence of a magnetic field, it has been assumed that the solar wind is more likely to sweep away an atmosphere, and this idea has been invoked to explain what happened on Mars. But Venus doesn't have a magnetic field either, and recent observations have shown that Earth leaks as much atmosphere to space as do the planets that lack magnetic fields.
- Will there be a way to slow or stop the rise in greenhouse gases on Earth? Climate scientists worry that current changes are abrupt compared with the natural cycles of changes in climate that take place gradually over thousands of years. Will there be an international agreement to reduce the production of these gases, as there was to reduce the use of chemicals that created the ozone hole?

Questions and Problems

Test Your Understanding

1. Place in chronological order the following steps in the formation and evolution of Earth's atmosphere.
   a. Plant life converts carbon dioxide (CO_2) to oxygen.
   b. Hydrogen and helium are lost from the atmosphere.
   c. Volcanoes, comets, and asteroids increase the inventory of volatile matter.
   d. Hydrogen and helium are captured from the protoplanetary disk.
   e. Oxygen enables the growth of new life-forms.
   f. Life releases CO_2 from the subsurface into the atmosphere.

2. On which of these planets is the atmospheric greenhouse effect strongest?
   a. Venus
   b. Earth
   c. Mars
   d. Mercury

3. The oxygen molecules in Earth's atmosphere
   a. were part of the primary atmosphere.
   b. arose when the secondary atmosphere formed.
   c. are the result of life.
   d. are being rapidly depleted by the burning of fossil fuels.

4. The differences in the climates of Venus, Earth, and Mars are caused primarily by
   a. the composition of their atmospheres.
   b. their relative distances from the Sun.
   c. the thickness of their atmospheres.
   d. the time at which their atmospheres formed.

5. The words *weather* and *climate*
   a. mean essentially the same thing.
   b. refer to very different timescales.
   c. refer to very different size scales.
   d. both b and c

6. Less massive molecules tend to escape from an atmosphere more often than more massive molecules because
   a. the gravitational force on them is less.
   b. they are moving faster.
   c. they are more buoyant.
   d. they are smaller and so experience fewer collisions on their way out.

7. Venus is hot and Mars is cold primarily because
   a. Venus is closer to the Sun.
   b. Venus has a much thicker atmosphere.
   c. the atmosphere of Venus is dominated by CO_2, but the atmosphere of Mars is not.
   d. Venus has stronger winds.

8. Studying climate on other planets is important to understanding climate on Earth because (select all that apply)
   a. underlying physical processes are the same on every planet.
   b. other planets offer a range of extremes to which Earth can be compared.
   c. comparing climates on other planets helps scientists understand which factors are important.
   d. other planets can be used to test atmospheric models.

9. The atmosphere of Mars is often pink-orange because
   a. it is dominated by carbon dioxide.
   b. the Sun is at a low angle in the sky.
   c. Mars has no oceans to reflect blue light to the sky.
   d. winds lift dust into the atmosphere.

10. Auroras are the result of
    a. the interaction of particles from the Sun and Earth's atmosphere and magnetic field.
    b. upper-atmosphere lightning strikes.
    c. the destruction of stratospheric ozone, which leaves a hole.
    d. the interaction of Earth's magnetic field with Earth's atmosphere.

11. The ozone layer protects life on Earth from
    a. high-energy particles from the solar wind.
    b. micrometeorites.
    c. ultraviolet radiation.
    d. charged particles trapped in Earth's magnetic field.

12. Hadley circulation is broken into zonal winds by
    a. convection from solar heating.
    b. hurricanes and other storms.
    c. interactions with the solar wind.
    d. the planet's rapid rotation.

13. The __________ of greenhouse gas molecules affects the temperature of an atmosphere.
    a. percentage
    b. fraction
    c. number
    d. mass

14. Over the past 800,000 years, Earth's temperature has closely tracked
    a. solar luminosity.
    b. oxygen levels in the atmosphere.
    c. the size of the ozone hole.
    d. carbon dioxide levels in the atmosphere.

15. Convection in the __________ causes weather on Earth.
    a. stratosphere
    b. mesosphere
    c. troposphere
    d. ionosphere

Thinking about the Concepts

16. Primary atmospheres of the terrestrial planets were composed almost entirely of hydrogen and helium. Explain why they contained only these gases and not others.

17. How were the secondary atmospheres of the terrestrial planets created?

18. Nitrogen, the principal gas in Earth's atmosphere, was not a significant component of the protostellar disk from which the Sun and planets formed. Where did Earth's nitrogen come from?

19. What are the likely sources of Earth's water?

20. In what way is the atmospheric greenhouse effect beneficial to terrestrial life?

21. In what ways does plant life affect the composition of Earth's atmosphere?

22. What is the difference between ozone in the stratosphere and ozone in the troposphere? Which is a pollutant, and which protects terrestrial life?

23. What is the principal cause of winds in the atmospheres of the terrestrial planets?

24. Global warming appears to be responsible for increased melting of the ice in Earth's polar regions.
    a. Why does the melting of Arctic ice, which floats on the surface of the Arctic Ocean, *not* affect the level of the oceans?
    b. How is the melting of glaciers in Greenland and Antarctica affecting the level of the oceans?

25. Why are we unable to get a clear view of the surface of Venus, as we have so successfully done with the surface of Mars?

26. What is the evidence that the greenhouse effect exists on Earth, Venus, and Mars?

27. Explain why surface temperatures on Venus hardly vary between day and night and between the equator and the poles.

28. Why do scientists think that Mars and Venus were once more habitable, but no longer are?

29. Examine the Process of Science Figure. The last step is one that anyone can carry out about any complex issue. Write down your current take on the issue of anthropogenic climate change: do you accept the evidence or not? Then write down a piece of scientific evidence that would convince you to change your mind. This exercise may help you to think critically about any issue.

30. Given the current conditions on Venus and Mars, which planet might be easier to engineer to make it habitable to humans? Explain.

Applying the Concepts

31. Study Figure 9.21.
    a. Are the axes linear or logarithmic?
    b. Compare the CO_2 levels (top) with the temperature relative to present (middle). How would you describe the relationship between the two graphs?
    c. How much higher is the current CO_2 level than the previous highest value?

32. Study Figure 9.23.
    a. When (approximately) did greenhouse gases begin rising exponentially?
    b. These graphs show that several greenhouse gases have behaved similarly in recent times. Was this true in the past (in general)?
    c. Speculate on possible causes for the common behavior of greenhouse gases in modern times.

33. Study Figure 9.6. Why do commercial jet planes fly at those altitudes?

34. Commercial jets are pressurized. If you take a bag of chips on a commercial jet airplane, the bag puffs up as you travel to the cruising altitude of 14 km.
    a. Is the pressure in the cabin higher or lower than the pressure on the ground?
    b. If there were a second bag attached to the outside of the plane, which bag would puff up more? About how much more (assume an unbreakable bag)? (See Figure 9.6.)

35. Atmospheric pressure is caused by the weight of a column of air above you pushing down. At sea level on Earth, this pressure is equal to 10^5 newtons per square meter (N/m^2).
    a. Estimate the total force on the top of your head from this pressure.
    b. Recall that the acceleration due to gravity is $9.8\ m/s^2$. If the force in part (a) were caused by a kangaroo sitting on your head, what would the mass of the kangaroo be?
    c. Assume a typical kangaroo has a mass of 60 kg. How many kangaroos would have to be sitting on your head to be equal to the extremely massive kangaroo in part (b)?
    d. Why are you not crushed by this astonishing force on your head?

36. Repeat the calculations in question 35 for Venus.

37. Repeat the calculations in question 35 for Mars.

38. Increasing the temperature of a gas inside a closed, rigid box increases the pressure. (This is why you do not put an unopened can of soup directly on the stove!) Explain how Figure 9.6 shows this phenomenon at work in Earth's atmosphere.

39. The total mass of Earth's atmosphere is 5×10^{18} kg. Carbon dioxide (CO_2) makes up about 0.06 percent of Earth's atmospheric mass.
   a. What is the mass of CO_2 (in kilograms) in Earth's atmosphere?
   b. The annual global production of CO_2 is now estimated to be 3×10^{13} kg. What annual fractional increase does this represent?
   c. The mass of a molecule of CO_2 is 7.31×10^{-26} kg. How many molecules of CO_2 are added to the atmosphere each year?
   d. Why does an increase in CO_2 have such a big effect, even though it represents a small fraction of the atmosphere?

40. The ability of wind to erode the surface of a planet is related in part to the wind's kinetic energy.
   a. Compare the kinetic energy of a cubic meter of air at sea level on Earth (mass 1.23 kg) moving at a speed of 10 m/s with a cubic meter of air at the surface of Venus (mass 64.8 kg) moving at 1 m/s.
   b. Compare the kinetic-energy value you determined for Earth in part (a) with that of a cubic meter of air at the surface of Mars (mass 0.015 kg) moving at a speed of 50 m/s.
   c. Why do you think there is not more evidence of wind erosion on Earth?

41. Suppose you seal a rigid container that has been open to air at sea level when the temperature is 0°C (273 K). The pressure inside the sealed container is now exactly equal to the outside air pressure: 10^5 N/m^2.
   a. What would be the pressure inside the container if it were left sitting in the desert shade where the surrounding air temperature was 50°C (323 K)?
   b. What would be the pressure inside the container if it were left sitting out in an Antarctic night where the surrounding air temperature was −70°C (203 K)?
   c. What would you observe in each case if the walls of the container were not rigid?

42. Oxygen molecules (O_2) are 16 times as massive as hydrogen molecules (H_2). Carbon dioxide molecules (CO_2) are 22 times as massive as H_2.
   a. Compare the average speed of O_2 and CO_2 molecules in a volume of air.
   b. Does this ratio of the speeds in part (a) depend on air temperature?

43. Calculate the average speed of a carbon dioxide molecule in the atmospheres of Earth and Mars. Compare these speeds with their respective escape velocities. What does this tell you about each planet's hold on its atmosphere?

44. The average surface pressure on Mars is 6.4 mb. Using Figure 9.6, estimate how high you would have to go in Earth's atmosphere to experience the same atmospheric pressure that you would experience if you were standing on Mars.

45. Water pressure in Earth's oceans increases by 1 bar for every 10 meters of depth. Compute how deep you would have to go to experience pressure equal to the atmospheric surface pressure on Venus.

USING THE WEB

46. Look up the data on this year's ozone hole. NASA's "Ozone Hole Watch" website (http://ozonewatch.gsfc.nasa.gov) shows a daily image of southern ozone, as well as animations for current and previous years and some comparative plots. Other comparative plots are available on NOAA's "Southern Hemisphere Ozone Hole Area" Web page (http://www.cpc.ncep.noaa.gov/products/stratosphere/sbuv2to/gif_files/ozone_hole_plot.png). At what time of year is the hole the largest, and why? How do the most recent ozone holes compare to previous ones in size and minima? Do they seem to be getting smaller?

47. Mars:
   a. Go to http://www.planetfour.org, a Zooniverse Citizen Science Project in which people examine images of the surface of Mars. Log in or create a Zooniverse account if you don't have one. Read through "About": Where did these data come from? What are the goals of this project? Why is it useful to have many people look at the data? Read through "Classify": "Show Tutorial" and "See Examples" and "FAQs." Now classify some images.
   b. Go to the website for the *MAVEN* mission, which entered the orbit of Mars in 2014. (http://lasp.colorado.edu/home/maven). What are the scientific goals of the mission? Is this mission a lander, an orbiter, or a flyby? What instruments are on this mission? How will this mission contribute to the understanding of climate change on Mars? Go to the NASA Web page for *MAVEN* (http://www.nasa.gov/mission_pages/maven/main/index.html). Are there any results?

48. Earth:
   a. Go to the National Snow & Ice Data Center (NSIDC) websites (http://nsidc.org/data/seaice_index/ and http://nsidc.org/arcticseaicenews/). What are the current status and the trend of the Arctic sea ice? How does it compare with previous years and with the median shown? Is anything new reported about Antarctic ice? Qualitatively, how might a change in the amount of ice at Earth's poles affect the albedo of Earth, and how does the albedo affect Earth's temperature?

b. Go to the website for NASA's Goddard Institute for Space Studies (http://www.giss.nasa.gov), click on "Datasets & Images," and select "Surface Temperatures." The graphs are updated every year. Note that the temperature is compared to a baseline of the average temperature in the period 1951–1980. What has happened with the temperature in the past few years? If the annual mean decreased, does that change the trend? What does the 5-year running mean show? How much warmer is it on average now than in 1880?

c. Go to NOAA's "Trend in Atmospheric Carbon Dioxide" Web page on carbon dioxide levels at the observatory on Mauna Loa (http://esrl.noaa.gov/gmd/ccgg/trends/mlo.html). What is the current level of CO_2? How does this compare with the level from 1 year ago? Scroll down the page and click on "A description of how we make measurements at Mauna Loa." Why is this a good site for measuring CO_2? What exactly is measured? Are the numbers cross-checked with other measurements?

49. Climate change:

a. Go to the timeline on the "Discovery of Global Warming" Web page of the American Institute of Physics (http://aip.org/history/climate/timeline.htm). When did scientists first suspect that CO_2 produced by humans might affect Earth's temperature? When were other anthropogenic greenhouse gases identified? When did scientific opinion about global warming start to converge? Click on "Venus & Mars": How did observations of these planets add to an understanding of global climate change? Click on "Aerosols": How do these contribute to "global dimming"?

b. The Fifth Assessment report from the Intergovernmental Panel on Climate Change (IPCC) was released in October 2014. Go to the IPCC website section on the 2014 Synthesis report (http://ipcc.ch/report/ar5/syr/) and watch the 16-minute video. What are some of the causes of the increase in warming? What are some of the effects of warming seen in the polar regions? How are measurements from the past and present used to predict the climate in the future?

c. Advanced: Go to the website for "Educational Global Climate Modeling," or EdGCM (http://edgcm.columbia.edu). This is a version of the NASA GISS modeling software that will enable students to run a functional three-dimensional global climate model on their laptop computers. Download the trial version and install it on your computer. What can you study with this program? What factors that contribute to global warming or to global cooling on Earth can you adjust in the model? Your instructor may give you an assignment using this program and the Earth Exploration Toolbook (http://serc.carleton.edu/eet/envisioningclimatechange/index.html).

50. Mars movies:

a. Watch a science fiction film about people going to Mars. How does the film handle the science? Can people breathe the atmosphere? Are the low surface gravity and atmospheric pressure correctly portrayed? Do the astronauts have access to water?

b. At the end of the film *Total Recall* (1990), Arnold Schwarzenegger's character presses an alien button, the martian volcanoes start spewing, and within a few minutes the martian sky is blue, the atmospheric pressure is Earth-like, and the atmosphere is totally breathable. (Probably you can find the scene online.) What, scientifically, is wrong with this scene? That is, why would volcanic gases *not* quickly create a breathable atmosphere on Mars?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

EXPLORATION

digital.wwnorton.com/astro5

One prediction about climate change is that as the planet warms, ice in the polar caps and in glaciers will melt. Such melting certainly seems to be occurring in the vast majority of glaciers and ice sheets around the planet. It is reasonable to ask whether this actually matters, and why. In this Exploration, we will explore several consequences of the melting ice on Earth.

Experiment 1: Floating Ice

For this experiment, you will need a permanent marker, a translucent plastic cup, water, and ice cubes. Place a few ice cubes in the cup and add water until the cubes float (that is, they don't touch the bottom). Mark the water level on the outside of the cup with the marker, and label this mark "Initial water level."

1 As the ice melts, what do you expect to happen to the water level in the cup?

Wait for the ice to melt completely, then mark the cup again.

2 What happened to the water level in the cup when the ice melted?

3 Given the results of your experiment, what can you predict will happen to global sea levels when the Arctic ice sheet, which floats on the ocean, melts?

Experiment 2: Ice on Land

For this experiment, you will need the same materials as in experiment 1, plus a paper or plastic bowl. Fill the cup about halfway with water and then mark the water level, labeling the mark "Initial water level." Poke a hole in the bottom of the bowl and set the bowl over the cup. Add some ice cubes to the bowl.

4 As the ice melts, what do you expect will happen to the water level in the cup?

Wait for the ice to melt completely, then mark the cup again.

5 What happened to the water level in the cup when the ice melted?

6 In this experiment, the water in the cup is analogous to the ocean, and the ice in the bowl is analogous to ice on land. Given the results of your experiment, what can you predict will happen to global sea levels when the Antarctic ice sheet, which sits on land, melts?

Experiment 3: Why Does It Matter?

Search online using the phrase "Earth at night" to find a satellite picture of Earth taken at night. The bright spots on the image trace out population centers. In general, the brighter a spot is, the more populous the area is (although there is a confounding factor relating to technological advancement).

7 Where do humans tend to live—near coasts or inland? Coastal regions are, by definition, near sea level. If both the Greenland and Antarctic ice sheets melted completely, sea levels would rise by as much as 80 meters. How would a sea-level rise of a few meters (in the range of reasonable predictions) over the next few decades affect the global population? (Note that one story of a building is about 3 meters.)

10 Worlds of Gas and Liquid—The Giant Planets

Unlike the solid planets of the inner Solar System, the four worlds in the outer Solar System were able to capture and retain gases and volatile materials from the Sun's protoplanetary disk and swell to enormous size and mass. These planets have dense cores, very large atmospheres, and rotate faster than Earth.

LEARNING GOALS

By the conclusion of this chapter, you should be able to:

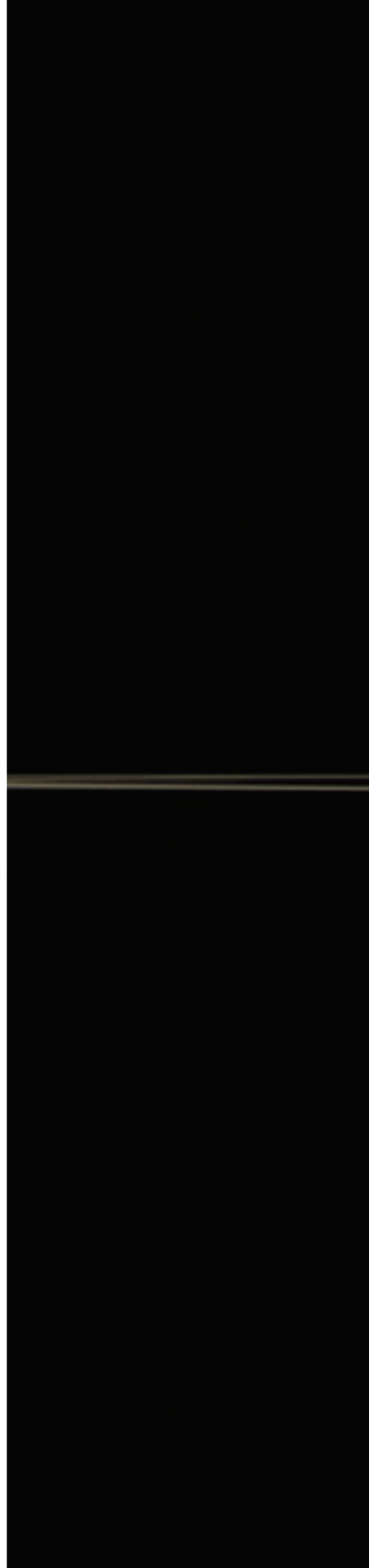
LG 1 Differentiate the giant planets from each other and from the terrestrial planets.

LG 2 Describe the atmosphere of each giant planet.

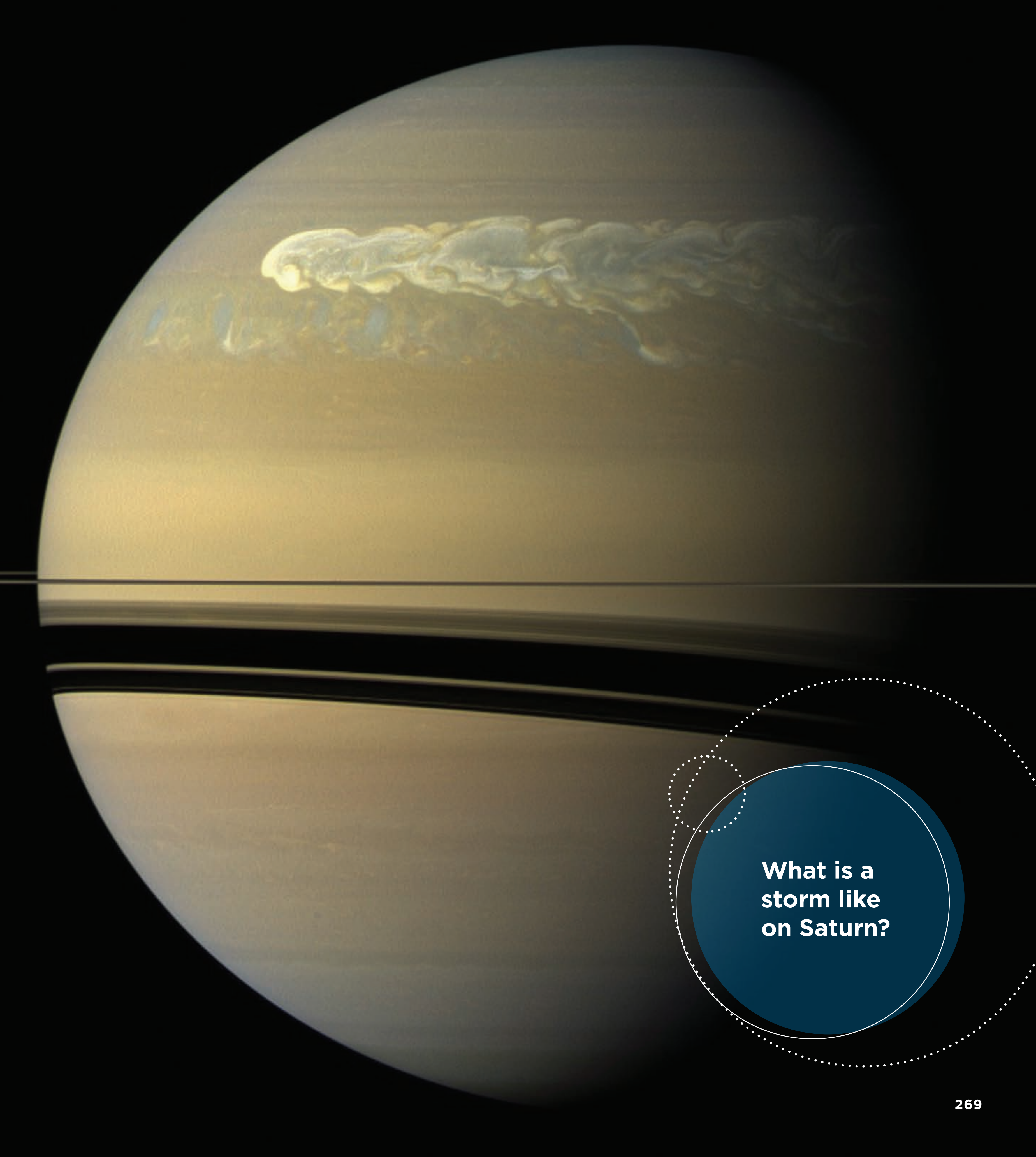
LG 3 Explain the extreme conditions deep within the interiors of the giant planets.

LG 4 Describe the magnetosphere of each of the giant planets.

LG 5 Compare the planets of our Solar System to those in extrasolar planetary systems.



This *Cassini* image was taken at the end of a massive storm in 2010–2011. The red, orange, and green clouds are in false color to highlight more details. ▶▶▶



What is a storm like on Saturn?

TABLE 10.1 Physical Properties of the Giant Planets

	Jupiter	Saturn	Uranus	Neptune
Orbital semimajor axis (AU)	5.20	9.6	19.2	30
Orbital period (Earth years)	11.9	29.5	84.0	164.8
Orbital velocity (km/s)	13.1	9.7	6.8	5.4
Mass ($M_{Earth} = 1$)	317.8	95	14.5	17.1
Equatorial radius (km)	71,490	60,270	25,560	24,300
Equatorial radius ($R_{Earth} = 1$)	11.2	9.5	4.0	3.8
Oblateness	0.065	0.098	0.023	0.017
Density (water = 1)	1.33	0.69	1.27	1.64
Rotation period (hours)	9.9	10.7	17.2	16.0
Tilt (degrees)	3.13	26.7	97.8	28.3
Surface gravity (relative to Earth's)	2.53	1.07	0.89	1.14
Escape speed (km/s)	59.5	35.5	21.3	23.5

10.1 The Giant Planets Are Large, Cold, and Massive

Collectively, Jupiter, Saturn, Uranus, and Neptune are known as the *giant planets*. They are sometimes referred to as the *Jovian planets*, after Jupiter, the largest of the giant planets. (*Jove* is another name for Jupiter, the highest-ranking deity of ancient Rome.) As with the terrestrial planets, we learn much about the giant planets by comparing them to each other. We begin our discussion of the giant planets by comparing their physical properties and their compositions, shown in **Table 10.1**. Comparative planetology is useful both within planetary groups and between groups. Throughout most of the chapter, we will be comparing giant planets with giant planets. But it is useful to fix in your mind as a reference point a comparison of at least one giant planet with Earth. For example, to understand the size of the giant planets, it is helpful to know that Jupiter is 11 times larger than Earth, and its mass is 318 times greater than Earth's. In this section, we examine the physical properties of the giant planets.

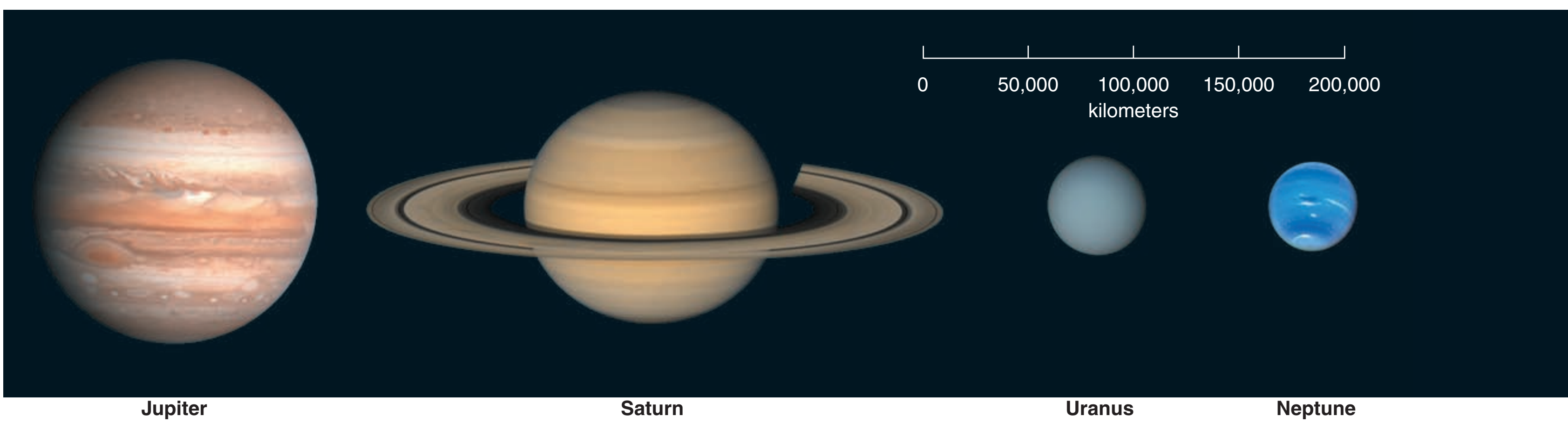
Characteristics of the Giant Planets

The giant planets orbit the Sun far beyond the orbits of Earth and Mars. Jupiter, the closest giant planet, is more than 5 astronomical units (AU) from the Sun. At this distance, the Sun is very faint and provides very little warmth. From Jupiter, the Sun appears to be a tiny disk, 1/27 as bright as it appears from Earth. At the distance of Neptune, the Sun no longer looks like a disk at all: it appears as a brilliant star about 500 times brighter than the full Moon is in Earth's sky. Daytime on Neptune is only as bright as twilight on Earth. With so little sunlight available for warmth, daytime temperatures hover around 123 kelvins (K) at the cloud tops on Jupiter, and they can dip to just 58 K on Neptune.

Jupiter, Saturn, Uranus, and Neptune are enormous compared to the rocky terrestrial planets. Jupiter is the largest of the eight planets and is more than 1/10 the diameter of the Sun. Saturn is slightly smaller than Jupiter, with a diameter of

Figure 10.1 (a) Images of the giant planets, shown to the same physical scale. (b) The same images, scaled according to how the planets would appear as seen from Earth.

(a)



G X U V I R

9.5 Earths. Uranus and Neptune are each about 4 Earth diameters across. **Figure 10.1** compares the actual relative diameters of the giant planets with their apparent relative diameters as seen from Earth.

The most accurate method of finding the diameter of a giant planet is to observe a **stellar occultation**, which occurs when the planet eclipses a star in the sky. As shown in **Figure 10.2**, the star disappears behind the planet and then reappears a short while later. Because we know the relative orbital speeds of Earth and the giant planets, we can calculate the size of the eclipsing giant planet from the length of time the star is eclipsed. Occultations of the radio signals transmitted from orbiting spacecraft and images taken by spacecraft cameras also provide accurate measures of the diameters and shapes of planets and their moons.

Although far away, the giant planets are so large that all but Neptune can be seen with the unaided eye. Jupiter and Saturn were known to the ancients, but Uranus was not discovered until 1781, when William Herschel accidently noticed a tiny disk in the eyepiece of his 6-inch telescope. At first he thought he had found a comet, but the object's slow nightly motion soon convinced him that it was a planet beyond the orbit of Saturn. During the decades that followed Herschel's discovery, astronomers found that Uranus's position differed from the path predicted by Newton's laws of motion and suggested that the gravitational pull of an unknown planet caused Uranus's surprising behavior. Using the astronomers' measured positions of Uranus, two young mathematicians—Urbain-Jean-Joseph Le Verrier (1811–1877) in France and John Couch Adams (1819–1892) in England—independently predicted the location of the hypothetical planet. The German astronomer Johann Gottfried Galle (1812–1910) found the planet on his first observing night, just where Le Verrier and Adams had predicted it would be. Thus, Galle's discovery of Neptune in 1846 became a triumph for mathematical prediction based on physical law—and for the subsequent confirmation of theory by observation (**Process of Science Figure**). Neptune remains

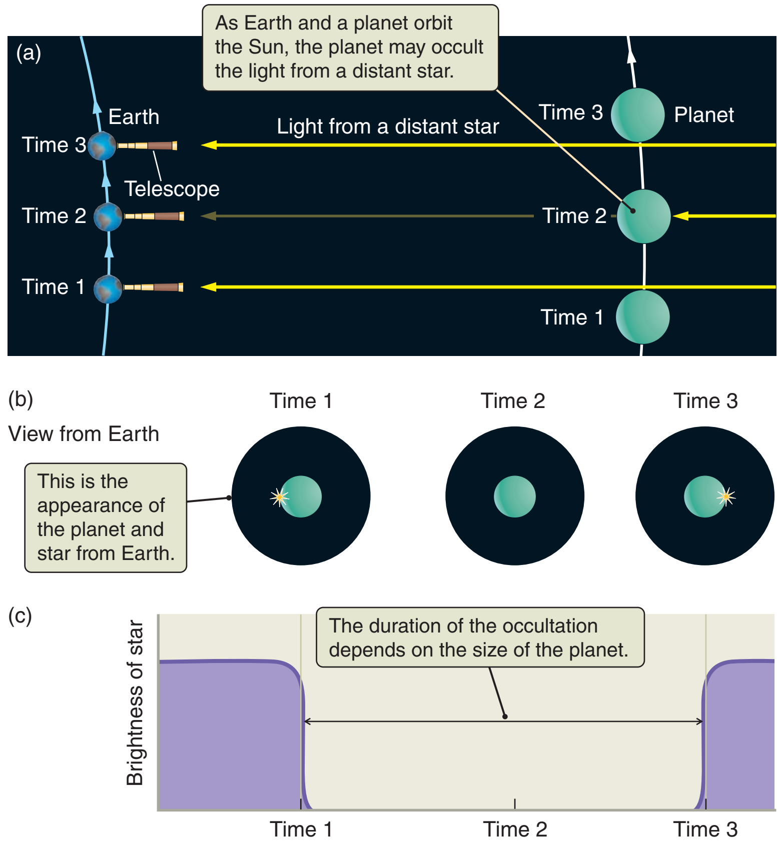
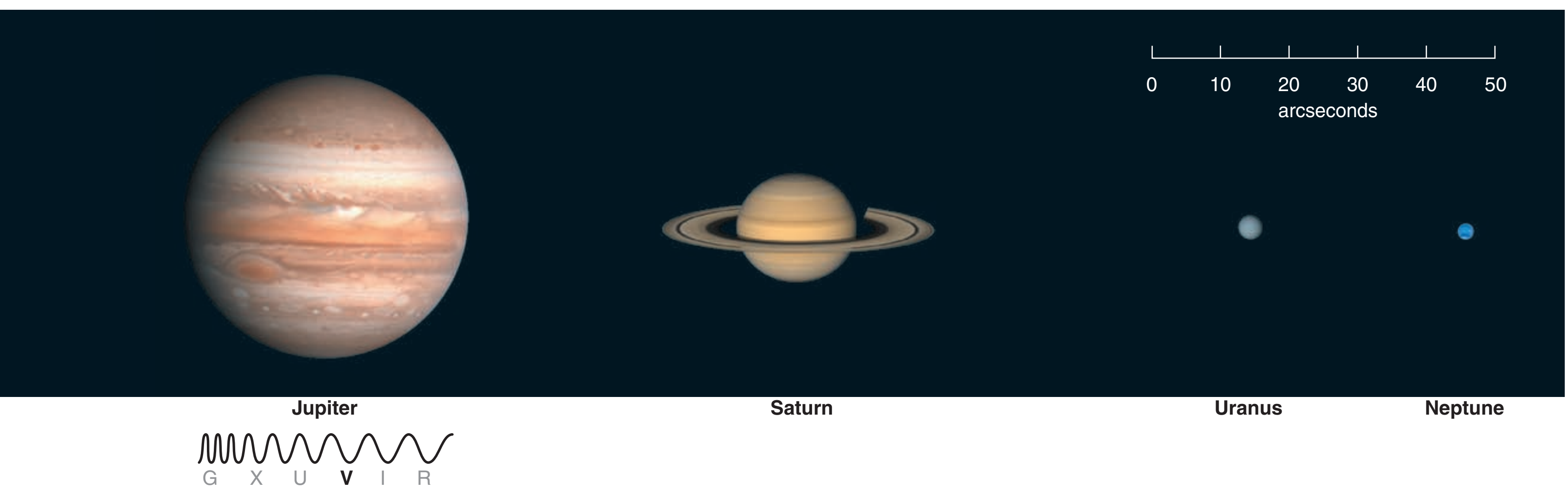


Figure 10.2 (a) Occultations occur when a planet, moon, or ring passes in front of a star. (b) As the planet moves (from right to left as seen from Earth), the starlight is blocked. (c) The amount of time that the star is hidden combined with information about how fast the planet is moving gives the size of the planet.

(b)



Process of Science

SCIENTIFIC LAWS MAKE TESTABLE PREDICTIONS

Newton's laws of motion and gravity do more than describe what we see. They also enable us to predict the existence of things as yet unseen.

Uranus is discovered in 1781.

That's odd. Uranus's orbit does not match predictions.

Could another planet's gravitational pull be acting on Uranus?

Mathematicians use observations of Uranus and Newton's laws to predict the location of another planet.

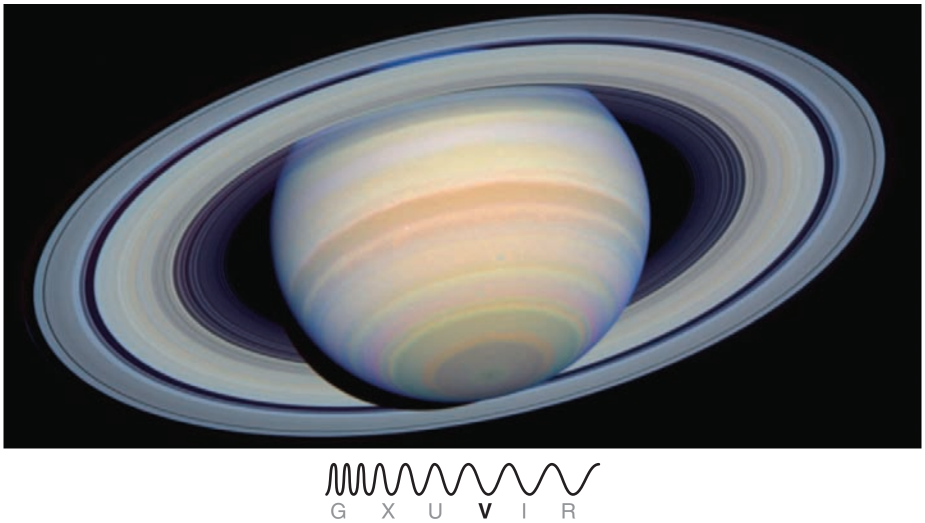
Neptune is discovered in 1846.

Newton's laws pass another test!

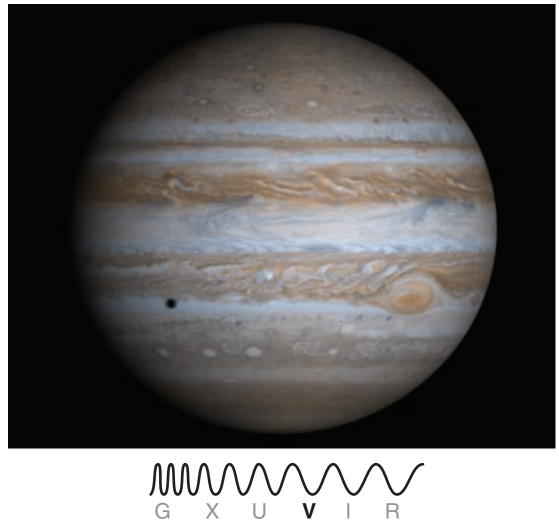
Laws make predictions that can be tested, in order to verify or falsify them. Each test that does not falsify a scientific law strengthens confidence in its predictions.

Figure 10.3 (a) The gas giants: Saturn, seen via the Hubble Space Telescope (HST), and Jupiter, imaged by *Cassini*. (b) The ice giants: Uranus and Neptune, imaged in visible light by *Voyager*.

(a) Saturn



Jupiter



the outermost planet in the Solar System and cannot be seen without the aid of binoculars.

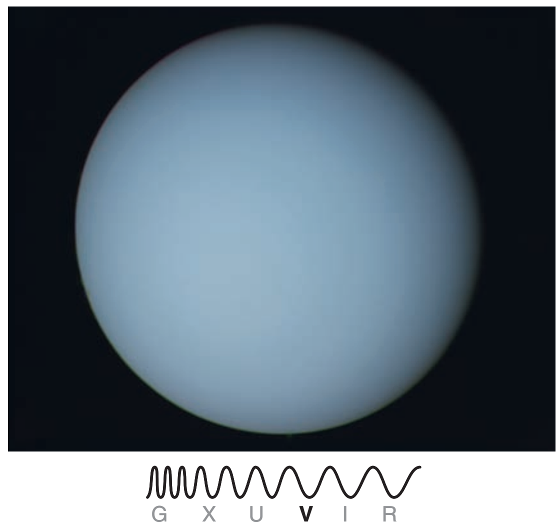
The giant planets contain 99.5 percent of all the nonsolar mass in the Solar System. All other Solar System objects—terrestrial planets, dwarf planets, moons, asteroids, and comets—make up the remaining 0.5 percent. Even though Jupiter is only about a thousandth as massive as the Sun, it contains more than twice the mass of all the other planets combined. Jupiter is 318 times as massive as Earth, 3.3 times as massive as Saturn, and about 20 times as massive as either Uranus or Neptune.

The mass of a planet can be calculated by observing the motions and orbital size of a planet's moon. In Chapter 4, you saw that Newton's law of gravitation and Kepler's third law together show a relation between the motion of an orbiting object and the mass of the body it is orbiting. Planetary spacecraft now make it possible to measure the masses of planets even more accurately. As a spacecraft flies by a planet, the planet's gravity deflects it. By tracking and comparing the spacecraft's radio signals using several antennae here on Earth, astronomers can detect tiny changes in the spacecraft's path and accurately measure the planet's mass.

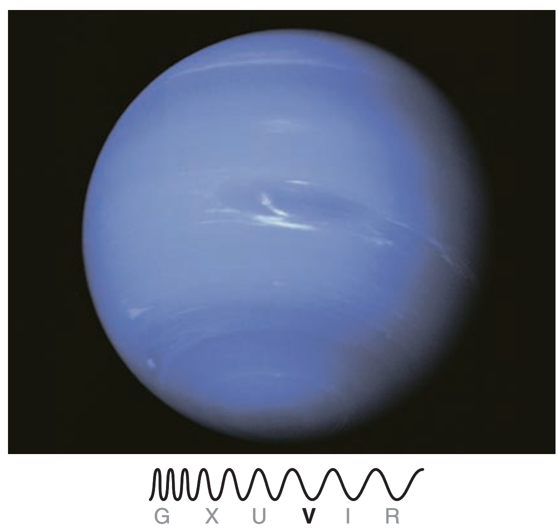
Composition of the Giant Planets

The giant planets are made up primarily of gases and liquids. Jupiter and Saturn are composed of hydrogen and helium and are therefore known as **gas giants**. Uranus and Neptune are known as **ice giants** because they both contain much larger amounts of water and other ices than Jupiter and Saturn. On a giant planet, a relatively shallow atmosphere merges seamlessly into a deep liquid ocean, which in turn merges smoothly into a denser liquid or solid core. There is no abrupt transition from atmosphere to solid ground, as is found on the terrestrial planets. Although the atmospheres of the giant planets are shallow compared with the depth of the liquid layers below, they are still much thicker than the atmospheres of the terrestrial planets—thousands of kilometers rather than hundreds. As with Venus, only the very highest levels of the atmospheres of the gas giants are visible to us. In the case of Jupiter and Saturn, we see the top of a layer of thick clouds that obscures deeper layers (**Figure 10.3a**). There are only a few

(b) Uranus



Neptune



thin clouds visible on Uranus, although atmospheric models suggest that thick cloud layers must lie below. Neptune displays a few high clouds with a deep, clear atmosphere showing between them (Figure 10.3b).

As discussed in Chapter 8, the terrestrial planets are composed mostly of rocky minerals, such as silicates, along with various amounts of iron and other metals. While the atmospheres of the terrestrial planets contain lighter materials, the masses of these atmospheres—and even of Earth's oceans—are insignificant compared with the total planetary masses. The terrestrial planets are the densest objects in the Solar System, with densities ranging from 3.9 (Mars) to 5.5 (Earth) times the density of water. In contrast, the giant planets have lower densities because they are composed almost entirely of lighter materials, such as hydrogen, helium, and water. Among the giant planets, Neptune has the highest density, about 1.6 times that of water. Saturn has the lowest density, only 0.7 times the density of water. This means that Saturn would float—if you had an immobile and deep enough body of water—with 70 percent of its volume submerged. Jupiter and Uranus have densities between those of Neptune and Saturn.

Jupiter's chemical composition is quite similar to that of the Sun—mostly hydrogen and helium. (Recall Figure 5.16, the astronomer's periodic table.) Only 2 percent of Jupiter's mass is made up of **heavy elements**, which astronomers define as all elements more massive than helium. Many of these heavy elements combine chemically with hydrogen (H). For example, atoms of oxygen (O), carbon (C), nitrogen (N), and sulfur (S) combine with hydrogen to form molecules of water (H_2O), methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S). More complex combinations produce materials such as ammonium hydrosulfide (NH_4HS). Jupiter's liquid core, which contains most of the planet's iron and silicate and much of its water, is leftover from the original rocky planetesimals around which Jupiter grew. Computer models of the density are required for an understanding of compositions deep in the cores of the giant planets.

The principal compositional differences among the four giant planets lie in the amounts of hydrogen and helium that each of them contains. Because of its larger mass, Jupiter accumulated more hydrogen and helium when it formed than the other planets did. Saturn is more abundant in heavy elements than Jupiter and therefore less abundant in hydrogen and helium. Heavy elements are significant components of Uranus and Neptune. Methane is a particularly important molecule in the atmospheres of these two planets, giving them their characteristic blue-green color. These differences in composition are important clues to understanding how the giant planets formed.

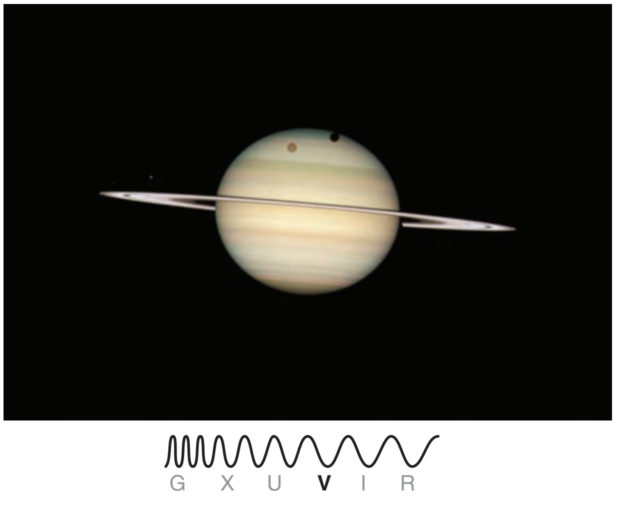


Figure 10.4 This Hubble Space Telescope image of Saturn was taken in 1999. The oblateness of the planet is apparent. The large orange moon Titan appears near the top of the disk of Saturn, along with its black shadow.

Days and Seasons on the Giant Planets

As shown in Table 10.1, giant planets rotate rapidly so their days are short, ranging from 10 to 17 hours. The rapid rotation of the giant planets distorts their shapes—if they did not rotate, they would be perfectly spherical. Instead, the rapidly rotating planets are oblate—they bulge at their equators and have an overall flattened appearance. Saturn's appearance is very oblate: its equatorial diameter is almost 10 percent greater than its polar diameter (**Figure 10.4** and Table 10.1). In comparison, the oblateness of Earth is only 0.3 percent.

Recall from Chapter 2 that the intensity of a planet's seasons is determined by the tilt of its axis. Earth's tilt of 23.5° causes our distinct seasons. The tilts of the giant planets are shown in Table 10.1. With a tilt of only 3°, Jupiter has almost no seasons at all. The tilts of Saturn and Neptune are slightly larger than those of

Earth or Mars, which causes moderate but well-defined seasons. Curiously, Uranus spins on an axis that lies nearly in the plane of its orbit—its tilt is about 98°. Uranus's high tilt causes its seasons to be extreme, with each polar region alternately experiencing 42 years of continual sunshine followed by 42 years of total darkness. Averaged over an entire orbit, the poles receive more sunlight than the equator—a situation quite different from that of any other Solar System planet.

Viewed from Earth, Uranus appears to be either spinning face-on to Earth or rolling along on its side (or something in between), depending on where Uranus happens to be in its orbit. A tilt greater than 90° indicates that the planet rotates in a clockwise direction when seen from above its orbital plane. Why is Uranus tilted so differently from most other planets? One possible explanation is that Uranus was "knocked over" by the impact of one huge or several large planetesimals near the end of its accretion phase. Venus, Pluto, Pluto's moon Charon, and Neptune's moon Triton also have tilts greater than 90°.

CHECK YOUR UNDERSTANDING 10.1

Uranus and Neptune are different from Jupiter and Saturn in that: (a) Uranus and Neptune have a higher percentage of ices in their interiors; (b) Uranus and Neptune have more hydrogen; (c) Uranus and Neptune have no storms; (d) Uranus and Neptune are closer to the Sun.

10.2 The Giant Planets Have Clouds and Weather

When we observe the giant planets through a telescope or in visible images from a spacecraft, we are seeing only the top layers of the atmosphere. In some cases, we can see a bit deeper into the clouds, but in essence, we are seeing a two-dimensional view of the cloud tops. The deeper cloud layers on these giant planets are inferred from physical models of temperature as a function of depth. In this section, we explore the atmospheres of the giant planets.

Viewing the Cloud Tops

Even when viewed through small telescopes, Jupiter is very colorful. Parallel bands, ranging in hue from bluish gray to various shades of orange, reddish brown, and pink, stretch out across its large, pale yellow disk. Astronomers call the darker bands *belts* and the lighter bands *zones*. Many clouds—some dark and some bright, some circular and others more oval—appear along the edges of, or within, the belts. The most prominent of these is a large, red, oval feature in Jupiter's southern hemisphere known as the **Great Red Spot**.

The Great Red Spot (**Figure 10.5**) was first observed more than three centuries ago, shortly after the telescope was invented. Since then, it has varied unpredictably in size, shape, color, and motion as it drifts among Jupiter's clouds. In the 1800s, the Great Red Spot was so large that three Earths could fit inside of it, but now it has shrunk to the size of one. Observations of small clouds circling the perimeter of the Great Red Spot show that it is an enormous atmospheric whirlpool, swirling in a counterclockwise direction with a period of about a week. Its cloud pattern looks a lot like that of a terrestrial hurricane, but it rotates in the

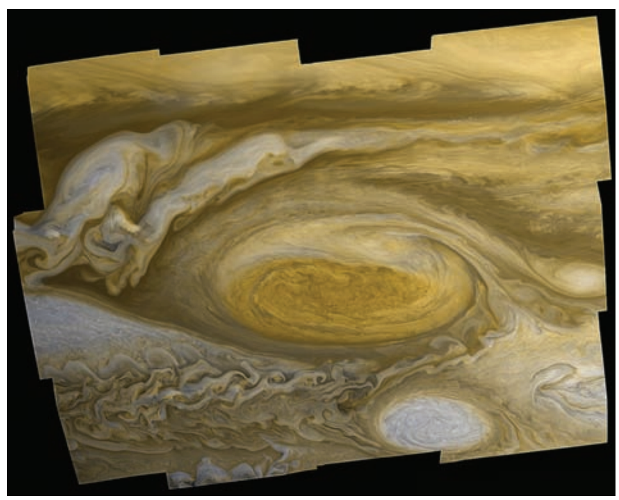


Figure 10.5 This is a digital enhancement of an image of Jupiter taken in 1979 by the *Voyager 1* spacecraft as it flew by Jupiter. The Great Red Spot is a hurricane larger than Earth.

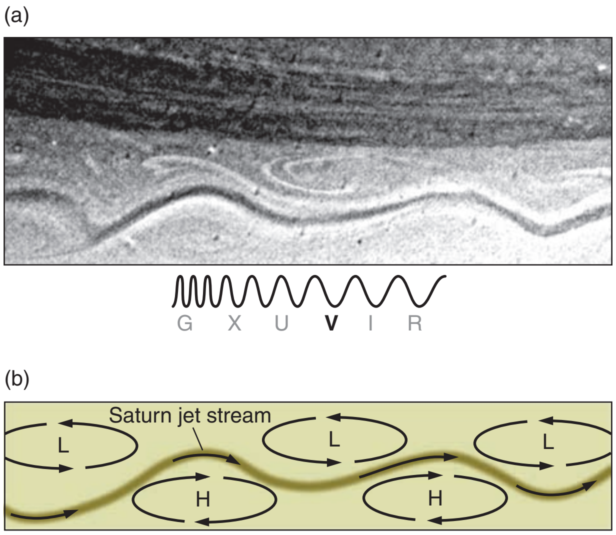


Figure 10.6 (a) This *Voyager* image of a jet stream in Saturn's northern hemisphere is similar to jet streams in Earth's atmosphere. (b) The jet stream dips equatorward below regions of low pressure and is forced poleward above regions of high pressure.

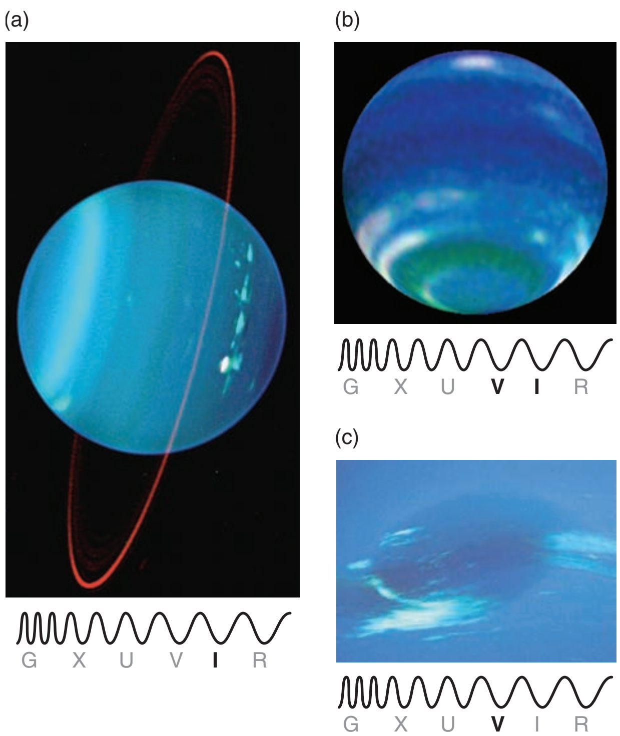


Figure 10.7 The ground-based Keck telescope image of Uranus (a) and Hubble Space Telescope (HST) image of Neptune (b) were taken at wavelengths of light that are strongly absorbed by methane. The visible clouds are high in the atmosphere. (c) The Great Dark Spot on Neptune disappeared between the time *Voyager 2* flew by Neptune in 1989 and the time HST images were obtained in 1994.

opposite direction, exhibiting *anticyclonic* rather than cyclonic flow, an indication of a high-pressure system. Comparable whirlpool-like behavior is observed in many of the smaller oval-shaped clouds found elsewhere in Jupiter's atmosphere and in similar clouds observed in the atmospheres of Saturn and Neptune. Whirlpool-like, swirling features are known as vortices (the singular is vortex). These vortices are familiar to us on Earth as high- and low-pressure systems, hurricanes, and supercell thunderstorms.

Jupiter is a turbulent, swirling giant with atmospheric currents and vortices so complex that scientists still do not fully understand the details of how they interact with one another, even after decades of analysis. In a series of time-lapse images, *Voyager 2* observed a number of Alaska-sized clouds being swept into the Great Red Spot. Some of these clouds were carried around the vortex a few times and then ejected, while others were swallowed up and never seen again. Other smaller clouds with structure and behavior similar to that of the Great Red Spot are seen in Jupiter's middle latitudes.

Because Saturn is farther away than Jupiter and somewhat smaller in radius, from Earth it appears less than half as large as Jupiter (see Figure 10.1b). Saturn also displays atmospheric bands, but they tend to be wider than those on Jupiter, and their colors and contrasts are much more subdued. A relatively narrow, meandering band in the mid-northern latitudes encircles the planet in a manner similar to Earth's jet stream (**Figure 10.6**). The largest atmospheric features on Saturn are about the size of the continental United States, but many are smaller than terrestrial hurricanes. Close-up views from the *Cassini* spacecraft show immense lightning-producing storms in a region of Saturn's southern hemisphere known as "storm alley." Individual clouds on Saturn are not seen often from Earth, but in December 2010 a large storm appeared (see the chapter-opening figure) that was visible in even small amateur telescopes. This large storm eventually wrapped itself around the planet.

From Earth, in most telescopes, Uranus and Neptune look like tiny, featureless, pale bluish green disks. But with the largest ground-based telescopes or the telescopes in space, optical and infrared imaging reveals a number of individual clouds and belts. Images show atmospheric bands and small clouds suggestive of those seen on Jupiter and Saturn, but more subdued (**Figure 10.7a**). The strong absorption of reflected sunlight by methane causes the atmospheres of Uranus and Neptune to appear dark in the near infrared, allowing the highest clouds and bands to stand out in contrast against the dark background.

A number of bright cloud bands appear in the Hubble Space Telescope (HST) image of Neptune's atmosphere (Figure 10.7b). Located near the planet's tropopause, these cloud bands cast their shadows downward through the clear upper atmosphere onto a dense cloud layer 50 km below. A large, dark, oval feature seen in the southern hemisphere first observed in images taken by *Voyager 2* in 1989 reminded astronomers of Jupiter's Great Red Spot, so they called it the Great Dark Spot (Figure 10.7c). However, the Neptune feature was gray rather than red, and it changed in length and shape more rapidly than the Great Red Spot. When HST observed Neptune in 1994, the Great Dark Spot had disappeared, but a different dark spot of comparable size had appeared briefly in Neptune's northern hemisphere.

The Structure Below the Cloud Tops

Although our visual impression of the giant planets from Earth is based on a two-dimensional view of their cloud tops, atmospheres are three-dimensional structures. As we saw when we discussed the terrestrial planets, atmospheric temperature, density, pressure, and even chemical composition vary with height and over horizontal distances. As a rule, atmospheric temperature, density, and pressure all decrease with increasing altitude, although temperature is sometimes higher at very high altitudes, as in Earth's thermosphere. The stratospheres above the cloud tops of the giant planets appear relatively clear, but closer inspection shows that they contain layers of thin haze that show up best when seen in profile above the edges of the planets. The composition of the haze particles remains unknown, but they may be smoglike products created when ultraviolet sunlight acts on hydrocarbon gases such as methane.

Water is the only substance in Earth's lower atmosphere that can condense into clouds, but the atmospheres of the giant planets have a much larger range of temperatures and pressures, so more kinds of volatiles can condense and form clouds. (Recall that volatiles are materials that become gases at moderate temperatures.) **Figure 10.8** shows how the ice layers are stacked in the tropospheres of the giant planets. Because each kind of volatile, such as water or ammonia, condenses at a particular temperature and pressure, each forms clouds at a different altitude. Convection carries volatile materials upward along with other atmospheric gases, and when each particular volatile reaches an altitude with its condensation temperature, most of that volatile condenses and separates from the other gases, so very little of it is carried higher aloft. These volatiles form dense layers of cloud separated by regions of relatively clear atmosphere.

The farther the planet is from the Sun, the colder its troposphere will be. Therefore, the distance from the Sun determines the altitude at which a particular volatile, such as ammonia or water, will condense to form a cloud layer on each of the planets. If temperatures are too high, some volatiles may not condense at all. The highest clouds in the frigid atmospheres of Uranus and Neptune are crystals of methane ice. The highest clouds on Jupiter and Saturn are made up of ammonia ice. Methane never freezes to ice in the warmer atmospheres of Jupiter and Saturn.

In 1995, an atmospheric probe on the *Galileo* spacecraft descended slowly via parachute into the atmosphere of Jupiter. Near the top of Jupiter's troposphere at a temperature of about 130 K (about –140°C), it found that ammonia had condensed. Next it found a layer of ammonium hydrosulfide clouds at a temperature of about 190 K (about –80°C). Soon after descending to an atmospheric pressure of 22 bars and a temperature of about 373 K (100°C), the *Galileo* probe failed, presumably because its transmitter got too hot. The *Juno* mission that is expected to enter an orbit around Jupiter in 2016 will use infrared and microwave instruments to further analyze the atmosphere.

Why are some clouds so colorful, especially Jupiter's? In their purest form, the ices that make up the clouds of the giant planets are all white, similar to snow on Earth. The colorful tints and hues must come from impurities in the ice crystals, similar to how syrups color snow cones. These impurities are elemental sulfur and phosphorus, as well as various organic materials produced when ultraviolet sunlight breaks up hydrocarbons such as methane, acetylene, and ethane. The molecular fragments can then recombine to form complex organic compounds that condense into solid particles, many of which are quite colorful. These reactions also occur in Earth's atmosphere. Some of the photochemical products produced close to the ground on Earth are called *smog*.

The atmospheric composition of Uranus and Neptune give these planets their bluish green color. The upper tropospheres of Uranus and Neptune are relatively

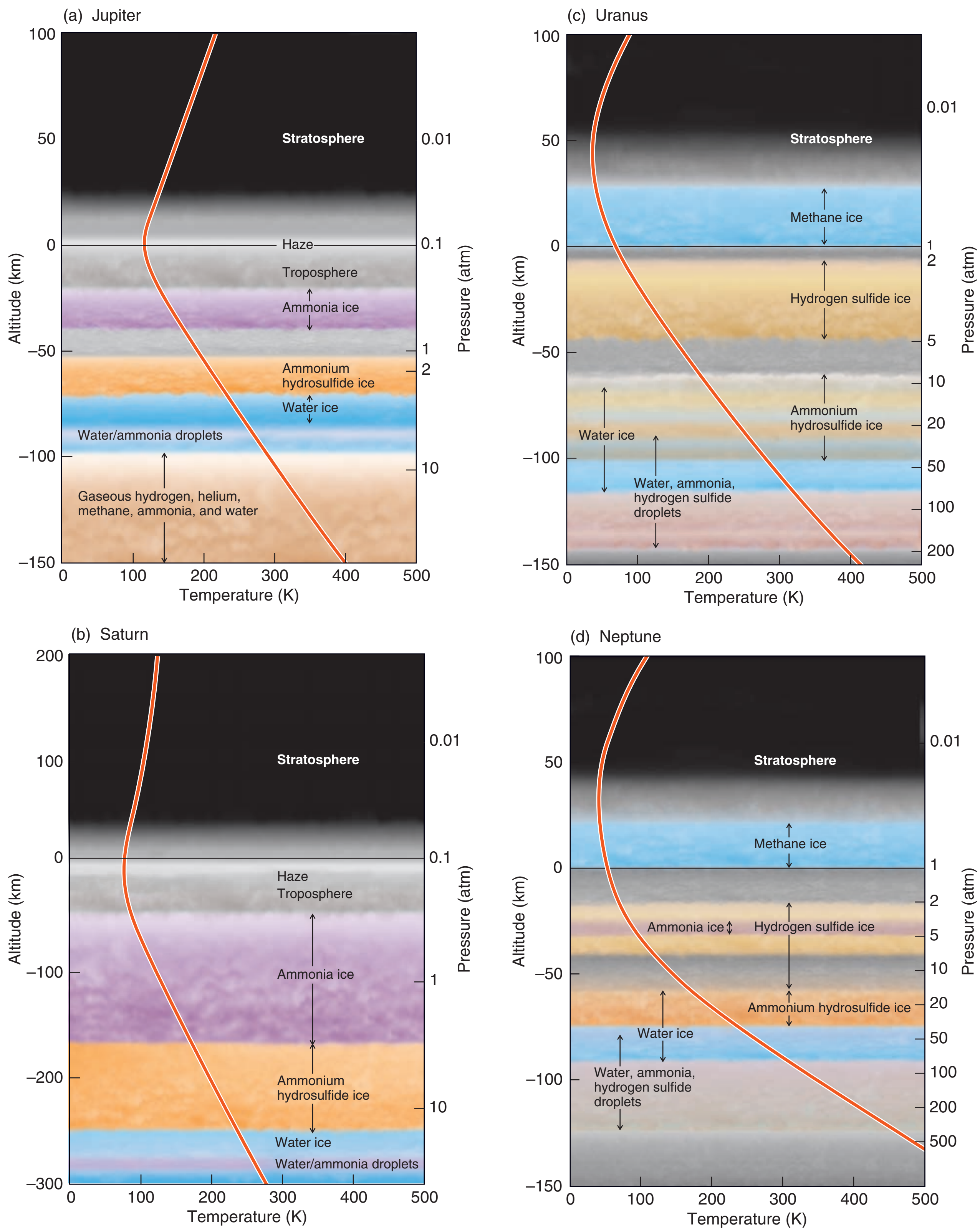


Figure 10.8 Volatile materials condense at different levels in the atmospheres of the giant planets, leading to chemically different types of clouds at different depths in the atmospheres. The red line in each diagram shows how atmospheric temperature changes with height. Because these planets have no solid surface, the zero point of altitude is arbitrary. In these figures, the arbitrary zero points of altitude are at 0.1 atmosphere (atm) for Jupiter (a) and Saturn (b) and at 1.0 atm for Uranus (c) and Neptune (d). The value of 1.0 atm corresponds to the atmospheric pressure at sea level on Earth. Note that Saturn's altitude scale is compressed to show the layered structure better.

clear, with only a few white clouds that are probably composed of methane ice crystals. Methane gas is much more abundant in the atmospheres of Uranus and Neptune than in those of Jupiter and Saturn. Like water, methane gas tends to selectively absorb the longer wavelengths of light—yellow, orange, and red. Absorption of the longer wavelengths leaves only the shorter wavelengths—green and blue—to be scattered from the atmospheres of Uranus and Neptune.

Winds and Weather

On the giant planets, the thermal energy that drives convection comes both from the Sun and from the hot interiors of the planets themselves. Recall from Chapter 9 that convection results from vertical temperature differences. As heating drives air up and down, the Coriolis effect shapes that convection into atmospheric vortices, visible as isolated circular or oval cloud structures, such as the Great Red Spot on Jupiter and the Great Dark Spot on Neptune. As the atmosphere rises near the center of a vortex, it expands and cools. Cooling condenses certain volatile materials into liquid droplets, which then fall as rain. As they fall, the raindrops collide with surrounding molecules, stripping electrons from the molecules and thereby developing tiny electric charges in the air. The cumulative effect of countless falling raindrops can be an electric field so great that it ionizes the molecules in the atmosphere and creates a surge of current and a flash of lightning. A single observation of Jupiter's night side by *Voyager 1* revealed several dozen lightning bolts within an interval of 3 minutes. *Cassini* has also imaged lightning flashes in Saturn's atmosphere, and radio receivers on *Voyager 2* picked up lightning static in the atmospheres of both Uranus and Neptune.

The giant planets have much stronger zonal winds than the terrestrial planets. Because they are farther from the Sun, less thermal energy is available. However, they rotate rapidly, which makes the Coriolis effect very strong. In fact, the Coriolis effect is more important than atmospheric temperature patterns in determining the structure of the global winds. If we know the radius of the planet, we can find out how fast the features are moving, as shown in **Working It Out 10.1**, and find rotation speeds and wind speeds. **Figure 10.9** shows the wind speeds at various latitudes on the different planets.

Jupiter On Jupiter, the strongest winds are equatorial, blowing from the west, at speeds up to 550 kilometers per hour (km/h), as seen in Figure 10.9a. At higher latitudes, the winds alternate between blowing from the west or east in a pattern that might be related to Jupiter's banded structure. Near a latitude of 20° south, the Great Red Spot vortex appears to be caught between a pair of winds blowing from the west and east with opposing speeds of more than 200 km/h. This indicates a relationship between zonal flow and vortices.

Saturn The equatorial winds on Saturn also blow from the west but are stronger than those on Jupiter. The maximum wind speeds at any given time vary between 990 km/h and 1,650 km/h. Saturn's winds appear to decrease with height in the atmosphere, so the apparent time variability of Saturn's equatorial winds may be nothing more than changes in the height of the cloud tops. Alternating winds blowing from the east or west also occur at higher latitudes; but unlike on Jupiter, this alternation seems to bear no clear association with Saturn's atmospheric bands, shown in Figure 10.9b. This is just one example of the many unexplained differences among the giant planets.

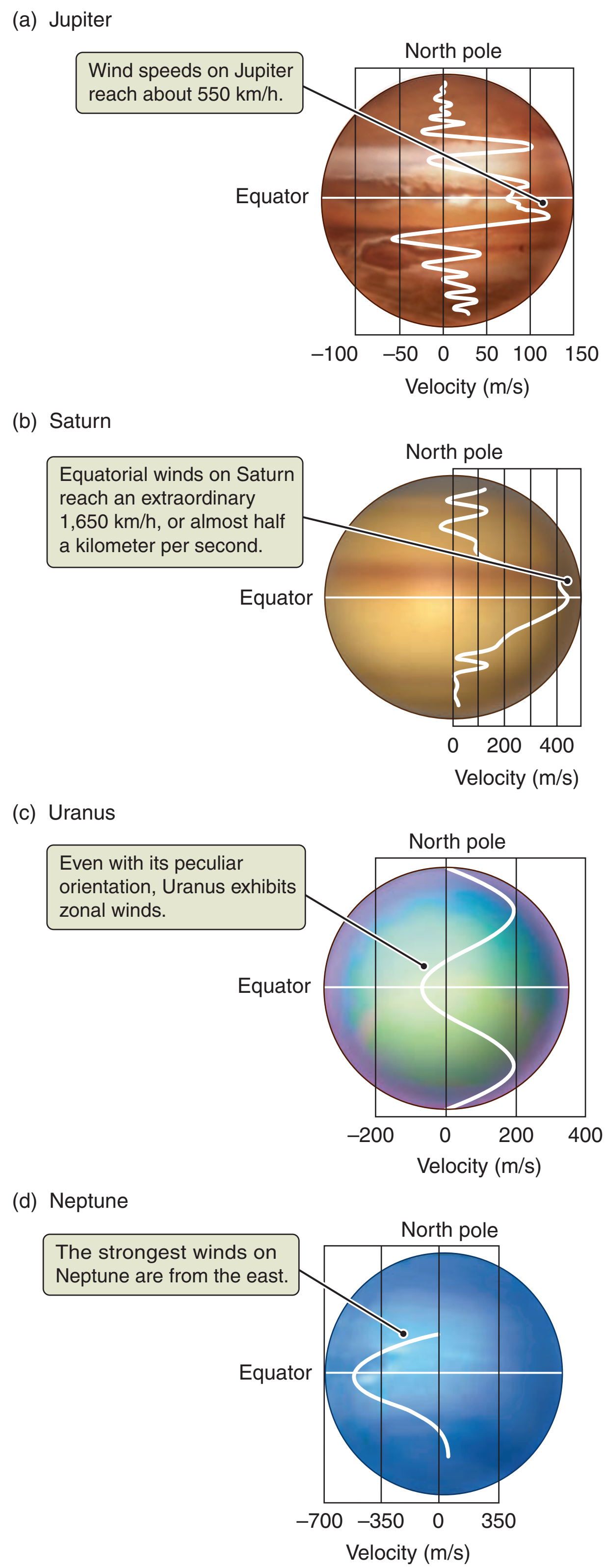


Figure 10.9 The speed of the wind at various latitudes on the giant planets is shown by the white line. When the speed is positive (to the right of zero), the wind is from the west. When the speed is negative (to the left of zero), the wind is from the east.

10.1 Working It Out Measuring Wind Speeds on Different Planets

How do astronomers measure wind speeds on planets that are so far away? As on Earth, clouds are carried by local winds. The local wind speed can be calculated by measuring the positions of individual clouds and noting how much they move during a time interval. To find the speed of the wind relative to the planet's rotating surface, the rotation speed of the planet must also be known. In the case of the giant planets, there is no solid surface against which to measure the winds. Scientists must instead assume a hypothetical surface—one that rotates as though it were somehow "connected" to the planet's deep interior. This is usually found from observing periodic bursts of radio waves that are generated as the planet's magnetic field rotates.

Let's look at an example of how this works using a small white cloud in Neptune's atmosphere. The cloud, on Neptune's equator, is observed to be at longitude 73.0° west on a given day. (This longitude system is anchored in the planet's deep interior.) The spot is then seen at longitude 153.0° west exactly 24 hours later. Neptune's equatorial winds have carried the white spot 80.0° in longitude in 24 hours.

The circumference, C, of a planet is given by $2\pi r$, where r is the equatorial radius. The equatorial radius of Neptune is 24,760 km. So Neptune's circumference is

$$C = 2\pi r = 2\pi \times 24{,}760\ \text{km} = 155{,}600\ \text{km}$$

There are 360° of longitude in the full circle represented by the circumference. The spot has moved 80°/360° of the circumference and thus has traveled

$$\frac{80}{360} \times 155{,}600\ \text{km} = 34{,}580\ \text{km}$$

in 24 hours. This means that the wind speed is given by

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}} = \frac{34{,}580\ \text{km}}{24\ \text{h}} = 1{,}440\ \text{km/h} = 400\ \text{m/s}$$

The equatorial winds are very strong and are blowing in a direction opposite to the planet's rotation. On Earth, the much slower equivalents of these winds are called *trade winds*.

Saturn's jet stream, at latitude 45° north, is a narrow meandering river of atmosphere with alternating crests and troughs, curving around regions of high and low pressure to create a wavelike structure. It is similar to Earth's jet streams, where high-speed winds blow generally from west to east but wander toward and away from the poles. Nested within the crests and troughs of Saturn's jet stream are anticyclonic and cyclonic vortices. They appear remarkably similar in both form and size to terrestrial high- and low-pressure systems, which bring alternating periods of fair and stormy weather.

Uranus Less is known about global winds on Uranus, illustrated in Figure 10.9c, than about those on the other giant planets. When *Voyager 2* flew by Uranus in 1986, the few visible clouds were in the southern hemisphere because the northern hemisphere was in complete darkness at the time. The strongest winds observed were 650 km/h from the west in the middle to high southern latitudes, as shown in Figure 10.9c, and no winds from the east were seen. Because Uranus's peculiar orientation makes its poles warmer than its equator, some astronomers had predicted that the global wind system of Uranus might be very different from that of the other giant planets. But *Voyager 2* observed that the Coriolis force dominate on Uranus as they do on other planets, so the dominant winds on Uranus are zonal, just as they are on the other giant planets.

As Uranus moves along in its orbit, regions previously unseen by modern telescopes have become visible (**Figure 10.10**). Observations by HST and ground-based telescopes showed bright cloud bands in the far north extending more than 18,000 km in length and revealed wind speeds of up to 900 km/h. As Uranus approaches northern summer solstice in the year 2027, much more about its northern hemisphere will be learned.

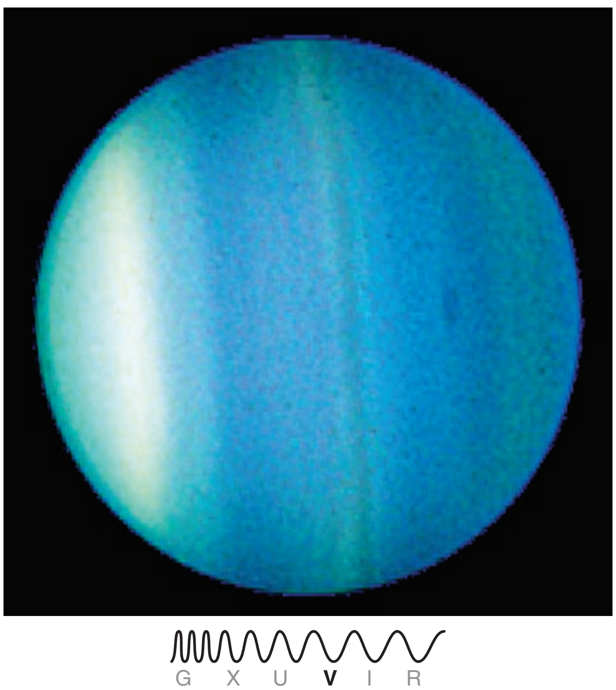


Figure 10.10 Uranus is approaching equinox in this 2006 HST image. Much of its northern hemisphere is becoming visible. The dark spot in the northern hemisphere (to the right) is similar to but smaller than the Great Dark Spot seen on Neptune in 1989.

Neptune On Neptune, the southern hemisphere's summer solstice occurred in 2005, so much of the north is still in darkness. Observers will have to wait until Neptune's equinox in 2045 to see its northern hemisphere. As shown in Figure 10.9d, the strongest winds on Neptune occur in the tropics, similar to winds on Jupiter and Saturn. However, on Neptune the winds are from the east rather than from the west, with speeds in excess of 2,000 km/h. Winds from the west with speeds higher than 900 km/h have been seen in Neptune's south polar regions. With wind speeds 5 times greater than those of the fiercest hurricanes on Earth, Neptune and Saturn are the windiest planets known.

CHECK YOUR UNDERSTANDING 10.2

Why is Jupiter reddish in color? (a) because it is very hot; (b) because of the composition of its atmosphere; (c) because it is moving very quickly; (d) because it is rusty, like Mars.

10.3 The Interiors of the Giant Planets Are Hot and Dense

At the center of each giant planet is a dense, liquid core consisting of a very hot mixture of heavier materials such as water, molten rock, and metals. **Figure 10.11** illustrates the interior structure of the giant planets. As you can see, the gas giants differ from the ice giants in their amounts of hydrogen and ices. We will look at each in turn.

The Cores of Jupiter and Saturn

The overlying layers of Jupiter and Saturn press down upon the liquid core, which raises the temperature. For example, the pressure at Jupiter's core is about 45 million bars, and this high pressure heats the fluid to 35,000 K. Central temperatures and pressures of the other, less massive giant planets are correspondingly lower than those of Jupiter. Water is still liquid at these temperatures of tens of thousands of degrees because the extremely high pressures at the centers of the giant planets prevent water from turning to steam.

The internal energy that lies deep within the giant planets is a leftover from their formation. The giant planets are still contracting and converting their gravitational potential energy into thermal energy today as they did when they first formed, but they are doing it more slowly. The annual amount of contraction necessary to sustain their internal temperature is only a tiny fraction of their radius. Jupiter, for example, is contracting by about 2 centimeters per year (cm/yr). The thermal energy from the core drives convection in the atmosphere and eventually escapes to space as radiation (**Working It Out 10.2**). In addition, in Saturn's case, and perhaps Jupiter's, under the right conditions, liquid helium separates from a hydrogen-helium mixture and rains downward toward the core. As the droplets of liquid helium sink, they release their gravitational potential energy as thermal energy. Planetary physicists think that most of Saturn's internal energy and perhaps some of Jupiter's internal energy come from this separation of liquid helium. The continual production of thermal energy is sufficient to replace the energy that is escaping from their interiors.

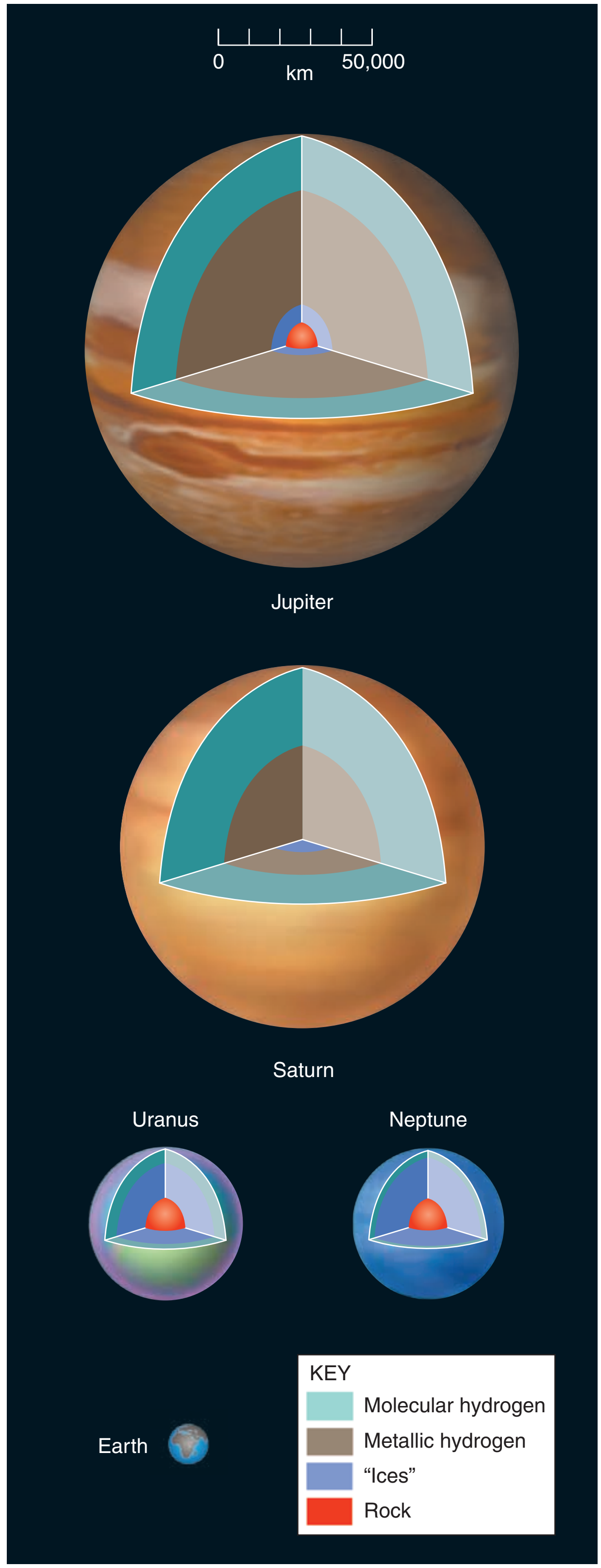


Figure 10.11 The interiors of the giant planets have central cores and outer liquid shells. Only Jupiter and Saturn have significant amounts of the molecular and metallic forms of liquid hydrogen surrounding their cores.

10.2 Working It Out Internal Thermal Energy Heats the Giant Plants

Chapter 5 described the equilibrium between the absorption of sunlight and the radiation of infrared light into space, and in Chapter 9 we explained how the resulting equilibrium temperature is modified by the greenhouse effect on Venus, Earth, and Mars. When we calculate this equilibrium for the giant planets, it doesn't match the measurements. According to these calculations, the equilibrium temperature for Jupiter should be 109 K, but when it is measured, scientists find instead an average temperature of about 124 K. A difference of 15 K might not seem like much, but remember that according to the Stefan-Boltzmann law, the energy radiated by an object depends on its temperature raised to the fourth power. Applying this relationship to Jupiter, we get:

$$\left(\frac{T_{\text{actual}}}{T_{\text{expected}}}\right)^4 = \left(\frac{124\text{ K}}{109\text{ K}}\right)^4 = 1.67$$

This implies that Jupiter is radiating roughly two-thirds more energy into space than it absorbs from sunlight. Similarly, the internal energy escaping from Saturn is observed to be about 1.8 times greater than the sunlight that it absorbs. Neptune emits 2.6 times more energy than it absorbs from the Sun. Therefore, these planets are not in equilibrium; they are slowly contracting and thus generating more heat. However, the internal energy escaping from Uranus is small compared to the absorbed solar energy.

The pressure within the atmospheres of Jupiter and Saturn increases with depth because overlying layers of atmosphere press down on lower layers. At depths of a few thousand kilometers, the atmospheric gases of Jupiter and Saturn are so compressed by the weight of the overlying atmosphere that they turn to liquid. This roughly marks the lower boundary of the atmosphere. The difference between a liquid and a highly compressed, very dense gas is subtle, so on Jupiter and Saturn there is no clear boundary between the atmosphere and the ocean of liquid that lies below. Jupiter's atmosphere is about 20,000 km deep, and Saturn's atmosphere is about 30,000 km deep; at these depths, the pressure climbs to 2 million bars and the temperature reaches 10,000 K (hotter than the surface of the Sun). Under these conditions, hydrogen molecules are battered so violently that their electrons are stripped free, and the hydrogen acts like a liquid metal. In this state, it is called metallic hydrogen. These oceans of hydrogen and helium are tens of thousands of kilometers deep. Uranus and Neptune are less massive than Jupiter and Saturn, have lower interior pressures, and contain a smaller fraction of hydrogen—their interiors probably contain only a small amount of liquid hydrogen, with little or none of it in a metallic state.

Differentiation has occurred and is still occurring in Saturn, and perhaps in Jupiter, too. On Saturn, helium condenses out of the hydrogen-helium oceans. Helium can also be compressed to a metal, but it does not reach this metallic state under the physical conditions existing in the interiors of the giant planets. Because these droplets of helium are denser than the hydrogen-helium liquid in which they condense, they sink toward the center of the planet, converting gravitational energy to thermal energy. This process heats the planet and enriches the helium concentration in the core while depleting it in the upper layers. In Jupiter's hotter interior, by contrast, the liquid helium is mostly dissolved together with the liquid hydrogen.

The heavy-element components of the cores of Jupiter and Saturn have masses of about 5–20 Earth masses. Jupiter and Saturn have total masses of 318 and 95 Earth masses, respectively. The heavy materials in their cores contribute little to their average chemical composition. This means Jupiter and Saturn have approximately the same composition as the Sun and the rest of the universe: about 98 percent hydrogen and helium, leaving only 2 percent for everything else.

The Cores of Uranus and Neptune

Uranus and Neptune are less massive than Jupiter and Saturn, have lower interior pressures, and contain smaller fractions of hydrogen—their interiors probably contain only a small amount of liquid hydrogen, with little or none of it in a metallic state. Uranus and Neptune are made of denser material than Saturn and Jupiter. Neptune, the densest of the giant planets, is about 1.6 times denser than water and only about half as dense as rock. Uranus is less dense than Neptune. These observations tell us that water and other low-density ices, such as ammonia and methane, must be the major compositional components of Uranus and Neptune, along with lesser amounts of silicates and metals. The total amount of hydrogen and helium in these planets is probably limited to no more than 1 or 2 Earth masses, and most of these gases reside in the relatively shallow atmospheres of the planets. Computer simulations suggest that under their conditions of high pressure and temperature, the water that makes up so much of Uranus and Neptune might be *super-ionic*, a state in-between a liquid and a solid that behaves like both.

Why do Jupiter and Saturn have so much hydrogen and helium compared with Uranus and Neptune? We have seen that although each of the giant planets formed around cores of rock and metal, they turned out differently. These differences are an important clue to their origins. The variation may be due to the time that it took for these planets to form and to the distribution of material from which they formed. The cores of Uranus and Neptune were smaller and formed much later than those of Jupiter and Saturn, at a time when most of the gas in the protoplanetary disk had been blown away by the emerging Sun. The icy planetesimals from which they formed were more widely dispersed at their greater distances from the Sun. With more space between planetesimals, their cores would have taken longer to build up. Saturn may have captured less gas than Jupiter both because its core formed somewhat later and because less gas was available at its greater distance from the Sun. As we will discuss in the Origins section later, some astronomers hypothesize that Uranus and Neptune might have formed in a location different from where they are now.

CHECK YOUR UNDERSTANDING 10.3

The interiors of the giant planets are heated by gravitational contraction. We know this because: (a) the cores are very hot; (b) the giant planets radiate more energy than they receive from the Sun; (c) the giant planets have strong winds; (d) the giant planets are mostly atmosphere.

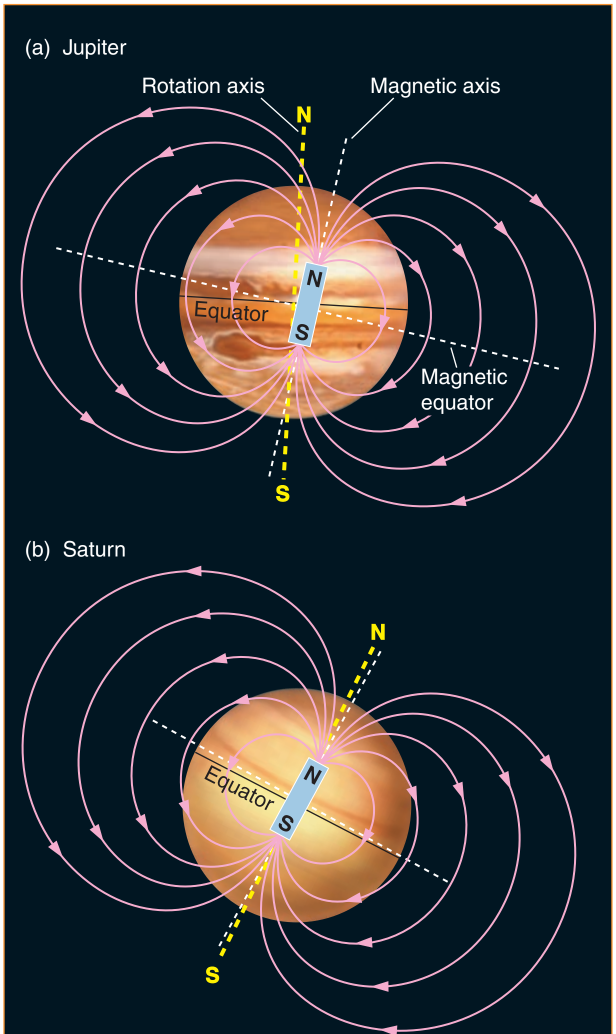
10.4 The Giant Planets Are Magnetic Powerhouses

All of the giant planets have magnetic fields that are much stronger than Earth's: their field strengths range from 50 to 20,000 times stronger. However, because field strength falls off with distance, fields at the cloud tops of Saturn, Uranus, and Neptune are comparable in strength to Earth's surface field. Even in the case of Jupiter's exceptionally strong field, the field strength at the cloud tops is only about 15 times that of Earth's surface field. In Jupiter and Saturn, circulating currents within deep layers of metallic hydrogen generate magnetic fields. In Uranus and Neptune, magnetic fields arise within deep oceans of water and ammonia made electrically conductive by dissolved salts or ionized molecules. The magnetospheres of the giant planets are very large and interact with both the solar wind (as Earth's does) and the rings and moons that orbit the giant planets.

The Size and Shape of the Magnetospheres

Just as Earth's magnetic field traps energetic charged particles to form Earth's magnetosphere, the magnetic fields of the giant planets also trap energetic particles to form magnetospheres of their own. By far, the most colossal of these is Jupiter's magnetosphere. Its radius is 100 times that of the planet itself, roughly 10 times the radius of the Sun. Even the relatively weak magnetic fields of Uranus and Neptune form magnetospheres that are comparable in size to the Sun. Evidence of the giant planets' magnetospheres comes from spacecraft in the outer Solar System, from telescopes orbiting Earth, and from radio emissions received on Earth.

Figure 10.12 illustrates the geometry of the magnetic fields of the giant planets as if they came from bar magnets. The differences in the orientations of the magnetic field axes are not well understood. Jupiter's magnetic axis is inclined 10° to its rotation axis—an orientation similar to Earth's—but it is offset about a tenth of a radius from the planet's center. Saturn's magnetic axis is located almost precisely at the planet's center and is almost perfectly aligned with the rotation axis. The magnetic axis of Uranus is inclined nearly 60° to its rotation axis and is offset by a third of a radius from the planet's center. The orientation of Neptune's rotation axis is similar to that of Earth, Mars, and Saturn. But Neptune's magnetic-field axis is inclined 47° to its rotation axis, and the center of this magnetic field is displaced from the planet's center by more than half the radius—an offset even greater than that of Uranus. The field is displaced primarily toward Neptune's southern hemisphere, thereby creating a field 20 times stronger at the southern



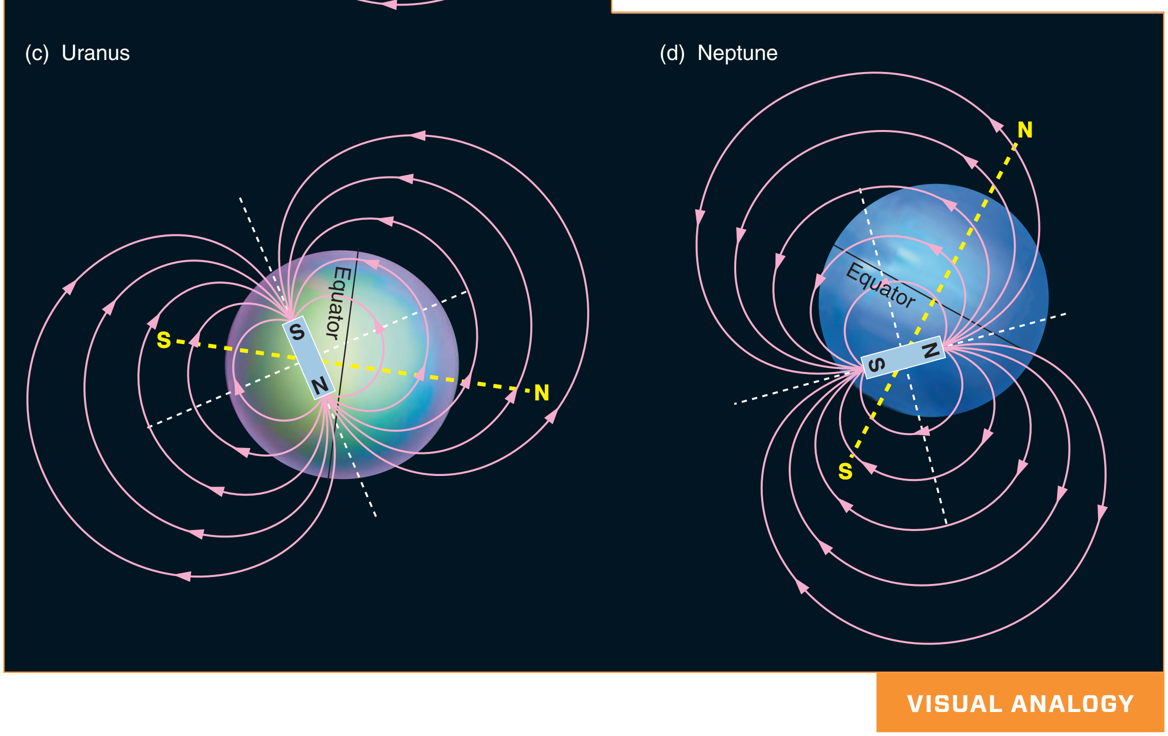


Figure 10.12 The magnetic fields of the giant planets can be approximated by the fields from bar magnets offset and tilted with respect to the planets' axes. Compare these with Earth's magnetic field, shown in Figure 8.12.

cloud tops than at the northern cloud tops. The reason for the unusual geometries of the magnetic fields of Uranus and Neptune remains uncertain, but it is not related to the orientations of their rotation axes.

The magnetosphere is also influenced by solar wind. Recall from Chapter 9 that the solar wind supplies some of the particles for a magnetosphere. In addition, the pressure of the solar wind also pushes on and compresses a magnetosphere, so the size and shape of a planet's magnetosphere depends on how the solar wind is blowing at any particular time. Planetary magnetic fields also divert the solar wind, which flows around magnetospheres the way a stream flows around boulders. Just as a rock in a river creates a wake that extends downstream as illustrated in **Figure 10.13a**, the magnetosphere of a planet produces a wake that can extend for great distances.

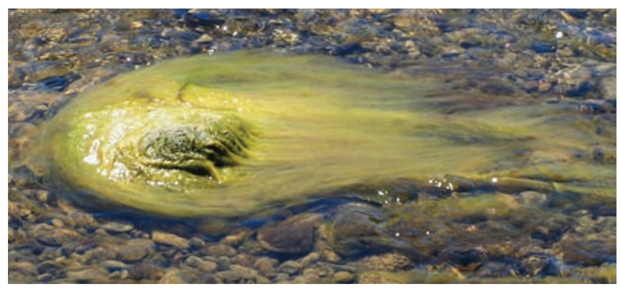
Figure 10.13b shows that the wake of Jupiter's magnetosphere extends well past the orbit of Saturn. Jupiter's magnetosphere is the largest permanent "object" in the Solar System, surpassed in size only by the tail of an occasional comet. If your eyes were sensitive to radio waves, then the second-brightest object in the sky would be Jupiter's magnetosphere. The Sun would still be brighter, but even at a distance from Earth of 4.2–6.2 AU, Jupiter's magnetosphere would appear roughly twice as large as the Sun in the sky.

Saturn's magnetosphere would also be large enough to see, if we could see radio waves, but it would be much fainter than Jupiter's. Even though Saturn has a strong magnetic field, pieces of rock, ice, and dust in Saturn's spectacular rings act like sponges, soaking up magnetospheric particles soon after those particles enter the magnetosphere. With far fewer magnetospheric electrons, there is much less radio emission from Saturn. The magnetic tails of Uranus and Neptune have a curious structure. For both Uranus and Neptune, the tilt and the large displacement of the magnetic field from the center of each planet cause the magnetosphere to wobble as the planet rotates. This wobble causes the tail of the magnetosphere to twist like a corkscrew as it stretches away.

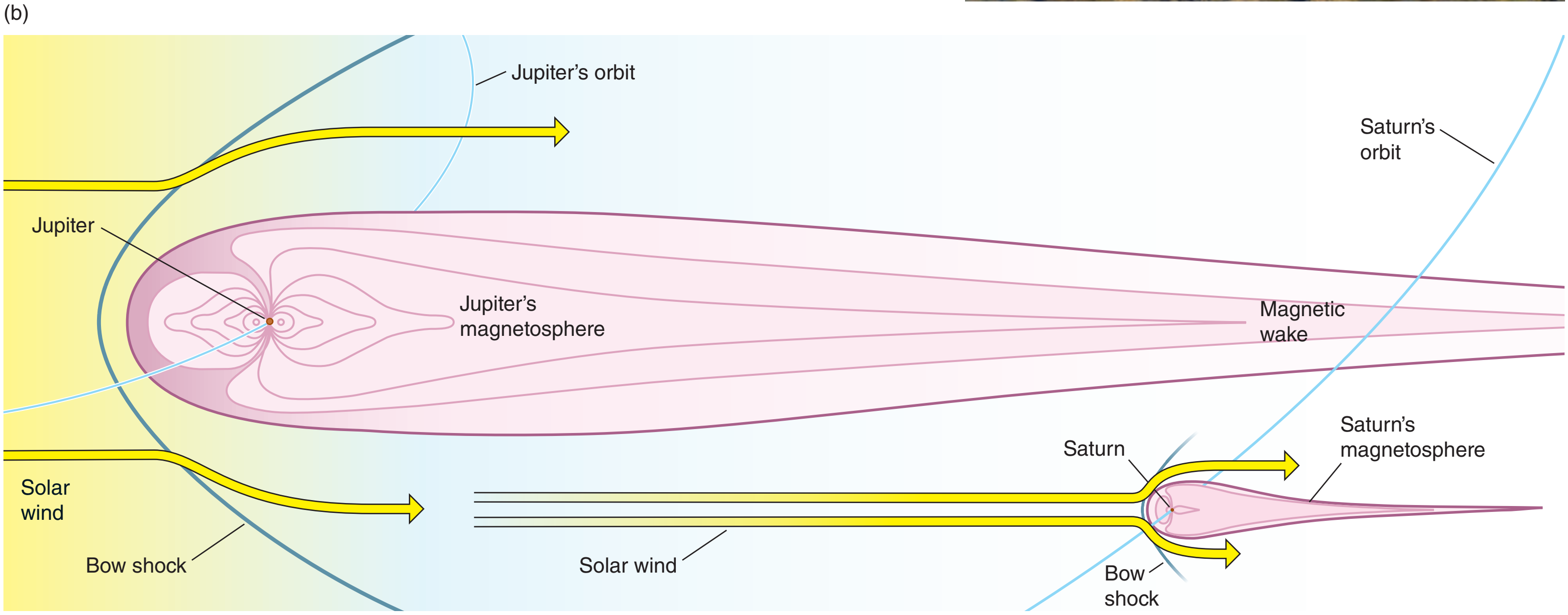
Rapidly moving electrons in planetary magnetospheres spiral around the magnetic field lines, and as they do so they emit a type of radiation, known as

Figure 10.13 (a) Water flowing past a rock sweeps the algae against the rock and into a "tail" pointing in the direction of the water's flow. (b) The solar wind compresses Jupiter's (or any other) magnetosphere on the side toward the Sun and draws it out into a magnetic tail away from the Sun. Jupiter's tail stretches beyond the orbit of Saturn. Note that this drawing is not to scale.

(a)



(b)



synchrotron radiation, concentrated in the low-energy radio part of the spectrum. Precise measurement of periodic variations in the radio signals "broadcast" by the giant planets indicates the planets' true rotation periods. The magnetic field of each planet is locked to the conducting liquid layers deep within the planet's interior, so the magnetic field rotates with exactly the same period as the deep interior of the planet. Given the fast and highly variable winds that push around clouds in the atmospheres of the giant planets, measurement of radio emission is the only way to determine the true rotation periods of the giant planets.

Radiation Belts and Auroras of the Giant Planets

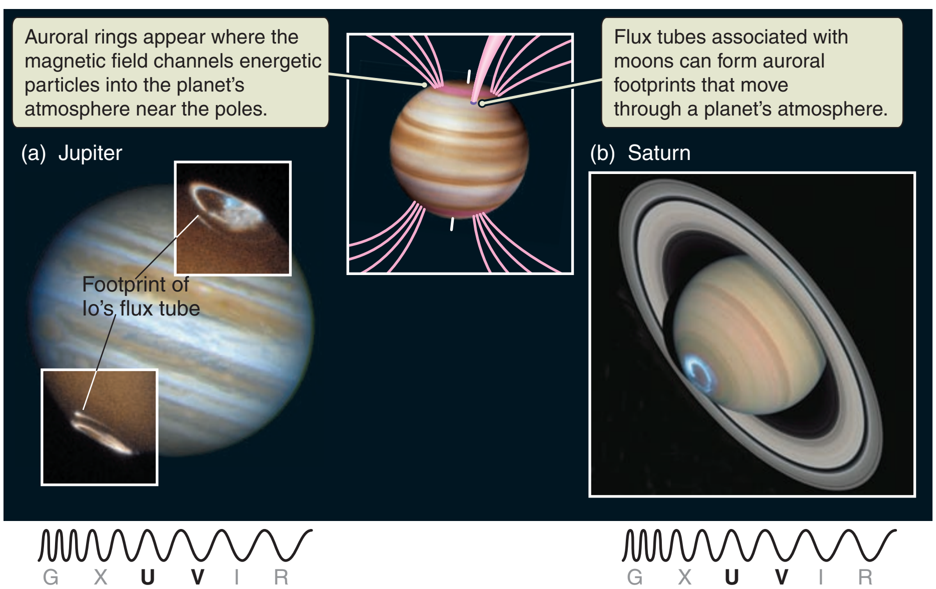
As a planet rotates on its axis, it drags its magnetosphere around with it, and charged particles are swept around at high speeds. These fast-moving charged particles slam into neutral atoms, and the energy released in the resulting high-speed collisions heats the **plasma** to extreme temperatures. (A plasma is a gas consisting of electrically charged particles.) In 1979, while passing through Jupiter's magnetosphere, *Voyager 1* encountered a region of tenuous plasma with a temperature of more than 300 million K, 20 times the temperature at the center of the Sun. *Voyager 1* did not melt when passing through this region because the plasma is so tenuous that the plasma's particles were very far apart in space. Although each particle was extraordinarily energetic, there were so few of them that the probe passed unscathed through the plasma.

Charged particles trapped in planetary magnetospheres are concentrated in *radiation belts*. Although Earth's radiation belts are severe enough to worry astronauts, the radiation belts that surround Jupiter are searing in comparison. In 1974, the *Pioneer 11* spacecraft passed through the radiation belts of Jupiter. Several of the instruments onboard were permanently damaged as a result, and the spacecraft itself barely survived to continue its journey to Saturn.

In addition to protons and electrons from the solar wind, the magnetospheres of the giant planets contain large amounts of various elements, some ionized, including sodium, sulfur, oxygen, nitrogen, and carbon. These elements come from several sources, including the planets' extended atmospheres and the moons that orbit within them. The most intense radiation belt in the Solar System is a doughnut-shaped ring of plasma associated with Io, the innermost of Jupiter's four Galilean moons. As we will discuss in more detail in Chapter 11, the moon Io has low surface gravity and violent volcanic activity. Some of the gases erupting from Io's interior escape and become part of Jupiter's radiation belt. As charged particles are slammed into Io by the rotation of Jupiter's magnetosphere, even more material is knocked free of its surface and ejected into space. Images of the region around Jupiter, taken in the light of emission lines from atoms of sulfur or sodium, show a faintly glowing ring of plasma supplied by Io. Other moons also influence the magnetospheres of the planets they orbit. *Cassini* found that Saturn's moon Enceladus leaks ionized molecules (including nitrogen), water vapor, and ice grains from icy geysers and provides most of the torus of plasma in Saturn's magnetosphere.

Charged particles spiral along the magnetic-field lines of the giant planets, bouncing back and forth between each planet's two magnetic poles, just as they do

Figure 10.14 The Hubble Space Telescope took images of auroral rings around the poles of Jupiter (a) and Saturn (b). The auroral images (bright rings near the poles) were taken in ultraviolet light and then superimposed on visible-light images. (High-level haze obscures the ultraviolet views of the underlying cloud layers, as the insets show.) The bright spot and trail outside the main rings of Jupiter's auroras are the footprint and tail of Io's flux tube.



around Earth. As is the case with Earth, these energetic particles collide with atoms and molecules in a planet's atmosphere, knocking them into excited energy states that decay and emit light. The results are bright auroral rings, shown in **Figure 10.14**. These auroral rings surround the magnetic poles of the giant planets, just as the aurora borealis and aurora australis ring the north and south magnetic poles of Earth.

Jupiter's auroras have an added twist that is not seen on Earth. As Jupiter's magnetic field sweeps past Io, electrons spiral along Jupiter's magnetic-field lines. The result is a magnetic channel, called a **flux tube**, that connects Io with Jupiter's atmosphere near the planet's magnetic poles (**Figure 10.15**). Io's flux tube carries power roughly equivalent to the total power produced by all electrical generating stations on Earth. Much of the power generated within the flux tube is radiated away as radio energy. These radio signals are received at Earth as intense bursts. However, a substantial fraction of the energy of particles in the flux tube is also deposited into Jupiter's atmosphere. At the very location where Io's flux tube intercepts Jupiter's atmosphere, there is a spot of intense auroral activity. As Jupiter rotates, this spot leaves behind an auroral trail in Jupiter's atmosphere. The footprint of Io's plasma torus, along with its wake, can be seen outside the main auroral ring in Figure 10.14a.

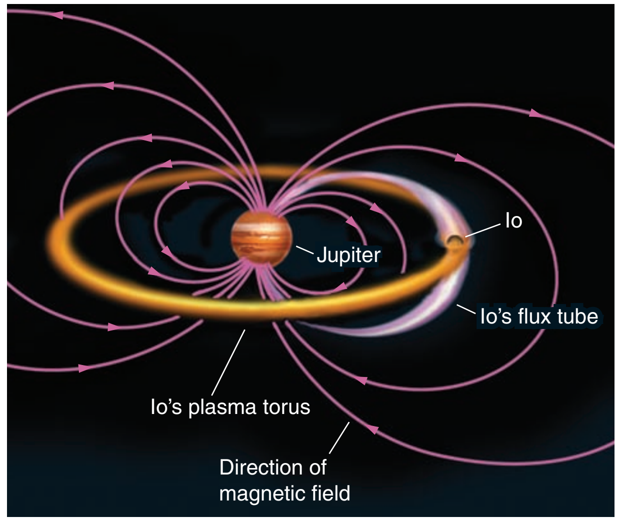


Figure 10.15 This illustration shows the geometry of Io's plasma torus and flux tube.

CHECK YOUR UNDERSTANDING 10.4

The radiation belts around Jupiter are much stronger than those found around Earth because: (a) Jupiter has larger storms than Earth; (b) Jupiter is colder than Earth; (c) Jupiter rotates faster than Earth; (d) Jupiter has a stronger magnetic field than Earth.

10.5 The Planets of Our Solar System Might Not Be Typical

In the past three chapters, we have discussed the planets of our Solar System in detail. The categories of inner terrestrial rocky planets versus outer gas and ice giants was based on our eight planets—but how typical are these categories when compared with the numerous extrasolar planets that have been detected? Do other multiplanet systems resemble our own? As the number of confirmed extrasolar planets increases, astronomers can compare them statistically with those of our own system. Planetary scientists were surprised to find that extrasolar planets differ from those of our Sun. In this section, we will examine some of these differences.

Different Types of "Jupiters"

As noted in Chapter 7, the first exoplanets were discovered using the radial velocity method, which measures the wobble of a star caused by the gravity of its planet. This method is most successful at finding a massive planet located close to its star, where the planet's gravitational tug on the star is stronger than if the planet were of smaller mass or far away. These *hot Jupiters* are gas giants, within a few percent of an AU to half an AU from their respective stars, with correspondingly short and sometimes highly elliptical orbits. Current models of planetary formation suggest that there would not have been enough excess hydrogen that close to their stars for these planets to form there. Some of these planets may be

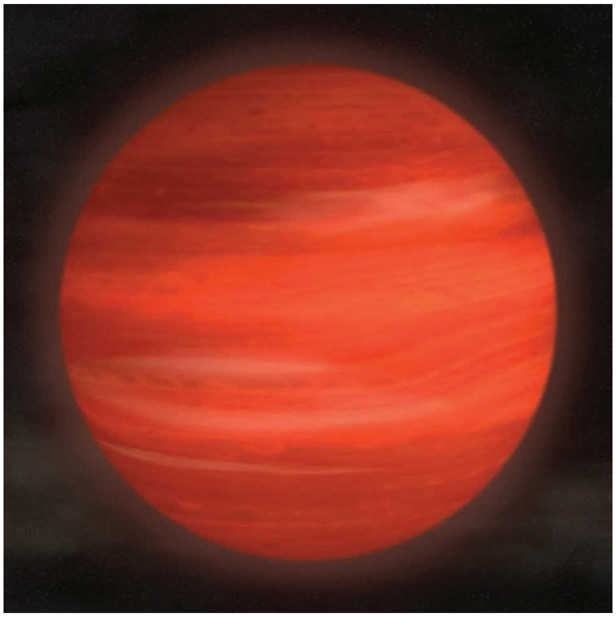


Figure 10.16 This image is an artist's depiction of the super-Jupiter planet Kappa Andromedae b.

puffy Jupiters, with a larger radius and a lower density than Jupiter, the density closer to that of Saturn. The larger radius is thought to come from a heated and thus expanding gaseous atmosphere.

Astronomers have identified several hundred extrasolar planets with masses of about 2–13 times the mass of Jupiter, known as *super-Jupiters*. Some are also hot Jupiters, but most of them are not. Their higher mass gives them stronger gravitational contraction than that in planets with Jupiter's mass, so they shrink over time. As a result, most of them have a higher density than Jupiter. The gases can be compressed by self-gravity so much that the super-Jupiter could be denser than Earth. The stronger gravitational contraction would create hotter cores, so they might have more intense winds and weather than Jupiter. An artist's depiction of the super-Jupiter planet Kappa Andromedae b, with about 13 times the mass of Jupiter, is shown in **Figure 10.16**.

Super-Earths to Mini-Neptunes

Currently, observations suggest that the most common size of planet is one with a radius between that of Earth and that of Neptune (4 times larger than Earth). However, no planet in our Solar System falls in this range. Planets with about 1.5–10 M_{Earth} are called *super-Earths*. Up to about 2 R_{Earth}, these planets get denser as they get larger, as expected for rocky planets. But above 2 R_{Earth}, most planets are puffier—a gaseous envelope surrounds the rocky core. **Figure 10.17** shows a plot of radii versus density for some of these observations. These gaseous planets at the higher end of this range are sometimes called *mini-Neptunes* or *gas dwarfs*. Some planets don't quite fit these rules; for example, KOI-314c has Earth's mass but 1.6 times Earth's radius, which gives it a density more like Neptune than like Earth (that is, a mini-Neptune). Kepler 10c has 2.3 R_{Earth} and a mass as high as 17 M_{Earth}—making it a rocky planet with a surprisingly high mass.

In Chapter 7, we presented a scenario in which the gaseous giant planets formed in the cold outer Solar System and the small rocky terrestrial planets formed in the warm inner Solar System. This model seemed to make sense chemically and physically, so astronomers were quite shocked when the hot Jupiters were first discovered in the mid-1990s. To explain hot Jupiters, astronomers worked with computer models, which showed that gravitational interactions between a planet and the protoplanetary disk or among the planets could cause planets to migrate to different orbital distances from where they had formed. As more exoplanets that were not hot Jupiters were discovered, computer models suggested that migration might explain their locations, too, especially for super-Earths close in to their respective stars.

To date, the mix of planet types in our Solar System—outer giant gaseous planets and inner, small rocky planets, all with nearly circular orbits—has not been seen in several hundred extrasolar multiplanet systems. Observations and computer models show that many combinations of planetary sizes, masses, and compositions can exist within planetary systems. It is not yet known if planetary systems like ours are rare or if they just haven't yet been discovered. Current observations favor the detection of large, short-period planets. More time is needed to find out the answer to this question.

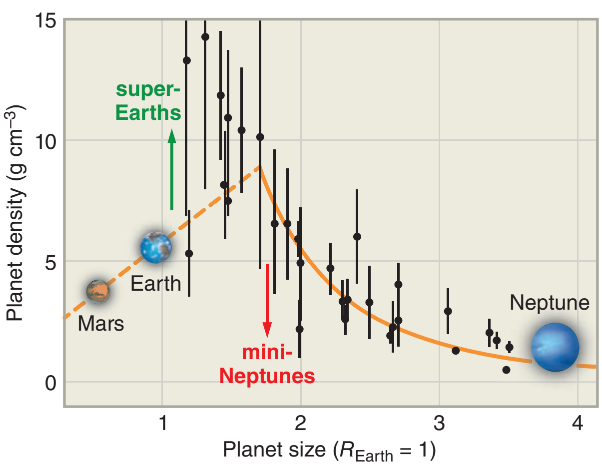


Figure 10.17 Data on nearby super-Earths suggest that at about 2 R_{Earth}, planet density decreases with size because the planet has more gas accumulated on its rocky core.

CHECK YOUR UNDERSTANDING 10.5

Place in order of increasing diameter the following types of extrasolar planets: (a) super-Earths; (b) puffy Jupiters; (c) super-Jupiters; (d) mini-Neptunes.

Origins

Giant Planet Migration and the Inner Solar System

Newton's law of gravitation is not complicated: as long as only two objects are involved, the resulting motions are simple. Kepler's laws describe the regular, repeating elliptical orbits of planets around the Sun. When more than two objects are involved, however, the resulting motions may be anything but simple and regular. Each planet in the Solar System moves under the gravitational influence of the Sun combined with that of all the other planets. Although these extra influences are small, they are not negligible. Over millions of years, they lead to significant differences in the locations of planets in their orbits. In many possible extrasolar planetary systems, such interactions among planets might cause planets to dramatically change their orbits or even be ejected from the system entirely.

Computer models developed to understand the extrasolar planet systems have been applied to the Solar System as well, and the results are intriguing. Computer models of the formation of the Solar System show that the giant planets may not have formed in their current locations and could have migrated substantially in the early Solar System. A key point seems to be the gravitational influence of Saturn on Jupiter, especially the ratio of their orbital periods. **Figure 10.18** shows one type of migration model. When Saturn's orbital period became twice that of Jupiter, their respective orbits became more elongated. The result was an outward migration of Uranus and Neptune, whose orbits grew larger. Uranus and Neptune may actually have switched places with each other. This shuffling cleared away nearby planetesimals, sending some to the inner Solar System, and made the planetary orbits more stable. In another set of models, Jupiter migrated inward to 1.5 AU—the current orbital distance of Mars. Then Saturn migrated inward even faster to a point at which its orbital period was 1.5 times that of Jupiter, and then they both migrated outward, pushing Uranus and Neptune into larger orbits. Some of these computer models could explain the lower mass of Mars (at 1.5 AU) and the distribution of material in the small bodies of the Solar System.

In some extrasolar planetary systems, gas giants are observed at the right distance from their respective stars to be in the habitable zone (see Chapter 7), but it is not known whether gas giants can support life. Super-Earths are also sometimes found in the habitable zone of their stars. In the Solar System, migrations of the giant planets could have helped confine and stabilize the orbits of the inner planets, so that they reside in or near the habitable zone. Migration of Jupiter may have scattered nearby planetesimals and kept Mars small, thereby reducing the ability of Mars to hold on to its atmosphere and its liquid water, and making it a less likely starting point for life. The shuffling about of the outer planets may be responsible for the period of heavy bombardment, which brought at least some of the atmospheric gases, water, and possibly organic molecules that were needed for life to form on Earth.

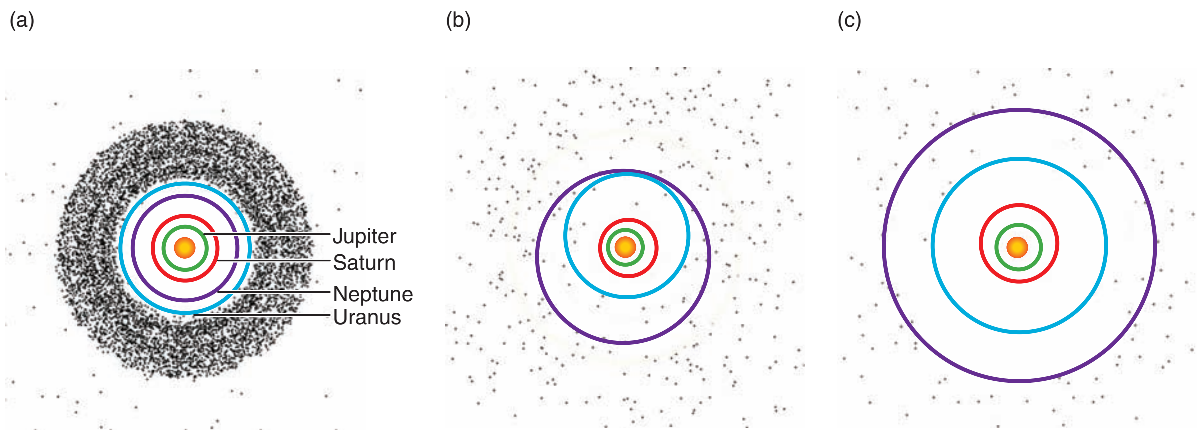


Figure 10.18 These three snapshots from computer simulations of planet migration show the effects of Jupiter and Saturn on the outer Solar System. The four circles are the orbits of the Jovian planets, and the black dots are planetesimals. (a) The orbital period of Saturn becomes twice that of Jupiter. (b) Planetesimals are scattered as the giant planets change orbits. (c) In some models, Neptune and Uranus change places. The inner Solar System is left more stable.

READING ASTRONOMY NEWS

ARTICLES QUESTIONS

Jupiter's Great Red Spot has been observed for several hundred years, but now it is getting smaller.

Hubble Sees Jupiter's Red Spot Shrink to Smallest Size Ever

By **BOB KING, UniverseToday.com**

Earlier this year we reported that amateur astronomers had observed and photographed the recent shrinking of Jupiter's iconic Great Red Spot. Now, astronomers using the Hubble Space Telescope concur:

"Recent Hubble Space Telescope observations confirm that the spot is now just under 10,250 miles (16,500 km) across, the smallest diameter we've ever measured," said Amy Simon of NASA's Goddard Space Flight Center in Maryland, USA (**Figure 10.19a**).

Using historic sketches and photos from the late 1800s, astronomers determined the spot's diameter then at 25,475 miles (41,000 km) across (Figure 10.19b). Even the smallest telescope would have shown it as a huge red hot dog. Amateur observations starting in 2012 revealed a noticeable increase in the spot's shrinkage rate.

The spot's "waistline" is getting smaller by just under 620 miles (1,000 km) per year while its north-south extent has changed little. In a word, the spot has downsized and become more circular in shape. Many who've attempted to see Jupiter's signature feature have been frustrated in recent years not only because the spot's pale color makes it hard to see against adjacent cloud features, but because it's physically getting smaller.

Jupiter's Great Red Spot or GRS is located in a "bay" or hollow south of the swirly South Equatorial Belt. A titanic storm that has raged hurricane-like for at least 400 years, the top of the spot's cloud deck rises 5 miles (8 km) above the planet's clouds and rotates in an anticlockwise direction about once every 4 days.

As to what is causing the drastic downsizing, there are no firm answers yet:

"In our new observations it is apparent that very small eddies are feeding into the storm," said Simon. "We hypothesized that these may be responsible for the accelerated change by altering the internal dynamics of the Great Red Spot."

The Great Red Spot has been a trademark of the planet for at least 400 years—a giant hurricane-like storm whirling in the planet's upper cloud tops with a period of 6 days. But as it has shrunk, its period has likewise grown shorter and now clocks in at about 4 days.

The storm appears to be conserving angular momentum by spinning faster the same way an ice-skater spins up when she pulls in her arms. Wind speeds are increasing too, making one wonder whether they'll ultimately shrink the spot further or bring about its rejuvenation.

Definitely worth keeping an eye on.

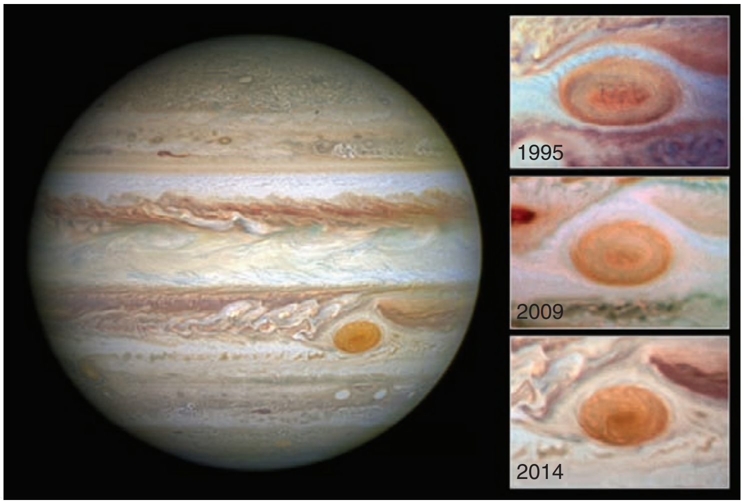


Figure 10.19 In this comparison of the Great Red Spot (insets) as seen by the Hubble Space Telescope, the top photograph was taken in 1995 and shows the spot at a diameter of just under 13,050 miles (21,000 km); the middle photograph was taken in 2009 and shows the spot at a diameter of just under 11,180 miles (18,000 km); and the bottom photograph was taken in 2014 and shows the spot at its smallest size yet, with a diameter of just 9,940 miles (16,000 km).

ARTICLES QUESTIONS

1. Why has the Great Red Spot been seen for only 400 years?
2. Explain how astronomers measure the size of the Great Red Spot.
3. Why is it difficult for astronomers to understand what is happening below the cloud tops?
4. Why might it be difficult to drop a probe into the Great Red Spot?
5. Search for news on Jupiter's Great Red Spot. Is it still shrinking?

Summary

The giant planets are much larger and less dense than the terrestrial planets, consist primarily of light elements rather than rock, and their outer atmospheres are much colder. Because of their rapid rotation and the Coriolis effect, zonal winds are very strong on these planets. Storms, such as those on Saturn, tend to be larger and longer-lived than storms on Earth. Volatiles become ices at various heights in these atmospheres, leading to a layered cloud structure. Jupiter, Saturn, and Neptune are still shrinking, and their gravitational energy is being converted to thermal energy, heating both the cores and the atmospheres from the inside. Uranus does not seem to have as large a heat source inside. Temperatures and pressures in the cores of the giant planets are very high, leading to unusual states of matter, such as metallic hydrogen and super-ionic water. The current locations of these planets might be very different from where they formed: models suggest that their positions may have migrated.

LG1 **Differentiate the giant planets from each other and from the terrestrial planets.** Uranus and Neptune were discovered by telescope, unlike all the other planets, which have been known since ancient times. The giant planets can be divided into two classes: Jupiter and Saturn are gas giants, and Uranus and Neptune are ice giants. Jupiter and Saturn are made up mostly of hydrogen and helium—a composition similar to that of the Sun. Uranus and Neptune contain larger amounts of ices such as water, ammonia, and methane than that found in Jupiter and Saturn. These compositions set them apart from the terrestrial planets. In addition, all four giant planets are much larger than Earth.

LG 2 **Describe the atmosphere of each giant planet.** We see only atmospheres on the giant planets because solid or liquid surfaces, if they exist, are deep below the cloud layers. Clouds on Jupiter and Saturn are composed of various kinds of ice crystals colored by impurities. Uranus and Neptune have relatively few clouds, and so their atmospheres appear more uniform. The most prominent atmospheric feature is the Great Red Spot in Jupiter's southern hemisphere.

LG 3 **Explain the extreme conditions deep within the interiors of the giant planets.** The ongoing collapse of the giant planets converts gravitational energy to thermal energy. This process heats most of the giant planets from within, producing convection. Powerful convection and the Coriolis effect drive high-speed winds in the upper atmospheres of all of the giant planets. The interiors of the giant planets are very hot and very dense because of the high pressures exerted by their overlying atmospheres.

LG 4 **Describe the magnetosphere of each of the giant planets.** The giant planets have enormous magnetospheres that emit synchrotron radiation and interact with their moons. The rotation speed of a gas giant is found from periodic bursts of radio waves that are generated as the planet's magnetic field rotates.

LG 5 **Compare the planets of our Solar System to those in extrasolar planetary systems.** Systems of extrasolar planets found to date do not contain our Solar System's division of small, rocky inner planets and large, giant outer planets. Most of the planets found to date fall between Earth and Neptune in size. Our understanding of how solar systems form is incomplete.

? UNANSWERED QUESTIONS

- Did the Solar System start with more planets? In the same types of computer models of the early Solar System that we discussed in Origins, astronomers are able to run simulations with different types of initial configurations of planets to see which configurations evolve over time and then compare these to what is observed today. In one set of models, astronomers found that starting with five giant planets best reproduced the current outer Solar System. The fifth planet would have been kicked out of the Solar System after a close encounter with Jupiter, and it may still be wandering through the Milky Way.
- What are the mass and size of the core of each giant planet? Is there a rocky core underneath the thick atmosphere? Is the core the size of a terrestrial planet or larger? There may be an answer in a few years for Jupiter. The NASA *Juno* mission en route to Jupiter, with a scheduled arrival in 2016, will measure Jupiter's gravitational and magnetic fields and map the amount and distribution of mass in its core and atmosphere.

Questions and Problems

Test Your Understanding

1. The following steps lead to convection in the atmospheres of giant planets. After (a), place (b)–(f) in order.
   a. Gravity pulls particles toward the center.
   b. Warm material rises and expands.
   c. Particles fall toward the center, converting gravitational energy to kinetic energy.
   d. Expanding material cools.
   e. Thermal energy heats the material.
   f. Friction converts kinetic energy to thermal energy.

2. Deep in the interiors of the giant planets, water is still a liquid even though the temperatures are tens of thousands of degrees above the boiling point of water. This can happen because
   a. the density inside the giant planets is so high.
   b. the pressure inside the giant planets is so high.
   c. the outer Solar System is so cold.
   d. space has very low pressure.

3. Assume you want to deduce the radius of a planet in our Solar System as it occults a background star when the relative velocity between the planet and Earth is 30 km/s. If the star crosses through the middle of the planet and disappears for a total of 26 minutes, what is the planet's radius?
   a. 3,000 km
   b. 23,000 km
   c. 15,000 km
   d. 5,000 km

4. Neptune's existence was predicted because
   a. Uranus did not seem to obey Newton's laws of motion.
   b. Uranus wobbled on its axis.
   c. Uranus became brighter and fainter in an unusual way.
   d. some of the solar nebula's mass was unaccounted for.

5. Which of the giant planets has the most extreme seasons?
   a. Jupiter
   b. Saturn
   c. Uranus
   d. Neptune

6. The magnetic fields of the giant planets
   a. align closely with the rotation axis.
   b. extend far into space.
   c. are thousands of times stronger at the cloud tops than at Earth's surface field.
   d. have an axis that passes through the planet's center.

7. An occultation occurs when
   a. a star passes between Earth and a planet.
   b. a planet passes between Earth and a star.
   c. a planet passes between Earth and the Sun.
   d. Earth passes between the Sun and a planet.

8. Occultations directly determine a planet's
   a. diameter.
   b. mass.
   c. density.
   d. orbital speed.

9. The chemical compositions of Jupiter and Saturn are most similar to those of
   a. Uranus and Neptune.
   b. the terrestrial planets.
   c. their moons.
   d. the Sun.

10. Individual cloud layers in the giant planets have different compositions. This happens because
    a. the winds are all in the outermost layer.
    b. the Coriolis effect only occurs close to the "surface" of the inner core.
    c. there is no convection on the giant planets.
    d. different volatiles freeze out at different temperatures.

11. The Great Red Spot on Jupiter is
    a. a surface feature.
    b. a storm that has been raging for more than 300 years.
    c. caused by the interaction between the magnetosphere and Io.
    d. about the size of North America.

12. Uranus and Neptune are different from Jupiter and Saturn in that
    a. Uranus and Neptune have a higher percentage of ices in their interiors.
    b. Uranus and Neptune have no rings.
    c. Uranus and Neptune have no magnetic field.
    d. Uranus and Neptune are closer to the Sun.

13. What could have caused the planets to migrate through the Solar System?
    a. gravitational pull from the Sun
    b. interaction with the solar wind
    c. accreting gas from the solar nebula
    d. gravitational pull from other planets

14. Zonal winds on the giant planets are stronger than those on the terrestrial planets because
    a. they have more thermal energy.
    b. the giant planets rotate faster.
    c. the moons of giant planets provide additional pull.
    d. the moons feed energy to the planet through the magnetosphere.

15. A "hot Jupiter" gets its name from the fact that
    a. its temperature has been measured to be higher than Jupiter's.
    b. it is located around a much hotter star than the Sun.
    c. it has very high density, and therefore its temperature is high.
    d. it orbits very close to its central star.