11TH EDITION

# DISCOVERING THE UNIVERSE

Neil F. Comins

The four 1.8 m telescopes at the European Southern Observatory's Paranal Observatory in Chile. These telescopes can be moved and they are used in support of the Observatory's four 8.2 m Very Large Telescopes. (J. Colosimo/ESO)

R I V U X G

# CHAPTER 3 Light and Telescopes

## WHAT DO YOU THINK?

1. What is light?
2. Which type of electromagnetic radiation is most dangerous to life?
3. What is the main purpose of a telescope?
4. Why do research telescopes that collect electromagnetic radiation use mirrors, rather than lenses, to collect light?
5. Why do stars twinkle?
6. What are cosmic rays? Where do they come from?

*Answers to these questions appear in the text beside the corresponding numbers in the margins and at the end of the chapter.*

With our eyes alone we can see visible light from several thousand stars. Until the seventeenth century, few people even dreamed that there were more of them. It was then that telescopes revolutionized human understanding of the universe, showing for the first time how little of the cosmos we normally see. The process of discovery continues, as telescopes reveal new things in space nearly every day. We can think of the radiation emitted by objects out there as the most important medium of natural cosmic communication, and telescopes as the means by which we gather and read those cosmic messages.

We have also discovered that visible light is only a tiny fraction of the energy emitted by objects in space. Indeed, such phenomena as interstellar clouds of gas and dust, the bodies lying behind these clouds, newly forming stars, intergalactic gas clouds, and a variety of exotic objects, such as black holes and neutron stars, are nearly invisible to even our best optical telescopes. However, many of these objects strongly emit a variety of nonvisible radiations (namely, radio waves, microwaves, infrared and ultraviolet radiations, X-rays, and gamma rays) that we now have the technology to detect.

Besides electromagnetic radiation, astronomers now have technology to detect particles from space and tiny ripples in the fabric of spacetime called gravitational radiation, all of which we will study in this chapter.

### IN THIS CHAPTER YOU WILL DISCOVER

- **the connection between visible light, radio waves, X-rays, and other types of electromagnetic radiation**
- **the debate in past centuries over what light is and how Einstein resolved this question**
- **how telescopes collect and focus light**
- **the limitations of telescopes, especially those that use lenses to collect light**
- **why different types of telescopes are used for different types of research**
- **how astronomers use the entire spectrum of electromagnetic radiation to observe the stars and other astronomical objects and events**
- **what the latest generations of land-based and space-based high-technology telescopes can do**
- **new insights into the nature of matter provided by solar neutrinos**
- **that high-energy, high-speed particles called cosmic rays travel through interstellar space**
- **that some particles, called neutrinos, travel all the way through stars like the Sun and planets like Earth**
- **that space sometimes vibrates as gravitational waves travel through it**
- **that astronomers also have telescopes to observe cosmic rays, neutrinos, and gravitational waves**

## ELECTROMAGNETIC RADIATION OBSERVATORIES

So far in this text we have used the word *light* in its everyday sense—the stuff to which our eyes are sensitive. This is more properly called *visible light*, and it is a form of **electromagnetic radiation**. Perhaps contrary to one's intuition, this radiation is composed of particles, called *photons,* that also have properties of waves. Detecting electromagnetic radiation with telescopes is the essence of observational astronomy. Although human perception of objects here on Earth and in space comes primarily from the visible light that our eyes detect, visible light is only a tiny fraction of all the electromagnetic radiation emitted by objects in the universe. The rest of this radiation, invisible to our eyes, is detected by high-tech sensors attached to specially designed telescopes. In this chapter, we examine telescopes for all types of electromagnetic radiation. To understand how telescopes work, we begin by exploring the properties of the electromagnetic radiation that they collect.

### 3-1 Newton discovered that white is not a fundamental color and proposed that light is composed of particles

From the time of Aristotle (in the fourth century B.C.E.) until the late seventeenth century C.E., most people believed that white is the fundamental color of light. The colors of the rainbow (or, equivalently, the colors created by light passing through a prism) were believed to be added or created somehow as white light went from one medium through another. Isaac Newton performed experiments during the late 1600s that disproved these beliefs. He started by passing a beam of sunlight through a glass prism, which spread the light out into the colors of the rainbow **(Figure 3-1a)**. The change in direction as light travels from one medium into another is called **refraction**, and the resulting spread of colors (complete or with colors missing) is called a **spectrum** (plural, **spectra**).

Then, Newton selected a single color and sent it through a second prism (Figure 3-1b). The light that emerged from the first prism was refracted by the second prism, but *it remained the same color.* The fact that individual colors of refracted light were unchanged by the second prism led Newton to conclude that the colors of a full spectrum (shades of red, orange, yellow, green,

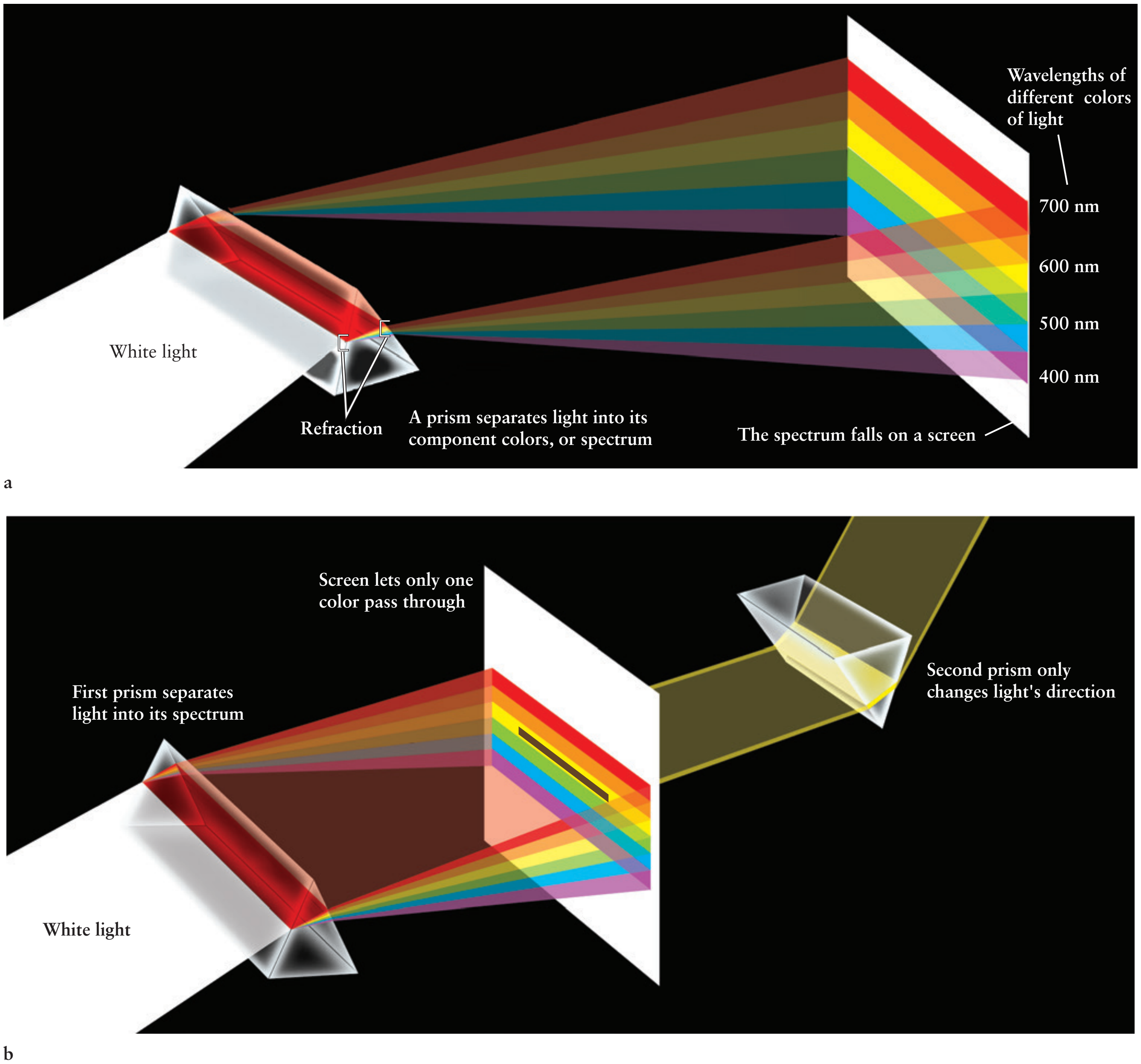


**FIGURE 3-1 Prisms and a Spectrum** (a) When a beam of white light passes through a glass prism, the light is separated or refracted into a rainbow-colored band called a spectrum. The numbers on the right side of the spectrum indicate wavelengths in nanometers (1 nm = $10^{-9}$ m). (b) This drawing of Newton's experiment illustrates that glass does not add to the color of light, it only changes its direction. Because color is not added, this experiment shows that color is an intrinsic property of light.

blue, and violet; indigo is not considered a separate color in astronomy) were in fact properties of the light itself, and that white light is a mixture of colors. To prove this last point, he recombined all the spectrum colors, thereby recreating white light. Thus, different colors of the spectrum are different entities. But what, Newton wondered, is the nature of light that it could break apart into distinct colors and then be completely reconstituted?

Back in the mid-1600s, the Dutch scientist Christiaan Huygens (1629–1695) proposed that light travels in the form of waves. Newton, on the other hand, performed many experiments in optics that convinced him that light is composed of tiny particles of energy. It turns out that both ideas were right.

In 1801, the English physicist Thomas Young (1773–1829) demonstrated that light is indeed composed of waves. Young sent light of a single color through two parallel slits (Figure 3-2a). He reasoned that if the light were waves, then these waves would behave the way waves on the surface of water behave, flowing through similar gaps (Figure 3-2b). In particular, he theorized that the light waves from each slit would interact with light waves from

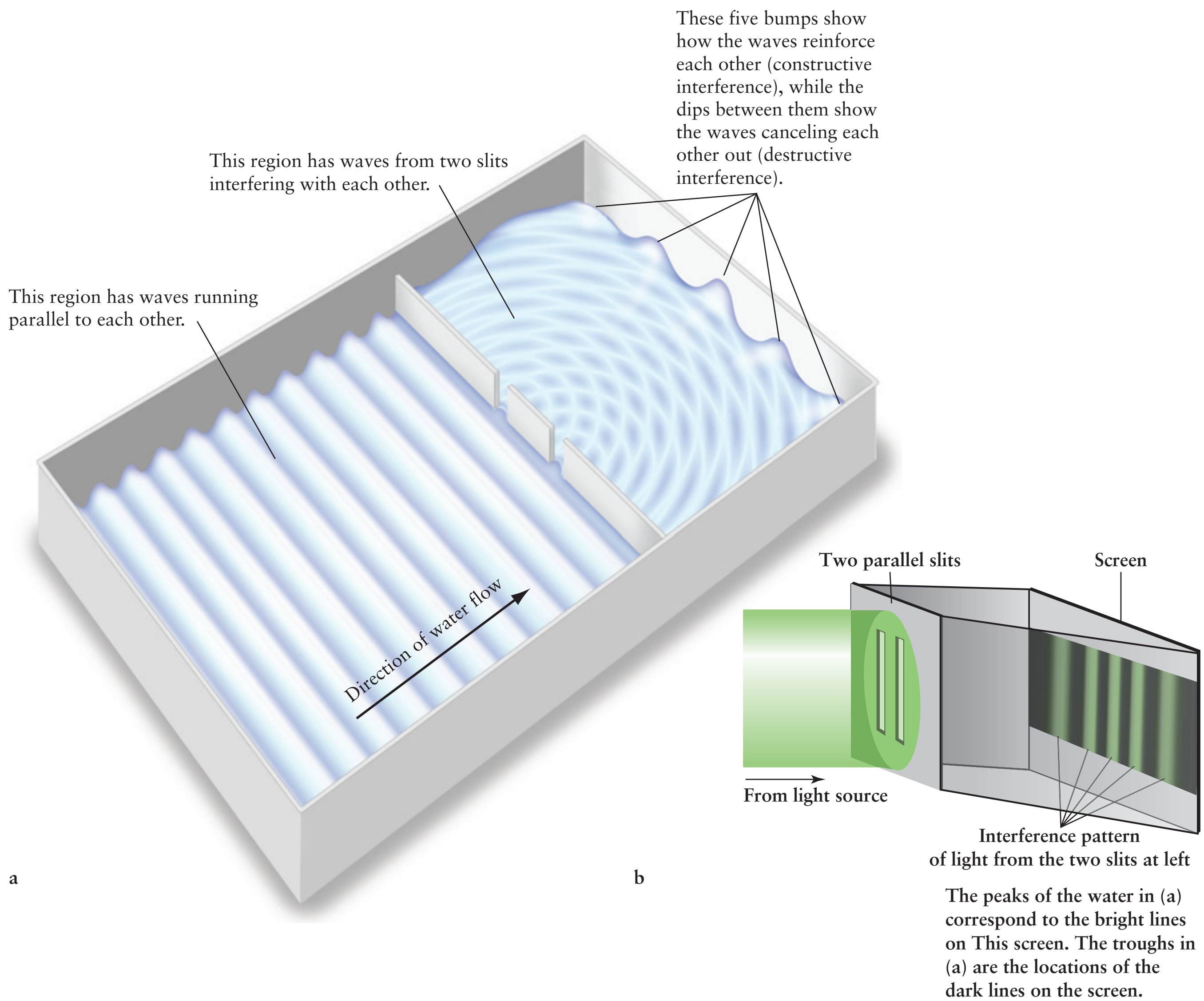


**FIGURE 3-2 Wave Travel** (a) Water waves passing through two slits in a ripple tank create interference patterns. The water waves interfere with each other, creating constructive interference (crests) and destructive interference (troughs) throughout the right side of the tank and on the far right wall. (b) Electromagnetic radiation also travels as waves. Thomas Young's interference experiment shows that light of a single color passing through a barrier with two slits behaves as waves that create alternating light and dark patterns on a screen. (Adapted from University of Colorado, Center for Integrated Plasma Studies, Boulder, CO)

the other. For example, when two light waves meet, with one wave going up and the other going down, they would interfere with each other and partially or totally cancel each other out, leaving dark regions on the screen. When two waves that are both moving up or both moving down meet, they would reinforce each other and create bright regions. As you can see in Figure 3-2, this is precisely what happened. (If light were just random particles going through the slits, they would not interfere with each other in this way, and the pattern on the screen would just yield two bright regions, one behind each slit.) The analogy with water waves ends here. For example, light waves do not have to travel through a medium, unlike water waves, which travel through the liquid medium of water.

Further insight into the wave character of light came from calculations by the Scottish physicist James Clerk Maxwell (1831–1879) in the 1860s. Maxwell unified the descriptions of the basic properties of electricity and magnetism into four equations. By combining these equations, he demonstrated that electric and magnetic effects should travel through space together in the form of coupled waves (Figure 3-3) that have equal amplitudes. Maxwell's suggestion that some of these waves, now called *electromagnetic radiation,* are observed as visible light was soon confirmed by a variety of experiments. Despite the name electromagnetic radiation, neither visible light nor any other type of electromagnetic radiation is electrically charged.

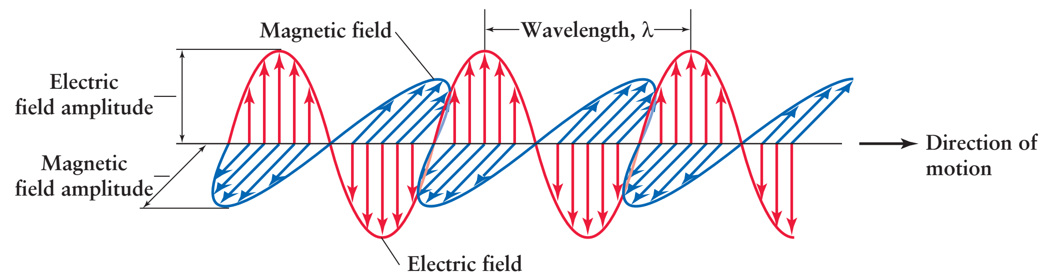


**FIGURE 3-3 Electromagnetic Radiation** All forms of electromagnetic radiation (radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays) consist of combined electric and magnetic fields oscillating perpendicular to each other and to the direction in which they move. In empty space this radiation travels at a speed of $3 \times 10^5$ km/s. The distance between two successive crests, denoted by $\lambda$, is called the wavelength of the light.

Newton showed that sunlight is composed of all the colors of the rainbow. Young, Maxwell, and others showed that light travels as waves. What makes the colors of the rainbow distinct from each other? The answer is surprisingly simple: Different colors are waves with different wavelengths. A **wavelength**, usually designated by $\lambda$, the lowercase Greek letter lambda, is the distance between two successive wave crests (see Figure 3-3).

The wavelengths of all colors are extremely small, less than a thousandth of a millimeter. To express these tiny distances conveniently, scientists use a unit of length called the *nanometer* (nm), where 1 nm = $10^{-9}$ m. Another unit you might encounter when talking to astronomers is the *angstrom* (Å), where 1 Å = 0.1 nm = $10^{-10}$ m. Experiments demonstrate that visible light has wavelengths ranging from about 400 nm for the shortest wavelength of violet light to about 700 nm for the longest wavelength of red light. Intermediate colors of the rainbow fall between these wavelengths (see Figure 3-1a). The complete spectrum of colors from the longest wavelength to the shortest is red, orange, yellow, green, blue, and violet. Referring to Figure 3-1, you can also see that the amount of refraction that different colors undergo depends on their wavelengths: *The shorter the wavelength, the more the light is refracted.*

## 3-2 Light travels at a finite but incredibly fast speed

The fact that we see lightning before we hear the accompanying thunderclap tells us that light travels faster than sound. But does that mean that light travels instantaneously from one place to another, or does it move with a measurable speed?

The first evidence for the finite speed of light came in 1675, when Ole Rømer (1644–1710), a Danish astronomer, carefully timed eclipses of Jupiter's moons (Figure 3-4). Rømer discovered that the moment at which a moon enters Jupiter's shadow depends on the distance between Earth and Jupiter. When Jupiter is in opposition—that is, when Jupiter and Earth are on the same side of the Sun (see **Figure 2-4**)—the Earth–Jupiter distance is relatively short compared to when Jupiter is near conjunction. At opposition, Rømer found that eclipses occur slightly earlier than predicted by Kepler's laws, and they occur slightly later than predicted when Jupiter is near conjunction.

Rømer correctly concluded that light travels at a finite speed, and so it takes more time to travel longer distances across space. The greater the distance to Jupiter, the longer the image of an eclipse takes to reach our eyes. From his timing measurements, Rømer concluded that it takes 162 minutes for visible light to traverse the diameter of Earth's orbit (2 au). Incidentally, Rømer's interpretation of the data requires a heliocentric cosmology—that both Earth and Jupiter orbit the Sun.

**Margin Question 3-1**
What color is refracted least?

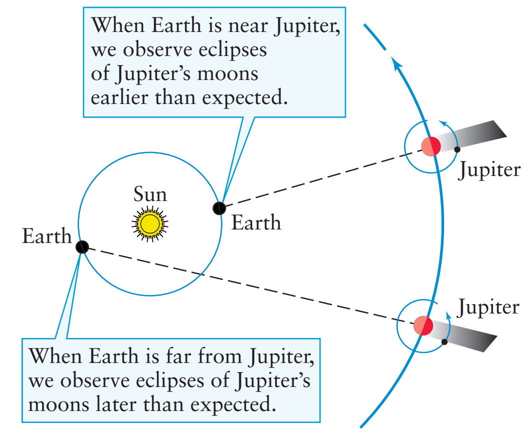


**FIGURE 3-4 Evidence that Light Travels at a Finite Speed** The times of the eclipses of Jupiter's moons as seen from Earth depend on the relative positions of Jupiter, Earth, and the Sun. Rømer correctly attributed the variations in these times to the variations in the time that it takes light from these events to reach Earth.

Rømer's subsequent calculation of the speed of light was off by 25% because the value for the astronomical unit (the average distance from Earth to the Sun) that existed at that time was highly inaccurate. Nevertheless, he proved his main point—light travels at a finite speed. The first accurate laboratory measurements of the speed of visible light were performed in the mid-1800s.

Maxwell's equations also reveal that light of all wavelengths travels at the same speed in a vacuum (a region that contains no matter), and, despite a few atoms per cubic meter, the space between planets and stars is a very good vacuum. The constant speed of light in a vacuum, usually designated by the letter *c*, has been measured to be 299,792.458 km/s, which we generally round to

$$c = 3.0 \times 10^5 \text{ km/s} = 1.86 \times 10^5 \text{ mi/s}$$

(Standard abbreviations for units of speed, such as *km/s* for kilometers per second and *mi/s* for miles per second, will be used throughout the rest of this book.) Light that travels through air, water, glass, or any other substance always moves more slowly than it does in a vacuum.

The value *c* is a fundamental property of the universe. The speed of light appears in equations that describe, among other things, atoms, gravity, electricity, magnetism, distance, and time. Light has extraordinary properties. For example, if you were traveling in space at 99% of the speed of light, 0.99*c*, you would still measure the speed of any light beam moving toward you as *c*, which is also the speed you would measure for any light beam moving away from you!

**Margin Question 3-2**
The speed of sound is about 0.34 km/s (0.21 mi/s). How can these numbers and the information in this section be used to determine a person's distance from a lightning strike?

## 3-3 Einstein showed that light sometimes behaves as particles that carry energy

1 By 1905, scientists were comfortable with the wave nature of light. However, in that year, Albert Einstein (1879–1955) threw a monkey wrench into that theory when he proposed that light is composed of particles that have wave properties, creating what is now called the *wave-particle duality.* He used this idea to explain the *photoelectric effect.* Physicists knew that electrons are bound onto a metal's surface by electric forces and that it takes energy to overcome those forces. Shorter wavelengths of light can knock some electrons off the surfaces of metals, while longer wavelengths of light cannot, no matter how intense the beam of long-wavelength light. Because some colors (or, equivalently, wavelengths) can remove the electrons and others cannot, the electrons must receive different amounts of energy from different colors of light. But how? Einstein proposed that light travels as waves enclosed in discrete packets, now called **photons,** and that photons with different wavelengths have different amounts of energy. Specifically, the shorter the wavelength, the higher a photon's energy.

$$\text{Photon energy} = \frac{\text{Planck's constant} \times \text{the speed of light}}{\text{Wavelength}}$$

where Planck's constant, named for the German physicist Max Planck (1858–1947) has the value $6.67 \times 10^{-34}$ J · s, where J is the unit of energy called a *joule* (see **An Astronomer's Toolbox 3-1: Photon Energies, Wavelengths, and Frequencies**), and the wavelength, the distance between wave crests or troughs, is shown in Figure 3-3. (J · s stands for joules multiplied by seconds, or *joule-seconds.*) Einstein's concept of light, confirmed in numerous experiments, means that light can act both as waves (as when passing through slits) and as particles (as when striking matter).

The waves shown in Figure 3-3 are moving to the right. If you count the number of wave crests that pass a given point per second, you have found the **frequency** of the photon. The unit of frequency is the *hertz*, named for the German physicist Heinrich Hertz (1857–1894). One hertz means that 1 cycle per second—or that 1 wave crest per second—passes any point. A thousand hertz means a thousand cycles per second, and so on. The frequency is used, among many other things, to identify radio stations. For example, WCPE radio in Wake Forest, North Carolina, has a frequency of 89.7 megahertz (a megahertz is a million hertz or a million cycles per second). Frequency is discussed further in An Astronomer's Toolbox 3-1.

Returning to the photoelectric effect, all photons with the same wavelength are identical to each other, and, therefore, every photon of a given wavelength carries the same amount of energy as every other photon with that wavelength. The energy delivered by a photon is either enough to eject an electron from the surface of the metal or it is not; there is no middle ground. Extensive testing in the twentieth century confirmed both the wave and particle properties of light.

While the energy of a single photon is fixed by its wavelength, the total number of photons passing per second from that source with a given energy determines the intensity of the electromagnetic radiation at that wavelength (that is, how bright the object appears to be). The more photons detected, the higher the intensity, and vice versa. However, the intensity of light does not change the energy per photon. If one photon is unable to eject an electron from a metal, then billions of photons with that energy will still be unable to remove that electron.

# AN ASTRONOMER'S TOOLBOX 3-1

## Photon Energies, Wavelengths, and Frequencies

All photons with the same energy are identical. This energy depends solely on the photon's wavelength or, equivalently, its frequency. The wavelength, $\lambda$, and frequency, $f$, of a photon are related by the simple equation

$$c = f\lambda \text{ or, equivalently, } f = c/\lambda$$

where $c$ is the speed of light in a vacuum. Knowing either the wavelength or frequency, you can calculate the other value with these equations. Also, if you know either of them, you also know the photon's energy, as introduced in the equation from Section 3-3,

$$E = hc/\lambda \quad \text{or} \quad E = hf$$

Planck's constant, $h$, is $6.67 \times 10^{-34}$ J · s and the speed of light, $c$, is 300,000 km/s.

**Example:** A photon of red light has a wavelength of 700 nm. What is its energy? *Note:* All distances in the following equation must be converted to the same units, such as meters.

$$E_{\text{red}} = \frac{(6.67 \times 10^{-34}\ \text{J}\cdot\text{s})(300{,}000\ \text{km/s})}{700\ \text{nm}}$$

Simplifying, we find $E_{\text{red}} = 2.86 \times 10^{-19}$ J, meaning that each photon of red light with wavelength 700 nm has an energy of $2.86 \times 10^{-19}$ J.

An aside on units: Just as the numbers in the numerator of an equation multiply together, the numbers in the denominator multiply together, and the resulting numerator is divided by the denominator, so are units combined in the same way. The same units found in both the numerator and denominator cancel. For example, a result such as 7 km s/s would have the seconds cancel on the top and bottom, leaving 7 km as the answer.

Furthermore, in any equation, the units of the same type (such as length) must all be converted to the same standard, so that they can be combined or canceled. In our case, we would convert both nanometers and kilometers to meters, combine the resulting powers of 10, and cancel the units on the top and bottom. For example, 1 km/1 nm = $10^3$ m/$10^{-9}$ m = $10^{+12}$ (with no units). The cancellation of units in the equation left just *joules*, as it should, because we were calculating an energy.

**Compare:** In 1 s, a 25-watt lightbulb emits 25 J of energy.

**Try these questions:** A photon has an energy of $4.90 \times 10^{-19}$ J. Calculate its wavelength in nanometers. Referring to Figure 3-1: What is this photon's color? What is the wavelength of a photon with twice this energy? What is the energy of a green photon?

(Answers appear at the end of the book.)

## 3-4 Visible light is only one type of electromagnetic radiation

We now know that visible light occupies only a tiny fraction of the full range of possible wavelengths, collectively called the **electromagnetic spectrum.** Visible light has the range of wavelengths from 400 to 700 nm. However, Maxwell's equations place no length restrictions on the wavelengths of electromagnetic radiation. What lies on either side of this interval? Around 1800, the British astronomer William Herschel (1738–1822) discovered **infrared radiation** in an experiment with a prism. When he held a thermometer just beyond the red end of the visible spectrum, the thermometer registered a temperature increase, indicating that it was being heated by an invisible form of energy (Figure 3-5). Infrared radiation, discovered before Maxwell's equations were formulated, was later identified as electromagnetic radiation with wavelengths slightly longer than red light. Our bodies detect infrared radiation as heat.

In experiments with electric sparks in 1888, Hertz succeeded in producing electromagnetic radiation a few centimeters in wavelength, now known as **radio waves**.

At wavelengths shorter than those of visible light, **ultraviolet (UV) radiation** extends from about 400 nm to 10 nm. In 1895, Wilhelm Roentgen (1845–1923) invented a machine that produces electromagnetic radiation with wavelengths shorter than 10 nm, now called **X-rays**. Modern versions of Roentgen's machine are found in medical and dental offices. X-rays have wavelengths between about 10 and 0.01 nm. Photons with even shorter wavelengths are called **gamma rays.** With the exception of visible light, these boundaries are arbitrary and primarily used as convenient divisions in the electromagnetic spectrum, which is actually continuous.



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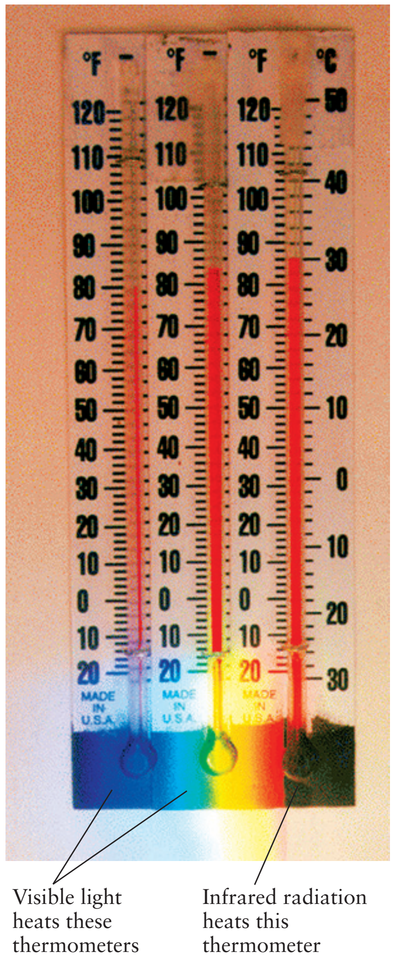



**FIGURE 3-5 Experimental Evidence for Infrared Radiation** This photograph shows the visible colors separated by a prism. The two thermometers in the region illuminated by visible light have temperatures less than the thermometer to the right of red. Therefore, there must be more radiation energizing (that is, heating) the warmest thermometer. This energy is what we call infrared radiation—invisible to the human eye but detectable as heat. (NASA/JPL- Cal Tech)

As shown in Figure 3-6, the electromagnetic spectrum stretches from the longest-wavelength radio waves, through microwaves, infrared radiation, visible light, ultraviolet radiation, and X-rays, to gamma rays, the shortest-wavelength photons. On the long-wavelength side of the visible spectrum, infrared radiation covers the range from about 700 nm to 1 mm. Astronomers interested in infrared radiation often express wavelength in *micrometers* or *microns* (abbreviated μm), where 1 μm = 1000 nm = $10^{-6}$ m. From roughly 1 mm to 10 cm is the range of microwaves. Microwaves are sometimes considered as a separate class of photons and sometimes categorized as infrared radiation or radio waves. Formally, radio waves are all electromagnetic waves longer than 10 cm.

**Margin Question 3-3**
Which has more energy, an infrared photon or an ultraviolet photon?

The various types of electromagnetic radiation share many basic properties. For example, they are all photons, they all travel at the same speed, and they all sometimes behave as particles and sometimes as waves. But, because of their different wavelengths (and therefore different energies), they interact very differently with matter. For example, X-rays penetrate deeply into your body tissues, while visible light is mostly stopped and scattered by the surface layer of skin; your eyes respond to visible light but not to infrared radiation; and your radio detects radio waves but not ultraviolet radiation.

Earth's atmosphere is relatively transparent to visible light, radio waves, microwaves, short-wavelength infrared, and long-wavelength ultraviolet. As a result, these radiations pass through the atmosphere without much loss and can be detected by ground-based telescopes sensitive to them. Astronomers say that the atmosphere has *windows* for these parts of the electromagnetic spectrum (Figure 3-7).

The longest-wavelength ultraviolet radiation, called UVA, causes tanning and sunburns. Ozone ($O_3$) in Earth's atmosphere normally screens out intermediate-wavelength ultraviolet radiation, or UVB. Until recently, the ozone in the *ozone layer* high in the atmosphere was being depleted by human-made chemicals, such as chlorofluorocarbons (CFCs) and bromine-rich gases. As a result, more UVB is reaching Earth's surface, and these highly energetic photons severely damage living tissue, causing a surge in the rates of skin cancer and glaucoma, among other diseases.

**2** Earth's atmosphere is completely opaque to the other types of electromagnetic radiation, meaning that they do not reach Earth's surface. (This opacity is a good thing, because short-wavelength ultraviolet radiation [UVC], X-rays, and gamma rays are devastating to living tissue. Gamma rays, packing the highest energies, are the deadliest.) Direct observations of these wavelengths must be performed high in the atmosphere or, ideally, from space.

As noted earlier, photons with different energies interact with matter in different ways. Higher-energy photons will pass through or rip apart material from which lower-energy photons will bounce off. Telescope designs for collecting and focusing radiation, therefore, differ depending on the energies or, equivalently, the wavelengths of interest. Knowing the energies of photons and their effects on matter enables astronomers to design telescopes and recording devices sensitive to them. In the next section we will consider the lengths to which astronomers have gone to capture visible and invisible (or nonoptical) electromagnetic radiation.

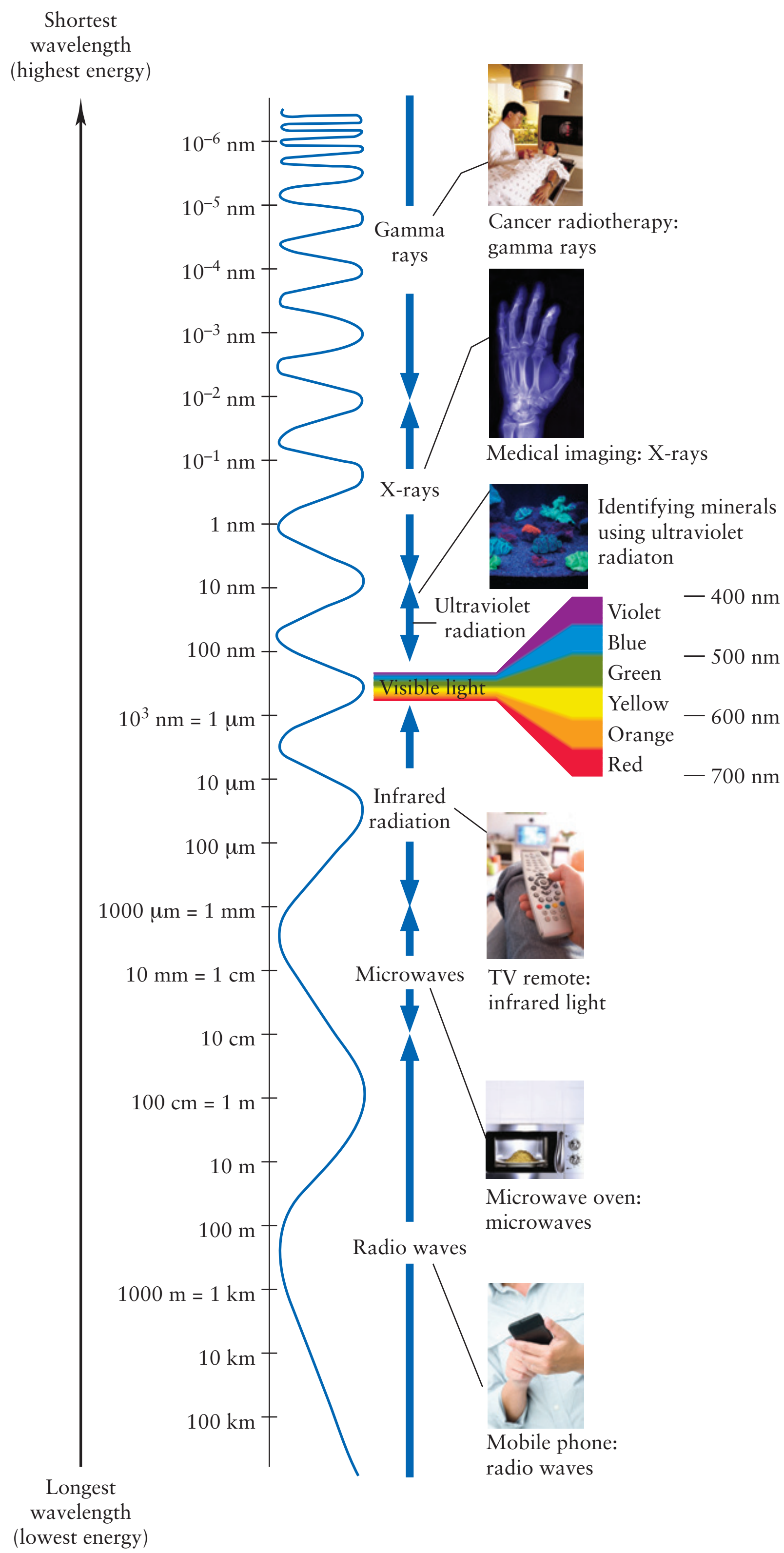



**FIGURE 3-6 The Electromagnetic Spectrum** The full array of all types of electromagnetic radiation is called the electromagnetic spectrum. It extends from the longest-wavelength radio waves to the shortest-wavelength gamma rays. Visible light forms only a tiny portion of the full electromagnetic spectrum. Note that 1 μm (micrometer) is $10^{-6}$ m, and 1 nm (nanometer) is $10^{-9}$ m. The insets show how we are now using all parts of the electromagnetic spectrum here on Earth. (From top: Will & Deni McIntyre/Science Source; Ted Kinsman/Science Source; Chris Martin-Bahr/Science Source; Bart Broek/Getty Images; Michael Haegele/Corbis/Getty Images; franckreporter/E+/Getty Images)

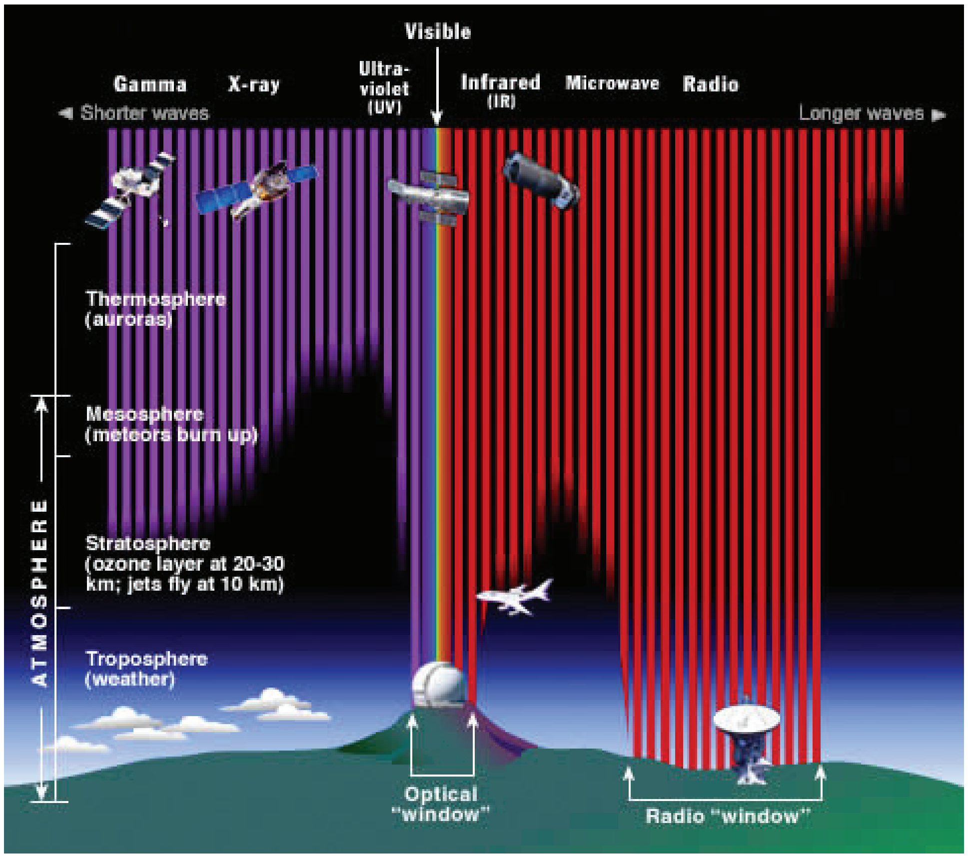



**FIGURE 3-7 "Windows" Through the Atmosphere** Different types of electromagnetic radiation penetrate into Earth's atmosphere in varying amounts. Visible light, radio waves, microwaves, short-wavelength infrared, and long-wavelength ultraviolet reach all the way to Earth's surface. The other types of radiation are absorbed or scattered by the gases in the air at different characteristic altitudes (indicated by where the colored lines end in the atmosphere). Although the atmosphere does not have actual windows, astronomers use the term to characterize the passage of radiation through it. (STScI/JHU/NASA)

## OPTICS AND TELESCOPES

3 Since the time of Galileo, astronomers have been designing instruments to collect more light than the human eye can gather on its own. Collecting more light enables us to see things more brightly, in more detail, and at a greater distance. There are two basic types of telescopes—those that collect light through lenses, or **refracting telescopes**, and those that collect it from mirrors, or **reflecting telescopes** (**reflectors**). The earliest telescopes, such as Galileo's, used lenses, which have a variety of shortcomings as light-gathering devices. Consequently, all modern research telescopes use mirrors to collect light. Lenses are still used in the eyepieces of all home telescopes to straighten the gathered light, so when we look through these telescopes directly, our brains can accurately interpret what we see. Lenses are also used to collect light in binoculars and cameras. Reflecting and refracting telescopes have the same main purpose—to collect as many photons as possible so we can better observe the sky. Because astronomers exclusively use reflecting telescopes to observe photons from objects in space, we will begin exploring telescopes by discussing how these telescopes work. Then we will consider how lenses collect light, how refracting telescopes work, and then how astronomers have developed telescopes to see nonvisible electromagnetic radiation. Moving to the other sources of information about the cosmos, we then examine cosmic ray detectors, neutrino detectors, and gravitational radiation detectors.

### 3-5 Reflecting telescopes use mirrors to concentrate incoming starlight

The first reflecting telescope was built in the seventeenth century by Isaac Newton (Figure 3-8). To understand how these telescopes work, consider a flow of photons, more commonly called a *light ray,* moving toward a flat mirror. In Figure 3-9a, a light ray strikes the mirror, and we imagine a perpendicular line coming out of the mirror at that point. According to the principle of **reflection**, the angle between the incoming light ray and the perpendicular (dashed line) is always equal to the angle between the outgoing, reflected light ray and


**FIGURE 3-8 Replica of Newton's Reflecting Telescope** Built in 1672, this reflecting telescope has a spherical primary mirror 3 cm (1.3 in.) in diameter. Its magnification was 40×, meaning that as seen through the telescope, the images are 40 times larger in angle than they appear to the naked eye. (Photo 12/Ann Ronan Picture Library/Alamy)

that perpendicular. This principle is often stated as, "The angle of incidence equals the angle of reflection." This rule also applies if the mirror is curved (Figure 3-9b).

Using this principle, Newton determined that a concave (hollowed-out) mirror, ground in the shape of a parabola, causes all parallel incoming light rays that strike the mirror to converge to a **focal point** (Figure 3-9b). The distance between this **primary mirror** and the focal point, where the image of the distant object is formed, is called the **focal length** of the mirror. Focal points exist for light from sources that are extremely far away, like the stars. (Figure 3-10 shows why stars can be considered "far away.") If the object is larger than a point, like the Moon or a planet, then the light will converge to a plane, called the **focal plane,** located at the distance of the focal length. Likewise, point objects

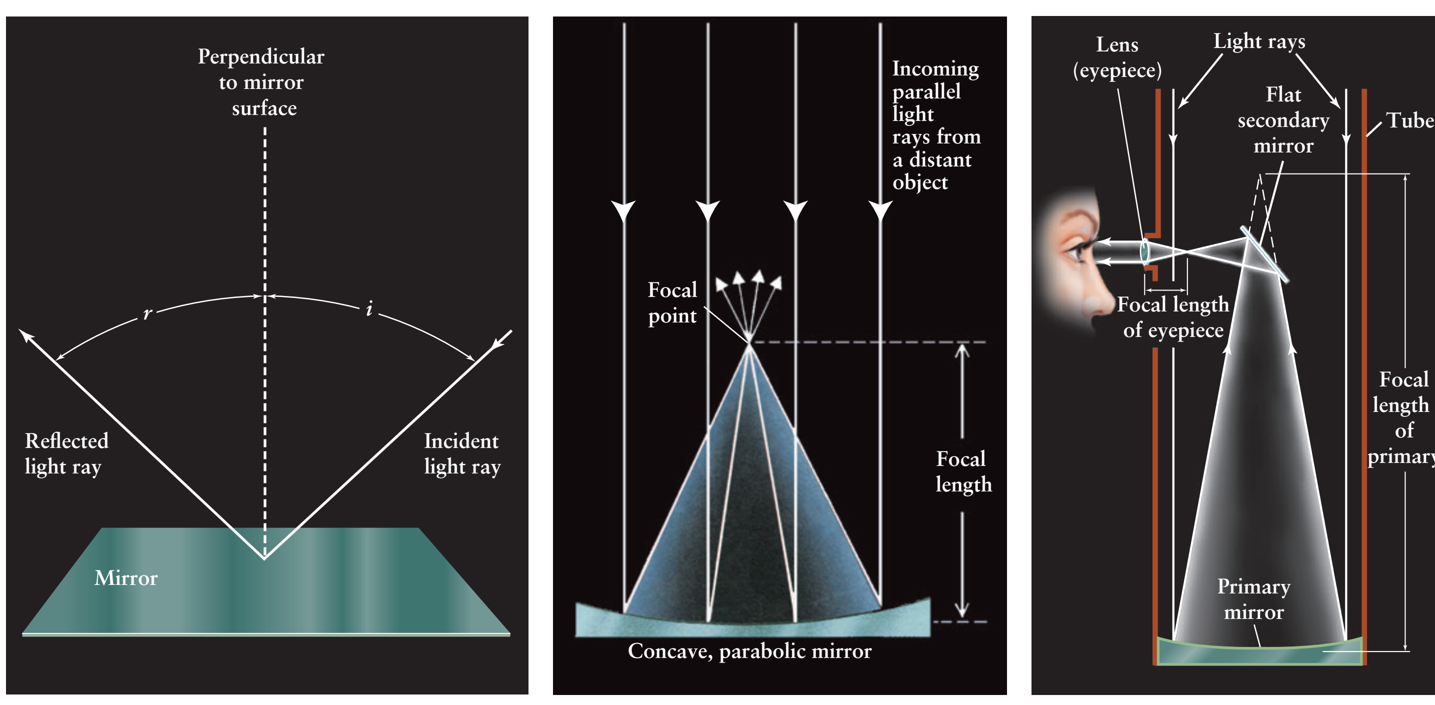



**FIGURE 3-9 Reflection** (a) The angle at which a beam of light strikes a mirror (the angle of incidence, *i*) is always equal to the angle at which the beam is reflected from the mirror (the angle of reflection, *r*). (b) A concave, parabolic mirror causes parallel light rays to converge and meet at the focal point. The distance between the mirror and focal point is the focal length. (c) A Newtonian telescope uses a flat mirror, called the secondary mirror, to send light toward the side of the telescope. The light rays are made parallel again, and therefore comprehensible to our brains, by passing through a lens, called the eyepiece. The dashed line shows where the focal point of this primary mirror would be if the secondary mirror were not in the way.

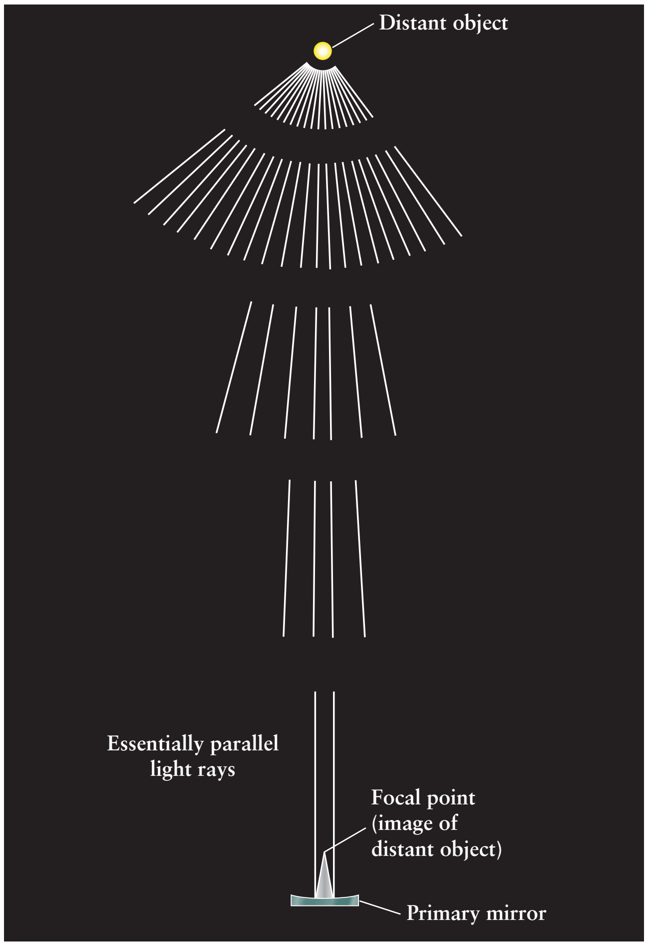



**FIGURE 3-10 Parallel Light Rays from Distant Objects** As light travels away from any object, the light rays, all moving in straight lines, separate. By the time light has traveled trillions of kilometers, only the light rays moving in virtually parallel tracks are still near each other.

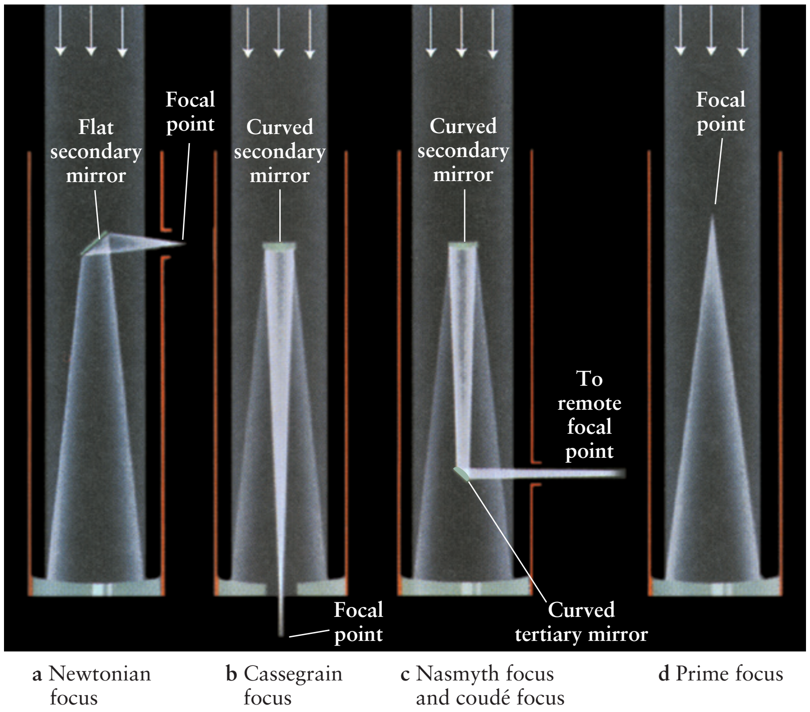



**FIGURE 3-11 Reflecting Telescopes** Four of the most common optical designs for reflecting telescopes: (a) Newtonian focus (popular among amateur astronomers), (b) Cassegrain focus (used by both amateurs and researchers), and the two other major designs, used by researchers (c) Nasmyth focus and coudé focus, and (d) prime focus.

like stars that are near each other on the celestial sphere also come into focus near each other on the focal plane.

To view the image, Newton placed a small, flat mirror at a 45° angle between the primary mirror and the focal point, as sketched in Figure 3-9c and Figure 3-11a. This **secondary mirror** reflects the light rays to one side of the telescope, and the viewer observes the image through an **eyepiece lens.** We will discuss how this lens works in Section 3-8. A telescope with this optical design is still called a **Newtonian reflector**. Suffice it to say for now that research telescopes do not use eyepieces. As we will see shortly, light-sensitive detectors are placed in their focal planes instead.

Newtonian telescopes are popular with amateur astronomers because they are convenient to use while the observer is standing up. However, they are not used in research observatories because they are lopsided. If astronomers attach their often heavy and bulky research equipment onto the side of a Newtonian telescope, the telescope twists and distorts the image in unpredictable ways. Making matters worse, these distortions change as the telescope tracks stars across the sky and therefore tilts at different angles.

Three basic designs exist for the reflecting telescopes used in research: Cassegrain, Nasmyth/coudé, and prime focus telescopes. In the first, a hole is drilled directly through the center of the primary mirror. A convex (outwardly curved) secondary mirror placed between the primary mirror and its focal point reflects the light rays back through the hole (Figure 3-11b). This design is called the **Cassegrain focus,** after a 1672 design by Laurent Cassegrain (1629–1693). This secondary mirror extends the telescope's focal length. Compact, relatively low-weight equipment is bolted to the bottom of the telescope, and the light is brought into focus in it. The advantage of this design over Newtonian telescopes is that the attached equipment is balanced and does not distort the telescope frame and, hence, the image.

The second design that astronomers use has two variations, both of which use a third mirror to direct light out the side of the telescope, at the place where it pivots (Figure 3-11c). Heavier or bulkier optical equipment that requires firmer mounting can be located at the *Nasmyth focus,* after Scottish engineer James Nasmyth (1808–1890), who developed it. If an extremely long focal length is desired, a **coudé focus** (named after a French word meaning "bent like an elbow") is used. Equipment that profits from the use of the Nasmyth focus and coudé focus includes a variety of *spectrographs,* instruments that separate light from objects into its individual colors to determine the objects' chemistries, surface temperatures, rotation rates, and motions toward or away from us.

In the third design used in research, an observing device is located at the undeflected focal point, directly in front of the primary mirror. This arrangement is called the **prime focus** (Figure 3-11d). This design has the advantages of making the brightest image (for a given exposure time) and having no secondary mirror, and therefore having the fewest reflections that otherwise would cause light loss and distortion.

The earliest telescopes were ground from a metal alloy called speculum metal that polished to a bright surface. However, it reflected only about two-thirds of the light that struck it and it tarnished rapidly. Modern primary telescope mirrors today are made from glass, which maintains its shape well. A highly reflective coating (usually aluminum, but new high-tech surfaces are being developed) is applied to the top surface of the mirror after it is ground and polished to the appropriate shape. In this design, the light never enters the mirror, unlike the mirrors we use in everyday life, with the reflective coating behind the glass.

## 3-6 Secondary mirrors dim objects but do not create holes in them

You have probably noticed (see Figure 3-11) that the secondary mirror of a reflector blocks some incoming light—one unavoidable price that astronomers must pay. Typically, a secondary mirror prevents about 10% of the incoming light from reaching the primary mirror. This problem is addressed by constructing primary mirrors with sufficiently large surface areas to compensate for the loss of light. You might also think that, because light is missing from the center of the telescope due to blockage by the secondary mirror, a corresponding central "hole" appears in the images. However, this problem does not occur, because light from all parts of each object being observed enters all parts of the telescope (Figure 3-12). Indeed, covering any part of the primary mirror darkens the image but does not limit which parts of the object you can see through the telescope. Likewise, blocking part of the opening of a telescope made just with lenses darkens the image but does not create a hole in the image.

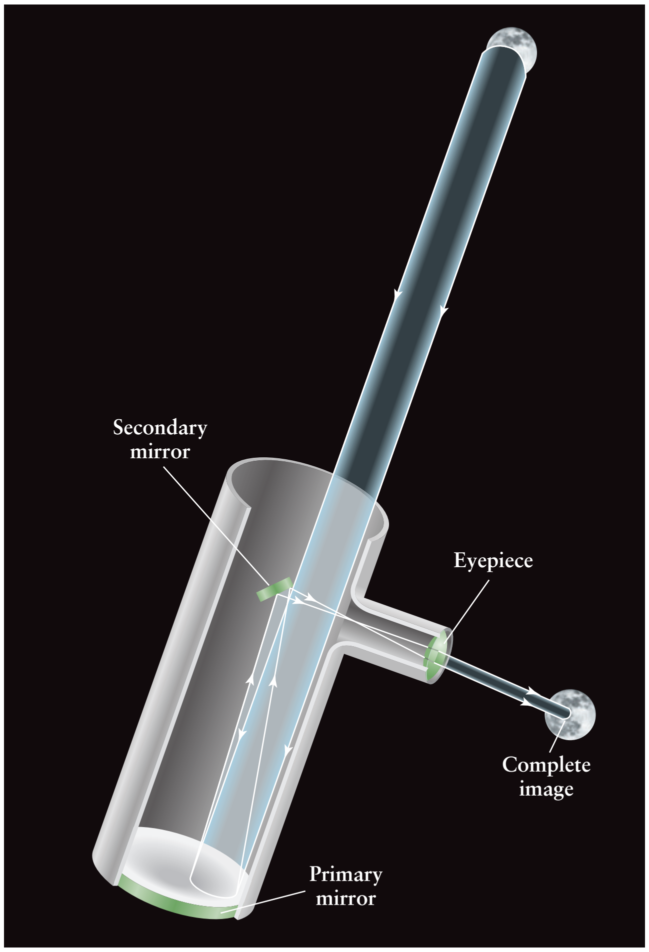



**FIGURE 3-12 Secondary Mirror of a Reflecting Telescope Does Not Create a Hole in the Image** Because the light rays from distant objects are parallel, light from the entire object (in this case, the crescent Moon) reflects off all parts of the primary mirror. Therefore, every part of the object sends photons to the eyepiece. This figure shows the reconstruction of the entire crescent Moon from light passing through just part of this telescope. The same drawing applies everywhere on the primary mirror that is not blocked by the secondary mirror.

## 3-7 Telescopes brighten, resolve, and magnify

As mentioned earlier, a telescope's most important function is to provide astronomers with as bright an image as possible. The brighter an object appears, the more information about it we can extract. The observed brightness of any object depends on the total number of photons collected from it, which, in turn, depends on the area of the telescope's primary mirror. Analogously, the pupils in our eyes get larger in dark environs to allow more photons to strike the retina and create a brighter image than otherwise. For exposures of equal times, a telescope with a large primary mirror produces brighter images and detects fainter objects than a telescope with a smaller primary mirror (Figure 3-13).

**Insight Into Science**

**Costs and Benefits** Science now relies heavily on technology to conduct experiments or to make observations. The cost of cutting-edge astronomical observations may run to hundreds of millions of dollars or more. The return on such investments is a better understanding of how the universe works, how we can harness its resources, and our place in it.

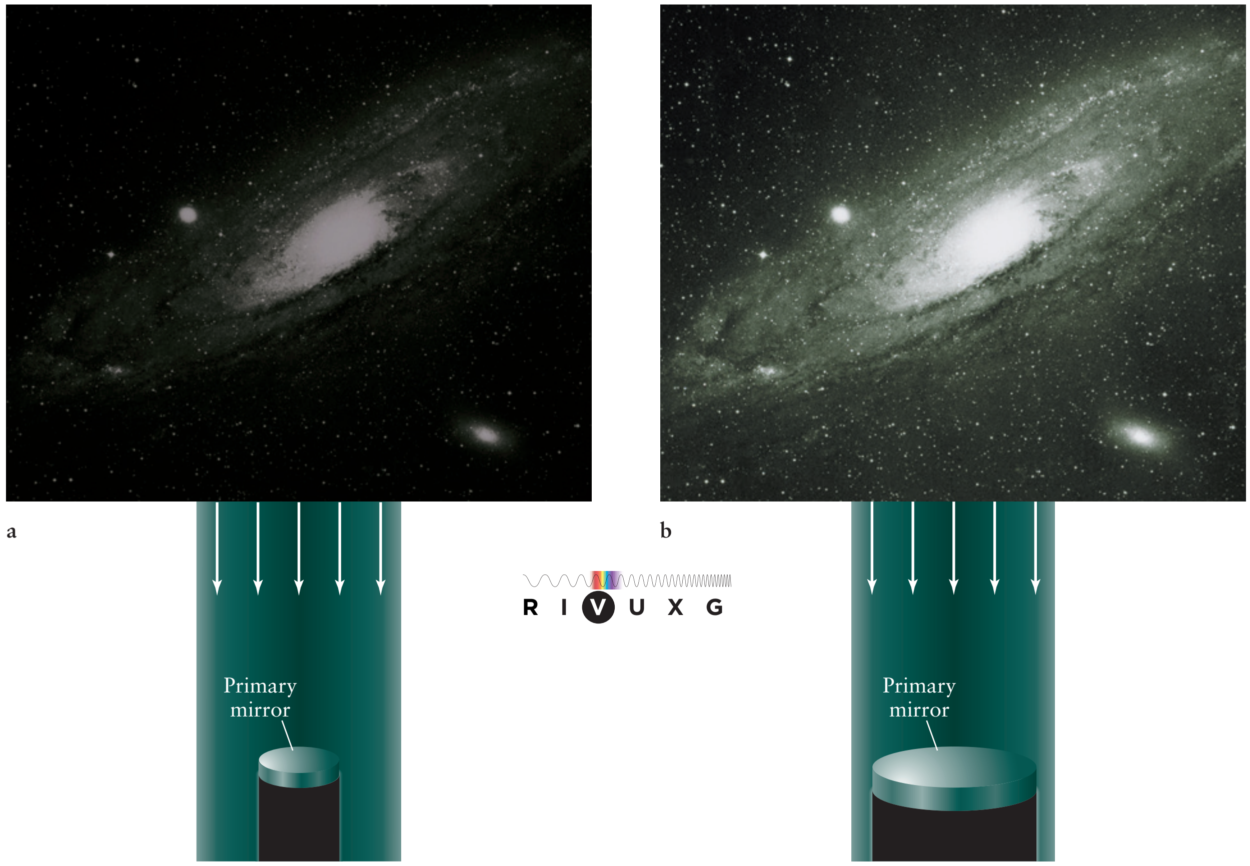



**FIGURE 3-13 Light-Gathering Power** Because a large primary mirror collects more starlight than does a smaller one, a larger telescope produces a brighter image than a smaller one, all other things being equal. The same principle applies to telescopes that collect light using just lenses. These two photographs of the Andromeda Galaxy (as well as other smaller galaxies and foreground stars in our Milky Way galaxy) were taken through telescopes with different diameters and were exposed for equal lengths of time at equal magnification. (Royal Observatory, Edinburgh/Science Source)

The **light-gathering power** of a telescope is directly related to the area of the telescope's primary mirror. Recall that the area and diameter of a circle are related by the formula

$$\text{Area} = \frac{\pi d^2}{4}$$

where $d$ is the diameter of the mirror and $\pi$ (pi) is about 3.14. Consequently, *a mirror with twice the diameter of another mirror has 4 times the area of the smaller mirror and, therefore, collects 4 times as much light as does the smaller one in the same amount of time*. For example, a 36-cm-diameter mirror has 4 times the area of an 18-cm-diameter mirror. Therefore, the 36-cm telescope has 4 times the light-gathering power of a telescope half its size.

Another vital function of any telescope is to reveal greater detail of objects that are more than just points of light. Such *extended objects* include the Moon, the Sun, planets, galaxies, interstellar gas clouds, and clusters of stars, among other things. A large telescope increases the sharpness of the image and the degree of detail that can be seen. **Angular resolution** (often just called *resolution*) measures the clarity of images (Figure 3-14). The angular resolution of a telescope is measured as the arc angle between two adjacent stars whose images can just barely be distinguished by the telescope. The smaller the angle, the sharper the image. Large, modern telescopes, like the Keck telescopes in Hawaii, have angular resolutions better than 0.1 arcsec. As a general rule, *a telescope with a primary mirror twice the diameter of another telescope's primary will be able to see twice as much detail as the smaller telescope*.

The final function of a telescope is to make objects appear larger. This property is called **magnification**. Magnification is associated with resolution, because the larger the image, the more detail of the image you can potentially see (Figure 3-15). The magnification of a reflecting telescope is equal to the focal length of the primary mirror divided by the focal length of the eyepiece lens

$$\text{Magnification} = \frac{\text{Focal length of primary}}{\text{Focal length of eyepiece}}$$

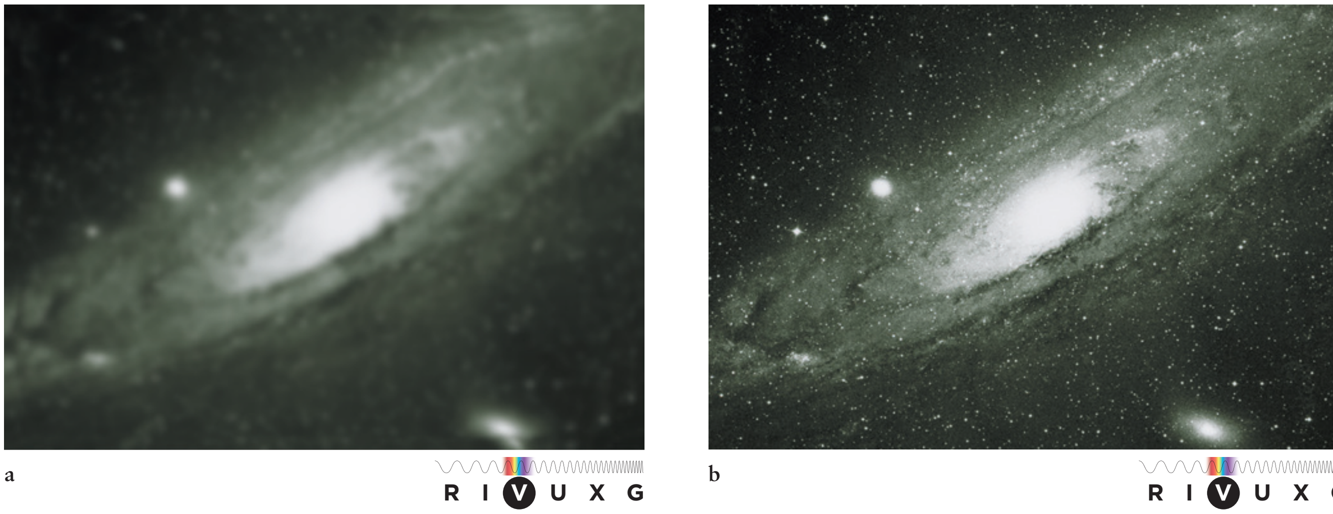



**FIGURE 3-14 Resolution** The larger the diameter of a telescope's primary mirror, the finer the detail the telescope can resolve. These two images of the Andromeda Galaxy, taken through telescopes with different diameters, show this effect. (a) A lower-resolution image taken through a smaller telescope. In this photograph most individual stars blur together to make the galaxies look like fuzzy blobs. (b) The same field of view through a larger-diameter telescope. Many more individual stars and interstellar gas clouds are visible here than in (a). Increasing the exposure time of the smaller-diameter telescope (a) will only brighten the image, not improve the resolution. (Royal Observatory, Edinburgh/Science Source)


**FIGURE 3-15 Magnification** The same telescope can magnify by different amounts, depending on the focal length of the eyepiece. (a) A low-magnification image of the Moon. (b) An image of the Moon taken with magnification 4 times greater than image (a). Note in this case that the increased magnification leads to increased resolution (that is, more detail can be seen in the larger image). (ClawsAndPaws/iStock/Getty Images)

For example, if the primary mirror of a telescope has a focal length of 100 cm and the eyepiece has a focal length of 0.5 cm, then the magnifying power of the telescope is

$$\text{Magnification} = \frac{100\ \text{cm}}{0.5\ \text{cm}} = 200$$

This property is usually expressed as 200×.

Eyepieces are removable. Eyepieces with different focal lengths change a telescope's magnification. However, there is a limit to the magnification of any telescope. Try to magnify beyond that limit, and the image becomes distorted. As a rule, *a telescope with*

**Margin Question 3-4**
Normal eyeglasses or contact lenses are designed to improve which aspect of vision presented in this section?

*a primary mirror twice the diameter of another telescope's primary will have twice the maximum magnification of the smaller telescope.* We now turn to a discussion of how refracting telescopes change the direction of the light that enters them.

## 3-8 Eyepieces, refracting telescopes, and binoculars use lenses to focus incoming light

Although light travels at about 300,000 km/s in a vacuum, it moves more slowly through any medium, such as air or glass. While the change in speed going from a vacuum into Earth's atmosphere is only about 90 km/s, in typical glass the speed is reduced by about 100,000 km/s. That is, it travels only about 2/3 as fast in glass as in vacuum. As light enters glass, it slows abruptly, much like a person walking from a hard pavement onto a sandy beach. Conversely, light that exits a piece of glass resumes its original speed, just as a person resumes his or her normal pace when stepping back from sand onto a solid surface.

As a result of changing speed, light also changes direction as it passes from one transparent medium into another. As noted earlier, this latter change is called *refraction*. You see refraction every day when looking through windows. Imagine a stream of photons from a star that enters a window, as shown in Figure 3-16a. As a light ray goes from the air into the glass, the light ray's direction changes so that it is more perpendicular to the surface of the glass than it was before entering. Once inside the glass, the light ray travels in a straight line. Upon emerging from the other side, the light ray bends once again, resuming its original direction and speed. The net effect is only a slight, uniform displacement of the objects beyond the glass.

Unlike windows, lenses have surfaces of varying thickness (Figure 3-16b). These curved surfaces force the light rays to emerge from the lens in different directions than they had before entering the lens. Lenses that are thicker at their centers than at their edges are called *convex* lenses and force the light that enters them to converge as it passes through. Conversely, lenses thinner at their centers than around their edges are called *concave* lenses. They cause light rays to diverge.

Large convex lenses called **objective lenses** were used instead of primary mirrors in research telescopes in the nineteenth century (and are still used in many telescopes built for home use today). Parallel light rays that enter an objective lens converge and meet at the focal point of the lens. The distance between the focal point and the lens is the lens's focal length (see Figure 3-16b). As with reflecting telescopes, if the object is close enough or large enough to be more than just a dot as seen through the telescope, all the light from it does not converge at the focal point, but rather focuses along the focal plane (Figure 3-17). When we want to look directly into the telescope, a small eyepiece lens is used to bring the light rays collected by the objective lens back to being parallel, so our brains can make sense of what we see.

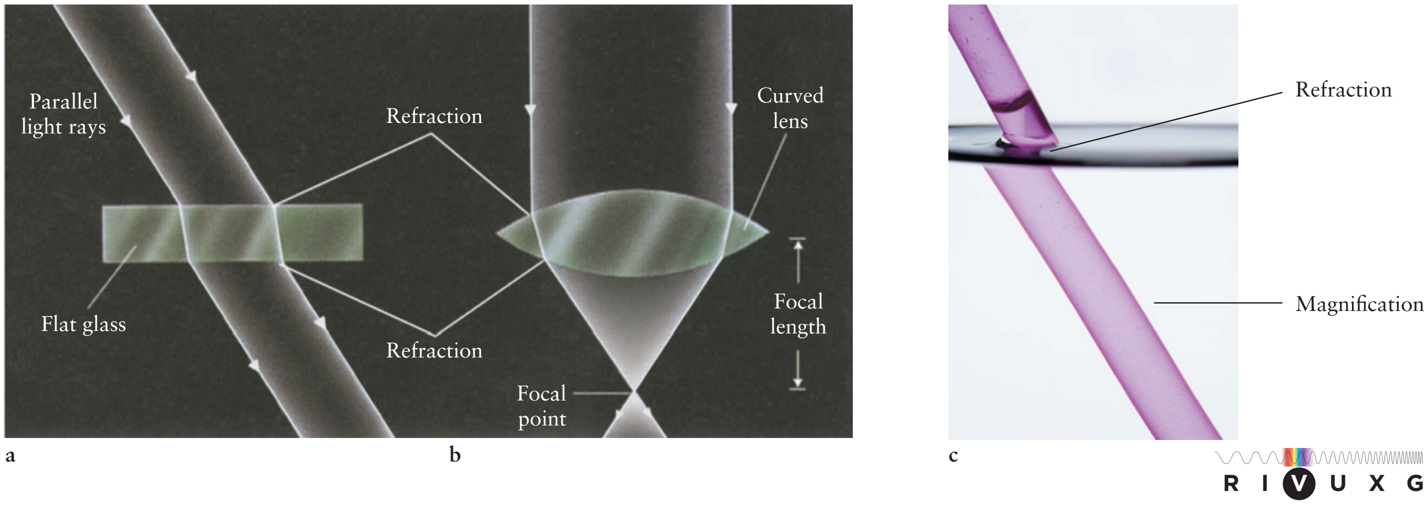



**FIGURE 3-16 Refraction Through Uniform and Variable Thickness Glasses** (a) Refraction is the change in direction of a light ray when it passes into or out of a transparent medium such as glass. A light ray that enters a denser medium, such as moving from air into water or glass, is bent or refracted to an angle more perpendicular to the surface than the angle at which it was originally traveling. If the glass is flat, then the light leaving it is refracted back to the direction it had before entering the glass. There is no overall change in the direction in which the light travels. (b) If the glass is in the shape of a suitable convex lens, parallel light rays converge to a focus at the focal point. As with parabolic mirrors, the distance from the lens to the focal point is called the focal length of the lens. (c) The straw as seen through the side of the liquid is magnified and offset from the straw above the liquid because the liquid is given a curved shape by the side of the glass. The straw, as seen above the top of the liquid, is refracted but does not appear magnified because the surface of the water is flat and the beaker has uniform thickness. (c: cheyennezj/Shutterstock.com)

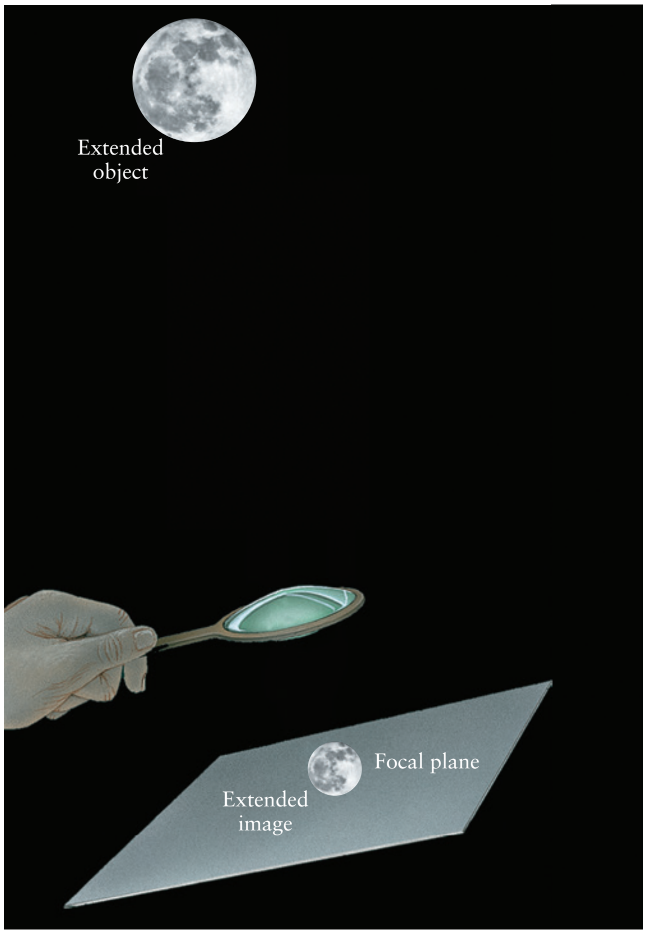



**FIGURE 3-17 Extended Objects Create a Focal Plane** Light from objects larger than points in the sky does not all converge to the focal point of a lens. Rather, an image of the object is created at the focal length in what is called the focal plane.

A refracting telescope or **refractor** (Figure 3-18) is therefore an arrangement of two lenses used to gather light. The objective lens at the top of the telescope has a large diameter and long focal length. Like a primary mirror, its purpose is to collect as much light as possible. The eyepiece lens, at the bottom of the telescope, is smaller and has a short focal length. The mathematics of magnification for a refracting telescope is the same as for a reflecting telescope with the focal length of the objective lens replacing the focal length of the primary mirror. Likewise, all of the rules for the limits on telescopes are the same for refractors as for reflectors.

The first refracting telescopes were designed and built in Holland in 1608. As with many scientific and engineering discoveries and developments, there have been several claims of original design for the telescope. Among these are Hans Lippershey, Jacob Metius, and Zacharias Janssen, all Dutch lensmakers.

The largest refracting telescope in the world, completed in 1897 and located at the Yerkes Observatory in Williams Bay, Wisconsin, near Chicago (Figure 3-19), has an objective lens that is 102 cm (40 in.) in diameter with a focal length of $19\frac{1}{3}$ m ($63\frac{1}{2}$ ft). The lens was ground by the premier American lensmaker of the nineteenth century, Alvan Clark (1804–1887). The second-largest refracting telescope, located at Lick Observatory near San Jose, California, has an objective lens of 91 cm (36 in.) in diameter. No major refracting telescopes were constructed in the twentieth century or are planned for this century.

Refracting telescopes suffer from a variety of problems that have limited their use as research instruments. These problems include the following:

- It is difficult to grind a lens to the very complicated shape necessary to have all parallel light rays of any color passing through it converge to the same focal point. When, for example, the lens is given a spherical shape (relatively easy to manufacture), the light at different distances from the center of the lens has different focal lengths (Figure 3-20). This phenomenon is called **spherical aberration**. Such aberration does not occur for reflecting telescopes because the shape of a mirror needed to focus light from every part of the mirror to the same focal point is a simple parabola, which is easy to manufacture, as discussed in Section 3-9.
- Even when light passes through an ideally shaped lens, different colors of light are refracted by different amounts, so they have different focal lengths. This phenomenon is called **chromatic aberration** (Figure 3-21a). As a result of spherical and chromatic aberration, objects look blurred (Figure 3-21b). Chromatic and

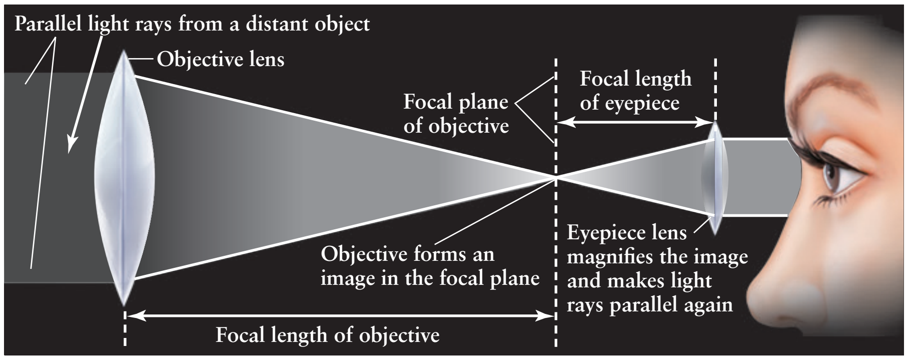



**FIGURE 3-18 Essentials of a Refracting Telescope** A refracting telescope consists of a large, long-focal-length objective lens that collects and focuses light rays and a small, short-focal-length eyepiece lens that restraightens the light rays. The lenses work together to brighten, resolve, and magnify the image formed at the focal plane of the objective lens.

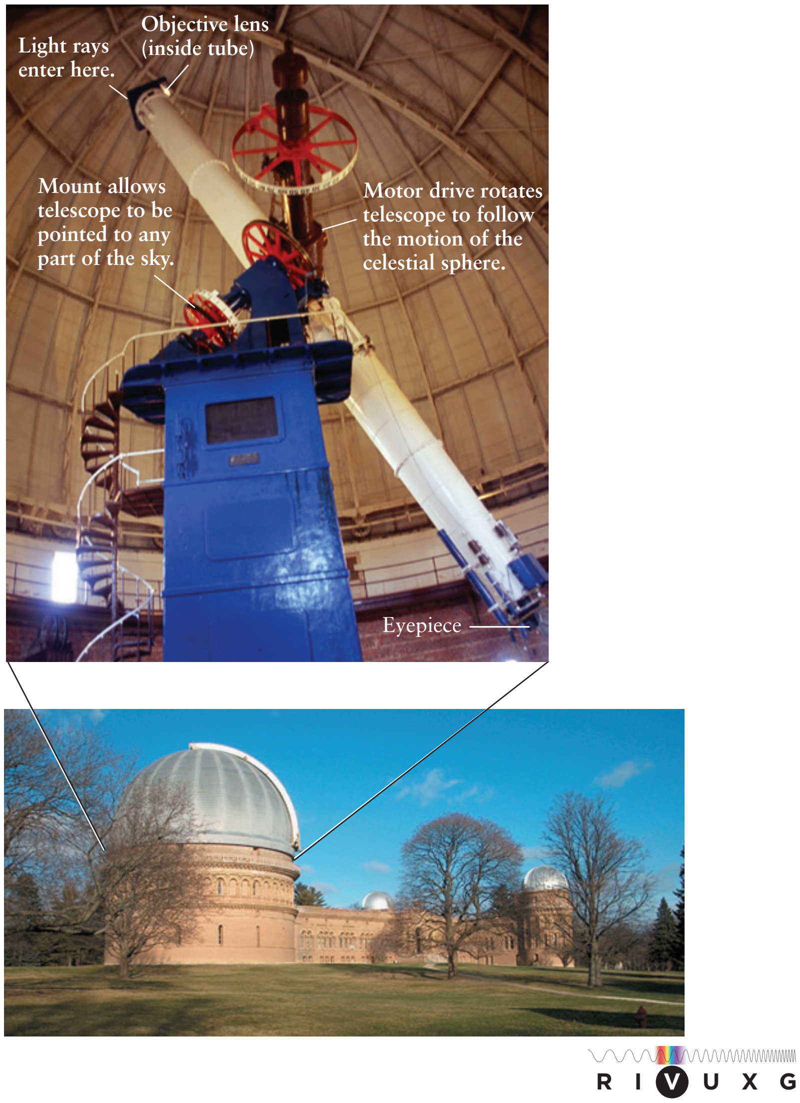



**FIGURE 3-19 The Largest Refracting Telescope** This giant refracting telescope, built in the late 1800s, is housed at Yerkes Observatory near Chicago. The objective lens is 102 cm (40 in.) in diameter, and the telescope tube is $19\frac{1}{3}$ m ($63\frac{1}{2}$ ft) long. (top: ALAN SOLOMON/Tribune News Service/LAKEGENEVA/WI/USA/Newscom; bottom: Kyle Cudworth)

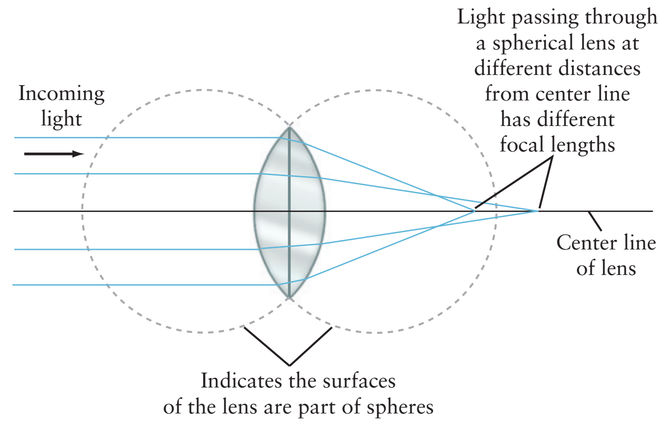
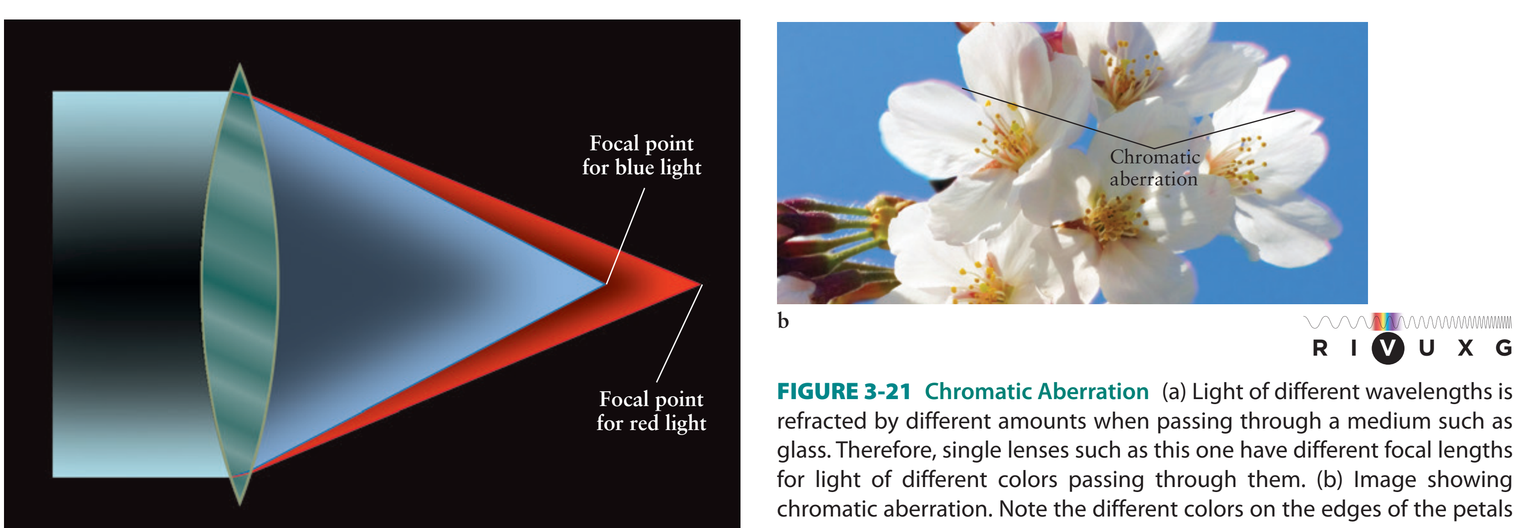



**FIGURE 3-20 The Geometry of a Spherical Lens** If both sides of a lens are spherical surfaces, as shown here, then light rays of the same color passing through at different distances from the center of the lens are refracted by different amounts. Therefore, spherical lenses have different focal lengths for these different light rays and so they give blurry images.

spherical aberration can be corrected (Figure 3-22) by adding a second lens with a different shape and made of a different type of glass (which refracts light by a different amount than does the first lens). Chromatic aberration is not a problem for reflectors because the reflecting surface is always on the top of the mirror; reflecting telescopes do not use refraction to focus light.

- A lens must be supported only around its edges to avoid blocking the light. The weight of a large lens can cause it to sag and thus distort the image. This distortion is not a problem with reflectors because the entire underside of the mirror can be supported, as necessary.
- Air bubbles in the glass cause unwanted refractions and, hence, distorted images.
- Glass does not allow all wavelengths to pass through it equally.




a The problem: Chromatic aberration

**FIGURE 3-21 Chromatic Aberration** (a) Light of different wavelengths is refracted by different amounts when passing through a medium such as glass. Therefore, single lenses such as this one have different focal lengths for light of different colors passing through them. (b) Image showing chromatic aberration. Note the different colors on the edges of the petals caused by light passing through a lens. (GYRO PHOTOGRAPHY/amanaimagesRF/Getty Images)

4 These last two points are not issues with reflectors because the light never enters the glass. The combination of all the problems listed here makes images from refractors less accurate than those obtained from reflecting telescopes, which explains why modern research telescopes are all reflectors. The mirrored surfaces of research telescopes are polished so smoothly that the highest bumps are less than 0.002 times the thickness of a human hair.

Although they are better light collectors than refracting telescopes, reflecting telescopes are not perfect; there are several prices to pay for the advantages they offer over refractors. Two of the most important prices to pay are blocked light, as discussed in Section 3-6, and spherical aberration, which we consider in the next section.

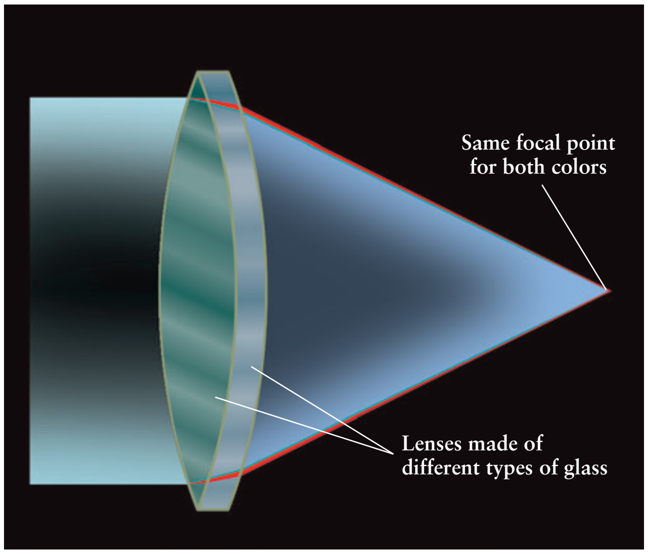
## 3-9 Shaping telescope mirrors and lenses is an evolving science

To make a reflector, an optician traditionally grinds and polishes a large slab of glass into a concave, spherical surface. Before computer control, grinding a spherical surface was much easier than grinding the ideal parabolic surface. However, light that enters a spherical telescope mirror at different distances from the mirror's center comes into focus at different focal lengths (Figure 3-23a). Images taken directly from such telescopes have the same spherical aberration as the refractors described above.

We can avoid spherical aberration in reflecting telescopes by making the mirror parabolic (Figure 3-23b) or by using a thin correcting lens, called a **Schmidt corrector plate**, with a spherical mirror. Developed in 1930 by the Estonian-Swedish optician Bernhard Schmidt (1879–1935), the corrector plate is located at the top of the telescope (Figure 3-23c). The light coming into the telescope is refracted by the plate just enough to compensate for spherical aberration and to bring all of the light into focus at the same focal length. These correctors have the added benefit of focusing light from a larger angle in the sky than would be in focus without the plate. A Schmidt corrector plate therefore enables astronomers to map large areas of the sky with relatively few photographs at moderately high magnification. In other words, the Schmidt corrector plate acts like a wide-angle lens on a camera. Schmidt corrector plates are often used in conjunction with Cassegrain mirrors to create *Schmidt-Cassegrain* telescopes, which are popular for home use because they are compact and give relatively wide-angled images. However, the plate does not allow for as much magnification as a telescope with a parabolic mirror. (If you are interested in learning about telescope mounts or the related matter of buying a telescope, see Appendix H.)

**Margin Question 3-5**
How do human eyes focus light?

Although some parabolic primary mirrors have been meticulously hand-ground over the past century, the advent of computer-controlled grinding and rotating furnaces (Figure 3-24), in which the liquid glass is actually spun into a parabolic shape, has now made it economical to cast parabolic mirrors with diameters of several meters. That spinning a liquid causes it to develop a parabolic surface was discovered by Isaac Newton in 1689, when he created the effect in a bucket of spinning water.




a The solution: Use two lenses


b

**FIGURE 3-22 Achromatic Lens** (a) By using two differently shaped lenses (often of different types of glass), light of different wavelengths can be brought into focus at the same focal length. Such achromatic lenses are used in cameras and many telescopes. (b) Same object as in Figure 3-21b imaged through an achromatic lens. Note that the colors on the edges of the petals seen in Figure 3-21b do not occur here. (GYRO PHOTOGRAPHY/amanaimagesRF/Getty Images)

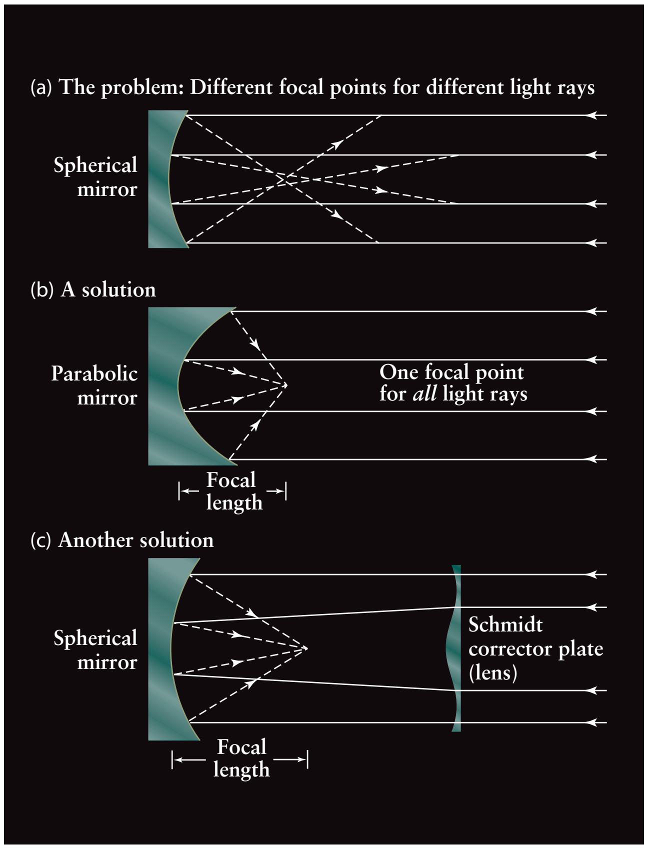


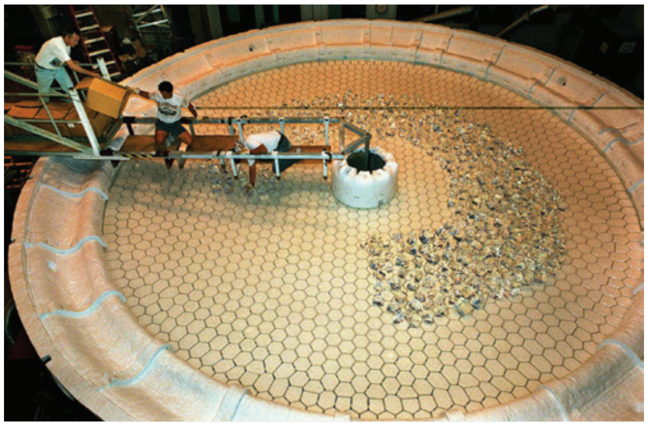

**FIGURE 3-23 Spherical Aberration** (a) Different parts of a spherically concave mirror reflect light to slightly different focal points. This effect, spherical aberration, causes image blurring. This problem can be overcome by (b) using a parabolic mirror or (c) using a Schmidt corrector plate (a specially curved lens) in front of a spherically concave telescope mirror.

## 3-10 Storing and analyzing light from space is key to understanding the cosmos

The invention of photography during the nineteenth century was a boon for astronomy. By taking a long exposure with a camera mounted at the focal plane of a telescope, an astronomer could record extremely faint features that could not be seen by just looking through the telescope. The reason photography is better is that our nervous system refreshes (that is, replaces) the images we receive from our eyes several times a second, whereas film adds up the intensity of all the photons that affect its emulsion. By keeping telescopes aimed precisely, so that images do not blur, exposures of an hour or more became quite routine. Astrophotographs and their modern electronic equivalents, discussed in the next few paragraphs, make all objects appear brighter and reveal greater detail in extended objects—such as galaxies, star clusters, and planets—than we could otherwise see.

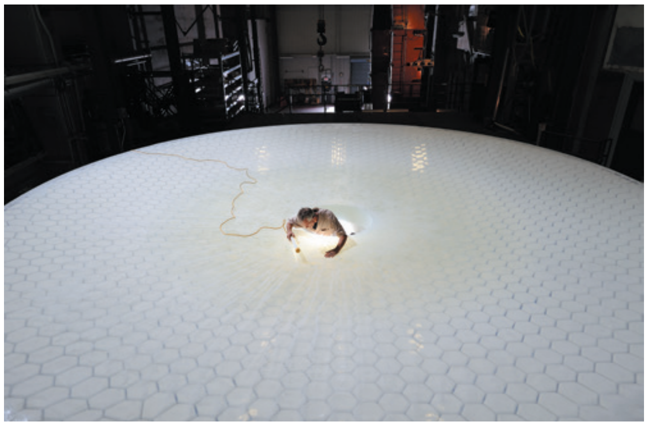
Astronomers have long known, however, that a photographic plate is an inefficient detector of light because it depends on a chemical reaction to produce an image. Typically, only 2% of the light striking film triggers a reaction in the photosensitive material. Thus, roughly 98% of the light falling onto a photographic plate is wasted.

Rapidly evolving technology has changed all that. We have replaced photographic film with highly efficient electronic light detectors called **charge-coupled devices (CCDs).** Very good CCDs respond to between 50% and 75% of the light falling on them; great CCDs are sensitive to more than 90% of the photons that strike them. Clearly CCD resolution is much better than that of film, and CCDs respond more uniformly to light of different colors. Divided into an array of small, light-sensitive squares called picture elements or, more commonly,



a

R I V U X G



b

R I V U X G

**FIGURE 3-24 Rotating Furnace for Making Parabolic Telescope Mirrors** (a) To make each 8.4-m primary mirror for the Large Binocular Telescope II on Mount Graham in Arizona, 40,000 pounds of glass are loaded into a rotating furnace and heated to 1450 K (2150°F). This image shows glass fragments loaded into the cylindrical furnace. (b) After melting, spinning, and cooling, the mirror's parabolic surface is ready for final smoothing and coating with a highly reflective material. (a: Roger Ressmeyer/Corbis/VCG/Getty Images; b: Joe McNally/Getty Images)

**pixels,** each CCD is a square or rectangle a few centimeters on a side. Several of them are often used together to create a larger image (Figure 3-25). Digital cameras and picture-taking cell phones use this same CCD technology. The largest grouping of CCDs used on a telescope has 1400 megapixels (a megapixel is 1 million pixels), compared to most digital cameras, which typically have between 12 and 24 megapixels. In 2022, a telescope named the Large Synoptic Survey Telescope is expected to be fully operational with a 3200 megapixel CCD array.

When an image from a telescope is focused on the CCD, an electric charge builds up in each pixel in direct proportion to the intensity of the light (number of photons) falling on that pixel. When the exposure is finished, the charge on each pixel is read into a computer. Figure 3-26 shows one photograph and two CCD

**Margin Question 3-6**
Why do the human eye and brain clear the images that they receive many times per second?

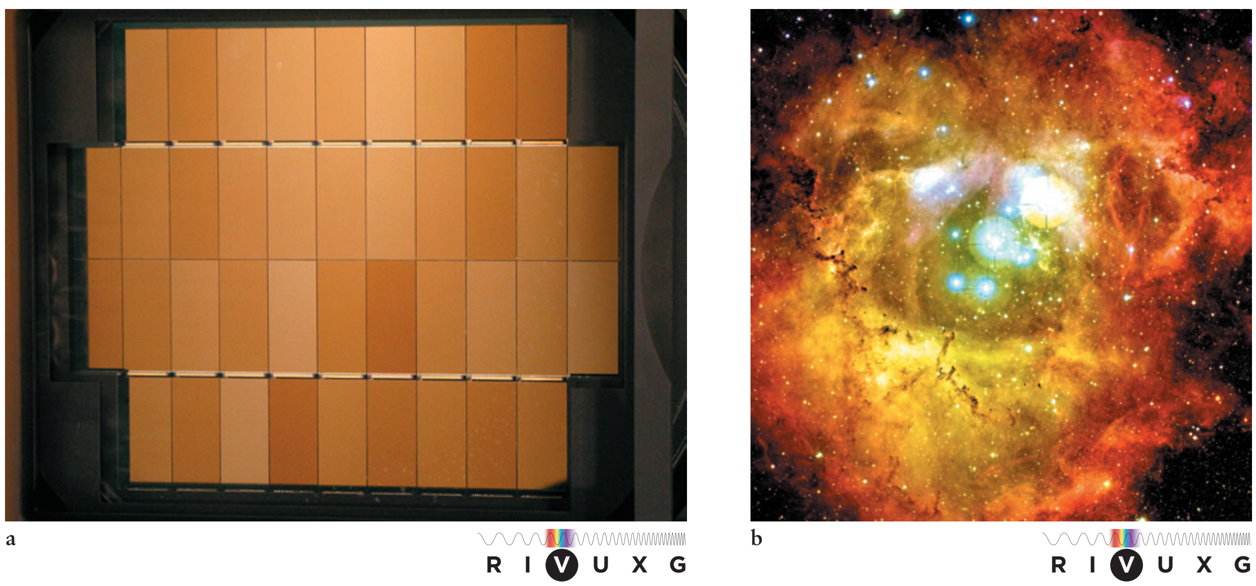



**FIGURE 3-25 Mosaic of Charge-Coupled Devices (CCDs)** (a) These 40 CCDs combine to provide up to 378 million light-sensitive pixels that store images collected by the Canada-France-Hawaii Telescope on the dormant volcano Mauna Kea in Hawaii. Electronic circuits transfer the data to a waiting computer. (b) This image of the Rosette Nebula, a region of star formation 5000 ly away in the constellation Monoceros (the Unicorn), was taken with the CCD in (a). The image shows the incredible detail that can be recorded by large telescopes and high-resolution CCDs. (a: J.C. Cuillandre, Canada-France Hawaii Telescope; b: CFHT/Science Source)

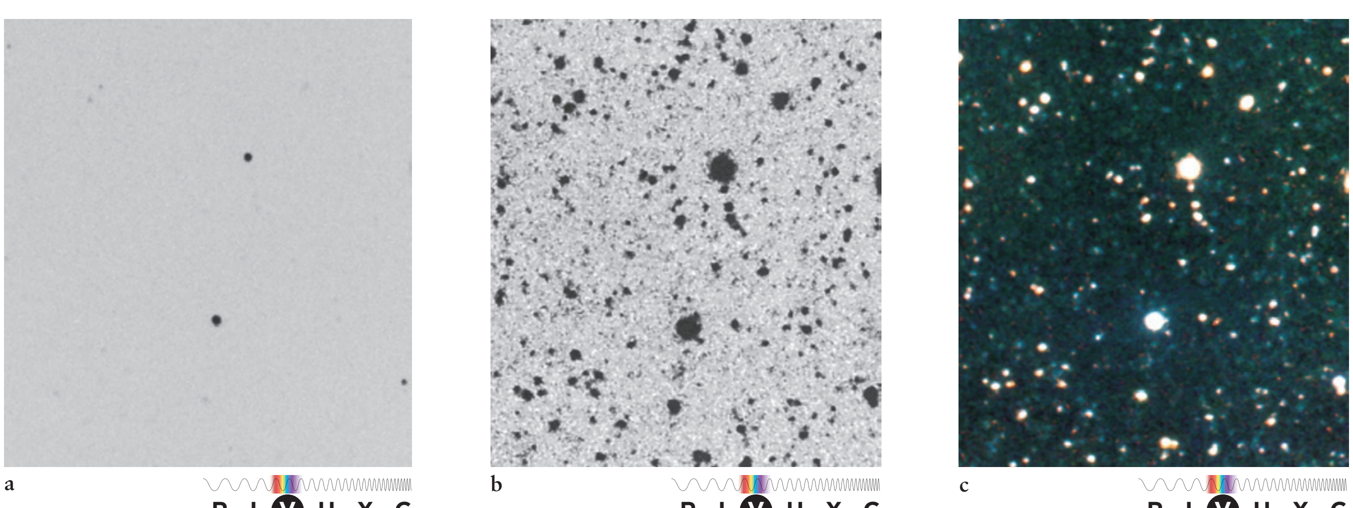



**FIGURE 3-26 Photography versus CCD Images** These three views of the same part of the sky, each taken with the same 4-m telescope, compare CCDs to photographic plates. (a) A negative print (black stars and white sky) of a photographic image. (b) A negative CCD image. Notice that many faint stars and galaxies that are invisible in the ordinary photograph can be seen clearly in this CCD image. (c) This (positive) color view was produced by combining a series of CCD images taken through colored filters. (Patrick Seitzer, NOAO)

images of the same region of the sky, all taken with the same telescope. You can see how many details visible in the CCD images are absent in the ordinary photograph.

## 3-11 Earth's atmosphere hinders astronomical research

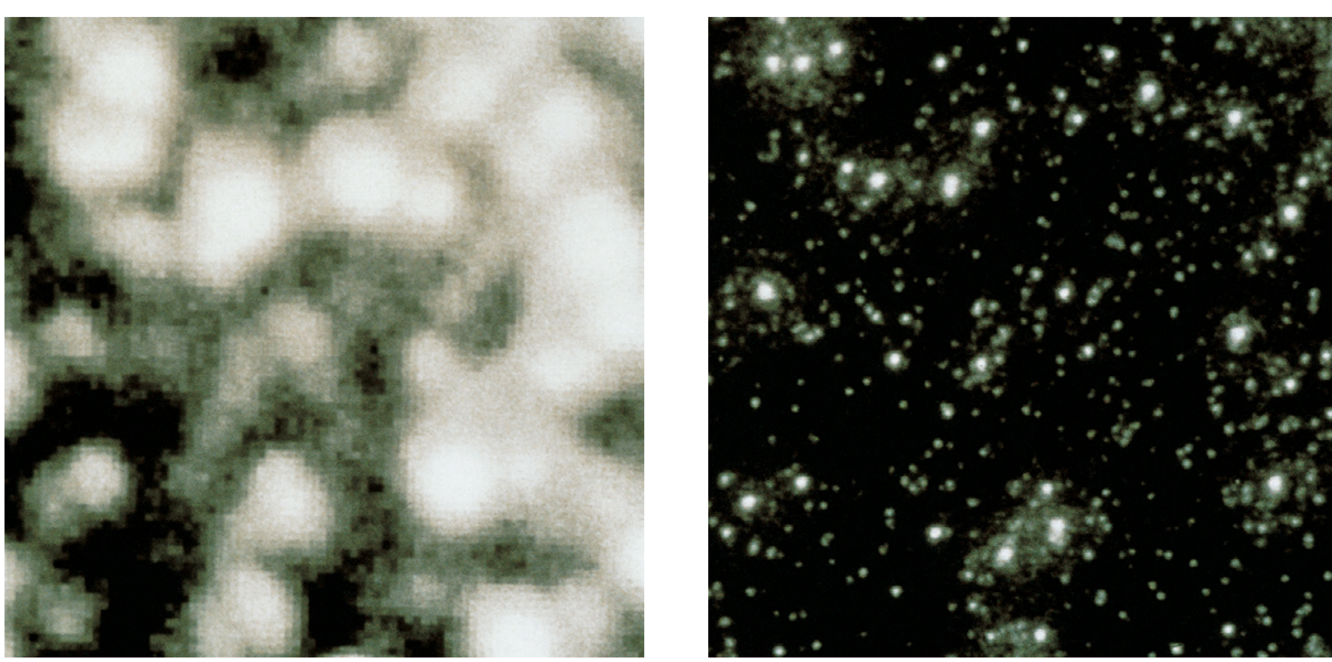
Earth's atmosphere affects the light from objects in space before it reaches ground-based telescopes. Even for those wavelengths that have windows through the atmosphere (see Section 3-4), some light is absorbed in the atmosphere, making all objects appear dimmer than they would appear from space. Also, the air is turbulent and filled with varying amounts of impurities and moisture. You have probably seen turbulence while driving in a car on a hot day, when the road ahead appears to shimmer. Blobs of air, heated by Earth, move upward to create this effect. Light passing through such a blob is refracted, because each hot air mass has a lower density than the cooler air around it. Because each blob behaves like a lens, images of objects beyond them appear distorted.

5 The atmosphere over our heads is similarly moving and changing density, and the starlight passing through it is similarly refracted. Because air density changes rapidly, the resulting changes in refraction make the stars appear to change brightness and position rapidly, an effect we see as **twinkling.** When photographed from Earth for more than a few seconds, twinkling smears out a star's image, causing it to look like a disk rather than a pinpoint of light (Figure 3-27a). Astronomers use the expression "seeing" to describe how steady the atmosphere is; when the seeing is bad, much twinkling is occurring and, therefore, telescopic images are spread out and blurry.

The angular diameter of a star's smeared-out image, called the **seeing disk**, is a realistic measure of the best possible resolution for conventional telescopes, as we have been discussing so far. The size of the seeing disk varies from one observatory site to another and by the hour (sometimes by the minute) at each site. At Palomar Observatory in California, the smallest seeing disk is roughly 1 arcsec (1″). The best conditions on Earth have been recorded at the observatory on the 14,000-ft summit of Mauna Kea, the tallest volcano on the island of Hawaii. The seeing disk there has been as small as 0.2″.

Without the effects of Earth's atmosphere, stars do not twinkle. As a result, photographs taken from telescopes in space reveal stars as much finer points (Figure 3-27b), and extended objects, such as planets and galaxies, appear in greater detail.

Light pollution, light that comes from nonastronomical sources, poses another problem for Earth-based telescopes (Figure 3-28). Keep in mind that the larger the primary mirror, the more light it gathers and, therefore, the more information astronomers can obtain from its images or spectra. The 5-m (200-in.) telescope at the Palomar Observatory between San Diego and Los Angeles was the first truly great large telescope, providing astronomers with invaluable insights into the universe for decades. However, light



a R I V U X G

b R I V U X G

**FIGURE 3-27 Effects of Twinkling** The same star field photographed with (a) a ground-based telescope, which is subject to poor seeing conditions that result in stars twinkling, and (b) the Hubble Space Telescope, which is free from the effects of twinkling. (NASA/ESA)

a

R I V U X G

b

R I V U X G

**FIGURE 3-28 Light Pollution** These two images of New York City, as seen from under the Brooklyn Bridge, show the increase of light in the sky from 1955 to 2010. Compare the skies just above the buildings. This light prevents New Yorkers from seeing dimmer stars that are visible in darker locations. Since 1972, light pollution, a problem for many observatories around the world, has been partially controlled by local ordinances passed by cities. (Left: D. CORSON/ClassicStock/Alamy; Right: Anhgemus Photography/Moment Open/Getty Images)

pollution from the two cities now fills the night sky, seriously reducing the ability of that telescope to collect light from objects in space. Not surprisingly, the best observing sites in the world are high on mountaintops, such as Mauna Kea—above smog, water vapor, and clouds, and far from city lights. An even better location, astronomers have discovered, is to observe space from space, eliminating the interference of both the lights of civilization and Earth's atmosphere. Removing these effects is why the Hubble Space Telescope and other orbiting telescopes achieve such magnificent resolution in the images they take.

**Margin Question 3-7**
Where in a typical house can the seeing problems described in Section 3-11 be observed?

**Insight Into Science**

**Research Requires Patience** Seeing conditions—indeed, most observing situations in science—are rarely ideal. Besides such natural phenomena, which are beyond their control, scientists must also contend with equipment failures, late deliveries of parts, and design flaws. Furthermore, because travel time is so long, some missions (like the robotic spacecraft roving on Mars or the New Horizons voyage to Pluto and the Kuiper belt) take years or even decades to complete.

**WHAT IF...**

**Stars actually twinkled?**
Stars appear to significantly change their brightness (twinkle) in fractions of a second. If they actually did vary in brightness as much as we see them vary, they would do so by changing size—bigger is brighter. If such expansion and contraction occurred, the rapid motion of their gases would cause stars to blow apart in a matter of seconds.

## 3-12 The Hubble Space Telescope provides stunning details about the universe

For decades, astronomers dreamed of observatories in space. Such facilities would eliminate the image distortion created by twinkling and by poor atmospheric transparency due to pollution, volcanic debris, and water vapor. These telescopes could operate 24/7 and over a wide range of wavelengths—from the infrared through the visible range and far out into the gamma-ray part of the spectrum. Since 1990, NASA and other space agencies have launched a variety of space telescopes, including four of what NASA called its Great Observatories. The first Great Observatory to go up was the Hubble Space Telescope (HST).

Soon after HST was placed in orbit from the space shuttle *Discovery* in 1990, astronomers discovered that the telescope's 2.4-m primary mirror had been ground to the incorrect shape. Therefore, it suffered from spherical aberration, which caused its images to be surrounded by a hazy glow. During a repair mission in December 1993, astronauts installed corrective optics that eliminated the problem (Figure 3-29). The telescope was further upgraded in 1997, 1999, 2002, and 2009. Now HST has a resolution of better than 0.1″, which is better than can be obtained by telescopes on Earth's surface without the use of advanced technology (as discussed in Section 3-13).


**FIGURE 3-29 The Hubble Space Telescope (HST)** This photograph of HST hovering above the space shuttle *Endeavor*'s cargo bay was taken in 1993, at completion of the first servicing mission. HST studies the heavens at infrared, visible light, and ultraviolet wavelengths. (NASA)

The observations taken by HST continue to stagger the imagination. Hubble has made discoveries related to the planets in our solar system, planetary systems around other stars, other galaxies and the distances to them, black holes, quasars, the formation of the earliest galaxies, the age of the universe, and many other topics.

## 3-13 Advanced technology is spawning a new generation of superb ground-based telescopes

The clarity of images taken by the HST and other space telescopes, along with the "seeing" issues described earlier may suggest that ground-based observational astronomy is a dying practice. For many observing projects, however, the resolution of conventional ground-based telescopes is completely adequate. Furthermore, "observing time" on telescopes in space is very competitive, and so most astronomers who need really high resolution images don't get "time" on them. Faced with the need, the scientific and engineering communities took on the challenge of developing higher-resolution ground-based telescopes. Two types of technologies have succeeded magnificently in that effort. Called *active optics* and *adaptive optics,* telescopes equipped with them are competitive with, and often better than, those in space.

**Margin Question 3-8**
Why are military and spy agencies around the world so interested in cutting-edge telescope technologies?

Historically, primary mirrors have been thick and heavy, to help keep them rigid and perfectly shaped. Nevertheless, these mirrors were not ideal because they would warp slightly as the telescope changed angle on the sky and the mirrors could not compensate for the seeing conditions, which causes the objects to move and therefore blur. However, in the 1980s, astronomers discovered that changing the shape of the primary mirror would enable them to compensate for these effects. By making thinner mirrors, the shape of the primary could be changed by pistons called *actuators* located under the mirror. Thus, the field of **active optics** was created. This technology finds the best orientation for the primary mirror in response to changes in temperature and the shape of the telescope mount. Actuators adjust the mirror every few seconds to help keep the telescope optimally aimed at its target. With active optics, the New Technology Telescope in Chile and the Keck telescopes in Hawaii routinely achieve resolutions as fine as 0.3″, whereas the resolution is much worse for telescopes without active optics at the same sites.

Even better resolution can be achieved with **adaptive optics,** which uses sensors to determine the amount of twinkling created by atmospheric turbulence. The caption for the figure on this book's cover briefly explains how adaptive optics works. The stellar motion due to this twinkling is neutralized by computer-activated, motorized supports that actually reshape a smaller mirror installed farther down the optical path of the telescope. Adaptive optics effectively eliminates atmospheric distortion and produces remarkably clear images with resolution as fine as 0.03″ (Figure 3-30). Many large ground-based telescopes now use adaptive optics on many observing runs, resulting in images comparable to those from HST (Figure 3-30c).

Until the 1980s, optical telescopes with primary mirrors of between 2 and 6 m were the largest in the world. Now, new technologies in mirror building and computer control allow us to construct much larger telescopes. At least 85 reflectors around the world today have primary mirrors measuring 2 m or more in diameter. Among these are 14 reflectors that have mirrors between 8 and 10.4 m in diameter, with at least 8 other very large telescopes under construction. Appendix G contains a list of the telescopes 2 m in diameter and larger that are in operation.

Because the cost of building very large mirrors is enormous, astronomers have devised less expensive ways to collect the same amount of light. One approach is to make a large mirror out of smaller pieces, fitted together like floor tiles. The largest examples of this segmented-mirror technique are the 10.4-m Gran Telescopio Canarias in the Canary Islands, and the 10-m (400-in.) Keck I and Keck II telescopes on the summit of Mauna Kea in Hawaii. In each of these telescopes, 36 curved hexagonal mirrors are mounted side by side to collect the same amount of light as a single primary mirror of 10.4 or 10 m, respectively (Figure 3-31). The Hobby-Eberly

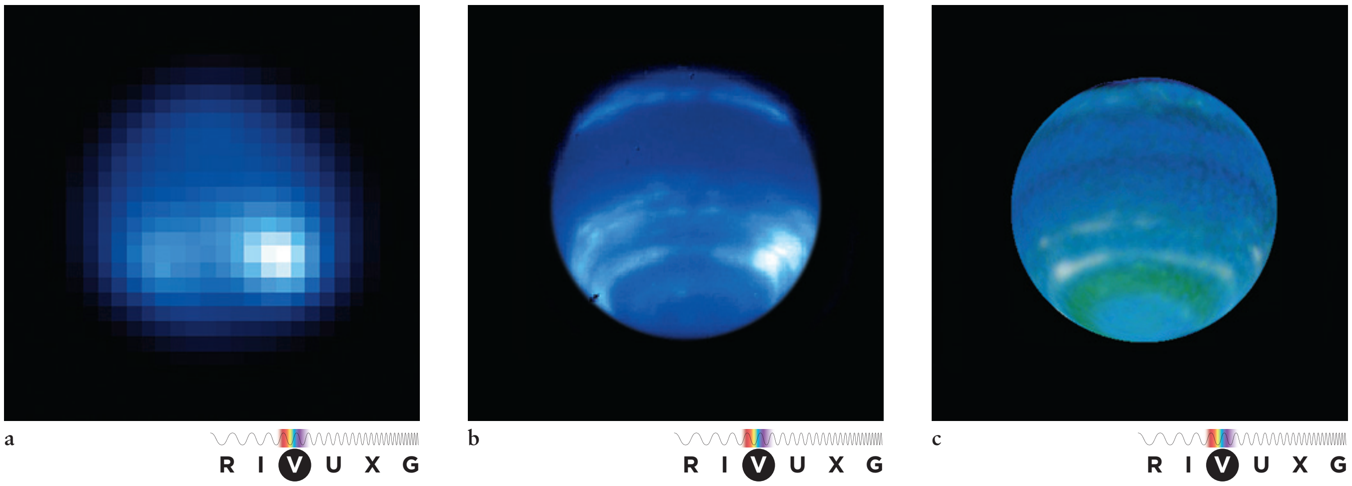



**FIGURE 3-30 Images from Earth and Space** (a) Image of Neptune from an Earth-based telescope without adaptive optics. (b) Image of Neptune from the same Earth-based telescope with adaptive optics. (c) Image of Neptune from the Hubble Space Telescope, which does not incorporate adaptive optics technology. (a & b: Courtesy of Center for Adaptive Optics, University of California; c: NASA, L. Sromovksy, and P. Fry, University of Wisconsin-Madison)

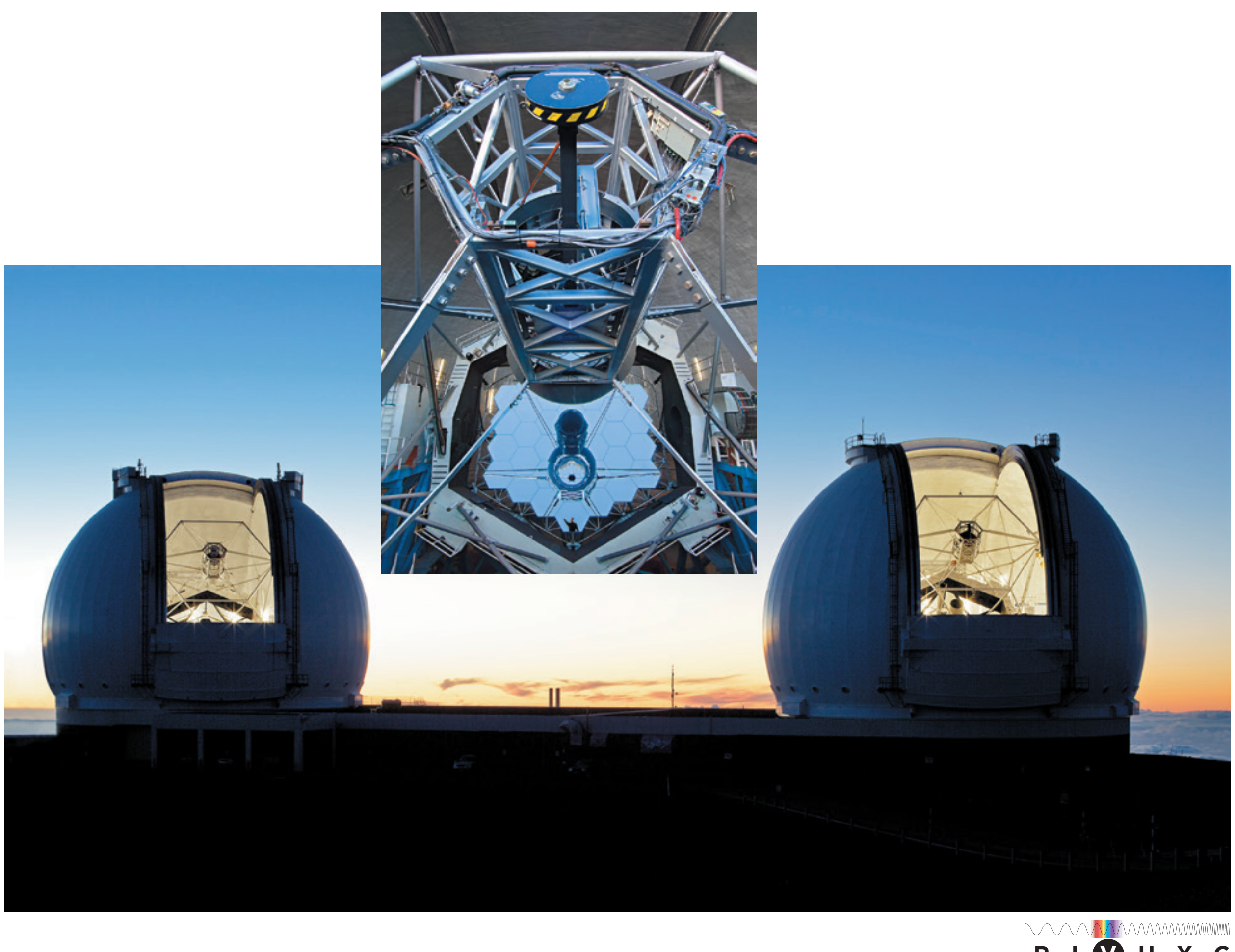



**FIGURE 3-31 The 10-m Keck Telescopes** Located on the dormant (and hopefully extinct) Mauna Kea volcano in Hawaii, these huge twin telescopes each consist of 36 hexagonal mirrors measuring 1.8 m (5.9 ft) across. Each Keck telescope has the light-gathering, resolving, and magnifying ability of a single mirror 10 m in diameter. Inset: View down the Keck I telescope. The hexagonal apparatus near the top of the photograph shows the housing for the 1.4-m secondary mirror. (Enrico Sacchetti/Science Source; inset: © Laurie Hatch)

telescope in Texas and the Southern African Large Telescope in South Africa each have 91 mirrors.

Another method to increase resolution, called **interferometry,** combines images from different telescopes. For example, used together to observe the same object, the two Keck telescopes have the resolving power of a single 85-m telescope. The four 8.2-m reflectors of the Very Large Telescope at the Paranal Observatory combine to create the resolution that would come from a single telescope 200 m in diameter. This observatory has an ideal resolution of about 0.002″.

## NONOPTICAL ASTRONOMY

Looking back at Figure 3-6, you can see that visible light represents a very tiny fraction of the electromagnetic spectrum. As late as the 1940s, astronomers had no idea how much nonvisible radiation is emitted by objects in space. However, today we know that many objects in space emit undetectable amounts of visible light, but release large amounts of nonvisible radiation. Specially designed telescopes gather electromagnetic energy in all of the nonvisible parts of the spectrum. From the radio waves and infrared radiation being emitted by vast interstellar gas clouds to the ultraviolet radiation and X-rays from the remnants of stars to bursts of gamma rays of extraordinary power from merging black holes and other sources, our growing ability to see the entire electromagnetic spectrum is revealing myriad intriguing phenomena. To get a sense of how much we do not see in the visible part of the spectrum, look at Figure 3-32, which shows visible, ultraviolet, and infrared images of the familiar constellation Orion.

### 3-14 A radio telescope uses a large concave dish to collect radio waves

The first evidence of nonvisible radiation from outer space came from the work of a young radio engineer, Karl Jansky (1905–1950), at Bell Laboratories in Holmdel, New Jersey. Using radio antennas, Jansky was investigating the sources of static that affect short-wavelength radiotelephone communication. In 1932, he realized that a certain kind of radio noise is strongest when the constellation Sagittarius is high in the sky. Because

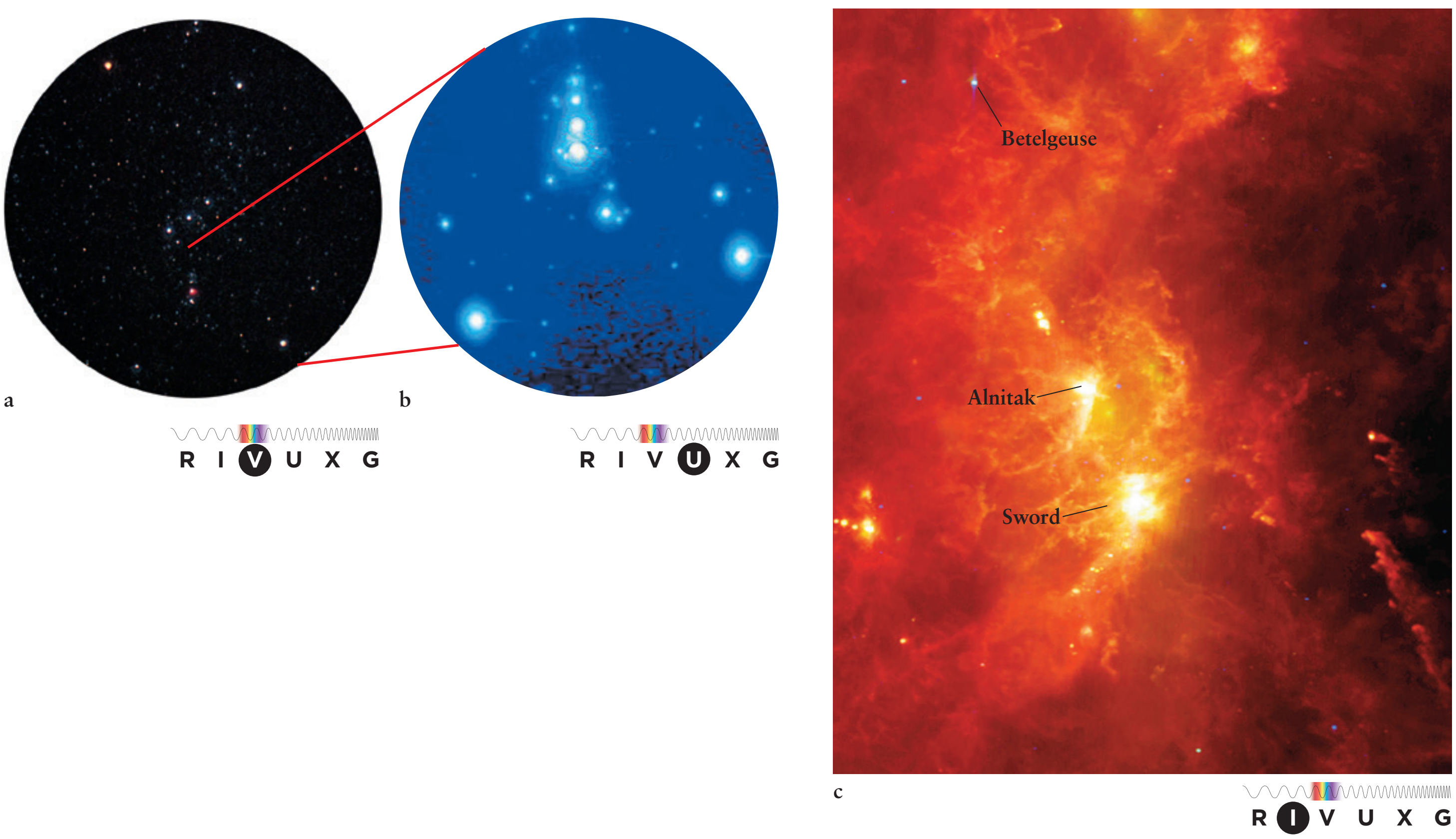



**FIGURE 3-32 Orion as Seen in Visible, Ultraviolet, and Infrared Wavelengths** In (a), an optical photograph of the constellation Orion, the bright upper-left star is Betelgeuse, Orion's right shoulder (as he is facing us in mythology). The left star in his belt (as we see it) is Altinak. His sword is located between his legs. (b) An ultraviolet image of Orion. (c) A false-color view from the Infrared Astronomical Satellite of the entire Orion asterism. Different colors indicate different intensities of infrared radiation. Clearly, different wavelengths provide different information about various objects in space. (a: peresanz/iStock/Getty Images; b: NASA/MSX/Johns Hopkins University Applied Physics Laboratory; c: NASA/JPL-Caltech)

the center of our Milky Way Galaxy is located in the direction of Sagittarius, Jansky correctly concluded that he was detecting radio waves from elsewhere in the Galaxy. Jansky's accidental discovery of radio signals from space led to a worldwide effort to "see" what nonvisible wavelengths could teach us about the cosmos.

### Insight Into Science

**Think "Outside the Box"** Observations and experiments often require making connections between seemingly unrelated concepts. Jansky's proposal that some radio waves originate in space is an example of connecting apparently disparate fields—astronomy and radio engineering.

**Radio telescopes** record radio signals from the sky. Just as a mirror reflects visible light, the metal surfaces of radio telescopes reflect radio waves. Each radio telescope has a large concave dish (Figure 3-33) that focuses radio photons in the same way that an optical telescope mirror focuses visible photons. A small antenna tuned to the desired wavelength is typically located at the telescope's prime focus or Cassegrain focus. The incoming signal is relayed to amplifiers and recording instruments. It is then converted into an image.

Radio waves have the longest wavelengths of all electromagnetic radiation. Because the angular resolution of any telescope decreases as the wavelengths it collects increases, a radio telescope gives a fuzzier picture than any other type of telescope with the same diameter. Indeed, the first small radio telescopes produced blurry, indistinct images.

Very large radio telescopes create sharper radio images because, as with optical telescopes, the bigger the dish, the better the angular resolution. For this reason, most modern radio telescopes have reflectors more than 25 m in diameter. Nevertheless, even the largest radio dish in existence (Five hundred meter Aperture Spherical Telescope—FAST—in Guizhou, China) cannot come close to the resolution of the best optical telescopes. For example, a 6-m optical telescope has 2000 times better resolution than a 6-m radio telescope that detects radio waves of 1-mm wavelength.

To overcome the limitation on resolution set by telescope diameter, radio astronomers often use interferometry to produce high-resolution radio images. Recall from Section 3-13 that interferometry combines the data received simultaneously by two or more telescopes. The telescopes can be kilometers, continents, or even worlds apart. The radio signals received by all of the dishes are made to "interfere," or blend together, and, with suitable computer-aided processing, the combined image of the source is sharp and clear. The results are impressive: The resolution of such a system is equivalent to that of

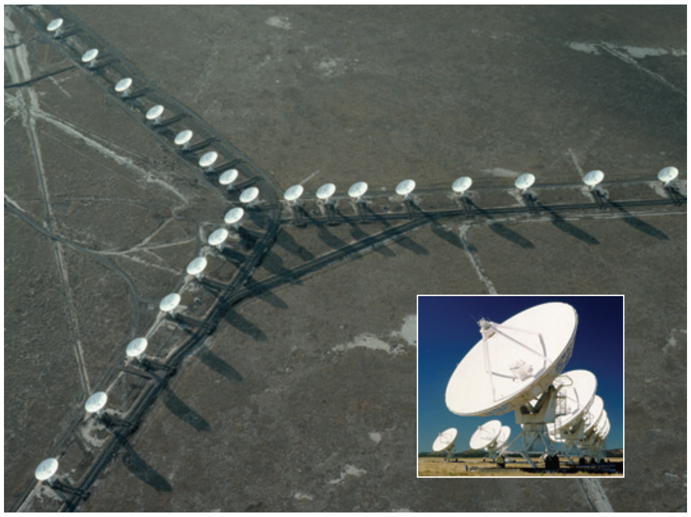
R I V U X G

**FIGURE 3-33 A Radio Telescope** Recall that the secondary mirror or prime focus on most telescopes blocks incoming light or other radiation. This radio telescope at the National Radio Astronomy Observatory in Green Bank, West Virginia, has its prime focus hardware located off-center from the telescope's 100-m by 110-m oval reflector. By using this new design, there is no such loss of signal from equipment covering part of the telescope. Such configurations are also common on microwave dishes used to receive satellite transmissions for home televisions. (NRAO/AUI/NSF)

one gigantic dish with a diameter equal to the distance between the farthest telescopes in the array.

Interferometry, exploited for the first time in the late 1940s, gave astronomers their first detailed views of "radio objects" in the sky. At least 30 arrays of radio telescopes are in operation around the world. One array, dating back to 1980, still operates on the plains of San Agustin near Socorro, New Mexico. Originally called the Very Large Array (VLA) and now upgraded and renamed the Karl G. Jansky Very Large Array, this system consists of 27 concave dishes, each 26 m (85 ft) in diameter (Figure 3-34). The 27 telescopes, which can be moved, are positioned along the three arms of a gigantic Y that can span a distance of 36 km (22 mi). Working together, they can create radio images with 0.1″ resolution. This system produces radio views of the sky with resolutions nearly comparable to those of the best optical telescopes.

More recently, radio telescopes separated by thousands of kilometers have been linked together in



R I V U X G

**FIGURE 3-34 The Karl G. Jansky Very Large Array** The 27 radio telescopes of the Jansky VLA system are arranged along the arms of a Y in central New Mexico. Besides being able to change the angles at which they observe the sky, astronomers can also move these telescopes by train cars so that the array can detect either wide areas of the sky (when they are close together, as in this photograph) or small areas with higher resolution (when they are farther apart). The inset shows the traditional secondary mirror assembly in the center of each of these antennas. (Jim Sugar/Getty Images; inset: D. Nunuk/Science Source)

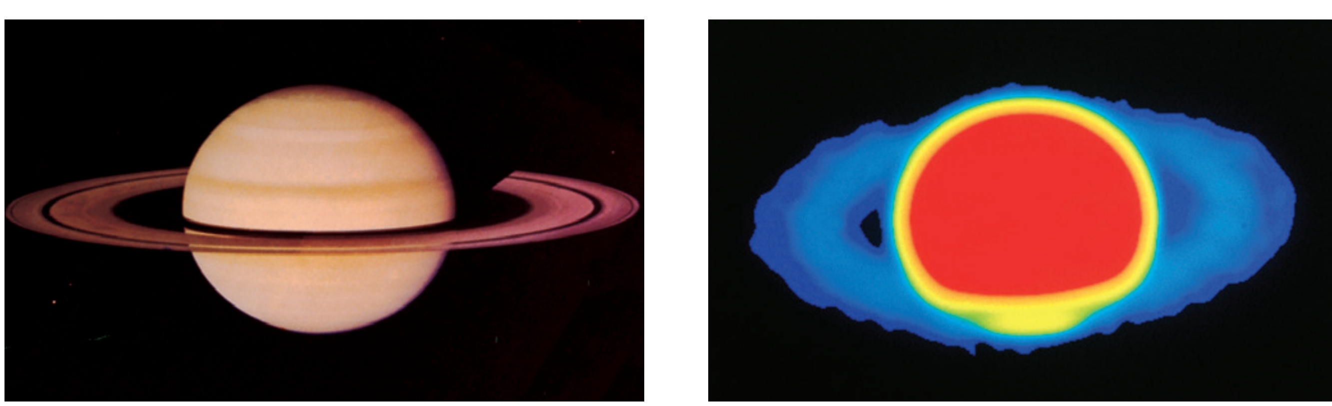
**very-long-baseline interferometry (VLBI).** The Very Long Baseline Array (VLBA) consists of ten 25-m radio telescopes located across the United States at sites from Hawaii to St. Croix on the Virgin Islands. With a maximum baseline of 8600 km, the VLBA has a resolving power of 0.001″.

The best angular resolution on Earth is obtained by combining radio data from telescopes on opposite sides of our planet. In that case, features as small as 0.00001″ can be distinguished at radio wavelengths—10,000 times sharper than the best views obtainable from single optical telescopes. Radio telescopes are also being put into space and thereby creating even longer-baseline interferometers.

To make radio images more comprehensible, radio astronomers often use gray scales (see Figure 1-3i) or false colors (Figure 3-35). The most intense radio emission is shown in red, the least intense in blue. Intermediate colors of the rainbow represent intermediate levels of radio intensity. Black indicates that there is no detectable radio radiation. Astronomers who work at other nonvisible-wavelength ranges also frequently use false-color techniques to display views obtained from their instruments.

Consider an example of how nonoptical astronomy, such as is done with these radio telescopes, can overcome limitations of optical telescopes. Late in the eighteenth century, the astronomer Sir William Herschel, mentioned in section 3-4, observed regions of our Milky Way from which no visible light was emitted. "Surely, there is a hole in the heavens," he reported on seeing the first such region. (He was not referring to a modern "black hole," but rather just to an area that was especially dark to his eyes.) In the twentieth century, astronomers discovered that these regions are actually clouds of interstellar gas and dust that prevent visible light from stars beyond them from reaching us, just as thick clouds of water vapor in our atmosphere obscure the Sun and darken the sky. However, radio waves and some other nonvisible wavelengths pass through interstellar clouds. With the advent of radio telescopes, astronomers got their first glimpses of the variety of objects that lie beyond these clouds.

On the boundary between radio and infrared radiation, several microwave telescopes have been orbited



a R I V U X G

b R I V U X G

**FIGURE 3-35 Visible and Radio Views of Saturn** (a) This picture was taken by a camera on board a spacecraft as it approached Saturn. The view was produced by sunlight scattered from the planet's cloudtops and rings. (b) This false-color picture, taken by the VLA (the predecessor of the Jansky VLA), shows radio emission from Saturn at a wavelength of 2 cm. (a: NASA; b: Image courtesy of NRAO/AUI/NSF) around Earth. Notable among these are the Cosmic Background Explorer (COBE), launched in 1989, the Wilkinson Microwave Anisotropy Probe (WMAP), launched in 2001, and Planck (launched 2009) (all three are no longer operational), Odin (2001), and Spektr-R (2011), both of which are still in use. Among other things, these telescopes observe star formation, atoms of different kinds in space, and perhaps most importantly, they gather data that provide us with the temperature of the universe in different directions, results that we will discuss in Chapter 19.

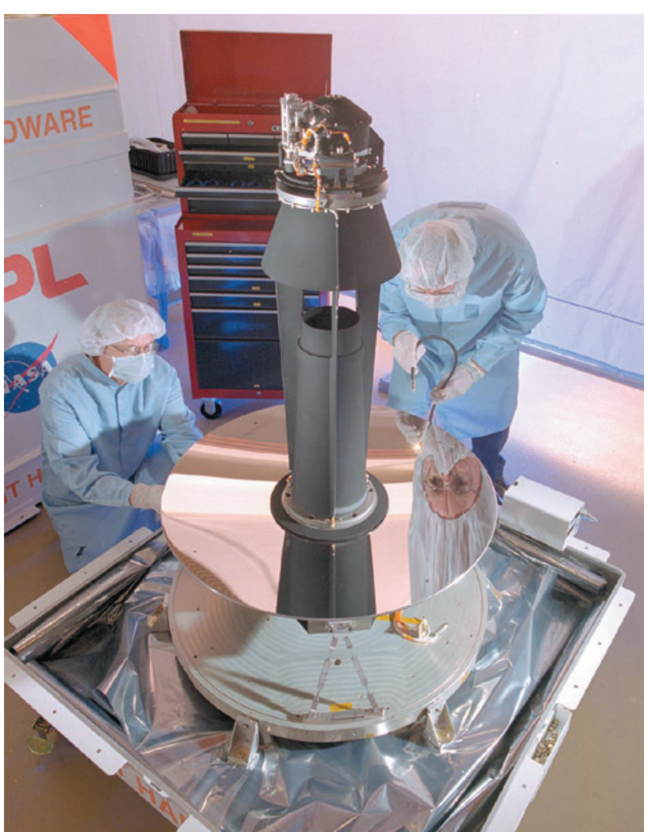
## 3-15 Infrared and ultraviolet telescopes also use reflectors to collect electromagnetic radiation

As with radio and microwave telescopes, infrared and ultraviolet telescopes are all reflectors. Indeed, using suitable CCDs, optical reflecting telescopes can also detect infrared and ultraviolet photons with wavelengths near visible light. The most sensitive infrared-detecting CCDs must be cooled to prevent the heat (and, hence, infrared photons) of the telescope from overwhelming the infrared radiation received from objects in space.

Because water vapor is the main absorber of infrared radiation from space, locating infrared observatories at sites of low humidity can overcome much of the atmosphere's hindrance. For example, the summit of Mauna Kea is exceptionally dry (most of the moisture in the air is below the height of this volcano). Infrared observations are made on the summit by the primarily optical-wavelength Subaru and two Keck telescopes, as well as by NASA's 3-m Infrared Telescope Facility (IRTF).

The best way to avoid the obscuring effects of water vapor is to place a telescope in orbit around Earth.

**Margin Question 3-9**
Where in a typical house would infrared detectors indicate the most activity?



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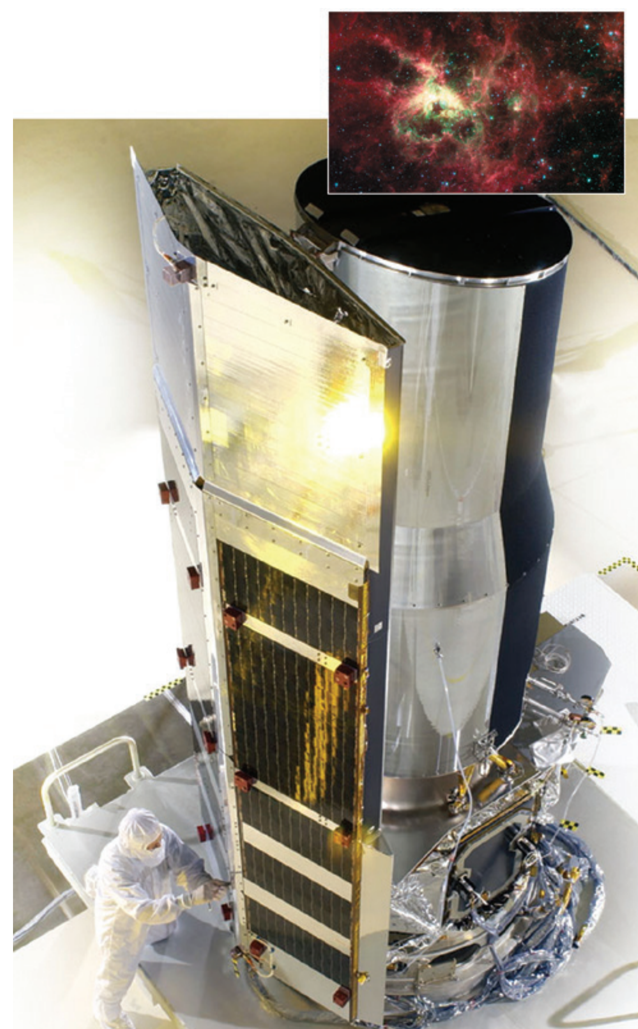

b

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**FIGURE 3-36 Spitzer Space Telescope** (a) The mirror assembly for the Spitzer Space Telescope showing the 85-cm objective mirror. (b) Launched in 2003, this Great Observatory is taking images and spectra of planets, comets, gas, and dust around other stars and in interstellar space, galaxies, and the large-scale distribution of matter in the universe. (a: Balz/SIRTF Science Center; b: NASA/JPL-Caltech)

The 1983 Infrared Astronomical Satellite (IRAS) and the Infrared Space Observatory (ISO) launched in 1995 (both now out of service), and Hubble Space Telescope's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) and the Spitzer Space Telescope launched in 2003 **(Figure 3-36)**, among others, have done much to reveal the full richness and variety of the infrared sky. Spitzer is the infrared equivalent to HST, one of NASA's Great Observatories. In 2010, NASA began flying a telescope called SOFIA (Stratospheric Observatory for Infrared Astronomy) in a modified Boeing 747. At altitude, a giant door in the side of the aircraft slides open and the telescope observes the night sky high above water vapor in the atmosphere. Perhaps the most exciting recent development in infrared astronomy is design and ongoing construction of the 6.5-m-diameter James Webb Space Telescope (see the first figure in the book), scheduled for launch in 2020.

Infrared telescopes detect radiation from small bodies in the solar system, as well as from the bands of dust in our Galaxy, newly formed stars, the dust disks around stars at various stages of their evolution, and the most distant galaxies, whose radiation arrives here primarily at infrared wavelengths, among other infrared-emitting objects. (The word *galaxy* when used alone is capitalized only when referring to our Milky Way Galaxy.) Astronomers have located more than a half-million infrared sources in the sky, most of which are invisible at optical wavelengths. As with radio waves, some infrared radiation passes through interstellar clouds of dust and gas, allowing astronomers to see, for example, individual stars at the center of our Galaxy some 245 trillion km (153 trillion mi) away **(Figure 3-37)**.

During the early 1970s, ultraviolet astronomy got off the ground—literally and figuratively. Both Apollo and Skylab astronauts used small telescopes above Earth's atmosphere to give us some of our first views of

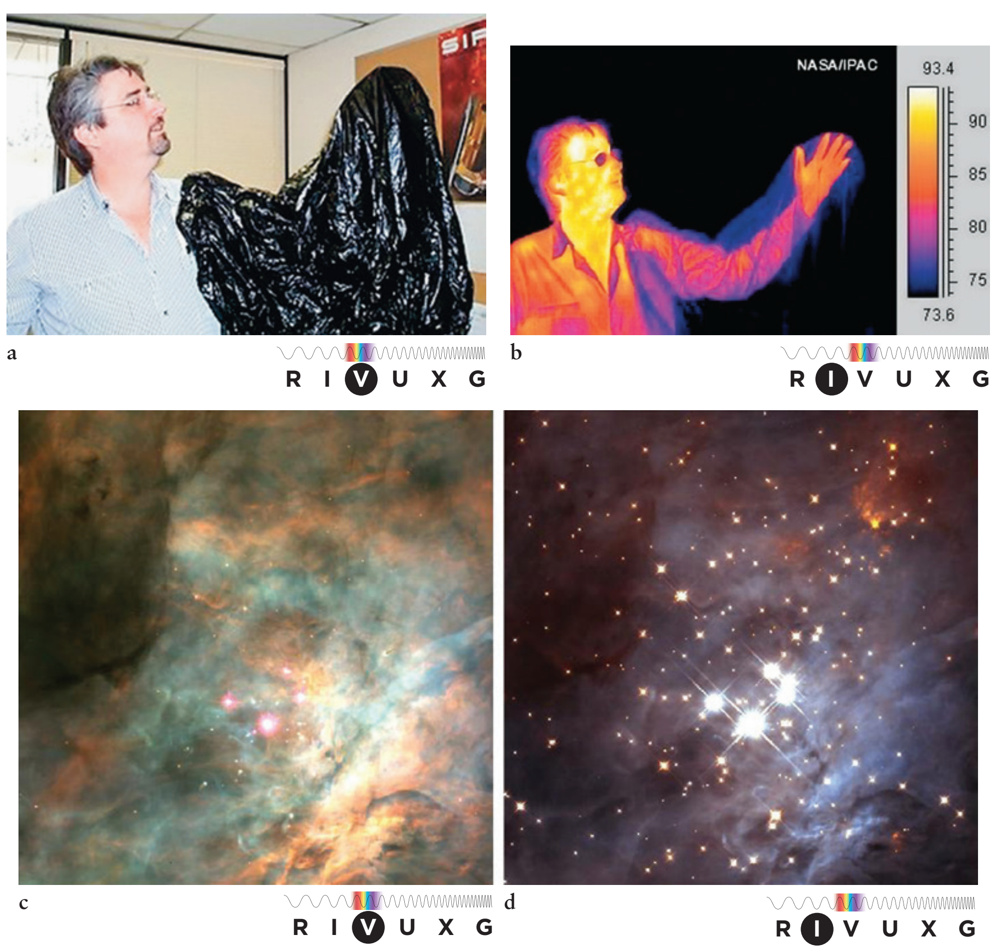



**FIGURE 3-37 Views of the Milky Way's Central Regions** (a) and (b) Infrared radiation can travel through media that block visible light. (c) An optical image of part of the Trapezium Cluster in the Orion Nebula. While a few stars are clearly visible, the interstellar gas and dust blocks the light from many other stars embedded in or behind this cloud. (d) An infrared image of the same area of the sky, showing many more distant stars whose infrared radiation passes through the clouds and is collected by our telescopes. (NASA/JPL-Caltech; NASA Image Collection/Alamy stockphoto)

the ultraviolet sources in space. Small rockets have also been used to place ultraviolet telescopes briefly above Earth's atmosphere. A typical ultraviolet view is shown in Figure 3-32b.

Some of the finest early ultraviolet astronomy was accomplished by the International Ultraviolet Explorer (IUE), which was launched in 1978 and functioned until 1996. Space shuttles were transformed into orbiting observatories twice in the 1990s, carrying aloft and then returning to Earth three ultraviolet telescopes. In 1992, the Extreme Ultraviolet Explorer (EUVE) was launched. As with infrared observations, ultraviolet images reveal sights previously invisible and often unexpected. Many objects in space emit ultraviolet radiation that astronomers can use to study the chemistries of these cosmic bodies. Therefore, in 1999, astronomers launched the Far Ultraviolet Spectroscopic Explorer (FUSE), which worked through 2007, and the Galactic Evolution Explorer (GALEX), which worked through 2013. These latter two telescopes provided information about such things as how much deuterium (hydrogen nuclei with one neutron) was created when the universe formed, the location of particularly hot interstellar gas and dust, and the stellar and chemical evolution of galaxies. Other ultraviolet telescopes are in orbit today.

Telescopes dedicated to studying the Sun have observed it from the ground since 1941, and solar telescopes have studied it continuously from space since 1984. Since 1995, the Solar and Heliospheric Observatory (SOHO) has investigated the Sun from space with ultraviolet detectors. More recent orbiting observatories include STEREO (Solar TErrestrial RElations Observatory), launched in 2006, and SDO (the Solar Dynamic Observatory), launched in 2010. These observatories, among others, observe the Sun's outer layers rising and sinking, along with a wide range of energetic activity emanating from it. These telescopes show us breathtaking ultraviolet images and movies, some in 3D, of our star. In Chapter 11 we will discuss these observations and their physical origins.

## 3-16 X-ray and gamma-ray telescopes cannot use normal reflectors to gather information

X-rays and gamma rays from space interact strongly with the particles in Earth's atmosphere, preventing these dangerous radiations from reaching our planet's surface. Therefore, direct observations of astronomical sources that emit these extremely short wavelengths must be made from space. Astronomers got their first look at X-ray sources during brief rocket flights in the late 1940s. Several small satellites, launched during the early 1970s, viewed the sources of both X-rays and gamma rays in space, revealing hundreds of previously unknown objects, including several black holes (see Chapter 15). X-ray telescopes have also been carried on space shuttle missions. The insets in Figure 3-38 show how different our Sun appears when seen through X-ray and visible-light "eyes."

X-ray photons are tricky to collect. Because of their high energies, X-rays penetrate even highly polished surfaces that they meet nearly head-on. Therefore, normal reflecting mirrors cannot be used to focus them. Instead, X-ray telescopes are designed to deflect photons at a fairly shallow angle because X-rays that are barely skimming or grazing a surface can be reflected and thereby focused. This process is analogous to skipping a flat rock on water; throw it at a steep angle and it immediately sinks; throw it at a shallow angle and it will skip off the surface. Figure 3-39 shows the design of such "grazing incidence" X-ray telescopes.

After being focused, X-rays are detected in several ways. As at infrared, visible, and ultraviolet wavelengths, CCDs can detect these photons. Other devices, called *scintillators*, detect the visible light created as X-rays pass through them. Still other instruments, called *calorimeters*, detect the heat generated by X-rays passing through the detector.

At least nine X-ray telescopes are orbiting Earth today. Among them, the Chandra X-ray Observatory, a NASA Great Observatory named after the Nobel laureate astronomer Subrahmanyan Chandrasekhar (1910–1995), provides images with 0.5″ resolution, and the European Space Agency's XMM-Newton has 6″ resolution. Other X-ray telescopes are carried high into the atmosphere by balloons. The balloons float at altitudes up to 40 km (25 mi) above Earth's surface and often stay up for several weeks. Whereas low-energy X-rays do not penetrate that far into the atmosphere, higher-energy X-rays do, giving these balloon-borne telescopes a wide range of objects to study.

More than 10,000 X-ray sources have been discovered all across the sky. Among these are planetary atmospheres, stars (see the Sun in Figure 3-38), stellar remnants, vast clouds of intergalactic gas, jets of gas emitted by galaxies, black holes, quasars, clusters of galaxies, and a diffuse X-ray glow that fills the universe.

The electromagnetic radiation with the shortest wavelengths and the most energy are gamma rays. In 1991, the Compton Gamma-ray Observatory, also a NASA Great Observatory, was carried into orbit by the space shuttle *Atlantis*. Named in honor of Arthur Holly Compton (1892–1962), an American physicist and Nobel laureate who made important discoveries about gamma rays, this orbiting observatory carried four instruments that performed a variety of observations, giving us tantalizing views of the gamma-ray sky until the telescope failed in 2000. At least 5 gamma-ray telescopes, including the *SWIFT* Gamma-Ray Burst Mission and the Fermi Large Area Telescope, are presently

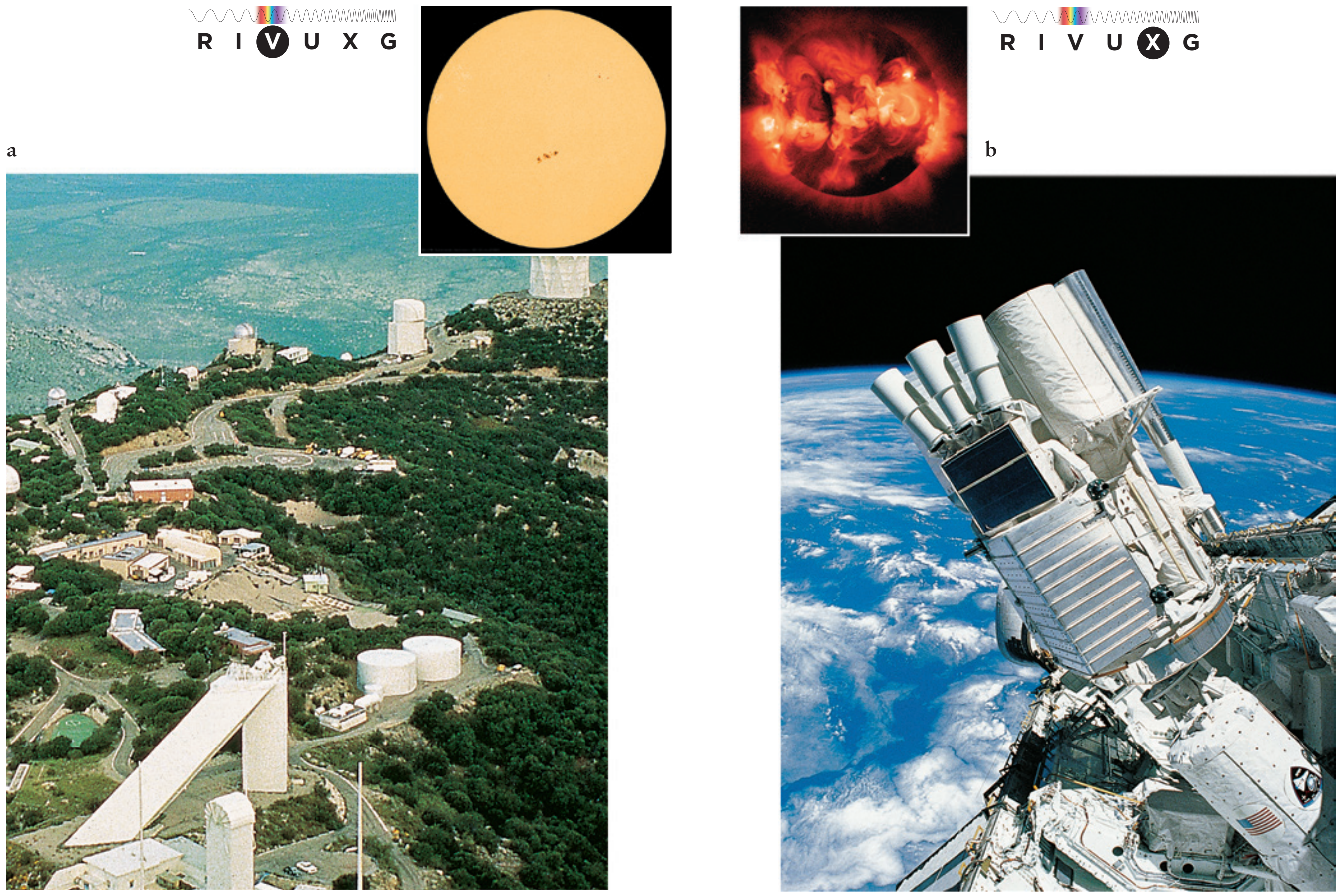



**Figure 3-38 Visible and Nonvisible Radiation** (a) The McMath-Pierce Solar Telescope at Kitt Peak Observatory near Tucson, Arizona (the inverted V-shaped structure), takes visible-light photographs of the Sun, such as the one shown in the inset. (b) This X-ray telescope was carried aloft in 1994 by the space shuttle. The inset shows an X-ray image of the Sun. Comparing the images in the two insets reveals how important observing nonvisible radiation from astronomical phenomena is to furthering our understanding of how the universe operates. (a: NOAO/AURA/NSF; inset: NASA/SDO/HMI; b: NASA; inset: The solar X-ray image is from the Yohkoh mission of ISAS, Japan. The X-ray telescope was prepared by the Lockheed-Martin Solar and Astrophysics Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS)

operating in space, and several have been flown on balloon missions.

Gamma-ray telescopes, such as the VERITAS and MAGIC arrays, are also operating here on Earth. As we noted earlier, gamma rays do not reach Earth's surface from space. However, when these photons strike atoms in Earth's atmosphere, they cause cascades of gas particles to rush earthward at high velocities. As these particles descend into the atmosphere, they give off flashes of visible and UV radiation called *Cherenkov radiation*. As the Russian physicist Pavel A. Cherenkov (pronounced *Che-REN-kov;* 1904–1990) first observed, the flash occurs whenever a particle moves through a medium, such as water, faster than light can. Such motion does not violate the tenet that the speed of light *in a vacuum* ($3 \times 10^5$ km/s) is the ultimate speed limit in the universe. Light is slowed considerably as it passes through water, and high-energy particles can exceed this reduced speed of light in a medium without violating the laws of nature. This radiation travels predictable angles from the particles that emit it and therefore detecting it enables astronomers to calculate from what direction the original gamma ray came.

Several thousand gamma-ray sources have been discovered. However, gamma rays are too powerful even for grazing incidence telescopes. Therefore, astronomers have devised other methods of detecting them and determining their origin. These include absorbing them in crystals; allowing them to pass through tiny holes called *collimators* whose directions are well determined; and using chambers in which the gamma rays transform into electrons and positrons (positively charged electrons), leaving a track whose direction can be determined. These techniques are not nearly as precise as those used in other parts of the spectrum, and the best resolution gamma-ray instruments are only accurate to about 5′ (see An Astronomer's Toolbox 1-1 to review the notation of angles used in astronomy).

We now have telescopes with which we can see the electromagnetic energy in the universe from virtually all parts of the spectrum (Figure 3-40). Telescopes provide us with

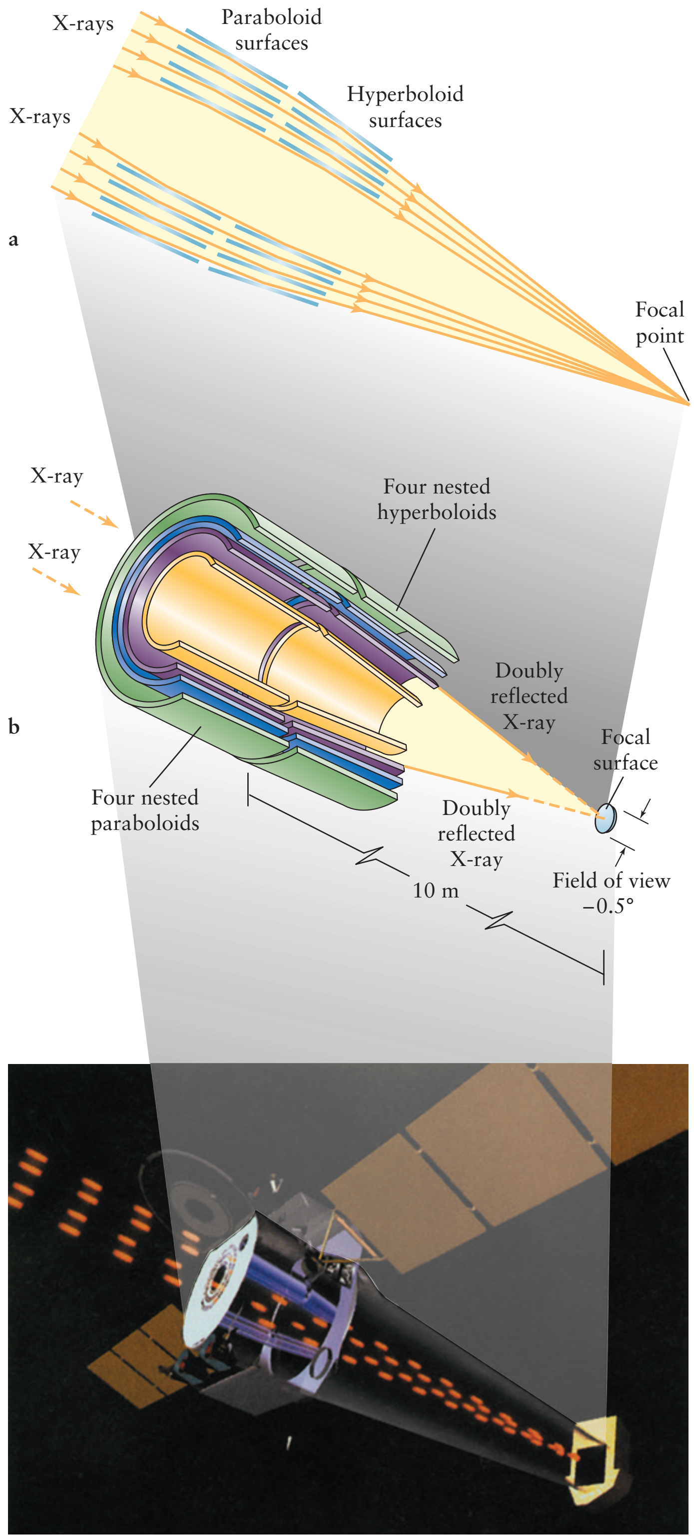



**FIGURE 3-39 Grazing Incidence X-ray Telescopes** (a) X-rays penetrate objects they strike head-on. In order to be focused, X-rays have to be gently nudged by skimming off cylindrical "mirrors." (b) The shapes of the mirrors optimize the focus. (c) The diagram shows how X-rays are focused in the Chandra X-ray Telescope. (a & b: NASA/JPL-Caltech; c: NASA/CXC/D. Berry & A. Hobart)

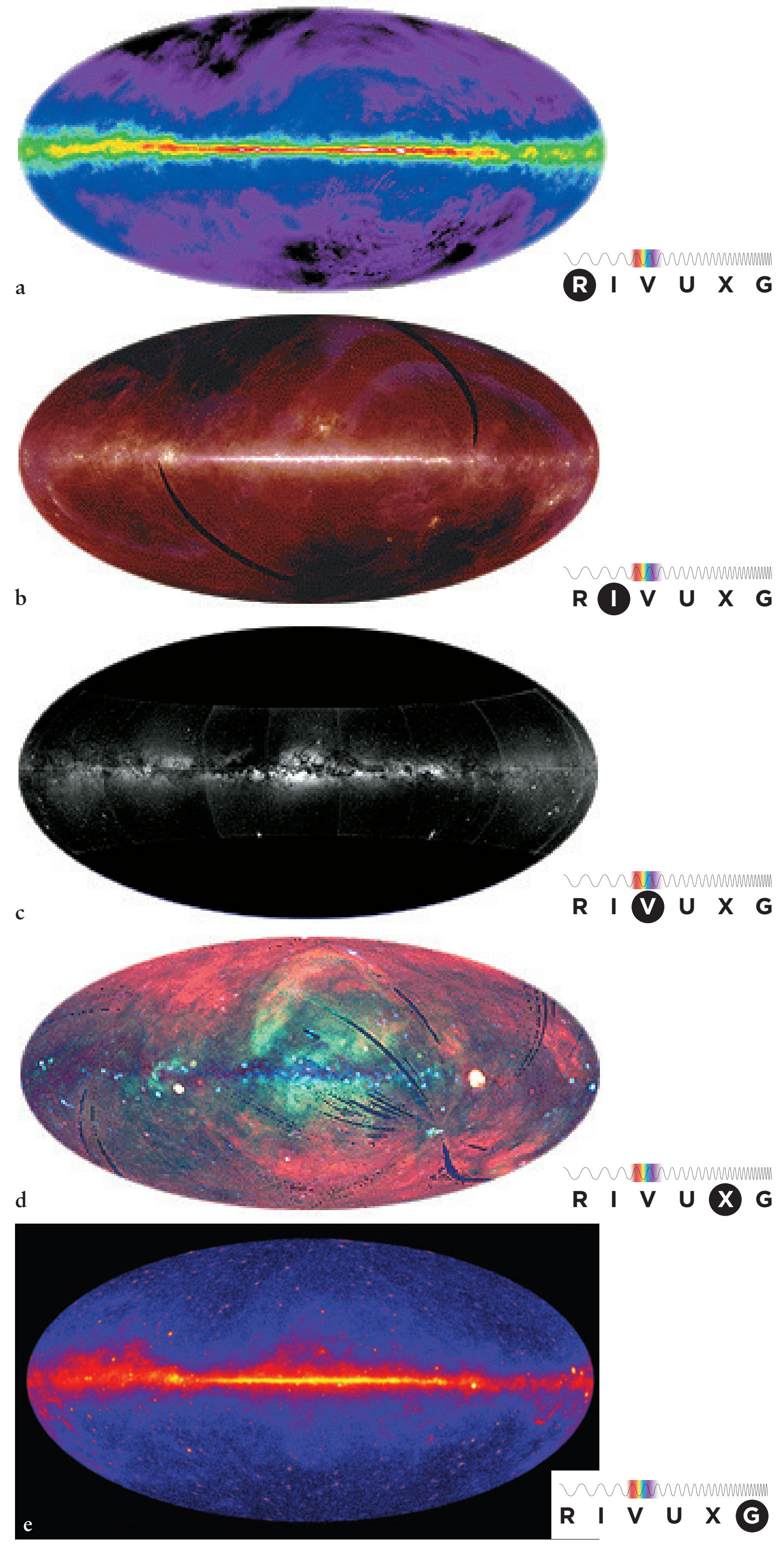



**FIGURE 3-40 Survey of the Universe in Various Parts of the Electromagnetic Spectrum** By mapping the celestial sphere onto a flat surface (like making a map of Earth), astronomers can see the overall distribution of strong or nearby energy sources in space. The center of our Galaxy's disk cuts these images horizontally in half. Because most of the emissions shown in these images fall in this region, we know that most of the strong sources of various electromagnetic radiation as seen from Earth (except X-rays) are in our Galaxy: (a) radio waves, (b) infrared radiation, (c) visible light, (d) X-rays, and (e) gamma rays. (a–d: GFSC/NASA; e: NASA/DOE/Fermi LAT Collaboration)

more than just stunning images of objects in space. They also provide information about the chemistry of stars and interstellar gas and dust, the motion of stars and galaxies toward or away from us, whether stars are rotating, the formation of galaxies and their groupings in the universe, and the expansion of the universe and its fate, among myriad other things. We will explore how we get this information when we study the various objects in space.

## COSMIC RAY OBSERVATORIES

### 3-17 Cosmic rays are not rays at all

6 Photons are not our only source of information about the cosmos. In this and the next two sections, we consider three additional sources: cosmic rays, neutrinos, and gravitational radiation, and the observatories that detect them. **Cosmic rays** are high-energy particles traveling at nearly the speed of light. They were named *rays* before their true identity as particles was known, and, as often happens, this misleading name has stuck. Cosmic rays were discovered in 1912 by Austrian-American physicist Victor Hess (1883–1964), who received the 1936 Nobel Prize in Physics for that work. About 90% of cosmic rays are protons (hydrogen nuclei); about 9% are helium nuclei (composed of two protons and two neutrons); and, the remaining 1% are electrons or nuclei of elements more massive than helium.

Cosmic rays are created by a variety of events. Until recently, astronomers thought that *moderate-energy cosmic rays* were emitted directly by powerful explosions of some stars called *supernovae*. This theory made sense because these explosions were the best-known source of the energy necessary to give these cosmic rays their tremendous speeds. However, observations by the Advanced Composition Explorer satellite reveal that the isotopes of nickel coming toward Earth in the form of cosmic rays are not the isotopes emitted by supernovae. (Different isotopes of an element have different numbers of neutrons in their nuclei.) Instead, evidence collected by the Fermi Gamma-ray Space Telescope in 2013 revealed that many moderate-energy cosmic rays are created when supernova debris slams into gas and dust already in space, causing some of this preexisting matter to accelerate and become cosmic rays. Besides emitting particles, supernovae create gamma rays when cosmic ray protons created as a result of the supernova smash into normal protons in interstellar space. These collisions create short-lived particles called pions that decay into pairs of gamma rays. Moderate-energy cosmic rays and gamma rays from the same direction in space are often detected together, with the gamma rays arriving shortly before the cosmic rays.

**Margin Question 3-10**
Why are gamma rays detected before the cosmic rays from the same event?

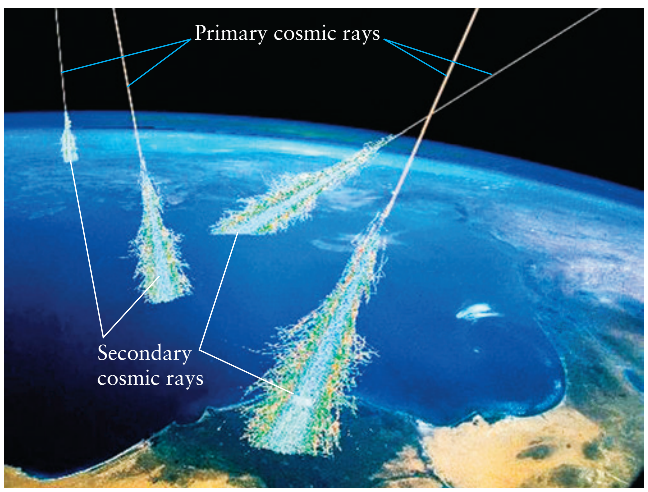
Much less common than moderate-energy cosmic rays are *ultrahigh-energy cosmic rays*, most of which come from outside our Galaxy. Each of these particles has as much kinetic energy as a baseball thrown by a major league pitcher. While some of them are believed to come from jets of gas called *active galactic nuclei* emitted by supermassive black holes in the centers of some galaxies, the origins of most of these particles are still unknown. We will explore these black holes and active galactic nuclei further in Chapter 18.

The Sun emits relatively low-energy cosmic rays called **solar energetic particles**. They occur primarily when the Sun is very active, emitting large quantities of gas, as well as its normal electromagnetic radiation. The activity on the Sun will be discussed in Chapter 11. Solar energetic particles are often released in large numbers over short periods of time (tens of minutes), so they can be dangerous to people in space who are not protected from them. Indeed, solar energetic particles pose sufficient hazards to astronauts, cosmonauts, GPS and other satellites in space, as well as energy grids on Earth, that the U.S. National Oceanographic and Atmospheric Administration's Space Weather Prediction Center monitors the Sun's activity and provides warnings, as necessary.

All cosmic rays in space are called **primary cosmic rays**, indicating that they were not created in Earth's atmosphere. Most primary cosmic rays and solar energetic particles coming in our direction collide with gas particles in the atmosphere some 15 km above Earth's surface. This is fortunate, because each cosmic ray packs an enormous amount of energy that potentially could harm living tissue. A collision in the air divides a cosmic ray's energy among several gas particles, which are shoved Earthward. These particles, in turn, often hit other gas atoms, creating a cascade of lower-energy particles that eventually reach Earth's surface as a **cosmic ray shower** (Figure 3-41). These cosmic rays created from atoms in our atmosphere are called **secondary cosmic rays.** Their passage is accompanied by the generation of ultraviolet radiation.

Because the secondary cosmic rays are moving in slightly different directions than the primarily cosmic rays from which they originate, a single cosmic ray detector on Earth can't tell us the direction from which the primary cosmic ray came. In 2005, the Pierre Auger Observatory, consisting of 1600 cosmic ray sensors designed to detect Cherenkov radiation created when secondary cosmic rays enter tanks of water on the ground was commissioned. Located on the Pampa Amarilla ("Yellow Prairie") in Argentina, when multiple secondary cosmic rays strike different tanks, astronomers can use their paths to calculate the direction from which the primary cosmic ray came. This observatory also has ultraviolet detectors to provide more information about the paths of the secondary cosmic rays. Observations of their paths support the belief that many primary cosmic rays come from active galactic nuclei associated with supermassive black holes. There are now about 10 ground-based ultrahigh-energy cosmic ray observatories in various countries around the world.

Detecting lower-energy cosmic rays is done by telescopes that are carried high in the atmosphere by balloons or by orbiting satellites, including one attached to the International Space Station.

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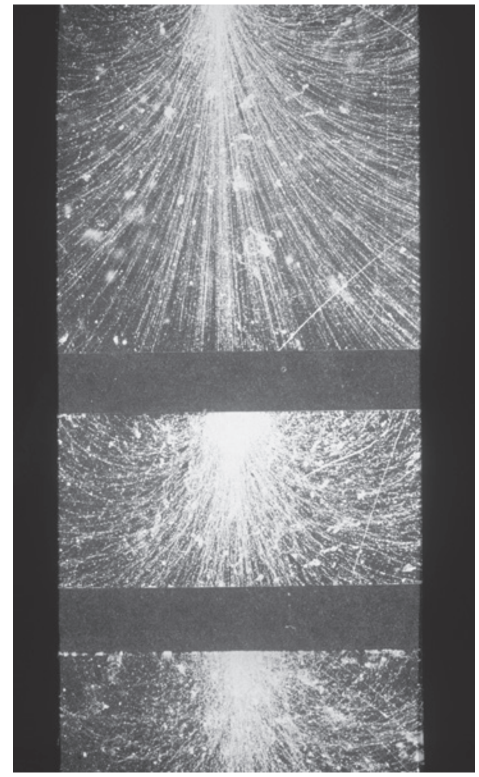

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**FIGURE 3-41 Cosmic Ray Shower** (a) Cosmic rays from space slam into particles in the atmosphere, breaking them up and sending them Earthward. These debris particles are called secondary cosmic rays. This process of impact and breaking up continues as secondary cosmic rays travel downward, creating a cosmic ray shower, as depicted in this artist's conception of four such events. (b) Photographs of the paths of cosmic rays passing through a cloud chamber on Earth. (a: Source: Simon Swordy (U. Chicago), NASA; b: SPL/Science Source)

## NEUTRINO OBSERVATORIES

### 3-18 The mystery of the missing neutrinos inspired development of telescopes to detect these elusive particles

**Neutrinos** are very low-mass, very high-speed particles that barely interact with other matter, compared to the interactions of all other known particles and radiation. Neutrinos are created during thermonuclear fusion, such as occurs in the Sun's core and inside all other stars (more on neutrino creation in Chapter 11). Because they interact so weakly with other matter, large quantities of neutrinos travel up through the entire Sun without interacting with other particles along their way. Virtually all the neutrinos created in the Sun emerge from its outer layer and travel into space.

Very occasionally, solar neutrinos strike neutrons and convert them into protons. If astronomers could detect even a few of these converted protons, it might be possible to build a "neutrino telescope" that could be used to detect the thermonuclear inferno in the Sun's core that is hidden from the view of telescopes that collect photons.

Inspired by such possibilities, the American chemist Raymond Davis (1914–2006) designed and built a large neutrino detector. This device consisted of a huge tank that contained 100,000 gallons of perchloroethylene ($C_2Cl_4$, the fluid your local dry cleaner uses) located deep in the Homestake gold mine in Lead, South Dakota. All neutrino experiments are performed underground to help prevent them from being contaminated by other sources of energy, like cosmic rays. Because matter is virtually transparent to neutrinos, most of the solar neutrinos that encountered Davis's tank passed right through it. On rare occasions, however, a solar neutrino hit the nucleus of one of the chlorine atoms in the cleaning fluid and converted one of its neutrons into a proton, creating a radioactive atom of argon. The rate at which argon was produced was therefore correlated with the number of solar neutrinos arriving at Earth.

On average, solar neutrinos created one radioactive argon atom every 3 days in Davis's tank. To the consternation of physicists and astronomers, this rate corresponds to only one-third of the neutrinos predicted to be created by fusion in the Sun's core. In other words, the theory of neutrino creation predicted one argon atom would be created each day. There were three possible explanations for this unexpected result: The experiment could be faulty; the Sun might not be fusing at the expected rate; or our understanding of the properties of neutrinos could be in error. This experiment, which began in the mid-1960s, was repeated with extreme care by other researchers around the world who got the same results, suggesting that the experiment was not at fault. Calculations of how much energy the Sun must generate to shine as it does confirmed the number of neutrinos created per second. The problem had to lie in our understanding of the neutrino, itself.

The existence of neutrinos, like the existence of the planet Neptune, was originally predicted because the established laws of nature required it. Back in the first few decades of the twentieth century, physicists observed neutrons in nuclei spontaneously transforming into protons and electrons. The transformation is a result of the *weak nuclear force,* discussed further in Chapter 4. When these scientists calculated the energy and momenta of the neutron and the particles into which it changed, the numbers didn't match—conservation of mass/energy and momentum (see Section 2-7) appeared to be violated. If this were indeed the case, it would have required a fundamental reworking of many of the laws of nature. A simpler solution was proposed in 1930 by the physicist Wolfgang Pauli (1900–1958), who posited the existence of a hard-to-detect particle that carried away the "lost" energy and momentum (this particle was named the *neutrino* in 1931 by physicist Enrico Fermi, 1901–1954).

Among the properties neutrinos had to have are *at most* very small masses compared to any other types of particles that have mass and very little interaction with other matter, as we have just discussed. Because electrons or positrons (identical to electrons, except with opposite electric charge) always accompany the formation of the neutrinos created in the Sun, they are often called *electron neutrinos.*

Two other kinds of neutrinos were subsequently proposed. One, the *muon neutrino,* is emitted in reactions in which elementary particles, called *muons* (or *antimuons*), are released, while the other, the *tau neutrino,* accompanies the formation of other elementary particles, the tau and antitau particles. The Sun emits neither muon nor tau neutrinos, and the first generation of detectors could only detect electron neutrinos. The solution to the neutrino rate dilemma lay in the existence of muon and tau neutrinos.

Initially, the three "flavors" of neutrinos (electron, muon, and tau) were thought to be completely massless, and, if so, the equations revealed that they could not change from one flavor into another. But if neutrinos have even the slightest mass, which as noted above was possible, then they can transform from one to another. The transformation of such low-mass neutrinos would occur spontaneously, meaning that if an electron neutrino left the Sun's core and sped toward Earth, there would be a finite probability (about 65%, actually) that by the time it got here, it would have become a tau or muon neutrino. So, if neutrinos have mass, we should observe only one-third of them with Ray Davis's detector, because the rest would have changed flavor before they got to us.

In 1998, the next-generation, Super-Kamiokande neutrino detector in Japan observed the other two types of neutrinos coming from the direction of the Sun. The observations were repeated in 2002 at the Sudbury Neutrino Observatory (Figure 3-42a) in Ontario, Canada. The total number of all three flavors of neutrinos coming from the Sun was as predicted by the equations describing thermonuclear fusion. There are at least 28 neutrino observatories (sometimes called neutrino detectors or neutrino telescopes) in operation around the world and several others under development. They are also looking for neutrinos from other stars and events such as supernovae.

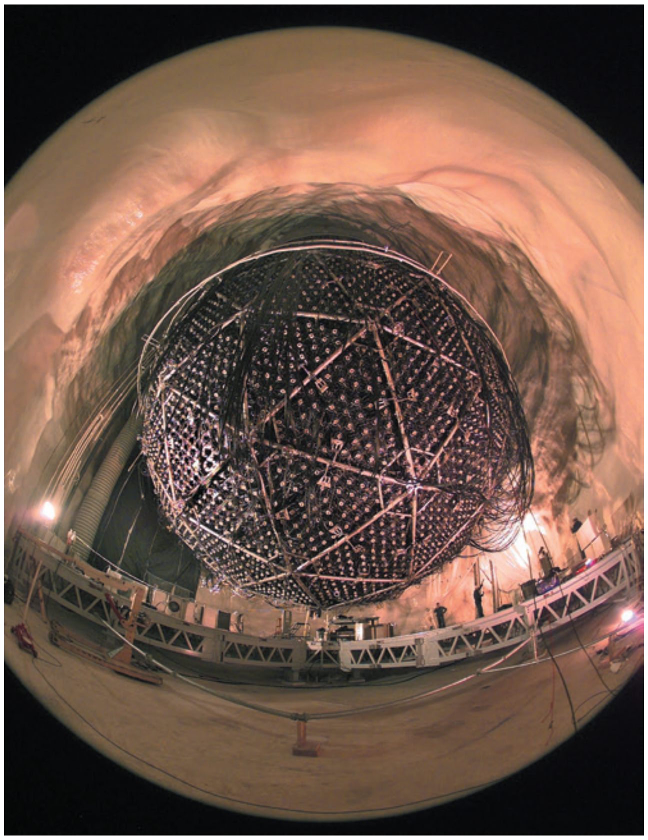
To understand how the present generation of neutrino observatories works, let us consider one of the several interactions that occur between neutrinos and other matter. The Sudbury Neutrino Observatory is filled with water that contains a rare type of hydrogen nucleus, called *deuterium,* which consists of a proton and a neutron. When a solar neutrino is absorbed by a deuterium nucleus, the nucleus breaks apart into two protons and an electron. As this electron rushes through the water, it emits Cherenkov radiation, introduced above and shown in Figure 3-42b.

Thus, scientists detect neutrinos by observing Cherenkov radiation flashes with light-sensitive devices, called *photomultipliers,* mounted in the water (see Figure 3-42a). The three flavors of neutrinos have different interactions with water, all of which have been detected. This evidence that neutrinos can change *requires* that they have mass, and it explains the earlier low rate of solar neutrino observations. The fact that neutrinos have mass was confirmed in 1998, although the amount of mass each has is still under investigation.

## GRAVITATIONAL WAVE OBSERVATORIES

### 3-19 Gravitational radiation observatories provide insights into very violent activities, such as the collisions of stellar remnants

In 1915, Albert Einstein published a set of equations that describe the force of gravity more accurately than Newton's law of gravity (introduced briefly in section 2-1). Called the theory of general relativity, Einstein's equations predict, among many other things, that matter literally changes the shape of the space it is in and that some of these changes create ripples in the fabric of spacetime called **gravitational radiation** or **gravitational waves** or **gravity waves** that travel at the speed of light. If this theory is correct, we should be able to detect the effects of gravitational radiation on the objects that emit it and also detect the gravitational radiation directly. The most powerful such ripples occur when matter undergoes a *quadrupole oscillation*. Consider as one example, a ring. It undergoes quadrupole oscillations if one pair of opposite sides move outward at the same time that the sides halfway in between these points move inward (Figure 3-43). Any object that has this kind of motion (opposite parts going outward while other opposite parts go inward) emits gravitational radiation. The ripples of gravity



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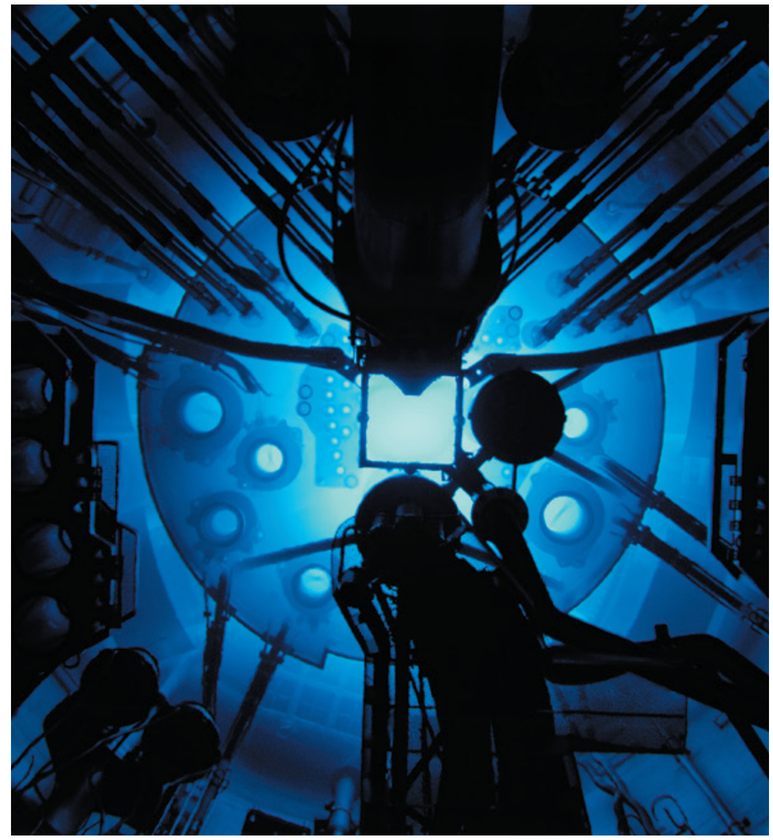

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**FIGURE 3-42 A Solar Neutrino Detector** (a) Located 2073 m (6800 ft) underground in the Creighton nickel mine in Sudbury, Canada, the Sudbury Neutrino Observatory is centered around a tank that contains 1000 tons of water. Occasionally, a neutrino entering the tank interacts with one or another of the particles already there. Such interactions create flashes of light, called Cherenkov radiation. Some 9600 light detectors sense this light. The numerous silver protrusions are the back sides of the light detectors prior to their being wired and connected to electronics in the lab (seen at the bottom of the photograph). (b) Cherenkov radiation glowing in a nuclear reactor in Australia. (a: LBNL/Roy Kaltschmidt/Science Source; b: ANSTO)

waves occur in the plane perpendicular to the direction of their motion.

The first (indirect) detection of gravitational radiation came from observing two spinning neutron stars that are orbiting each other. Neutron stars are the remnants of stars that had between 8 and 25 solar masses and which subsequently exploded as supernovae. Both neutron stars in this discovery contain magnetic fields, analogous to Earth's magnetic field, that spun with them. These rotating magnetic fields emit radio waves and other electromagnetic radiation that scientists can measure. Rotating neutron stars with trapped magnetic fields are called *pulsars* (discussed further in Chapter 14.)

As a result of their orbital motion around each other, neutron stars generate and emit gravitational radiation. This radiated energy comes from the energy associated with the stars orbiting together, which means that they lose orbital energy and spiral toward each other. This change in their orbits can be detected with radio telescopes, which see them orbiting each other faster and faster as they get closer and closer. The neutron stars in the first binary pulsar system to be discovered (in 1974) are spiraling toward each other on paths correctly predicted by general relativity. Their discovery earned the Nobel Prize in Physics in 1993 for Joseph Taylor (1941– ) and Russell Hulse (1950– ).

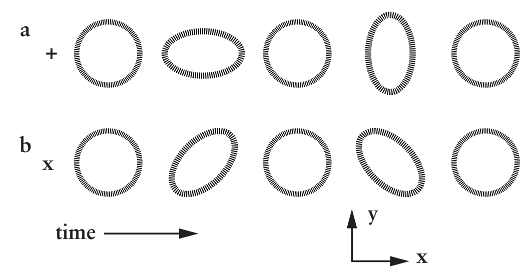


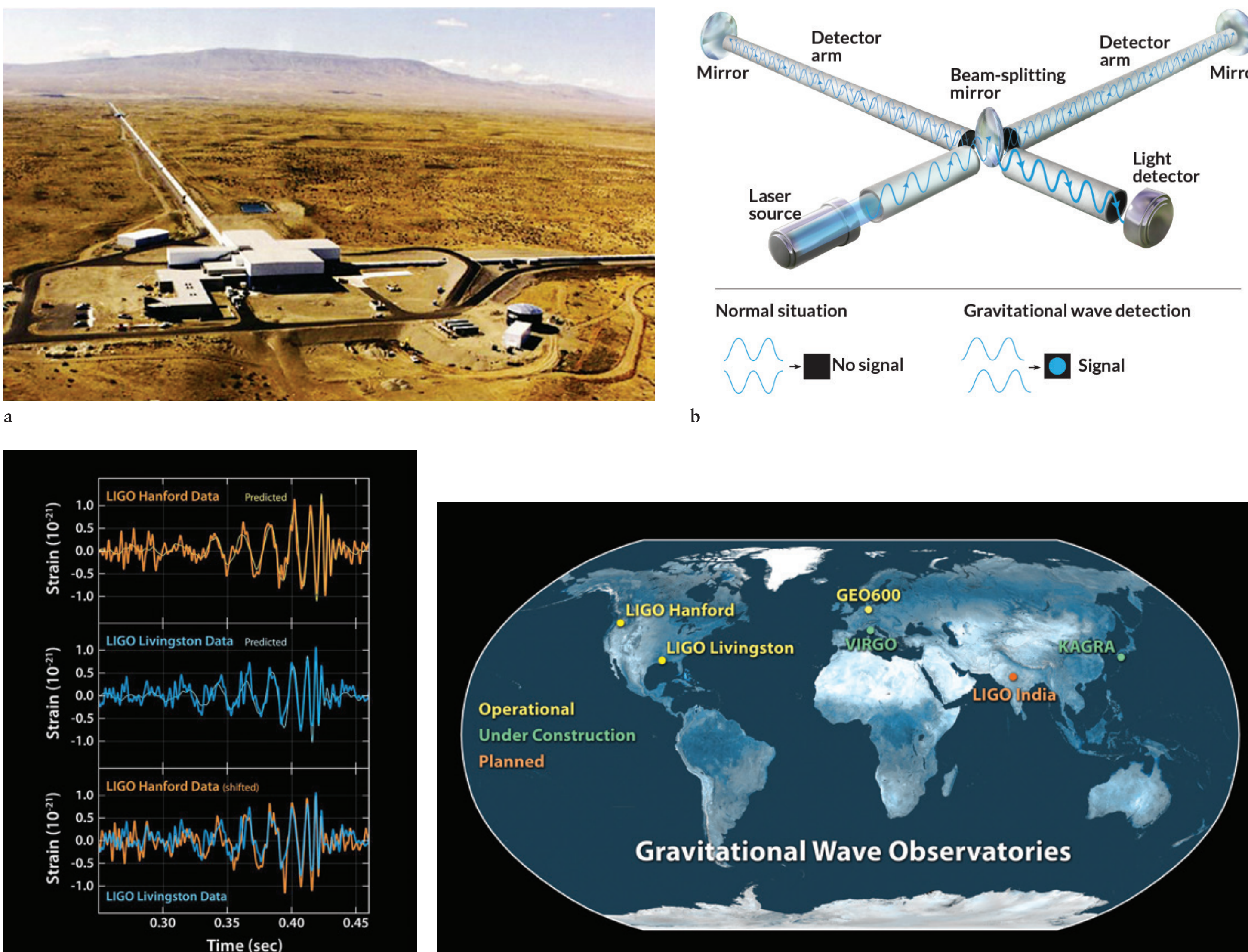

**Figure 3-43 Quadrupole Oscillations** Quadrupole oscillations take rings and extend them in one direction while compressing them in the other direction, as shown in (a) and (b) of this figure. If a ring (or any other distribution of matter) has any quadrupole oscillation, then it generates gravitational radiation. Because their ripples are perpendicular to the direction of motion, if these were gravity waves, they would be traveling either into or out of the page.

**Margin Question 3-11**
Why did the early neutrino detectors not detect the predicted number of neutrinos from the Sun?

The ripples in space-time created by gravitational waves from stars or stellar remnants are incredibly tiny. On Earth, each meter-wide volume of space changes by less than $10^{-20}$ m as these waves created by distant events pass by. Astronomers around the world are building *gravitational wave observatories* (also called *gravity wave detectors* or *gravity wave antennas)* to directly measure these small changes (Figure 3-44). The detectors each have two perpendicular, hollow tubes several kilometers long in which the air has been removed. The longer the tubes, the more sensitive the observatory is to gravity waves. A laser beam is split and half of it travels down each of the two beams, reflecting off mirrors at the ends of the tubes. The beams are then recombined, as shown. If a gravity wave passes through the detector, one arm will be stretched, while the other is shrunk. These changes are detected by comparing the laser beams that have traveled down the two arms. One beam will be slightly longer than the other, which shows up in patterns of light when the two beams are recombined.

**Margin Question 3-12**
From which two directions can the three gravity wave detectors in Figure 3-45 *not* determine the origin of the waves?

Because the changes in length generated by gravitational radiation are so small, tiny disturbances, such as trucks driving near an observatory or small




a b c d

**Figure 3-44 Laser Interferometer Gravitational Wave Observatory (LIGO)** (a) Located in Hanford, Washington, this is one of several gravitational wave observatories (colloquially, gravity wave detectors) around the world. It has two perpendicular arms, each 4 km long. (b) Gravity waves that pass through the detector cause unequal changes in the lengths of the arms. These changes are detected by lasers inside each arm. (c) The signals for the first detection of gravity waves. This event was caused by the merger of two orbiting black holes. The signals from the two detectors separately and combined, show that the vibrations both detectors experienced came from the same source. (d) Location of gravitational wave observatories around the world. (a: LIGO Laboratory ; b: Nicolle Rager Fuller/Science News; c: LIGO Hanford Observatory; d: LIGO Hanford Observatory) earthquakes can mimic the behavior of a gravity wave. Therefore, two or more gravity wave observatories are always used in tandem so that when a gravity wave goes by, it will affect both detectors in the same way and remove the false detections caused by local events. Gravitational radiation was detected directly for the first time on September 14, 2015, by the Laser Interferometer Gravitational-Wave Observatory (LIGO), a pair of detectors built in Hanford, Washington and Livingston, Louisiana. Similar to the spiraling inward of the pair of neutron stars that led to the indirect discovery of gravity waves, the first direct discovery of this radiation occurred when two black holes (remnants of even larger stars than those that create neutron stars), spiraled together and collided. We know that this was the mechanism that generated the gravity waves because the pattern of waves shown in Figure 3-44c is identical to computer calculations of the shape of the gravity waves such a collision should generate. As of April 2018, six gravity wave detections have been made, five of which were pairs of orbiting black holes merging and one was a pair of merging neutron stars, which is what will eventually happen to the neutron stars observed by Taylor and Hulse.

It takes at least three gravitational wave observatories to determine the direction from which a gravity wave comes. Because gravity waves move at a finite speed, namely the speed of light, they often strike the different gravity wave antennas at different times, just as water waves moving at an angle to a beach strikes different parts of it at different times. The delay between the signals being received by pairs of antennas in different locations enable astronomers to locate regions of space from which the gravity wave could have come. Two antennas yield a spread of regions (Figure 3-45), while the location can be pinpointed in most cases if

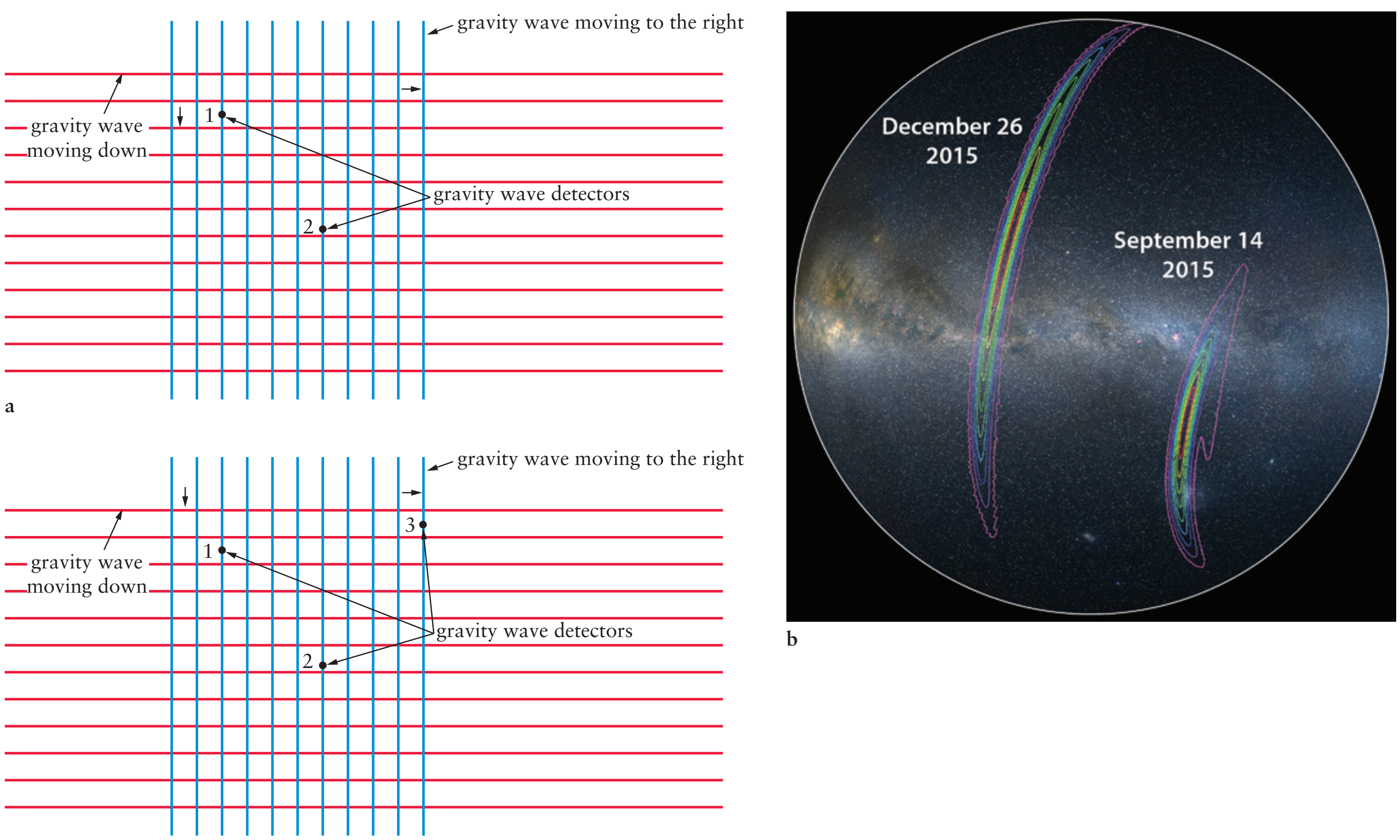



**FIGURE 3-45 How Three Gravity Wave Detectors Determine the Direction of the Wave** The straight lines in these drawings indicate the wave peaks of gravity waves traveling from the left **(blue)** or traveling from the top of the image **(red)**.This is a simplification of the gravity waves' motion for the purpose of visualizing their motion, since they actually cause space to change shape as quadrupoles (see Figure 3-43). The black dots are gravity wave detectors. In (a), the gravity wave coming from the left strikes detector 1 and then detector 2 with exactly the same time interval as the wave coming from the top of the same figure striking detector 1 and then detector 2. (b) The regions of the sky from which two actual pairs of gravity wave events detected by the two LIGO gravity wave detectors could have come. (c) By adding a third detector, it is possible to determine which is the actual direction because the third detector is struck earliest by the wave coming from the top of the figure and last by the wave coming from the left. (c: Axel Mellinger/LIGO)

three antennas receive a signal. The exception here is if the signal hits all three antennas at exactly the same time, in which case it could have come from either direction perpendicular to the plane defined by the locations of the three antennas.

The direct detection of gravity waves by these observatories earned Rainier Weiss (1932– ), Kip Thorne (1940– ), and Barry Barish (1936– ) the Nobel Prize in Physics in 2017. In at least one of these observations, a burst of gamma rays was detected at the same time. This event was the result of two neutron stars colliding, resulting in their merger into a single body. This is an excellent example of how observatories in different realms can detect the same events and thereby reinforce our knowledge about the underlying events. There are now four gravitational wave observatories in operation and others in development.

## 3-20 Frontiers yet to be discovered

Before the twentieth century, astronomers were like the blind men in the fable who are trying to describe an elephant. Their perceptions were piecemeal: We could describe parts of the universe but not the whole. Our ancestors did not have the technology that could enable them to see the big picture. However, we are beginning to see it, and, as you will learn in the chapters that follow, our understanding of the cosmos is therefore increasing dramatically. A vast amount of observational information remains to be gathered. Indeed, literally every planet, moon, piece of interplanetary debris, star, stellar remnant, gas cloud, galaxy, quasar, cluster of galaxies, and supercluster of galaxies has a story to tell. Observational astronomy in all realms is so new an activity that we are still making new and often unexpected discoveries almost daily. There is still a lot to discover using all the technologies available for observing the universe.

# SUMMARY OF KEY IDEAS

### Electromagnetic Radiation Observatories

- Photons, units of vibrating electric and magnetic fields, all carry energy through space at the same speed, the speed of light (300,000 /s in a vacuum, slower in any medium).
- From longest to shortest wavelengths, radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays are all the forms of electromagnetic radiation.
- Photons sometimes behave as particles, sometimes as waves.
- Visible light occupies only a small portion of the electromagnetic spectrum.
- The wavelength of a visible-light photon is associated with its color. Wavelengths of visible light range from about 400 nm for violet light to 700 nm for red light.

### Optics and Telescopes

- A telescope's most important function is to gather as much light as possible. When possible, it also resolves (reveals details) and magnifies an object.
- Reflecting telescopes, or reflectors, produce images by reflecting light rays from concave mirrors to a focal point or focal plane.
- Refracting telescopes, or refractors, produce images by bending light rays as they pass through glass lenses. Glass impurity, opacity to certain wavelengths, and structural difficulties make it inadvisable to build extremely large refractors. Reflectors are not subject to the problems that limit the usefulness of refractors.
- Earth-based telescopes are being built with active optics and adaptive optics. These advanced technologies yield resolving power comparable to the Hubble Space Telescope.

### Nonoptical Astronomy

- Radio telescopes have large, reflecting antennas (dishes) that are used to focus radio waves.
- Very sharp radio images are produced with arrays of radio telescopes linked together in a technique called interferometry.
- Earth's atmosphere is fairly transparent to most visible light and radio waves, along with some infrared and ultraviolet radiation arriving from space, but it absorbs much of the electromagnetic radiation at other wavelengths.
- For observations at other wavelengths, astronomers mostly depend upon space telescopes. Such satellite-based observatories are giving us a wealth of new information about the universe and permitting coordinated observation of the sky at many wavelengths.
- Charge-coupled devices (CCDs) record images on many telescopes used between infrared and X-ray wavelengths.

### Cosmic Ray Observatories

- Cosmic rays are high-energy, high-speed particles ejected by the Sun, other stars, and more powerful sources, such as supernova remnants colliding with interstellar gas and dust.
- We have cosmic ray observatories on Earth and in space to detect cosmic rays with different energies.
- Cosmic rays in space are primary cosmic rays, while cosmic rays passing through our atmosphere are secondary cosmic rays.

### Neutrino Observatories

- Neutrinos, high-speed particles created during thermonuclear fusion, were originally believed to be massless.
- The electron neutrinos generated and emitted by the Sun were originally detected at a lower rate than is predicted by our model of thermonuclear fusion.
- The discrepancy between the theory and early observations occurred because electron neutrinos have mass, which causes many of them to change into two other forms of neutrinos before they reach Earth.
- All three "flavors" of neutrino have now been detected.

### Gravitational Wave Observatories

- Many vibrations, most notably quadrupole oscillations, generate tiny changes in the fabric of spacetime called gravitational radiation or gravity waves.
- Gravity waves travel at the speed of light.
- The orbit of a pair of neutron stars has shown the effects of their emitting gravity waves.
- Gravity waves generated by the merger of pairs of black holes and by the merger of a pair of neutron stars have been observed.

## WHAT DID YOU THINK?

**1** *What is light?* Light—more properly "visible light"—is one form of electromagnetic radiation. All electromagnetic radiation (radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays) has both wave and particle properties.

**2** *Which type of electromagnetic radiation is most dangerous to life?* Gamma rays have the highest energies of all photons, so they are the most dangerous to life. However, ultraviolet radiation from the Sun is the most dangerous electromagnetic radiation that we commonly encounter.

**3** *What is the main purpose of a telescope?* A telescope is designed primarily to collect as much light as possible.

**4** *Why do research telescopes that collect electromagnetic radiation use mirrors, rather than lenses, to collect light?* Telescopes that use lenses have more problems, such as chromatic aberration, internal defects, complex shapes, and distortion from sagging, than do telescopes that use mirrors.

**5** *Why do stars twinkle?* Rapid changes in the density of Earth's atmosphere cause passing starlight to change direction, making stars appear to twinkle. Seen from space, stars do not twinkle.

**6** *What are cosmic rays? Where do they come from?* Cosmic rays are high-speed particles (mostly hydrogen and other atomic nuclei) in space. Many of them are created as supernova remnants collide with preexisting interstellar gas.

## KEY TERMS FOR REVIEW

active optics, 96
adaptive optics, 96
angular resolution (resolution), 86
Cassegrain focus, 84
charge-coupled device (CCD), 92
chromatic aberration, 89
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cosmic ray shower, 106
coudé focus, 84
electromagnetic radiation, 74
electromagnetic spectrum, 79
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refraction, 74
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Schmidt corrector plate, 91
secondary cosmic ray, 106
secondary mirror, 84
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solar energetic particle, 106
spectrum (*plural* spectra), 74
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twinkling, 94
ultraviolet (UV) radiation, 79
very-long-baseline interferometry (VLBI), 100
wavelength ($\lambda$), 77
X-ray, 79

## REVIEW QUESTIONS

*All computational problems are preceded by an asterisk (*). Answers appear at the end of the book.*

**1.** Describe reflection and refraction. How do these processes enable astronomers to build telescopes?

**2.** Give everyday examples of refraction and reflection.

**3.** Which side of the secondary mirror in Figure 3-9c is coated with aluminum? Justify your answer.

***4.** How much more light does a 3-m-diameter telescope collect than a 1-m-diameter telescope?

**5.** Explain some of the advantages of reflecting telescopes over refracting telescopes.

**6.** What are the three major functions of a telescope?

**7.** What is meant by the angular resolution of a telescope?

**8.** What limits the ability of the 5-m telescope at Palomar Observatory to collect starlight? There are several correct answers to this question.

**9.** Why will many of the very large telescopes of the future make use of multiple mirrors?

**10.** What is meant by adaptive optics? What problem does adaptive optics overcome?

**11.** Compare an optical reflecting telescope to a radio telescope. What do they have in common? How are they different?

**12.** Why can radio astronomers observe at any time of the day or night, whereas optical astronomers are mostly limited to observing at night?

**13.** Why must astronomers use satellites and Earth-orbiting observatories to study the heavens at X-ray wavelengths?

**14.** What are NASA's four Great Observatories, and in what parts of the electromagnetic spectrum do (or did) they observe?

**15.** Why did Rømer's observations of the eclipses of Jupiter's moons support the heliocentric, but not the geocentric, cosmology?

**16.** What is a neutrino, and why are astronomers so interested in detecting neutrinos from the Sun?

## ADVANCED QUESTIONS

**17.** Advertisements for home telescopes frequently give a magnification for the instrument. Is this a good criterion for evaluating such telescopes? Explain your answer.

*__18.__ The observing cage in which an astronomer sits at the prime focus of the 5-m telescope at Palomar Observatory is about 1 m in diameter. What fraction of the incoming starlight is blocked by the cage? *Hint:* The area of a circle of diameter $d$ is $\pi d^2/4$, where $\pi \approx 3.14$.

*__19.__ Compare the light-gathering power of the Palomar Observatory's 5-m telescope to that of the fully dark-adapted human eye, which has a pupil diameter of about 5 mm.

**20.** Show by means of a diagram why the image formed by a simple refracting telescope is "upside down."

*__21.__ Suppose your Newtonian reflector has a mirror with a diameter of 20 cm and a focal length of 2 m. What magnification do you get with an eyepiece whose focal length is

**a.** 9 mm, **b.** 20 mm, and **c.** 55 mm?

**22.** Why does no major observatory have a Newtonian reflector as its primary instrument, whereas Newtonian reflectors are popular among amateur astronomers?

**23.** From the ground, how can astronomers detect gamma-ray sources in space?

**24.** Why will many of the very large telescopes of the future have ultrathin primary mirrors?

## DISCUSSION QUESTIONS

**25.** Discuss the advantages and disadvantages of using a relatively small visible-light telescope in Earth's orbit (for example, the 2.4-m Hubble Space Telescope) versus a large visible-light telescope on a mountaintop (for example, the 8.3-m Subaru telescope on Mauna Kea, Hawaii).

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

**27.** Consider two identical Cassegrain telescope mirrors. One is set up as a prime focus telescope, whereas the other is used in a Cassegrain telescope.

**a.** Sketch both telescopes.

**b.** What are the differences between the two that make each useful in different observing situations?

## WHAT IF...

**28.** Telescopes were first invented today? What objects or areas of the sky would you recommend that astronomers explore first? Why?

**29.** We had eyes sensitive to radio waves? How would our bodies be different, and how would our visual perceptions of the world be different?

**30.** Humans were unable to detect any electromagnetic radiation? How would that change our lives, and what alternatives might evolve (some species indeed have done this) to provide information about distant objects?

## WEB QUESTIONS

**31.** Several telescope manufacturers build Schmidt-Cassegrain telescopes. These devices use a correcting lens in an arrangement like that shown in Figure 3-23c. Consult advertisements on the Web and list the dimensions, weights, and costs of some of these telescopes. Why are they popular among amateur astronomers?

**32.** Discuss the advantages and disadvantages of setting up an observatory on the Moon. *Hint:* To get a broad perspective on this question, you might find it useful to explore the Web for the challenges of living on the Moon.

**33.** The Large Zenith Telescope (LZT) in British Columbia, Canada, uses a 6-m liquid mirror made of mercury. Use the Web to investigate this technology. How can a liquid metal be formed into the necessary shape of a telescope mirror? What are the advantages and disadvantages of a liquid mirror?

**34.** Search the Web for all solar neutrino experiments. Make a list of them and indicate which are currently operating and which are still under construction. Summarize the results found by the active detectors.

## GOT IT?

**35.** Why do stars twinkle?

**36.** Why do all research telescopes use primary mirrors rather than objective lenses?

**37.** For the purpose of observing very faint objects, which of the following features of a telescope is most important? Explain your answer.

- **a.** its maximum magnification
- **b.** its ability to resolve colors
- **c.** the size of its objective lens or primary mirror
- **d.** the type of mount it has (if necessary, see Appendix H for information on mounts)
- **e.** its weight

**38.** Of the following types of electromagnetic radiation, which is most dangerous to life?

- **a.** radio waves
- **b.** X-rays
- **c.** ultraviolet radiation
- **d.** infrared radiation
- **e.** visible light

**39.** What are cosmic rays?

## OBSERVING PROJECT

**40.** During the daytime, obtain a telescope and several eyepieces of differing focal lengths. If you can determine the focal length of the telescope's objective lens or mirror (often printed on it), calculate and record the magnifying power for each eyepiece. Focus the telescope on some familiar object, such as a distant lamppost or tree. **DO NOT FOCUS ON THE SUN! Looking directly at the Sun through a telescope will cause blindness.** Describe the image you see through the telescope. Is it upside down? How does the image move as you slowly and gently shift the telescope left and right or up and down? Examine the distant objects under different magnifications. How does the field of view change as you go from low magnification to high magnification?

## *STARRY NIGHT*™ EXPLORATIONS

**41.** *Starry Night*™ can be used to measure the speed of light by simulating the observation of an event from two sites at different distances away from this event and measuring the difference of arrival times at the two sites. The event is the emergence of Jupiter's moon Io from Jupiter's shadow. The two observing locations from which you will time the arrival of that light signal are at the north poles of Earth and the planet Mercury, respectively. The difference in the distances between Io and these two locations at the time the signal arrives divided by the difference between the arrival times of the signal at the two locations will give you a measure of the speed of light. Open **Favorites > Explorations > Io from Earth**. The view is centered on Io, which at this time is hidden in Jupiter's shadow. Click **Play** to watch the moon emerge from this shadow. Then zoom in to fill the view with Io and use the time controls to freeze time at the point where half of Io's disk has emerged from eclipse. Record the universal time for this event from the on-screen info and then use the HUD to find the Distance from Observer of Io at this time. Now open **Favorites > Explorations > Io from Mercury** to observe this event from the north pole of Mercury. Again, use the time controls to find the time at which half of Io's disk has emerged from the shadow and record the universal time of the event and the distance to Io from this location. Use these observations to calculate the speed of light. First, calculate the difference of the distance, in au, of the two locations from Io. Then calculate the difference, in seconds, between the arrival times of the light signal at the two locations. Divide the difference in the distance by the difference in time to calculate the speed of light in au per second. Finally, convert this value to kilometers per second by multiplying the result by $1.496 \times 10^8$ (the number of kilometers in one au). (**a**) What result do you obtain for the speed of light and how does it compare to the accepted value of the speed of light of $2.9979 \times 10^5$ kilometers per second? (**b**) Your calculated value might not agree with the accepted value for the speed of light. Estimate what an error of 1 second in the timing difference would make to your value for this speed by recalculating your values with 1 fewer or 1 extra second for the time difference. Will such an observational error explain the inaccuracy in your measured value for the speed of light?

**42.** Use *Starry Night*™ to explore the difference between magnification and resolution. Select **Favorites > Explorations > Orion.** The view is centered upon the Great Orion Nebula. (**a**) Zoom in to a field of view about 7° wide. Would you say that the view has been magnified? What has happened to the size of the field of view? Has the resolution improved? (**b**) Note the two bright spots near the center of the nebula and observe them closely as you slowly zoom in to a field of view about 1° wide. Is more detail discernible in the nebula as you zoom in? What has become of the lower of the two bright spots? During the zoom, has magnification increased? Has the resolution improved? (**c**) Zoom in to a field of view about 25′ (arcminutes) wide. How did the zoom affect the image of the other bright spot in the nebula? Use the HUD to identify the components of this bright spot. With this zoom, has the magnification increased? Has the resolution improved? (**d**) Continue to zoom in on the image. As you zoom closer, does the clarity of the image improve, deteriorate, or remain unchanged? Explain your observations in terms of magnification and resolution.

**43.** Use *Starry Night™* to explore the effect of light pollution on the night sky. Click the **Home** button to view the sky from your home location. Click on the **Quick Search Items** button and open the **Options** panel. In this panel, expand the **Local View** layer and turn off the **Daylight** option to view the sky under ideal conditions of darkness. Survey the sky and use the HUD to find the apparent magnitude of the dimmest stars you can discern. (**a**) Return to the Options panel and click on the **Local Light Pollution** label in the Local View layer to open the Light Pollution options window. In this window, turn on **Local** light pollution, set the level to its maximum limit and click **OK**. Look around the sky again. What is the apparent magnitude of the dimmest discernible stars in this sky? How does this compare to the apparent magnitude limit under ideal conditions? (**b**) Estimate the fraction of the visible stars you can see under ideal conditions that are obscured by severe nearby light pollution. Open the **FOV Indicators** panel, expand the **All Charts** layer and turn on the **20 × 20 Degrees** indicator. Drag the view so that the square indicator encompasses a reasonable number of stars. Without changing the zoom, count the number of stars visible within this 20° × 20° area of the sky. Now reopen the **Options** panel, turn off **Local** light pollution and count the stars visible within the indicator under ideal conditions of darkness. Try this for one or two more areas in the sky and then turn off the 20° × 20° box in the FOV Indicators panel. Approximately what fraction of the stars that are visible under ideal conditions are obscured by severe local light pollution?

# WHAT IF... Humans Had Infrared-Sensitive Eyes?

Our eyes are sensitive to less than a trillionth of 1% of the electromagnetic spectrum—what we call visible light. But this minuscule resource provides an awe-inspiring amount of information about the universe. We interpret visible-light photons as the six colors of the rainbow—red, orange, yellow, green, blue, and violet. These colors combine to form all of the others that make our visual world so rich. But the Sun actually emits photons of all wavelengths. So, what would happen if our eyes had evolved to sense another part of the spectrum?

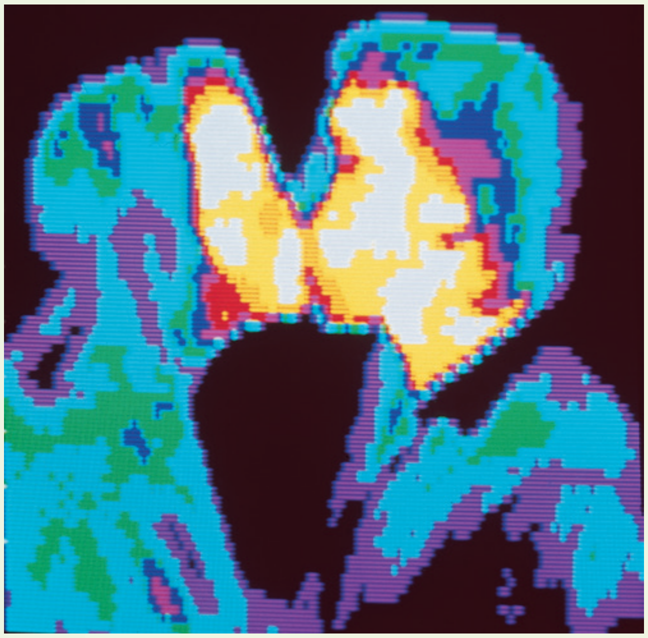
**A Darker Vision?** Gamma rays, X-rays, and most ultraviolet radiation do not pass through Earth's atmosphere. Because the world is illuminated by sunlight, Earth and the sky would look dark, indeed, if our eyes were sensitive only to these wavelengths. Radio waves, in contrast, easily pass through our atmosphere. But to see the same detail from radio waves that we now see from visible-light photons, our eyes would require a diameter 10,000 times larger. Each would be the size of a baseball infield!

What about infrared radiation? Although not all incoming infrared photons get through our atmosphere, short-wavelength ("near") infrared radiation passes easily through air. Depending on wavelength, the Sun emits between one-half and a ten-billionth as many infrared photons as red-light photons. Fortunately, most of these are in the near infrared.

**Heat-Sensitive Vision?** To see infrared photons, human eyes would need to be only 5 to 10 times larger. Some snakes have evolved infrared vision. Portable infrared "night vision" cameras and goggles are available to us humans. Because everything that emits heat emits infrared photons, infrared sight would be very useful. Also, not everything we see with infrared sight would be due just to reflected sunlight—hotter objects would be intrinsically brighter than cool ones. For example, seeing infrared would allow us to observe changes in a person's emotional state. Someone who is excited or angry often has more blood near the skin and, thus, releases more infrared radiation (heat) than normal. Conversely, someone who is scared has less blood near the skin and, thus, emits less heat.

**Night Vision?** The night sky would be a spectacular sight through infrared-sensitive eyes. Gas and dust clouds in the Milky Way absorb visible light, thus preventing the light of distant stars from getting to Earth. However, because most infrared radiation passes through these clouds unaided, we would be able to see distant stars that we cannot see today. On the other hand, the white glow of the Milky Way, which is caused by the scattering of starlight by interstellar clouds, would be dimmer, because the gas and dust clouds do not scatter infrared light as much as they do visible light. (The haze created by the Milky Way would not vanish, however, because when gas and dust clouds are heated by starlight, they emit their own infrared radiation.)

Our concept of stars would be different, too. Many stars, especially young, hot ones, are surrounded by cocoons of gas and dust that emit infrared radiation. This dust is heated by the nearby stars. Instead of appearing as pinpoints, many stars would appear to be surrounded by wild strokes of color, and we would have an impressionist sky.



**Kissing Is Hot** The infrared (heat) from this kissing couple has been converted into visible light colors so that we can interpret the invisible radiation. The hottest regions are white, with successively cooler areas shown in yellow, orange, red, green, sky blue, dark blue, and violet. (David Montrose, M.D./Custom Medical Stock Photo)