33. Today at the beach you see the highest of all high tides in the last month. You see the Moon in the daytime sky. What is the most likely Moon phase?
34. Why is the period of an open orbit undefined?
35. In what conditions do Newton's laws of motion and gravity need to be modified?
36. How does the first postulate of special relativity imply the second postulate?
37. When you ride a fast elevator upward, you feel slightly heavier as the trip begins and slightly lighter as the trip ends. How is this phenomenon related to the equivalence principle?
38. From your knowledge of general relativity, would you expect radio waves from distant galaxies to be deflected as they pass near the Sun? Why or why not?
39. How is gravity related to acceleration? Are all accelerations the result of gravity?
40. Near a massive planet, is gravitational acceleration large or small? Is space strongly curved, or not? What about near a small marble?
41. **How Do We Know?** Why would science be impossible if some natural events happened without causes?
42. **How Do We Know?** Why is it important that a theory make testable predictions?

Discussion Questions

1. How did Galileo idealize his inclines to conclude that an object in motion stays in motion until it is acted on by some force?
2. Give an example from everyday life to illustrate each of Newton's laws.
3. Where in the Universe can you be weightless?
4. People who lived before Newton may not have believed in cause and effect as strongly as you do. How do you suppose that affected how they saw their daily lives?
5. Is everything gravitationally attracted to other things in the Universe, and thus is everything in a state of falling?
6. Give an example from everyday life of kinetic energy and gravitational potential energy.
7. If Newton modified Kepler's laws and Einstein modified Newton's laws, is it possible Einstein's laws (postulates) might be modified?

Problems

1. This astronomy textbook is to be dropped from a tall building on Earth. One second after dropped, what are the textbook's speed, velocity, and acceleration? After 2 seconds? After 3 seconds? The book hits the ground; what are the book's speed, velocity, and acceleration?
2. Compared to the strength of Earth's gravity at its surface $r = R_E$ where R_E is the radius of Earth, how much weaker is gravity at a distance of $r = 10\ R_E$? At $r = 20\ R_E$?
3. Compare the force of gravity on a 1 kg mass on the Moon's surface with the force that mass on Earth's surface. Which force is greater, why, and by how much?
4. A satellite is in orbit at a distance r from the center of Earth. If the orbit radius is halved so that the satellite is orbiting closer to Earth's surface, will the field strength increase, decrease, or stay the same and by how much?
5. The International Space Station is in orbit around the Earth at a distance r from the center of Earth. A recent addition increased the Station's mass by a factor of 3. Did Earth's gravitational force on the Station increase, decrease, or stay the same and by how much?
6. If a small lead ball falls from a high tower on Earth, what will be its velocity after 2 seconds? After 4 seconds?
7. What is the circular velocity of an Earth satellite 1000 km above Earth's surface? (*Note:* Earth's average radius is 6371 km. *Hint*: Convert all quantities to m, kg, s.)
8. What is the circular velocity of an Earth satellite 36,000 km above Earth's surface? What is its orbital period? (*Note:* Earth's average radius is 6371 km. *Hint:* Convert all quantities to m, kg, s.)
9. What is the orbital speed at Earth's surface? Ignore atmospheric friction. (*Note:* Earth's average radius is 6371 km. *Hint:* Convert all quantities to m, kg, s.)
10. What is the orbital speed at Earth's surface? Ignore atmospheric friction. (*Note:* Earth's average radius is 6371 km. *Hint:* Convert all quantities to m, kg, s.)
11. Repeat the previous problem for Mercury, Venus, the Moon, and Mars. (*Note:* You can find the mass and radius of each of these objects in the Appendix A tables).
12. Describe the orbit followed by the slowest cannonball on page 88–89 pretending that the cannonball could pass freely through Earth. (Newton got this problem wrong the first time he tried to solve it.)
13. If you visited a spherical asteroid 30 km in radius with a mass of 4.0×10^{17} kg, what would be the circular velocity at its surface? A major league fastball travels about 90 mph. Could a good pitcher throw a baseball into orbit around the asteroid? (*Note:* 90 mph is 40 m/s.)
14. What is the orbital period of a satellite orbiting just above the surface of the asteroid in Problem 13?
15. What is the escape velocity from you if your mass is 60 kg and your radius is 1 m? Is it easy or difficult for a fly to leave your gravitational pull?
16. What would be the escape velocity at the surface of the asteroid in Problem 13? Could a major league pitcher throw a baseball off the asteroid so that it never came back?
17. A moon of Jupiter takes 1.8 days to orbit at a distance of 4.2×10^5 km from the center of the planet. What is the mass of Jupiter plus its moon? Which moon is it? (*Note:* One day is 86,400 seconds. *Hint:* See Appendix Table A-11.)

Learning to Look

1. Why can the object shown at the right be bolted in place and used 24 hours a day without adjustment?

Larry Mulvehill/The Image Works


NASA/JSC

2. What is the flux at position 2 compared to position 1 in Figure 5-5? How does the distance from the center to position 2 compare with the distance to position 1?
3. Why is it a little bit misleading to say that this astronaut is weightless?

Light and Telescopes 6

Guidepost In previous chapters of this book, you viewed the sky the way the first astronomers did, with the unaided eye. Then, in Chapter 4, you got a glimpse through Galileo's small telescope that revealed amazing things about the Moon, Jupiter, and Venus. Now you can consider the telescopes, instruments, and techniques of modern astronomers.

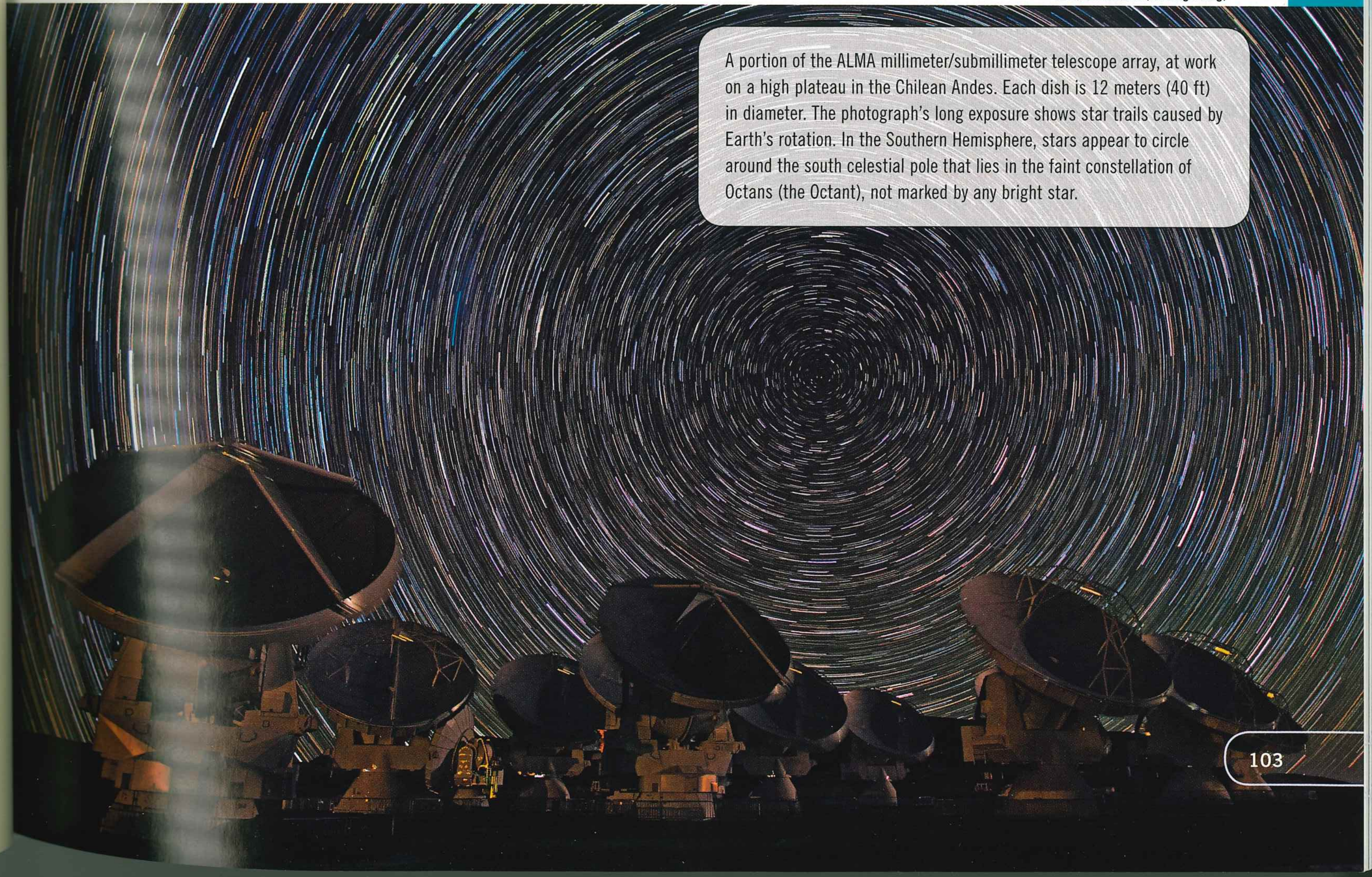
Telescopes gather and focus light, so you need to study what light is, and how it behaves, on your way to understanding how telescopes work. You will learn about telescopes that capture invisible types of light such as radio waves and X-rays. These enable astronomers to reach a more complete understanding of the Universe. This chapter will help you answer these five important questions:

- ▶ **What is light?**
- ▶ **How do telescopes work?**
- ▶ **What are the powers and limitations of telescopes?**
- ▶ **What kind of instruments do astronomers use to record and analyze light gathered by telescopes?**
- ▶ **Why are some telescopes located in space?**

Science is based on observations. Astronomers cannot visit distant stars and galaxies, so they must study them using telescopes. Twenty chapters of exploration remain, and everyone will present information gained by astronomers using telescopes.

> *The strongest thing that's given us to see with's*
> *A telescope. Someone in every town*
> *Seems to me owes it to the town to keep one.*
>
> ROBERT FROST, "THE STAR-SPLITTER"
>
> Reprinted by permission of Henry Holt & Company

ESO/B. Tafreshi (twanight.org)


A portion of the ALMA millimeter/submillimeter telescope array, at work on a high plateau in the Chilean Andes. Each dish is 12 meters (40 ft) in diameter. The photograph's long exposure shows star trails caused by Earth's rotation. In the Southern Hemisphere, stars appear to circle around the south celestial pole that lies in the faint constellation of Octans (the Octant), not marked by any bright star.

LIGHT FROM THE SKY is a treasure that links you to the rest of the Universe. Astronomers strive to study light from the Sun, planets, moons, asteroids, comets, stars, nebulae, and galaxies, extracting information about their natures. Most celestial objects are very faint sources of light, so large telescopes are built to collect the greatest amount of light possible.

Some types of telescopes, for example radio telescopes like the ones featured on the previous page, gather light that is invisible to the human eye, but all telescopes work by the same basic principles. Some telescopes are used on Earth's surface, but others must go high in Earth's atmosphere, or even above the atmosphere into space, to work properly.

There is more to astronomy than amazing technology and brilliant scientific analysis. Astronomy helps us understand what we are. In the quotation that opens this chapter, the poet Robert Frost suggests that someone in every town should own a telescope to help us look upward and outward.

6-1 Radiation: Information from Space

Astronomers no longer spend their time mapping constellations or charting phases of the Moon. Modern astronomers analyze light using sophisticated instruments and techniques to investigate the temperatures, compositions, and motions of celestial objects to be able to make inferences about their internal processes and evolution. To understand how astronomers gain such detailed information about distant objects, you first need to learn about the nature of light.

Light as Waves and Particles

When you admire the colors of a rainbow, you are seeing an effect of light acting as a wave (Figure 6-1a). When you use a digital camera to take a picture of the same rainbow, the light acts like particles as it hits the camera's detectors (Figure 6-1b). Light has both wave-like and particle-like properties, and how it behaves depends partly on how you treat it.

◀ Figure 6-1 The wavelike properties of light produce a rainbow, whereas the particle-like properties are involved in the operation of a digital camera.

Panel a: © Gail Johnson/Shutterstock.com; Panel b: Roy McMahon/Cardinal/Corbis

Light is referred to as **electromagnetic radiation** because it is made up of both electric and magnetic fields. (You encountered the concept of a field in the previous chapter in the context of gravitational fields.) The word *light* is commonly used to refer to electromagnetic radiation that humans can see, but visible light is only one among many types of electromagnetic radiation that include X-rays and radio waves.

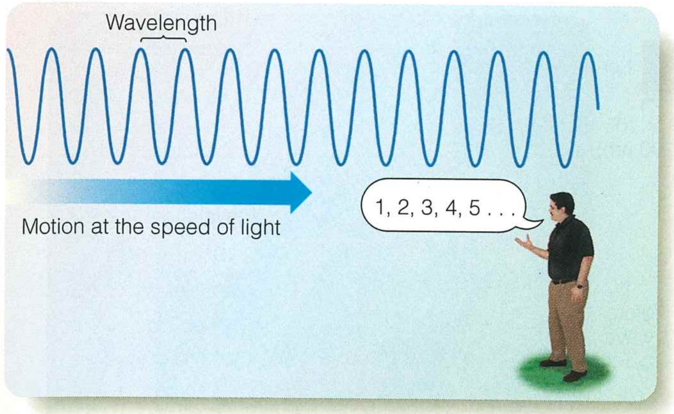
Some people are wary of the word *radiation,* but that involves a **Common Misconception.** *Radiation* refers to anything that radiates away from a source. Dangerous high-energy particles emitted from radioactive atoms are also called radiation, and you have learned to be concerned when you hear that word. But light, like all electromagnetic radiation, spreads outward from its origin, so you can correctly refer to light as a form of radiation.

Electromagnetic radiation travels through space at a speed of 3.00×10^8 m/s (186,000 mi/s). This is commonly referred to as the speed of light, symbolized by the letter *c*, but it is in fact the speed of all types of electromagnetic radiation.

Electromagnetic radiation can act as a wave phenomenon—that is, it is associated with a periodically repeating disturbance—a wave—that carries energy. You are familiar with waves in water: If you disturb a pool of water, waves spread across the surface. Imagine placing a ruler parallel to the travel direction of the wave. The distance between peaks of the wave is called the **wavelength**, usually represented by the Greek lowercase letter lambda (λ) (Figure 6-2).

Wavelength is related to **frequency**, the number of waves that pass a stationary point in 1 second. Frequency is often represented by the Greek lowercase letter *nu* (ν). The relationship among the wavelength, frequency, and speed of a wave can be expressed by:

$$\lambda\nu = c$$



▲ Figure 6-2 All electromagnetic waves travel at the speed of light. The wavelength is the distance between successive peaks. The frequency of the wave is the number of peaks that pass you in 1 second.

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If your favorite FM station is on the dial at 89.5, that means the station's radio waves have a frequency $\nu = 89.5$ megahertz. In other words, 89.5 million radio wave peaks pass by you each second. You already know that the radio waves are traveling at the speed of light $c = 3.00 \times 10^8$ m/s. Using the formula at the bottom of page 104, you can calculate that your favorite station is radiating radio waves with a wavelength of $\lambda = 3.35$ m. Note that wavelength and frequency have an inverse relationship: The higher the frequency, the shorter the wavelength.

Sound is another example of a wave—in this case, a periodically repeating pressure disturbance that moves from source to ear. Sound requires a medium, meaning a substance such as air, water, or rock to travel through. In contrast, light is made up of electric and magnetic fields that do not require a medium and can travel through empty space. For example, on the Moon, where there is no air, there can be no sound, but there is plenty of light. This brings up a **Common Misconception** that radio waves are related to sound. Actually, radio waves are a type of light (electromagnetic radiation) that your radio receiver transforms into sound so you can listen. Radio communication works just fine between astronauts standing on the airless Moon; radio signals travel through the vacuum, and then the spacesuit radios convert the radio signals to sound that is heard in the air inside their helmets.

Although electromagnetic radiation can behave as a wave, it can also behave as a stream of particles. A particle of electromagnetic radiation is called a **photon**. You can think of a photon as a packet of waves. The amount of energy a photon carries is inversely proportional to its wavelength. The following simple formula describes that relationship:

$$E = \frac{hc}{\lambda}$$

Here *h* is Planck's constant (6.63×10^{-34} joule s), *c* is the speed of light in meters per second, and λ is the wavelength in meters.

This equation expresses the important point that there is a relationship between the energy *E* of a photon, a particle property of light, and the wavelength λ, a wave property. The inverse proportion means that as λ gets smaller *E* gets larger: Shorter-wavelength photons carry more energy, and longer-wavelength photons carry less energy. You can see that the relationship between wavelength and frequency means there must also be a simple relationship between photon energy and frequency. That is, short wavelength, high frequency, and large photon energy go together; long wavelength, low frequency, and small photon energy go together.

The Electromagnetic Spectrum

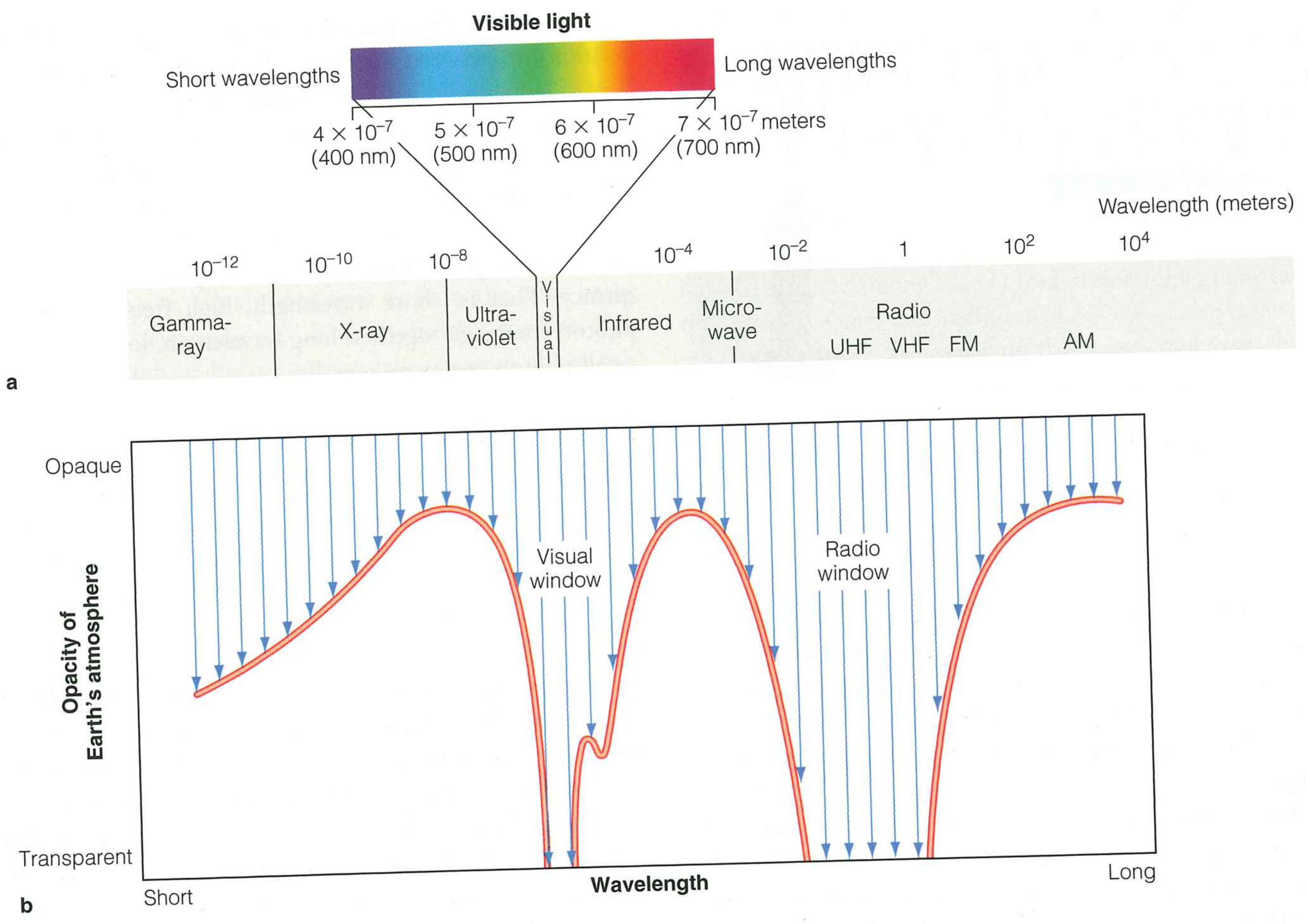
A **spectrum** is an array of electromagnetic radiation displayed in order of wavelength. You are most familiar with the spectrum of visible light that you see in rainbows. The colors of the rainbow differ in wavelength, with red having the longest wavelength and violet the shortest. The visible spectrum is shown in Figure 6-3a.

The average wavelength of visible light is about 0.0005 mm. This means that roughly 50 light waves would fit end to end across the thickness of a sheet of household plastic wrap. It is awkward to describe such short distances in millimeters, so scientists usually give the wavelength of light using **nanometer (nm)** units, equal to one-billionth of a meter (10^{-9} m). Another unit that astronomers commonly use is called the **angstrom (Å)**, named after the Swedish astronomer Anders Jonas Ångström. One angstrom is 10^{-10} m, that is, one-tenth of a nanometer. The wavelength of visible light ranges from about 400 to 700 nm (4000 to 7000 Å).

Just as you sense the wavelength of sound as pitch, you sense the wavelength of light as color. Light with wavelengths at the short-wavelength end of the visible spectrum (λ = about 400 nm) appears violet to your eyes, and light with wavelengths at the long-wavelength end (λ = about 700 nm) appears red.

Figure 6-3a shows that the visible spectrum makes up only a small part of the entire electromagnetic spectrum. Beyond the red end of the visible spectrum lies **infrared (IR)** radiation, with wavelengths ranging from 700 nm to about 1 mm (1 million nm). Your eyes do not detect infrared, but your skin senses it as heat. A heat lamp warms you by giving off infrared radiation. Infrared radiation was discovered in the year 1800, the first known example of "invisible light" (Figure 6-4).

Beyond the infrared part of the electromagnetic spectrum lie **microwaves** and **radio waves**. Microwaves, used for cooking food in a microwave oven, as well as for radar and some long-distance telephone communications, have wavelengths from a few millimeters to a few centimeters. The radio waves used for FM, television, military, government, and cell phone



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▲ **Figure 6-3** (a) The spectrum of visible light, extending from red to violet, is only part of the electromagnetic spectrum. (b) Most forms of light (electromagnetic radiation) are absorbed in Earth's atmosphere. Light can reach Earth's surface only through the visual and radio "windows."

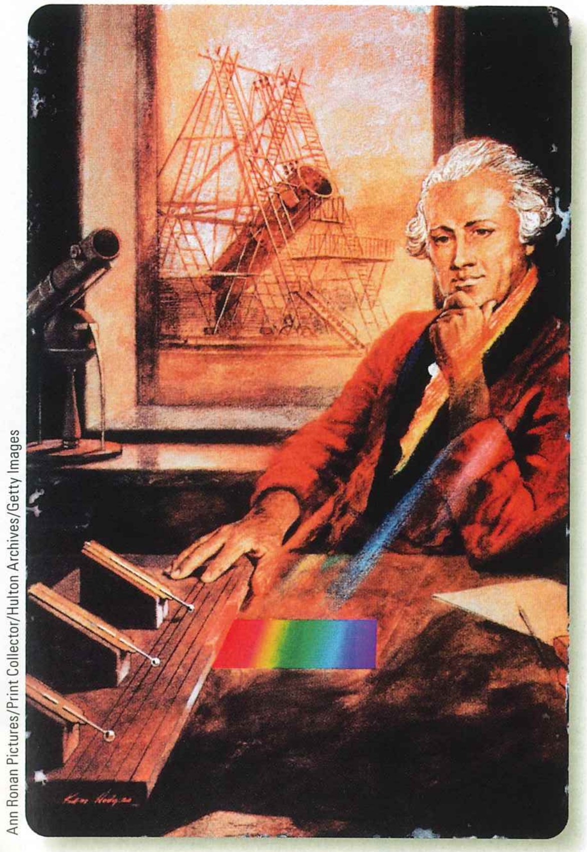
radio transmissions have wavelengths of a few centimeters to a few meters, whereas AM and other types of radio transmissions have wavelengths of a few hundred meters to a few kilometers.

Now look at the other end of the electromagnetic spectrum in Figure 6-3a and notice that electromagnetic waves shorter than violet are called **ultraviolet (UV)**. Electromagnetic waves that are even shorter are called **X-rays**, and the shortest are **gamma-rays**.

Recall the formula for the energy of a photon. Extremely short-wavelength, high-frequency photons, such as X-rays and gamma-rays, have high energies and can be dangerous. Even ultraviolet photons have enough energy to harm you. Small amounts of ultraviolet radiation produce a suntan, and larger doses cause sunburn and skin cancers. Contrast this to the lower-energy infrared photons. Individually they have too little energy to affect skin pigment, a fact that explains why you can't get a tan from a heat lamp. Only by concentrating many low-energy photons in a small area, as in a microwave oven, can you transfer significant amounts of energy.

The boundaries between these wavelength ranges are defined only by conventional usage, not by natural divisions. There is no real distinction between short-wavelength ultraviolet light and long-wavelength X-rays. Similarly, long-wavelength infrared radiation is indistinguishable from short-wavelength microwaves.

Astronomers collect and study electromagnetic radiation from space because it carries almost the only clues available about the nature of stars, planets, and other celestial objects. Earth's atmosphere is opaque to most electromagnetic radiation, as shown in the graph in Figure 6-3b. Gamma-rays and X-rays are absorbed high in Earth's atmosphere, and a layer of ozone (O_3) at altitudes of about 15 to 30 km (10 to 20 mi) absorbs most ultraviolet radiation. Water vapor in the lower atmosphere absorbs most long-wavelength infrared radiation and microwaves. Only visible light, some short-wavelength infrared radiation, and some radio waves reach Earth's surface through wavelength bands called **atmospheric windows**. Obviously, if you wish to study the Universe from Earth's surface, you have to "look through" one of those windows.



Ann Ronan Pictures/Print Collector/Hulton Archives/Getty Images

▲ **Figure 6-4** Depiction of Sir William Herschel discovering that sunlight contains radiation detectable by thermometers but not by human eyes. He named that invisible light "infrared," meaning "below red."

DOING SCIENCE

What would you see if your eyes were sensitive only to radio wavelengths? An important part of doing science is being able to observe and measure things that cannot be detected with unaided human senses.

The world is much richer and more complicated than the aspects we can see, hear, taste, smell, and feel. If you had radio vision, you would probably be able to see through walls because ordinary walls are transparent to most radio wavelengths. But remember that your eyes don't give off light; they only detect light that already exists. What you would see through the walls would be the many strong radio wave sources on Earth—radio and TV stations, cell phones, power lines, and even electric motors. Your radio eyes would see many bright "lights" nearby, but they would all be artificial.

As you have learned, Earth's atmosphere is mostly transparent to radio waves. If, after looking around the surface of Earth, you looked up at the sky, you would see the Sun and Jupiter, which are both strong natural radio sources, but probably nothing else in the Solar System. You would also see numerous radio stars arranged in unfamiliar constellations because few if any of the stars that are bright at visual wavelengths are also strong radio sources.

Now imagine a slightly different situation. ***Would you be in the dark if your eyes were sensitive only to X-ray wavelengths?***

6-2 Telescopes

Astronomers build telescopes to collect light from distant, faint objects for analysis. That requires very large telescopes built by careful optical and mechanical engineering work. You can understand these ideas more completely by learning about the two types of telescopes and their relative advantages and disadvantages.

Two Ways to Do It: Refracting and Reflecting Telescopes

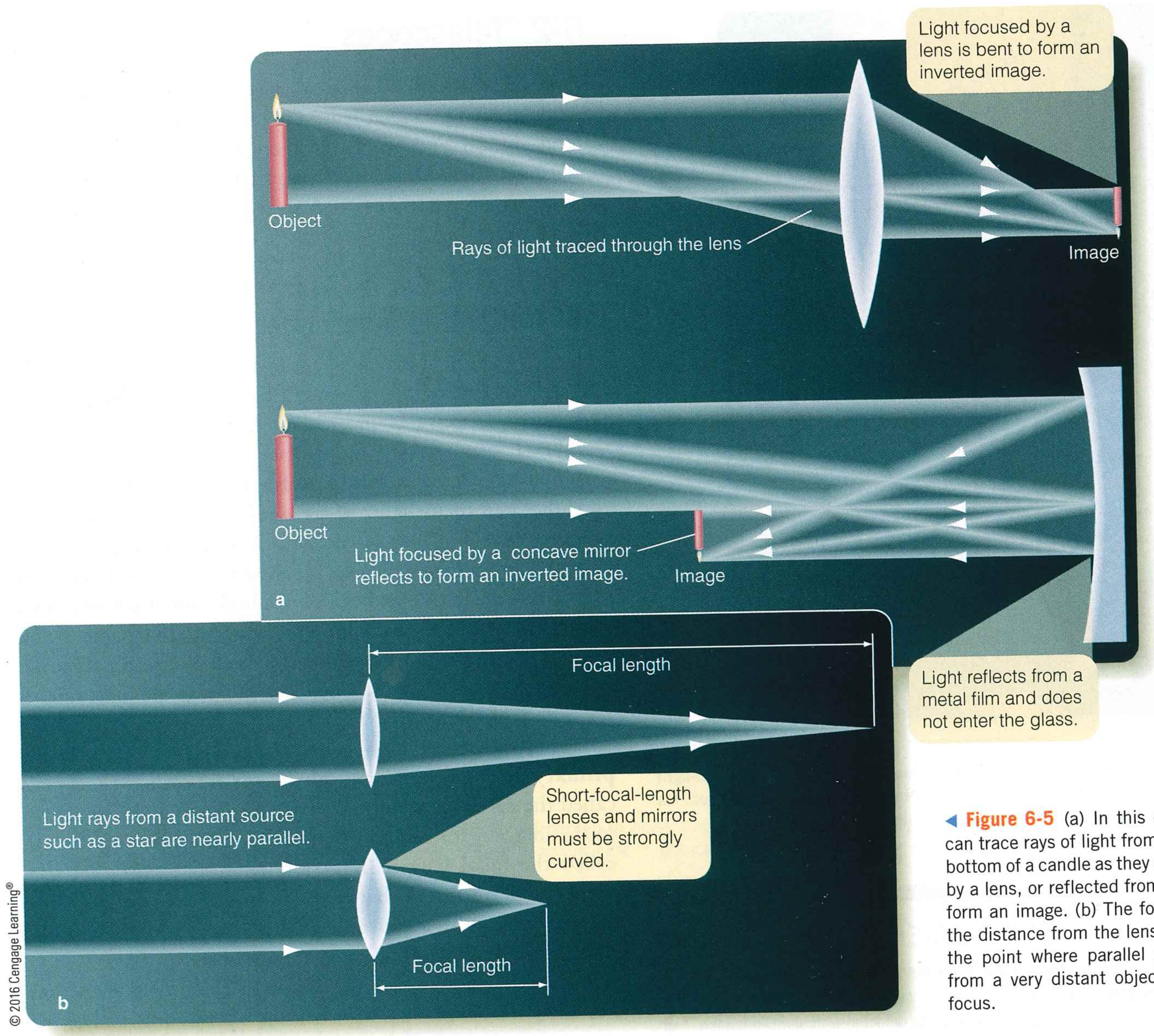
Light can be focused into an image in one of two ways (Figure 6-5). Either (1) a lens refracts ("bends") light passing through it, or (2) a mirror reflects ("bounces") light from its surface.

These two ways to manipulate light correspond to two astronomical telescope designs. **Refracting telescopes** use a lens to gather and focus light, whereas **reflecting telescopes** use a mirror (Figure 6-6). You learned in Chapter 4 that Galileo was the first person to systematically record observations of celestial objects using a telescope, beginning a little more than 400 years ago in 1610. Galileo's telescope was a refractor. In Chapter 5 you learned about the amazing range of Isaac Newton's scientific work; among his many accomplishments was the invention of the reflecting telescope.

The main lens in a refracting telescope is called the **primary lens**, and the main mirror in a reflecting telescope is called the **primary mirror**. The distance from a lens or mirror to the image it forms of a distant light source such as a star is called the **focal length**. Both refracting and reflecting telescopes form an image that is small, inverted, and difficult to observe directly, so a lens called the **eyepiece** normally is used to magnify the image and make it convenient to view.

Manufacturing a lens or mirror to the proper shape and necessary smoothness is a delicate, time-consuming, and expensive process. Short focal-length lenses and mirrors must be made with more curvature than ones with long focal lengths. The surfaces of lenses and mirrors then must be polished to eliminate irregularities larger than the wavelengths of light. Creating the optics for a large telescope can take months or years; involve huge, precision machinery; and employ several expert optical engineers and scientists.

Refracting telescopes suffer from a serious optical distortion that limits their use. When light is refracted through glass, shorter-wavelength light bends more than longer wavelengths; so, for example, blue light comes to a focus closer to the lens than does red light (Figure 6-7a). That means if you focus the eyepiece on the blue image, the other colors are out of focus, and you see a colored blur around the image. If you focus instead on the red image, all the colors except red are blurred, and so on. This color separation is called **chromatic aberration**. Telescope designers can grind a telescope lens with two components made of different kinds of glass and thereby bring two different



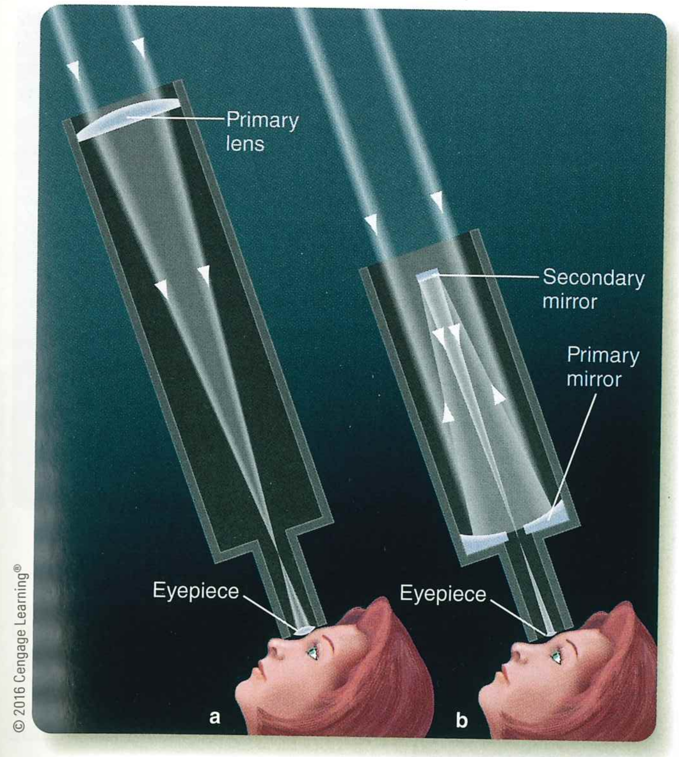
◀ **Figure 6-5** (a) In this diagram you can trace rays of light from the top and bottom of a candle as they are refracted by a lens, or reflected from a mirror, to form an image. (b) The focal length is the distance from the lens or mirror to the point where parallel rays of light from a very distant object come to a focus.

wavelengths to the same focus (Figure 6-7b). That improves the image, but these so-called **achromatic lenses** are not totally free of chromatic aberration. Even though two colors have been brought together, the others are still out of focus.

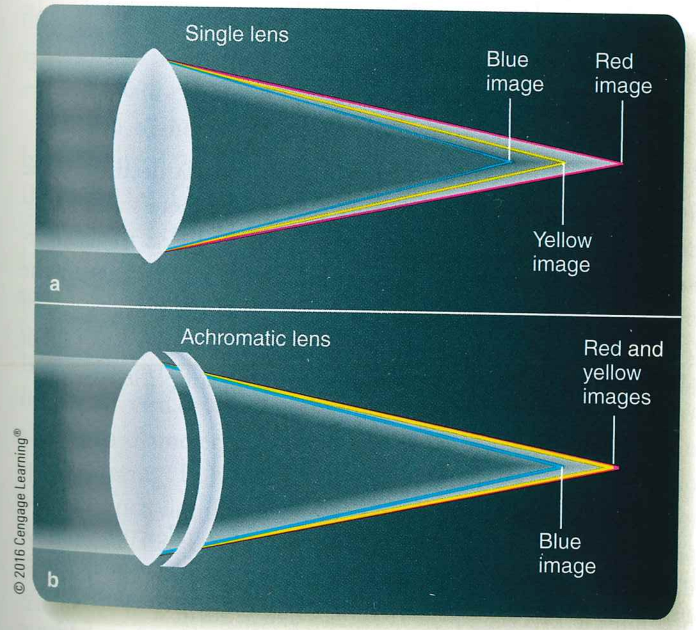
A refracting telescope's primary lens is much more difficult to manufacture than a mirror of the same size. The interior of the glass must be pure and flawless because the light passes through it. Also, if the lens is achromatic, it must be made of two different kinds of glass requiring four precisely ground surfaces. The largest refracting telescope in the world was completed in 1897 at Yerkes Observatory in Wisconsin. Its achromatic primary lens has a diameter of 1 m (40 in.) and weighs half a ton. Refracting telescopes larger than that would be prohibitively expensive.

The primary mirrors of reflecting telescopes are much less expensive than lenses because the light reflects off the front surface of the mirror. This means that only the front surface needs to be made with a precise shape and that surface is coated with a highly reflective surface of aluminum or silver. Consequently, the glass of the mirror does not need to be transparent, and the mirror can be supported across its back surface to reduce sagging caused by its own weight. Most important, reflecting telescopes do not suffer from chromatic aberration because the light does not pass through the glass, so reflection does not depend on wavelength. For these reasons, all large astronomical telescopes built since the start of the 20th century have been reflecting telescopes.

Telescopes intended for the study of visible light are called **optical telescopes** (**Figure 6-8a**). As you learned previously, radio waves as well as visible light from celestial objects can penetrate Earth's atmosphere and reach the ground. Astronomers gather radio waves using **radio telescopes** such as the one in Figure 6-8b that resemble giant TV satellite dishes. It is technically extremely difficult to make a lens that can focus radio waves, so all radio telescopes, including small ones, are reflecting telescopes; the dish is the primary mirror.



▲ **Figure 6-6** (a) A refracting telescope uses a primary lens to focus starlight into an image that is magnified by another lens called an eyepiece. The primary lens has a long focal length, and the eyepiece has a short focal length. (b) A reflecting telescope uses a primary mirror to focus the light by reflection. In this particular reflector design, called a Cassegrain telescope, a small secondary mirror reflects the starlight back down through a hole in the middle of the primary mirror to the eyepiece lens.



▲ **Figure 6-7** (a) An ordinary lens suffers from chromatic aberration because short wavelengths bend more than long wavelengths. (b) An achromatic lens, with two components made of two different kinds of glass, can bring any two colors to the same focus, but other colors remain slightly out of focus.

The Powers and Limitations of Telescopes

A telescope's capabilities are described in three important ways that are called the three powers of a telescope. The two most important of these powers depend on the diameter of the telescope.

Light-Gathering Power: Nearly all of the interesting objects in the sky are faint sources of light, so astronomers need telescopes that can collect large amounts of light to be able to study those objects. **Light-gathering power** refers to the ability of a telescope to collect light. Catching light in a telescope is like catching rain in a bucket—the bigger the bucket, the more rain it can catch (**Figure 6-9**).

Light-gathering power is proportional to the *area* of the telescope primary lens or mirror; a lens or mirror with a large area gathers a large amount of light. The area of a circular lens or mirror written in terms of its diameter D is $\pi D^2/4$. To compare the relative light-gathering powers (LGP) of two telescopes A and B, you can calculate the ratio of the areas of their primaries, which equals the ratio of the primaries' diameters squared:

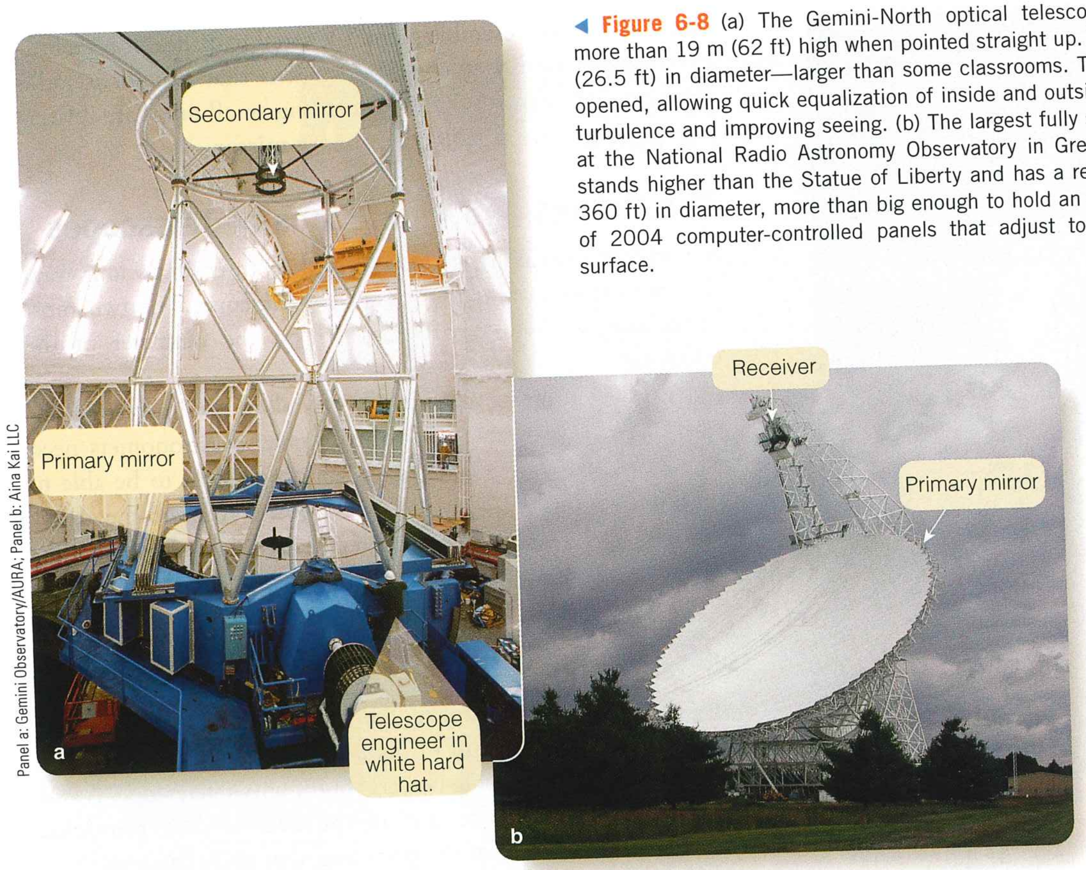
$$\frac{(LGP_A)}{(LGP_B)} = \left(\frac{D_A}{D_B}\right)^2$$

Suppose you compare telescope A, which is 24 cm in diameter, with telescope B, which is 4 cm in diameter. The ratio of their diameters is 24/4, or 6, but the light-gathering power increases as the ratio of their diameters *squared*, so telescope A gathers 36 times more light than telescope B. Because the diameter ratio is squared, even a small increase in diameter produces a relatively large increase in light-gathering power and allows astronomers to study significantly fainter objects. This principle holds not just at visual wavelengths but also for telescopes collecting any kind of radiation.

Resolving Power: The second power of a telescope, called **resolving power**, refers to the ability of the telescope to reveal fine detail. One consequence of the wavelike nature of light is that there is an unavoidable blurring called **diffraction fringes** around every point of light in an image, and you cannot see any detail smaller than the fringes (**Figure 6-10**).

Astronomers can't eliminate diffraction fringes, but the size of the diffraction fringes is inversely proportional to the diameter of the telescope. This means that the larger the telescope, the better its resolving power. However, the size of diffraction fringes is also proportional to the wavelength of light being focused. In other words, an infrared or radio telescope has less resolving power than an optical telescope of the same size.

You can imagine testing the resolving power of a telescope by measuring the angular distance between two stars that are



Panel a: Gemini Observatory/AURA; Panel b: Aina Kai LLC

◀ **Figure 6-8** (a) The Gemini-North optical telescope on Mauna Kea in Hawai'i stands more than 19 m (62 ft) high when pointed straight up. The primary mirror (at bottom) is 8.1 m (26.5 ft) in diameter—larger than some classrooms. The sides of the telescope dome can be opened, allowing quick equalization of inside and outside temperatures at sunset, reducing air turbulence and improving seeing. (b) The largest fully steerable radio telescope in the world is at the National Radio Astronomy Observatory in Green Bank, West Virginia. The telescope stands higher than the Statue of Liberty and has a reflecting surface 100 × 110 m (330 × 360 ft) in diameter, more than big enough to hold an entire football field. Its surface consists of 2004 computer-controlled panels that adjust to maintain the shape of the reflecting surface.

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▲ **Figure 6-9** Gathering light is like catching rain in a bucket. A large-diameter telescope gathers more light and produces a brighter image than a smaller telescope of the same focal length.

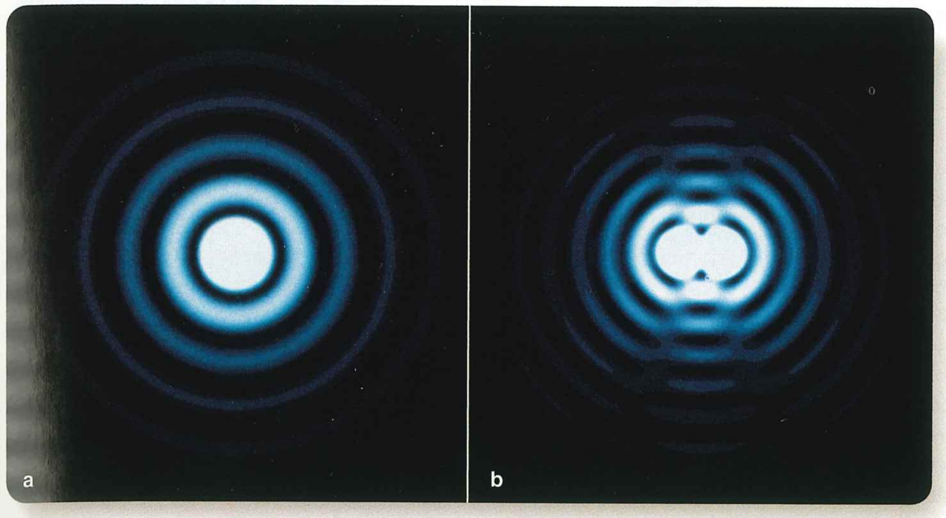
just barely distinguishable as separate objects (Figure 6-10b). The resolving power α in arc seconds of a telescope with primary diameter *D* that is collecting light of wavelength λ equals:

$$\alpha\,(\text{arc seconds}) = 2.06 \times 10^{5}\left(\frac{\lambda}{D}\right)$$

To use the formula correctly, the units of *D* and λ need to be the same, for example, meters and meters, or centimeters and centimeters. The multiplication factor of 2.06 × 10^5 is the conversion between radians and arc seconds that you first saw in the small-angle formula (Chapter 3, page 41). If the wavelength of light being studied is assumed to be 550 nm, in the middle of the visual band, then the preceding formula simplifies to:

$$\alpha\,(\text{arc seconds}) = \frac{0.113}{D}$$

For example, the resolving power of a telescope with a diameter of 0.100 m (about 4 in.) observing at visual wavelengths is about $\alpha = (2.06 \times 10^5) \times (550 \times 10^{-9})/(0.100) =$ 1.13 arc seconds. Or, equivalently, $\alpha = 0.113/0.100 = 1.13$ arc seconds. In other words, using a telescope with a diameter of 4 in., you should be able to distinguish as separate points of light any pair of stars farther apart than about 1.1 arc seconds if the optics are of good quality and if the atmosphere is not too turbulent. Stars any closer together than that will be blurred together into a single image by the diffraction fringes.



Michael A. Seeds

◀ **Figure 6-10** (a) Stars are so far away that their images are points, but the wavelike characteristic of light causes each star image to be surrounded with diffraction fringes, much magnified in this computer model. (b) Two stars close to each other have overlapping diffraction fringes and become impossible to detect separately.

Aside from diffraction, two other factors—optical quality and atmospheric conditions—limit resolving power. A telescope must have high-quality optics to achieve its full potential resolving power. Even a large telescope reveals little detail if its optical surfaces are marred by imperfections. Also, when you look through a telescope, you are looking up through miles of turbulent air in Earth's atmosphere, inevitably making images wiggle and blur to some extent. Astronomers use the term **seeing** to refer to the amount of image wiggling and blurring as a result of atmospheric conditions. A related phenomenon is the twinkling of stars. Star twinkles are caused by turbulence in Earth's atmosphere, and a star near the horizon, where you look through more air, will twinkle and blur more than a star overhead.

On a night when the atmosphere is unsteady, images are badly blurred, and astronomers say that "the seeing is bad" (**Figure 6-11a**). Generally, even under relatively good seeing conditions, the detail visible through a large telescope is limited not by its diffraction fringes but by the turbulence of the air through which the telescope must look. An optical telescope performs better on a high mountaintop where the air is thin and steady. But even in that situation, Earth's atmosphere spreads star images at visual wavelengths into blobs about 0.5 to 1.0 arc second in diameter. Radio telescopes are also affected by atmospheric seeing, but less than optical telescopes, so they do not benefit much in this respect by being located on mountains. You will learn later in this chapter about special techniques that improve seeing from ground-based telescopes and also about telescopes that orbit above Earth's atmosphere and are not limited by seeing.

Seeing and diffraction both limit the precision of any measurement that can be made using that image, and that limits the amount of information in the image. All measurements have some built-in uncertainty (**How Do We Know? 6-1**), and scientists must learn to work within those limitations. Have you ever tried to magnify a newspaper photo to distinguish some detail? Newspaper photos are composed of tiny dots of ink, and no detail smaller than a single dot will be visible no matter how much you magnify the photo. In an astronomical image, the resolution is limited by seeing, or diffraction, or both. You can't see any detail in the image that is smaller than the telescope's resolution. That's why stars look like fuzzy points of light no matter how big the telescope.

Courtesy of William Keel

▲ **Figure 6-11** (a) The left half of this photograph of a galaxy is from an image recorded on a night of poor seeing. Small details are blurred. (b) The right half of the photo is from an image recorded on a night when Earth's atmosphere above the telescope was steady and the seeing was better. Much more detail is visible under good seeing conditions.

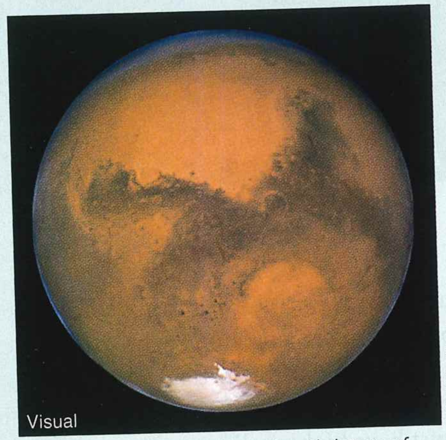
How Do We Know? 6-1

Resolution and Precision

What limits the precision of an observation? As an example, think about observations that are in the form of images. All images have limited resolution. You can see on your computer screen that images there are made up of picture elements, pixels. If your screen has low resolution, it has large pixels, and you can't see much detail. In an astronomical image, the practical size of a pixel is set by the resolution limit, a combination of atmospheric seeing, telescope optical quality, and telescope diffraction. You can't see details smaller than the resolution limit. This limitation on the level of detail viewable in an image is one example of the limited precision, and therefore unavoidable uncertainty, of all scientific measurements.

Now imagine a zoologist trying to measure the length of a live snake by holding it along a meter stick. Meter sticks are usually not marked with resolution smaller than millimeters. Also, the wriggling snake is hard to hold, so it is difficult to measure accurately. Both factors—the meter stick's resolution and the snake's wriggling—together limit the precision of the measurement. If the zoologist said the snake is 432.8932 mm long, you might wonder if that is really true. The best resolution possible in that zoologist's situation does not justify the precision implied by all those digits. Images made with even the largest and best telescopes do not show surface details on stars because of limits on precision (resolution) set by diffraction and atmospheric seeing (a stellar equivalent of the snake wriggling).

If you are a scientist, one question you must ask yourself routinely is: How precise are the measurements you and other investigators have made? Precision of measurements is limited by the resolution of the measurement technique such as the size of the pixels in a photograph or the finest markings on a meter stick as much as by variability in what is being observed such as the snake wriggling or atmospheric turbulence. And, because precision is always limited, uncertainty is always present.



NASA/ESA/STScI

A high-resolution visual-wavelength image of Mars made by the Hubble Space Telescope *reveals details such as mountains, craters, and the south polar cap.*

Magnifying Power: It is a **Common Misconception** that the purpose of an astronomical telescope is to magnify images. In fact, the **magnifying power** of a telescope—its ability to make images bigger—is the least important of the three powers. Because the amount of detail that a telescope can discern is limited generally either by its resolving power or the seeing conditions, very high magnification does not necessarily show more detail. The magnifying power of a telescope equals the focal length of the primary mirror or lens divided by the focal length of the eyepiece.

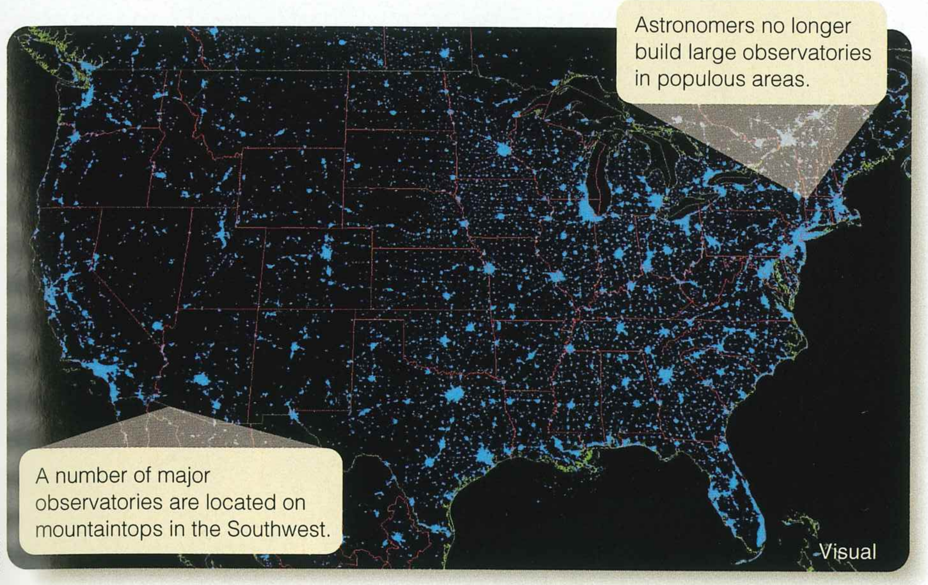
$$M = \left(\frac{F_p}{F_e}\right)$$

For example, if a telescope has a primary with a focal length $F_p = 80$ cm and you use an eyepiece with a focal length $F_e = 0.5$ cm, the magnification is 80/0.5, or 160. Radio telescopes, of course, don't have eyepieces, but they do have instruments that examine the radio waves focused by the telescope, and each such instrument would, in effect, have its own magnifying power.

As was mentioned previously, the two most important powers of the telescope—light-gathering power and resolving power—depend on the diameter of the telescope that is essentially impossible to change. In contrast, you can change the magnification of a telescope simply by changing the eyepiece. This explains why astronomers describe telescopes by diameter and not by magnification. Astronomers will refer to a telescope as a 4-meter telescope or a 10-meter telescope, but they would never identify a research telescope as being, say, a 1000-power telescope.

6-3 Observatories on Earth: Optical and Radio

The quest for light gathering power and good resolution explains why nearly all the world's major observatories are located far from big cities and, especially in the case of optical telescopes, usually on top of mountains. Astronomers avoid cities because **light pollution**, which is the brightening of the night sky by light scattered from artificial outdoor lighting, can make it impossible to see faint objects (**Figure 6-12**). In fact, many residents of cities are unfamiliar with the beauty of the night sky because they can see only the brightest stars. Even far from cities, the Moon, nature's own light pollution, is sometimes so bright it drowns out fainter objects, and astronomers are unable to perform certain types of observations during nights near full moon. On such nights, faint objects cannot be detected even with large telescopes at good locations.



NOAA

▲ **Figure 6-12** This satellite view of the continental United States at night shows the light pollution and energy waste resulting from outdoor lighting. Observatories are best located far from large cities.

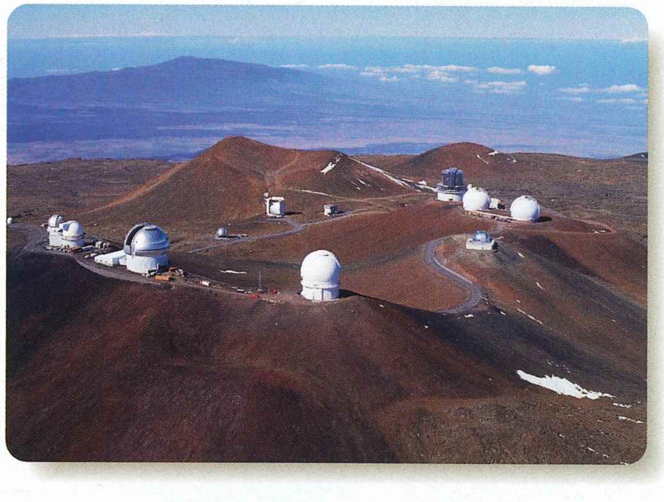
Radio astronomers face a problem of radio interference comparable to visible light pollution. Weak radio waves from the cosmos are easily drowned out by human-made radio noise—everything from automobiles with faulty spark plugs to poorly designed communication systems. A few narrow radio bands are reserved for astronomy research, but even those are often contaminated by stray signals. To avoid that noise and have the radio equivalent of a dark sky, astronomers locate radio telescopes as far from civilization as possible. Hidden in mountain valleys or in remote deserts, they are able to study the Universe protected from humanity's radio output.

As you have already learned, astronomers prefer to put optical telescopes on high mountains for several reasons. To find sites with the best seeing, astronomers carefully select mountains where the airflow is measured to be smooth and not turbulent. Also, the air at high altitude is thin, dry, and more transparent, which is important not only for optical telescopes but also for other types of telescopes. Building an observatory on top of a remote high mountain is difficult and expensive, as you can imagine from **Figure 6-13**, but the dark sky, good seeing, and transparent atmosphere make it worth the effort.

Modern Optical Telescopes

For most of the 20th century, astronomers faced a serious limitation on the size of astronomical telescopes. Telescope mirrors were made thick to avoid bending that would distort the reflecting surface, but those thick mirrors were heavy. The 5-m (200-in.) mirror on Mount Palomar weighs 14.5 tons. Those old-fashioned telescopes were massive and expensive. Today's astronomers have solved these problems in a number of ways. Look at **Modern Optical Telescopes** on pages 114–115 and notice three important points about telescope design and ten new terms that describe optical telescopes and their operation:

1. Conventional-design reflecting telescopes use large, solid, heavy mirrors to focus starlight to a *prime focus,* or by using a *secondary mirror,* to a *Cassegrain focus* (pronounced *KASS-uh-grain*). Other telescopes have a *Newtonian focus* or a *Schmidt-Cassegrain focus.*
2. Telescopes must have a *sidereal drive* to follow the stars. An *equatorial mount* with motion around a *polar axis* is the conventional way to provide that motion. Today, astronomers can build simpler, lighter-weight telescopes on *alt-azimuth mounts* that depend on computers to move the telescope so that it follows the apparent motion of stars as Earth rotates without having an equatorial mount and polar axis.
3. *Active optics,* computer control of the shape of a telescope's main mirrors, allows the use of thin, lightweight mirrors—either "floppy" mirrors or segmented mirrors. Reducing the weight of the mirror reduces the weight of the rest of the telescope, making it stronger and less expensive. Also, thin mirrors cool and reach a stable shape faster at nightfall, producing better images during most of the night.



Richard Wainscott, Aina Kai LLC

▲ **Figure 6-13** Aerial view of the optical, infrared, and radio telescopes on Mauna Kea in Hawai'i, 4200 m (nearly 14,000 ft) above sea level. The high altitude, low atmospheric moisture, lack of nearby large cities, and location near the equator make this mountain one of the best places on Earth to build an observatory.