3 LIGHT AND TELESCOPES

IN THIS CHAPTER YOU WILL DISCOVER

- the nature of visible light and other types of electromagnetic radiation
- how telescopes collect and focus light
- the limitation of telescopes
- why different types of telescopes are used for different types of research
- how astronomers are developing new generations of high-technology telescopes
- how astronomers use the entire spectrum of electromagnetic radiation to observe the stars and other astronomical objects and events

WEB LINK 3.1

Mauna Kea Observatories
Astronomers prefer to build ground-based observatories on isolated mountaintops far from city lights, and where the air is dry, stable, and cloud-free. Mauna Kea Observatories, on the island of Hawaii, is home for a dozen optical and infrared telescopes. The twin Keck Telescopes are visible on the right of the photograph. (Richard J. Wainscoat, University of Hawaii)

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 stars twinkle?
5. What type(s) of electromagnetic radiation can telescopes currently detect?

The telescope is the single most important tool of astronomy. Using a telescope, we see objects in space far more brightly and clearly and at greater distances than we can with the naked eye. Telescopes have played a major role in revealing the universe since Galileo viewed the craters on the Moon four centuries ago.

Refracting telescopes, which use large lenses to collect incoming starlight, were popular with astronomers 150 years ago. Modern astronomers strongly prefer reflecting telescopes, which gather light with large curved mirrors. In either case, the main purpose of a telescope is to collect as much light as possible. Astronomers attach a variety of equipment to telescopes to record incoming starlight.

THE NATURE OF LIGHT

Visible light is the form of electromagnetic energy to which our eyes are sensitive. But what exactly is visible light? How is it produced? What is it made of? How does it move through space? Scientists have struggled with these questions for the past 400 years.

3-1 Newton discovered that white light is not a fundamental color and debated whether light is particles or waves

From the time of Aristotle until the late seventeenth century, most people believed that white was a 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 somehow as white light went from one medium through another. Isaac Newton performed experiments during the late 1600s that provided our first insights into the nature of light and disproved these earlier beliefs. Newton started by passing a beam of sunlight through a glass prism, which spread the light out into the colors of the rainbow, as shown in Figure 3-1a.

This rainbow, called a **spectrum** (plural; **spectra**), suggested to Newton that white light is actually a mixture of all the primary colors and that these colors separate out by changing direction or *refracting* by different amounts while going through the prism. He then selected a single color and sent it through a second prism (Figure 3-1b). The light emerging from this prism was the same color, heading in a different direction. After discovering that individual colors could not be further separated, Newton recombined all the colors, thereby re-creating white light.

So different colors are different entities. But what? The two major issues were determining whether they were particles or waves and how rapidly light traveled.

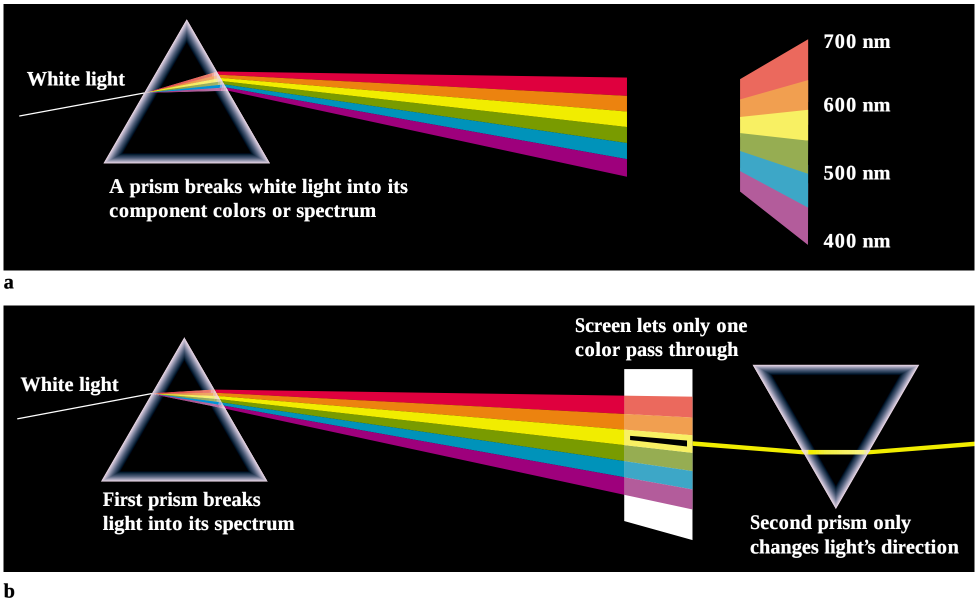


FIGURE 3-1 A Prism and a Spectrum (a) When a beam of white light passes through a glass prism, the light is separated or refracted into a rainbow-colored band called a spectrum. The numbers on the right side of the spectrum indicate wavelengths in nanometers (10^{-9} m). (b) Drawing of Newton's experiment showing that glass does not add to the color of light, only changes its direction.

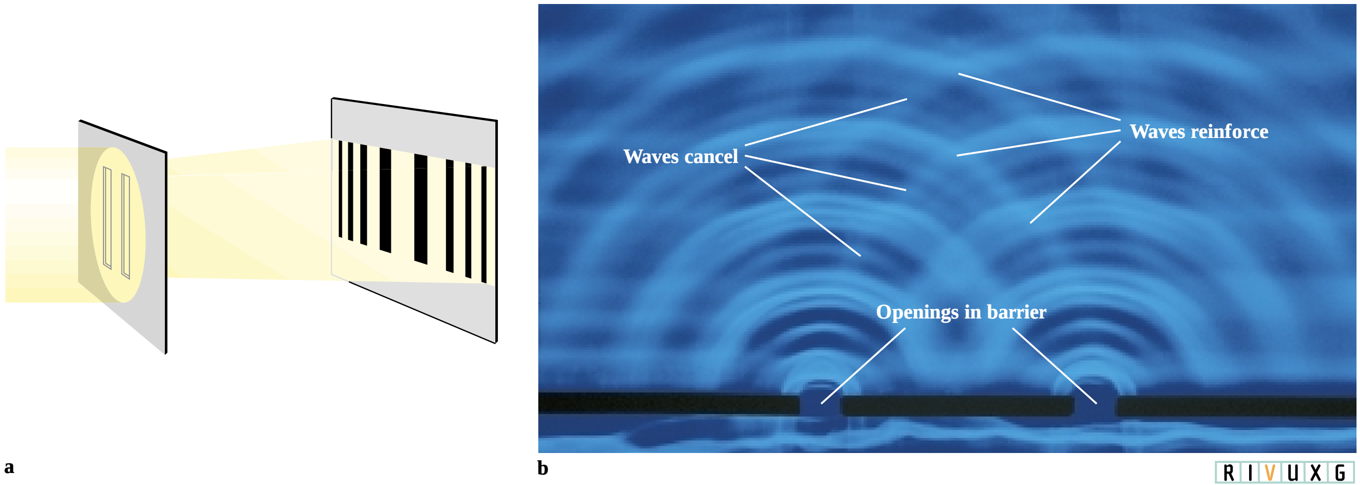


FIGURE 3-2 Electromagnetic Radiation Travels as Waves (a) Thomas Young's interference experiment shows that light of a single color passing through a barrier with two slits creates alternating light and dark patterns on a screen. (b) The intensity of light on the screen is analogous to the height of water waves that strike the shore after passing through a barrier with two openings. In certain places, ripples from both openings reinforce each other to produce extra high waves. At intermediate locations along the shoreline, ripples and troughs cancel each other, producing still water. (© Eric Schrempp/Photo Researchers)

In the mid-1600s, the Dutch scientist Christiaan Huygens proposed that light travels in the form of waves. Isaac Newton, on the other hand, performed many experiments in optics that convinced him that light is composed of tiny particles of energy.

The English physicist Thomas Young demonstrated in 1801 that light is composed of waves. Young showed that the shadows of objects in light of a single color are not crisp and sharp. Instead, the boundary between illuminated and shaded areas is overlaid with patterns of closely spaced dark and light bands. These patterns are similar to the patterns produced by water waves passing through a barrier in the ocean (Figure 3-2). Young showed that a wavelike description of light could explain the results of his experiment but Newton's particle theory could not. Analyses of similar experiments soon produced overwhelming evidence for the wavelike behavior of light.

Further insight into the wave character of light came from calculations by the Scottish physicist James Clerk Maxwell in the 1860s. Maxwell succeeded in describing all the basic properties of electricity and magnetism in four equations. By combining these equations, Maxwell demonstrated that electrical and magnetic effects should travel through space together in the form of waves. Maxwell's suggestion that some of these waves are observed as light was soon confirmed by a variety of experiments. Because of its electric and magnetic properties, visible light is a form of *electromagnetic radiation* (Figure 3-3).

Newton showed that sunlight is actually composed of all the colors of the rainbow. Young and others showed that light travels as waves. What makes the colors of the rainbow distinct from each other? The answer is surprisingly simple: The only difference between different colors is the distance between two successive wave crests in the light wave. This dis-

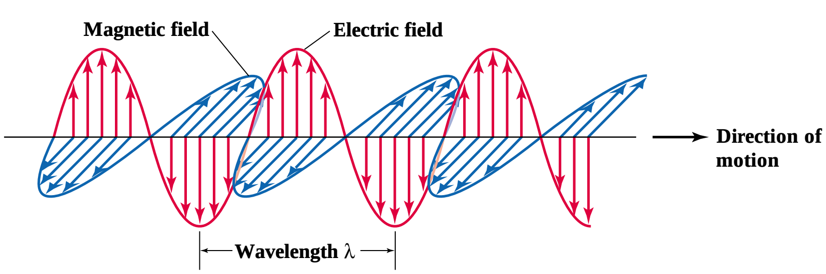
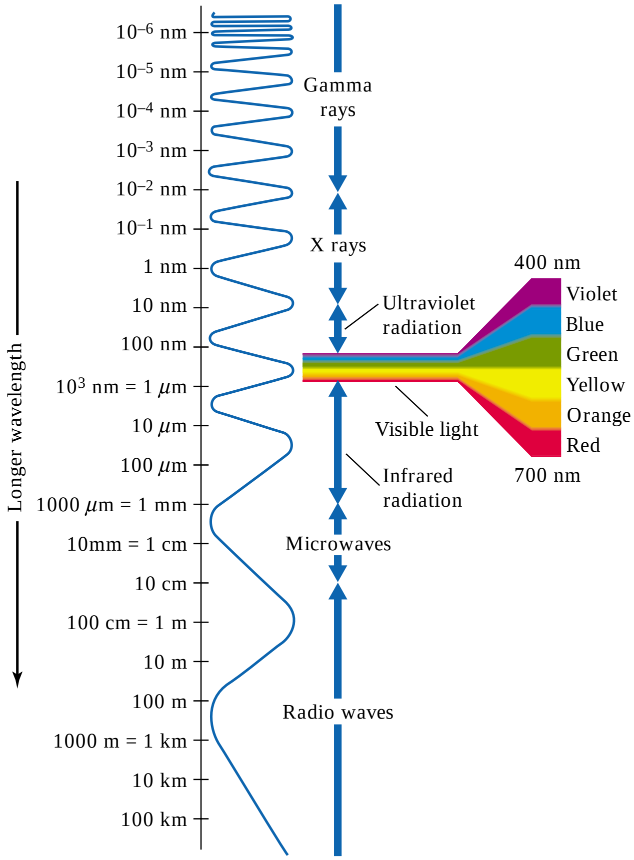


FIGURE 3-3 Electromagnetic Radiation All forms of electromagnetic radiation (radio waves, infrared radiation, visible light, ultraviolet radiation, X rays, and gamma rays) consist of oscillating electric and magnetic fields perpendicular to each other that move through empty space at a speed of 3×10^5 km/s. The distance between two successive crests is called the wavelength of the light.



IGURE 3-4 **The Electromagnetic Spectrum** The full array of all types of electromagnetic radiation is called the electromagnetic spectrum. It extends from the shortest-wavelength gamma rays to the longest-wavelength radio waves. Visible light forms only a tiny portion of the full electromagnetic spectrum. Note that 1 μm (one micrometer) is 10^{-6} meters.

tance is called the **wavelength** of the light, usually designated by the lowercase Greek letter λ (lambda; see Figure 3-3). Maxwell's calculations predicted that light waves all travel at the same speed in empty space, regardless of wavelength.

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. Experiments demonstrated that visible light has wavelengths covering the range 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 3-4). The complete spectrum of colors from the longest wavelength to the shortest is red, orange, yellow, green, blue, and violet.

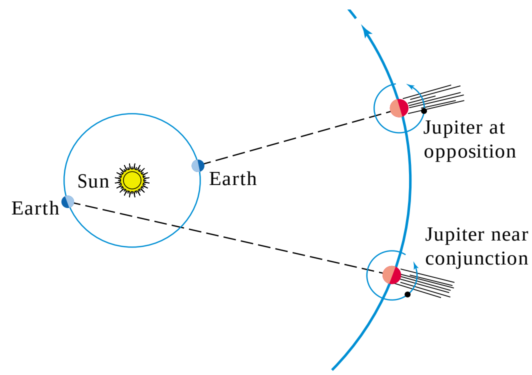
3-2 Light travels at a finite speed

Light of any color travels incredibly quickly, far faster than sound. This is why we see lightning before we hear the accompanying thunderclap. But does light travel instantaneously from one place to another, or does it move with a measurable speed?

It is interesting to see how the discovery of the Galilean moons set the stage for another discovery, the finite speed of light. The first evidence for the finite speed of light came in 1675, when Ole Rømer, a Danish astronomer, carefully timed eclipses of Jupiter's moons (Figure 3-5). Rømer discovered that the moment at which a moon enters Jupiter's shadow depends on the distance between the Earth and Jupiter. When Jupiter is in opposition, that is, when Jupiter and the Earth are on the same side of the Sun, the Earth-Jupiter distance is relatively short compared to when Jupiter is near conjunction. At opposition, Rømer found that eclipses occur slightly earlier than expected, while they occur slightly later than predicted by Kepler's laws when Jupiter is near conjunction.

Rømer correctly concluded that light 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 $16^{1}/_{2}$ minutes for visible light to traverse the diameter of the Earth's orbit (2 AU). Incidentally, Rømer's interpretation of the data makes sense only if both the Earth and Jupiter orbit the Sun. His experiment therefore supported the heliocentric cosmology but not the geocentric one.

Rømer's subsequent calculation of the speed of light was off by 25 percent, due to a highly inaccurate value for



IGURE 3-5 **Measuring the Speed of Light** An eclipse of one of Jupiter's moons seen at opposition (Earth and Jupiter on the same side of the Sun) appears to occur earlier than an eclipse seen near conjunction (Earth and Jupiter on opposite sides of the Sun). The differences in apparent times of the eclipses are due to the extra time it takes light to travel the additional distance when the planets are near conjunction. The actual time of the eclipse is determined using Kepler's laws.

AN ASTRONOMER'S TOOLBOX 3-1

Photon Energies

All photons with the same energy are identical: Their energy depends solely on the photon's wavelength. To find any photon's energy we use the equation

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

where Planck's constant h is 6.67×10^{-34} J s, the speed of light c is 300,000 km/s, and the photon's wavelength is λ.

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

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

$$E_{\text{red}} = 2.86 \times 10^{-19}\text{J}$$

(A joule, abbreviated J, is a unit of energy.) Each photon of red light with wavelength 700 nm has an energy of 2.86×10^{-19} J.

Compare! In 1 second a 25-watt light bulb emits 25 J.

Try these questions: A photon has energy 4.90×10^{-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? (*Clue:* See Figure 3-1.)

(Answers appear at the end of the book.)

the AU existing at that time. The first accurate laboratory measurements of the speed of visible light were performed in the mid-1800s. The constant speed of light in a vacuum, usually designated by the letter c, is now known 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 traveling through air, water, glass, or any other substance always moves more slowly than it does in a vacuum. Indeed, in 1999, scientists were able to get light slowed to 61 km/hr (38 mph) and in 2001 they were able to momentarily stop it altogether.

The value c is a fundamental property of the universe. It appears in equations that describe, among other things, atoms, gravity, electricity, magnetism, and time. Furthermore, according to Einstein's special theory of relativity (Chapter 13), nothing can travel faster than the speed of light in a vacuum.

3-3 Einstein showed that light sometimes behaves as particles and sometimes as waves

WEB LINK 3.3

In 1905, just as scientists were becoming comfortable with the wave nature of light, Albert Einstein proposed that light sometimes behaves as particles! Einstein used this idea to explain the photoelectric effect: 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. Einstein knew that electrons are bound onto a metal's surface by electric forces and that it takes energy to overcome those forces. 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 called **photons,** and that photons with different wavelengths have different amounts of energy. *Specifically, the shorter the wavelength, the higher a photon's energy.*

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

where Planck's constant (named for the German physicist Max Planck) has the value 6.67×10^{-34} J s, where J is the unit of energy called a joule (see An Astronomer's Toolbox 3-1). Einstein's concept of light means that it can act both as waves and as particles.

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 of that wavelength. The energy delivered by a photon is either enough to rip an electron off the surface of the metal or it is not. There is no middle ground, as there would be if light of one color came in packages with different numbers of waves so that photons of the same color could carry different amounts of energy. If this were the case, some photons of a certain color would have enough energy to free an electron, while other photons of the same color would not. Experimentally, this never happens. The concept of photons as just described has now been thoroughly proved, and astronomers incorporate it in their model of light.

3-4 Light is only one type of electromagnetic radiation

Visible light has a narrow range of wavelengths, from about 400 to 700 nm. But Maxwell's equations placed no length restrictions on the wavelengths of electromagnetic radiation. Researchers therefore began to look for forms of this radiation outside the range of wavelengths to which the cells of the human retina respond.

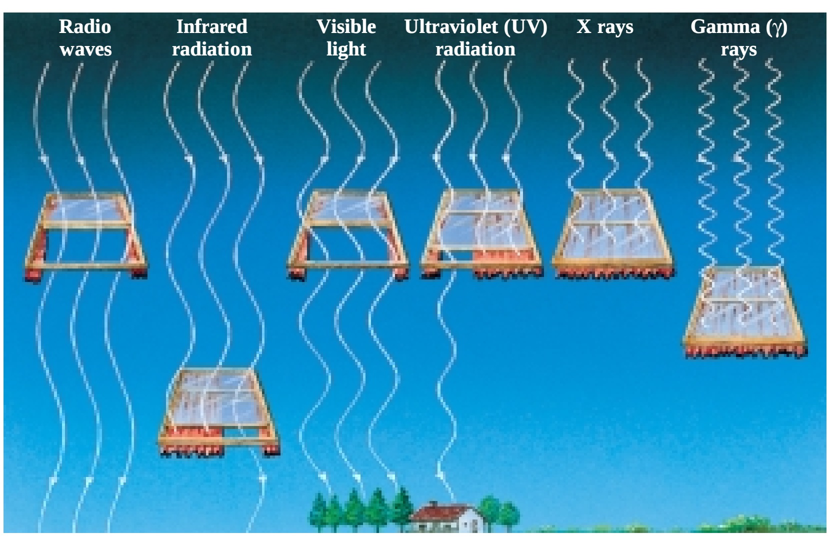
Around 1800 the British astronomer William Herschel discovered **infrared radiation** in an experiment with a prism. When he held a thermometer just beyond the red end of the visible spectrum, the thermometer registered a temperature increase, indicating that it was being heated by an invisible form of energy. Infrared radiation was identified as electromagnetic radiation with wavelengths slightly longer than red light. In experiments with electric sparks in 1888, the German physicist Heinrich Hertz first succeeded in producing electromagnetic radiation a few centimeters in wavelength, now known as **radio waves.** In 1895 Wilhelm Roentgen 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 and airport security checkpoints. Over the years, forms of radiation have been discovered with many other wavelengths.

We now know that visible light occupies only a tiny fraction of the full range of possible wavelengths, collectively called the **electromagnetic spectrum.** As shown in Figure 3-4, the electromagnetic spectrum stretches from the longest-wavelength radio waves, through infrared radiation, visible light, ultraviolet radiation, and X rays, to the shortest-wavelength photons, gamma rays. 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, which are sometimes considered to be infrared radiation and sometimes radio waves.

At wavelengths shorter than those of visible light, **ultraviolet (UV) radiation** extends from about 400 nm down to 10 nm. Next are X rays, with wavelengths between about 10 and 0.01 nm, and beyond them are **gamma rays.** It should be noted that these boundaries are approximate and are primarily used as convenient divisions in the electromagnetic spectrum, which is actually continuous.

These various types of electromagnetic radiation share many basic properties. For example, they are all photons, they all travel at the speed of light, 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. Your body tissues are nearly transparent to X rays but not to visible light; your eyes respond to visible light but not to infrared radiation; your radio detects radio waves but not ultraviolet radiation.

The Earth's atmosphere is relatively transparent to both visible light and radio waves, meaning that both pass through to reach ground-based telescopes sensitive to these forms of electromagnetic radiation. Astronomers say that the atmosphere has *windows* for these parts of the electromagnetic spectrum (Figure 3-6). Infrared radiation has a



IGURE 3-6 Windows Through the Atmosphere The Earth's atmosphere allows different types of electromagnetic radiation to penetrate into it in varying amounts. Visible light and radio waves reach all the way to the Earth's surface. Some infrared and ultraviolet radiation also can reach the ground. The other types of radiation are absorbed or reflected by the gases in the air at different characteristic altitudes. While the atmosphere does not have actual "windows," astronomers use the term to characterize the passage of radiation through it.

limited window through the atmosphere. We detect this radiation as heat.

Likewise, the longest-wavelength ultraviolet radiation, called UV-A, has a limited window. This radiation causes tanning and sunburns. Ozone (O_3) in the Earth's atmosphere screens out intermediate-wavelength ultraviolet radiation. This *ozone layer* is being depleted by human-made chemicals, such as chlorofluorocarbons (CFCs). As a result, more intermediate-wavelength ultraviolet, called UV-B, is reaching the Earth's surface, and these highly energetic photons damage living tissue, causing skin cancer and glaucoma, among other diseases.

The Earth's atmosphere is completely opaque to the other types of electromagnetic radiation, meaning that they do not reach the Earth's surface. (This is a good thing, because short-wavelength ultraviolet radiation called UV-C and X rays and gamma rays are devastating to living tissue.
2 Gamma rays are the deadliest.) Observations of these wavelengths must be performed high in the atmosphere or, ideally, from space.

Detecting electromagnetic radiation is the essence of observational astronomy. Until recently, photons were the only sources of detailed astronomical information that we had. However, in the past three decades, astronomers have built detectors of nonelectromagnetic energies and particles from space. Chapters 9 and 13 discuss two of these devices —neutrino detectors and gravity wave detectors.

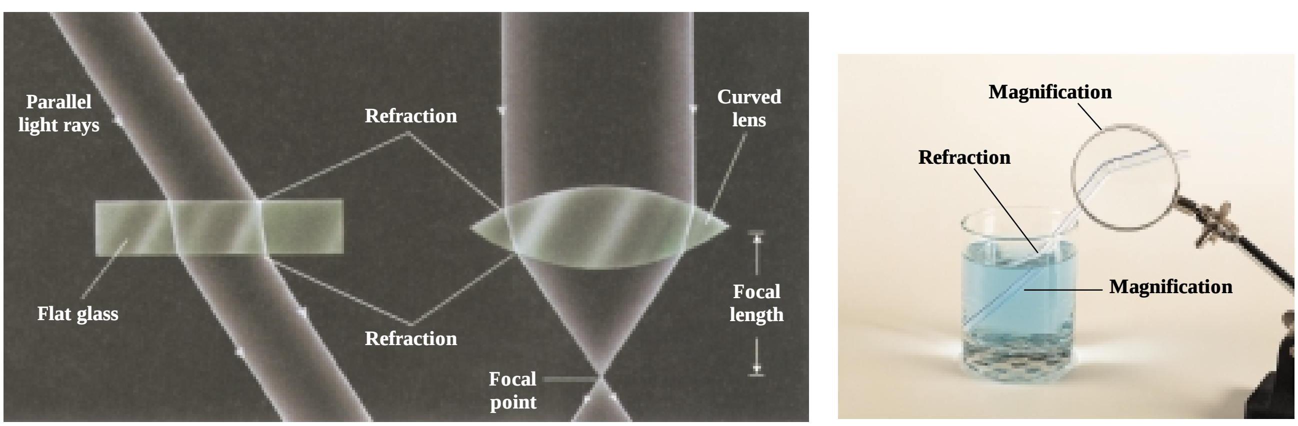
OPTICS AND TELESCOPES

Since the time of Galileo, astronomers have been designing instruments to collect more light than the human eye can collect on its own. Collecting more light enables us to see things more brightly, in more detail, and at a greater distance. There are just two basic types of telescopes—those that collect light through lenses and those that collect it from mirrors. Let's begin with the earliest telescopes, which used lenses.

3-5 A refracting telescope uses a lens to concentrate incoming light

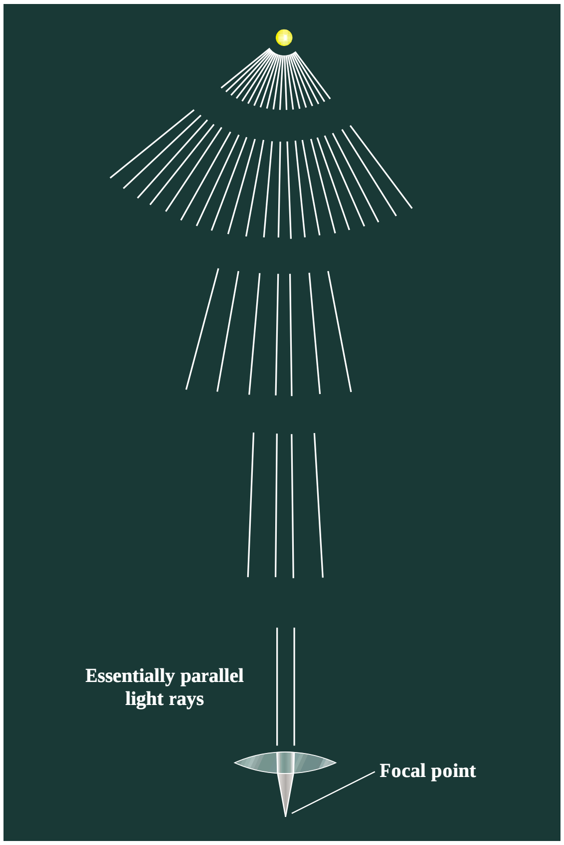
Although light travels at about 300,000 km/s in a vacuum, it moves more slowly through a dense substance such as glass. As light enters the glass, it slows abruptly, much like a person walking from a boardwalk onto a sandy beach: Her pace suddenly slows as she steps from the smooth pavement onto the sand. And just as the person stepping back onto the boardwalk easily resumes her original pace, light exiting a piece of glass resumes its original speed.

As a result of changing speed, light can also change direction as it passes from one transparent medium into another—a phenomenon called **refraction.** You see refraction every day when looking through windows. Imagine a stream of photons from a star entering a window, as shown in Figure 3-7a.

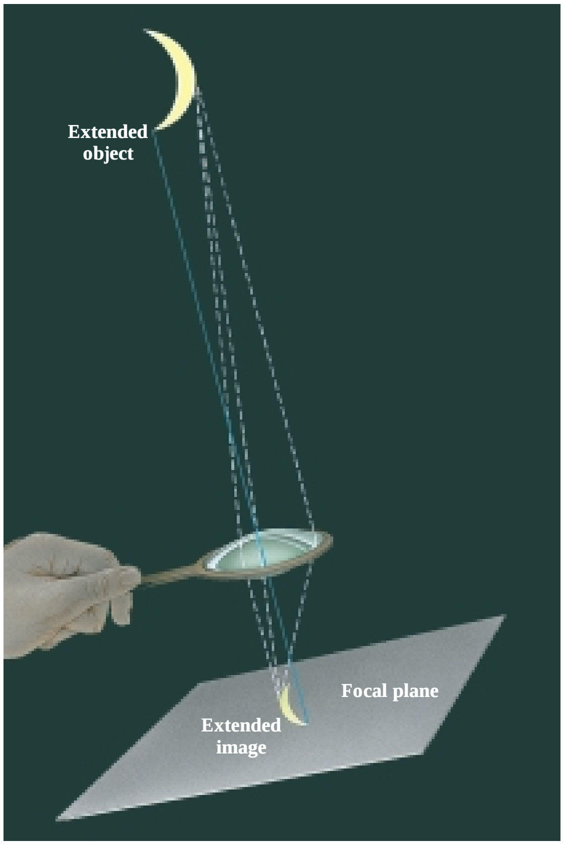


a b c

FIGURE 3-7 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. When light rays pass through a flat piece of glass, the two refractions bend the rays in opposite directions. 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 a special point called the focal point. The distance from the lens to the focal point is called the focal length of the lens. (c) A light ray entering a denser medium, like going 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 uniformly thick, then the light leaving the glass is refracted back to the direction it had before entering the glass. If the glass has curved surfaces (that is, a convex lens), then parallel light rays converge to a focus. Such focusing leads to magnification, as discussed in the text. 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 through the top of the liquid is refracted, but does not appear magnified because the top is flat. (c: Ray Moller/Dorling Kindersley)



IGURE 3-8 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 miles, only the light rays moving in parallel tracks are still near each other.



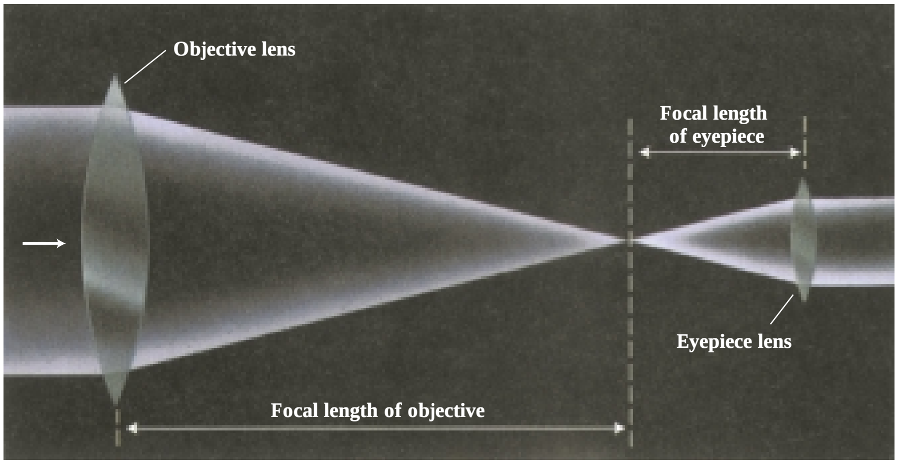
IGURE 3-9 Extended Objects Create a Focal Plane Light from objects larger than points in the sky does not all converge to the focal point of a lens. Rather, the object creates an image at the focal length in what is called the focal plane.

Astronomers call such photon flows *light rays.* 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.

A telescope lens uses refraction to collect light. Unlike a window, lenses have surfaces of varying thickness (Figure 3-7b). These curved surfaces force the light rays to emerge from the lens in different directions than they had before entering the lens. Different rays striking the top surface of the lens at different places are refracted by different amounts: If the lens is shaped correctly, parallel light rays start converging once they enter the glass. As the light emerges from the glass, it converges further.

Light rays meet at a point called the **focal point** of the lens. Its distance from the lens is the **focal length** (Figure 3-7b). Actually, only light rays that were *parallel* before entering the lens meet at the focal point. This occurs for light from sources that are extremely far away, like the stars (Figure 3-8 shows why). If the object is close 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 a surface, the **focal plane** (Figure 3-9). The Moon and planets are examples of objects with images that extend over the focal plane.

A **refracting telescope,** or **refractor** (Figure 3-10), is an arrangement of two lenses used to gather light. The resulting image is a brighter, and often a bigger and clearer, view of the object. The lens at the top of the telescope, called the **objective lens,** has a large diameter and long focal length. Its purpose is to collect as much light as possible. The lens at the bottom of the telescope, the **eyepiece lens,** is smaller and has a short focal length. It restraightens the light rays after they have passed through the focal point or focal plane of the objective lens, making them parallel once again. Because the light is now more concentrated, objects are brighter as seen through a telescope.



ANIMATION 3.1 **FIGURE 3-10** 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.

3-6 Telescopes brighten, resolve, and magnify

3 A telescope's most important function is to provide the astronomer with as many photons from the object as possible. The more photons, the more information the astronomer can extract—even if the object still appears as a pinpoint. For example, given enough photons, astronomers can measure the relative intensities of different wavelengths emitted by a star, which provides information about its temperature, chemical composition, age, and motion.

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 objective lens. A large objective lens intercepts and focuses more light than does a small objective lens. A large objective lens can therefore produce brighter images and detect fainter stars than a small objective lens can for an equal exposure time (Figure 3-11). No wonder telescopes are sometimes called "photon buckets."

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

The **light-gathering power** of a telescope is directly related to the area of the telescope's objective lens (or primary mirror; see Section 3-8). Recall that the area and diameter of a circle are related by

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

where d is the diameter of the lens and π (pi) is about 3.14.

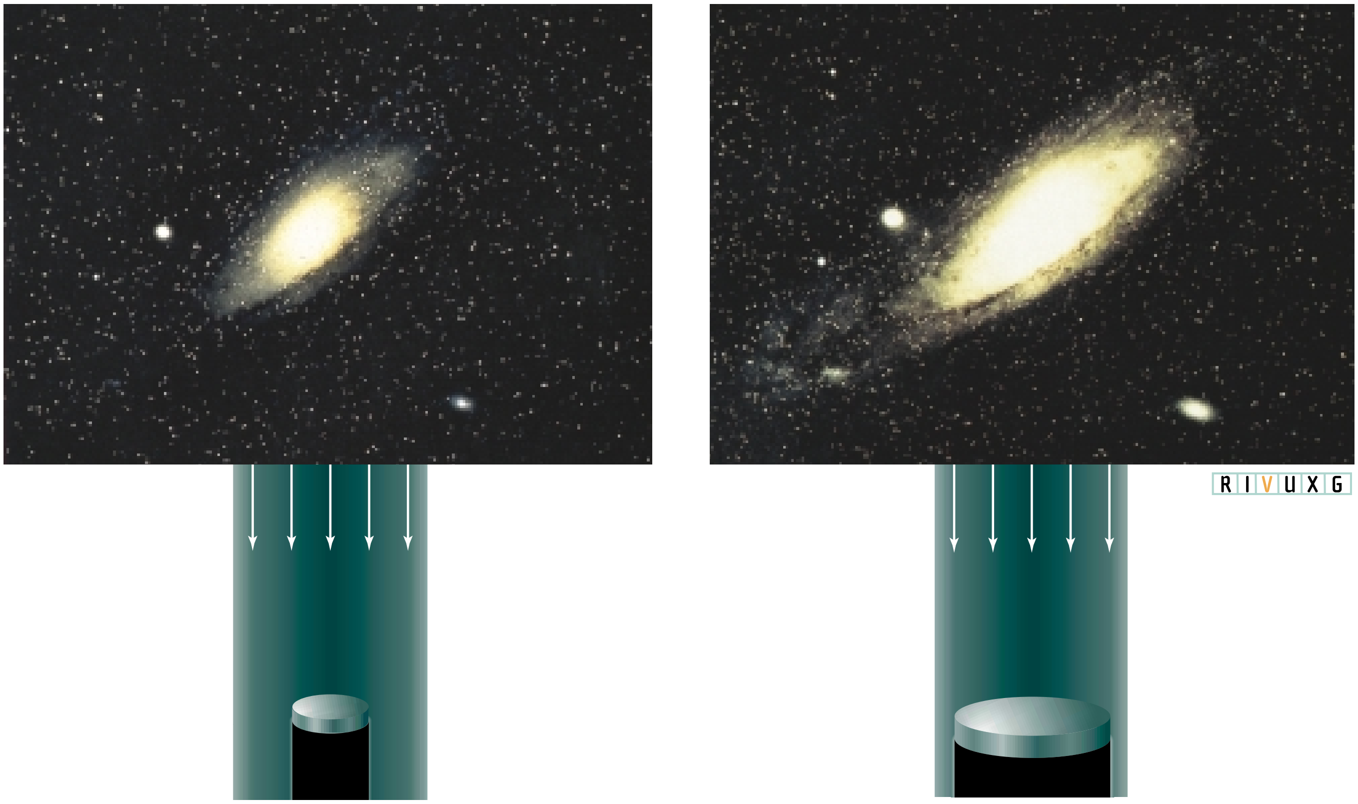
Consequently, a lens with twice the diameter of another lens has 4 times the area of the smaller lens and therefore collects 4 times as much light as the smaller one. For example, a 36-cm-diameter lens has 4 times the area of an 18-cm-diameter lens. Therefore, the 36-cm telescope has 4 times the light-gathering power of a telescope half its size. The general rule is: *Double the diameter, quadruple the light-gathering power.*

The second most important function of any telescope is to reveal more details of the extended objects under study. A large telescope increases the sharpness of the image and the degree of detail that can be seen. **Angular resolution** measures the clarity of images (Figure 3-12). Poor angular resolution causes images of galaxies or planets to be fuzzy and blurred. A telescope with good angular resolution produces images that are sharp.

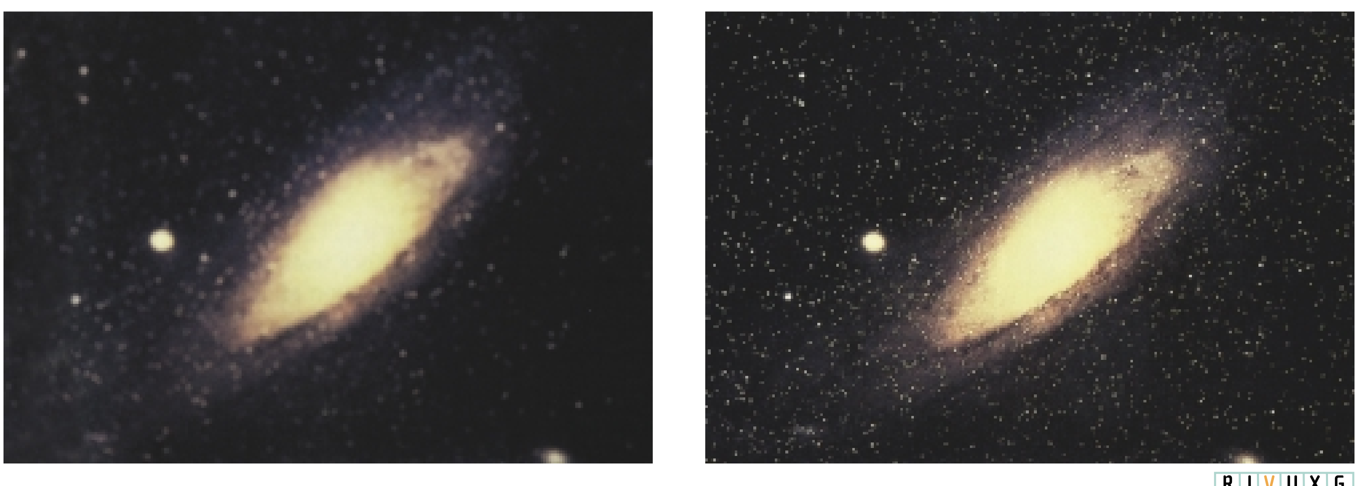
The angular resolution of a telescope is measured as the arc angle between two adjacent stars whose images can just barely be distinguished by that telescope. The smaller the angle, the sharper the image. Large, modern telescopes, like the Keck telescopes in Hawaii, which we will discuss later in this chapter, have angular resolutions better than 0.1 arcsec. As a general rule, *double the diameter, double the detail that can be seen.*

AIMM 3.1 The final function of a telescope—often the least important one—is to make objects appear larger. This property is called **magnification.** The magnification of a refracting telescope is equal to the focal length of the objective lens divided by the focal length of the eyepiece lens:

$$\text{Magnification} = \frac{\text{focal length of the objective}}{\text{focal length of the eyepiece}}$$

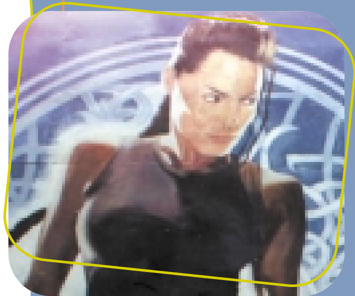


IGURE 3-11 Light-Gathering Power Because a large lens intercepts more starlight than a small lens, a large lens produces a brighter image. The same principle applies to telescopes that collect light using a primary mirror rather than an objective lens. The two photographs of the Andromeda galaxy were taken through telescopes with different diameters and were exposed for equal lengths of time at equal magnification. (AURA)



IGURE 3-12 Resolution The larger the diameter of a telescope's objective lens or primary mirror, the greater the detail the telescope can resolve. These two images of the Andromeda galaxy, taken through telescopes with different diameters, show this difference. Increasing the exposure time of the smaller diameter telescope (left), will only brighten the image, not improve the resolution. (AURA)

MOVIE MISCONCEPTIONS



Lara Croft: Tomb Raider (Paramount Pictures, 2001)
(Claro Cortez/Reuters)

So who is Lara Croft? She is a woman born into wealth, educated at the most elite schools and trained for combat. She travels to exotic and dangerous places around the world in search of adventure. In the movie *Lara Croft: Tomb Raider,* based on the popular video game of the same name, Lara faces her greatest challenge yet. The basic plot of this film is that every 5000 years all the planets align. This means that from Earth they all appear together as a single point in the sky. During an early scene in the movie, Lara Croft is shown lying down under an indoor telescope in a well-lit room. She is allegedly watching the planets align. She sees them as disks moving across her telescope's line of sight.

There are at least 4 scientific errors in the movie, as described in just this paragraph. What are they?

(Answers appear at the end of the book.)

For example, if the objective 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×.

There is a limit to the magnification of any telescope. Try to magnify beyond that limit and the image becomes distorted. As a rule, *double the objective lens's diameter, double the telescope's maximum magnification.*

3-7 Refracting telescopes have drawbacks

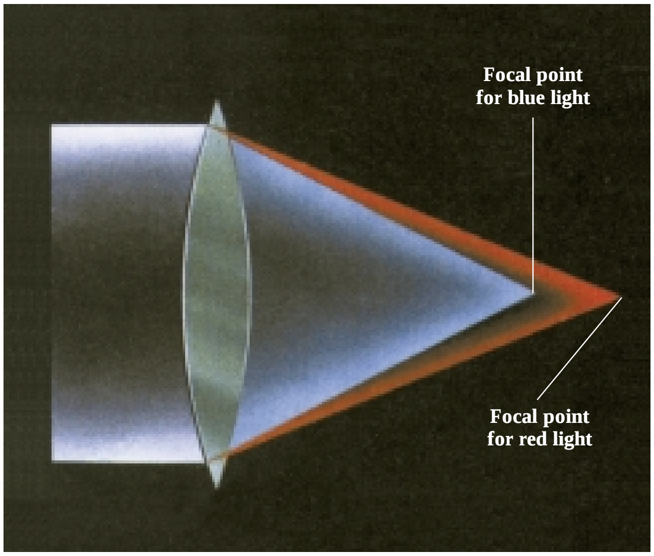
For convenience in manufacturing, objective lenses for refractors have spherical surfaces. However, a spherical lens distorts images, a problem called **spherical aberration.** This is only the first drawback of using objective lenses in large research telescopes.

The amount of refraction that light undergoes varies with color (recall Figure 3-1). Because different colors have different focal lengths, any lens distorts the colors of images (Figure 3-13), a problem called **chromatic aberration.** This problem is corrected with a *compound lens* composed of two different types of glass with different refractive properties. Because compound lenses in telescopes and cameras bring all the wavelengths into focus at the same focal length, they are called **achromatic lenses** (Figure 3-14).

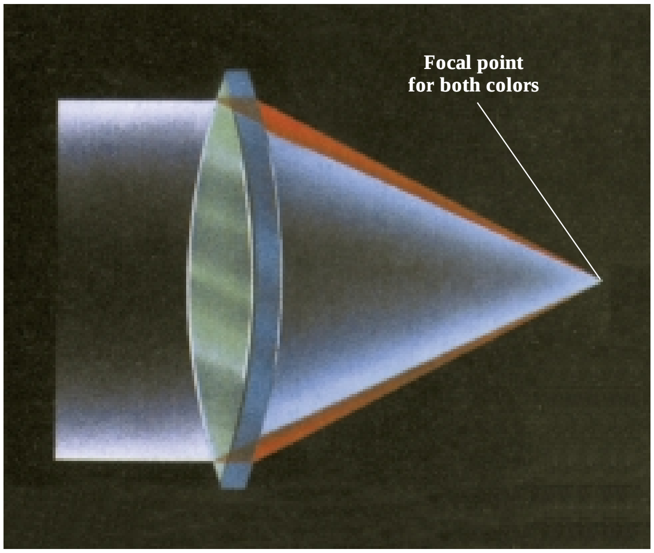
A third problem, *sagging* of large lenses, became apparent in the nineteenth century as larger, heavier lenses were developed. Despite their apparent rigidity, the shapes of glass structures, like extremely large lenses, distort under the pull of the Earth's gravity. This distortion occurs because the lens can only be supported around its edge, which is very thin. When a lens is larger than about a meter in diameter, its thick center weighs it down and causes the glass to deform. As a result, the image is distorted. Moreover, as the telescope *tracks*, or follows, a star, the orientation of the telescope changes and, along with it, the amount of distortion. There is no way of knowing the exact distortion that will occur. As a result, sagging causes the images of stars to move during a single observation, causing them to appear blurry on film or other recording medium. The largest diameter telescope objective lenses ever built are in the one-meter class. They do not distort their image by sagging, but larger glass lenses would do so, and hence larger refracting telescopes were never constructed.

Unwanted refractions are a fourth problem. Lenses are ground from large, thick disks of glass that are formed by pouring molten glass into a mold. As the liquid glass cools, gas in it becomes trapped, creating air bubbles in the solidified disk. When the lens is then ground into shape, any air bubbles inside it create unwanted and unpredictable extra refractions that blur the images. Part of a lensmaker's expertise was to choose a volume of glass for grinding with as few air bubbles as possible.

A fifth problem is that glass is *opaque* to certain ranges of wavelengths. These wavelengths of light cannot pass through glass lenses. Even visible light is dimmed substantially in passing through the glass lens at the front of a refractor, and ultraviolet radiation is largely absorbed by the glass.



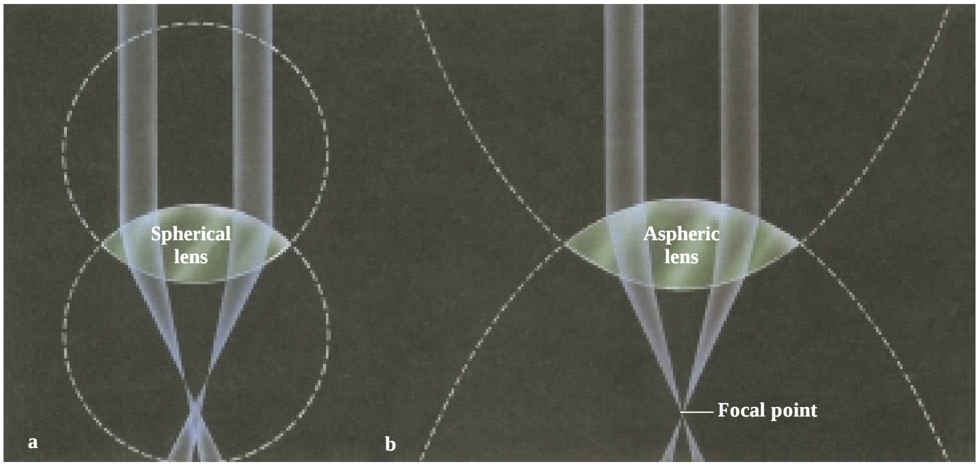
IGURE 3-13 Chromatic Aberration Spreads Colors Out Light of different colors passing through a lens is refracted by different amounts. This effect is called chromatic aberration. As a result, different-colored objects have different focal lengths. Consequently, the images seen through uncorrected lenses are blurred.



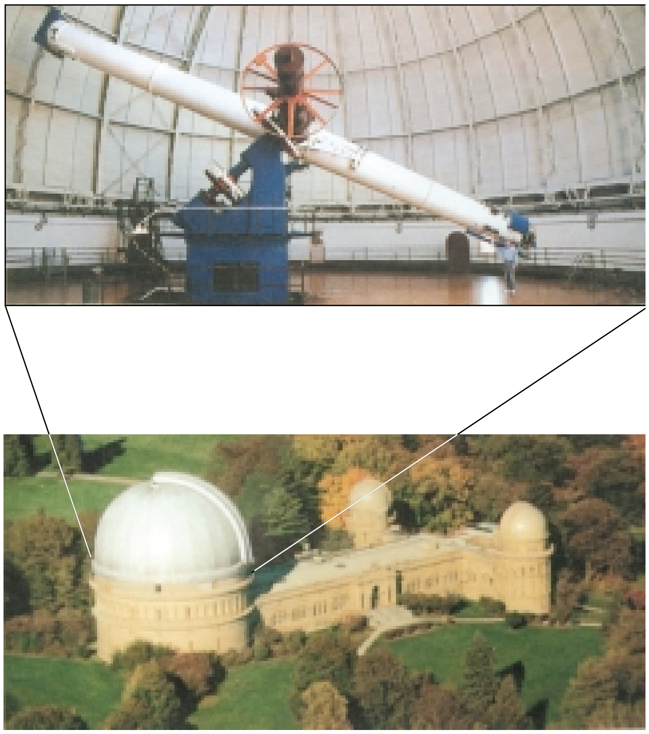
IGURE 3-14 An Achromatic Lens Corrects for Chromatic Aberration A second lens (not the eyepiece) that refracts colors by different amounts than does the objective lens can bring all colors into focus at the same focal length.

We have already mentioned that spherical lenses produce smeared images (Figure 3-15a). Spherical aberration is overcome by focusing light through complex aspheric (nonspherical) surfaces (Figure 3-15b), but grinding aspheric lenses is so difficult that for practical purposes, objective lenses always have spherical surfaces. Spherical aberration can also be minimized by making the objective lens so thin that its spherical surfaces nearly coincide with the appropriate aspheric surfaces. A thin lens, however, has an extremely long focal length, which is why research refracting telescopes are many meters long (Figure 3-16).

Nineteenth-century master opticians devoted their lives to overcoming the problems inherent in refracting telescopes, and several magnificent refractors were constructed in the late 1800s. The largest, completed in 1897 and located at the Yerkes Observatory near Chicago (see Figure 3-16), has an objective lens 102 cm (40 in.) in diameter with a focal length of $19\frac{1}{3}$ m (63.5 ft). 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.



IGURE 3-15 Spherical Aberration and Aspheric Lenses (a) Different parts of a spherical lens refract light to different focal points. (b) The ideal shape for a lens is a complex aspherical shape. Such a lens focuses all the light passing through it at the same focal length.



IGURE 3-16 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. (Yerkes Observatory)

3-8 Reflecting telescopes use mirrors to concentrate incoming starlight

Prompted by the problem of chromatic aberration, early in the eighteenth century Isaac Newton set about to replace the objective lens with a curved mirror to collect light. Called **reflecting telescopes** or **reflectors,** telescopes with mirrors easily overcome most of the problems inherent in refracting telescopes.

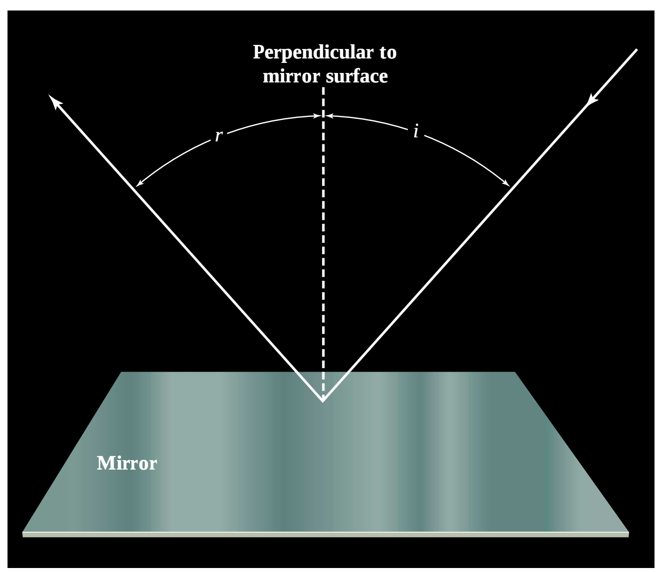
A mirror collects light using **reflection** rather than refraction. In Figure 3-17, the ray of light strikes a flat mirror, and we imagine a perpendicular line coming out of the mirror at that point. According to the principle of reflection, the angle between the arriving light ray and the perpendicular (dashed line) is always equal to the angle between the reflected light ray and the perpendicular. The rule is the same regardless of the light's wavelength or the mirror's shape.

Using this principle, Newton realized that a concave, parabolic mirror will cause parallel light rays to converge to a focal point, as shown in Figure 3-18b. The distance between the reflecting surface and the focal point, where the image of the distant object is formed, is the focal length of the mirror. The magnifying power of such a reflecting telescope is calculated in the same way as for a refractor: The focal length of the large or **primary mirror** is divided by the focal length of the eyepiece.

To view the image, Newton placed a small, flat mirror at a 45° angle in front of the focal point, as sketched in Figure 3-19a. This **secondary mirror** reflects the light rays to one side of the telescope, and the astronomer views the image through an eyepiece lens. A telescope with this optical design is still called a **Newtonian reflector.**

Newtonian telescopes are very 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 its side, the telescope sags and distorts the image in unpredictable ways.

Three basic designs exist for the reflecting telescopes used in research. In the first design, the astronomer actually sits at the undeflected focal point, directly in front of the primary mirror, and controls the light-collecting equipment located there. This arrangement is called a **prime focus** (Figure 3-19b). All telescopes must be kept at the same temperature as the outdoors to prevent a temperature difference from expanding or contracting the telescope, thereby distorting the image. It is therefore often a chilling experience to ride throughout a mountaintop winter night in the open prime focus "observing cage."



IGURE 3-17 Reflection 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).

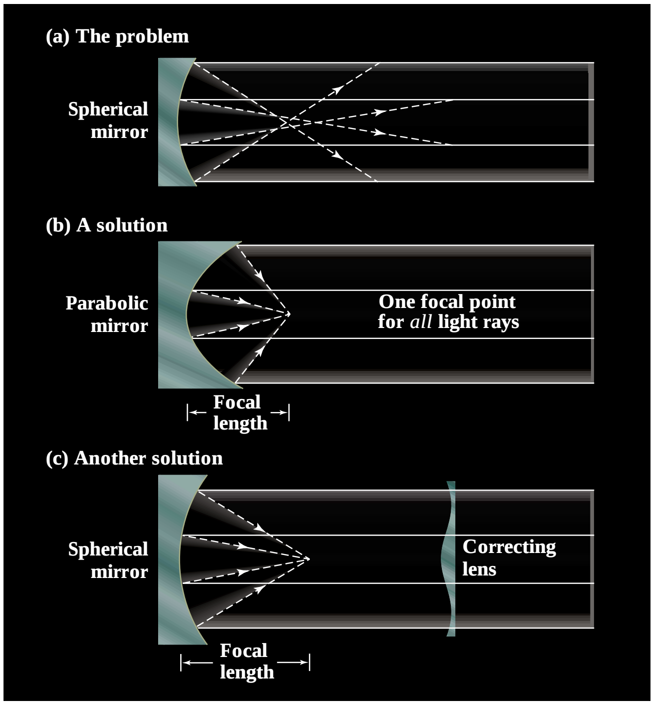


FIGURE 3-18 Spherical Aberration (a) Different parts of a spherically concave mirror reflect light to slightly different focal points. This effect, spherical aberration, causes image blurring. This problem can be overcome by (b) using a parabolic mirror or (c) using a Schmidt corrector plate (lens) in front of the telescope.

In a second popular design, the **Cassegrain focus,** a hole is drilled directly through the center of the primary mirror. A convex secondary mirror placed between the primary mirror and its focal point reflects the light rays back through the hole (Figure 3-19c). This curved secondary mirror extends the telescope's focal length. Light-gathering equipment is bolted to the bottom of the telescope, and the light is brought into focus in it. This design has an advantage over Newtonian telescopes, in that the attached equipment is balanced and does not distort the telescope frame and, hence, the image.

The third design is handy for long and bulky optical equipment that cannot be mounted directly on the telescope or for observations that benefit from extremely long focal lengths. In this design (Figure 3-19d), a series of mirrors channels the light rays away from the telescope to a remote focal point called the **coudé focus** (named after a French word meaning "bent like an elbow").

Reflecting telescopes have numerous advantages over refracting ones. First, they avoid the problem of chromatic aberration, because, unlike household mirrors, all telescope mirrors have coated top surfaces, and light never enters the glass at all. Second, the mirrors, which can weigh tons, do not warp at all, because they can be rigidly supported from underneath. Third, a mirror maker needs only to find a surface, rather than an entire volume, that is free of bubbles. Finally, because light does not enter the glass, the problem of a lens's opacity to different wavelengths never arises.

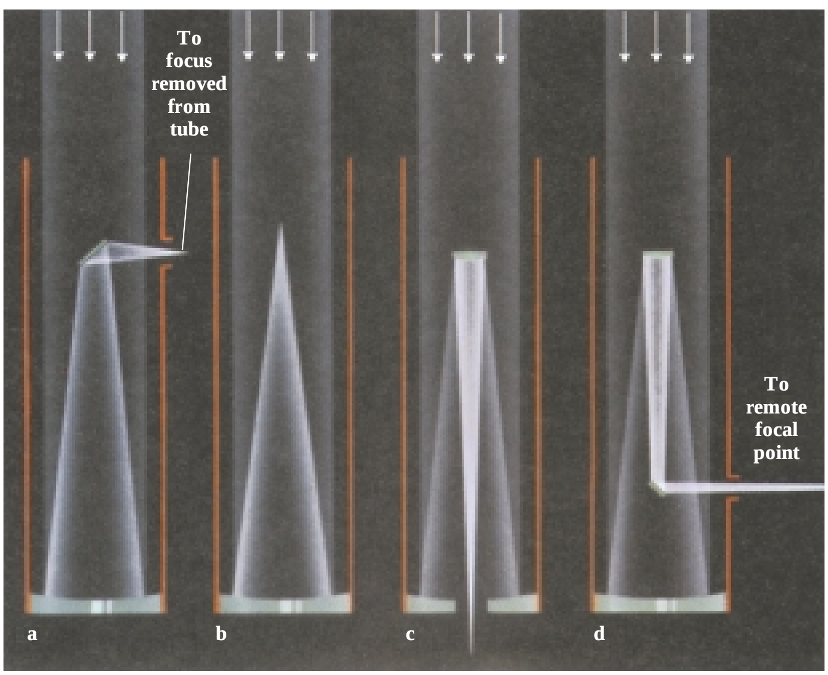


FIGURE 3-19 Reflecting Telescopes Four of the most popular optical designs for reflecting telescopes: (a) Newtonian focus (popular among amateur astronomers); and the three major designs used by researchers—(b) prime focus, (c) Cassegrain focus, and (d) coudé focus.

3-9 Reflecting telescopes also have limitations

The mirrored surfaces of research telescopes are polished so smoothly that the highest bumps are less than 1/500 the thickness of a human hair. Nonetheless, reflecting telescopes are not perfect; there are several prices to pay for the advantages reflectors offer over refractors. Two of the most important are *blocked light* and *spherical aberration*. Let's consider each problem briefly.

You have probably noticed 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 percent 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 think as well 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 enters all parts of the telescope (Figure 3-20).

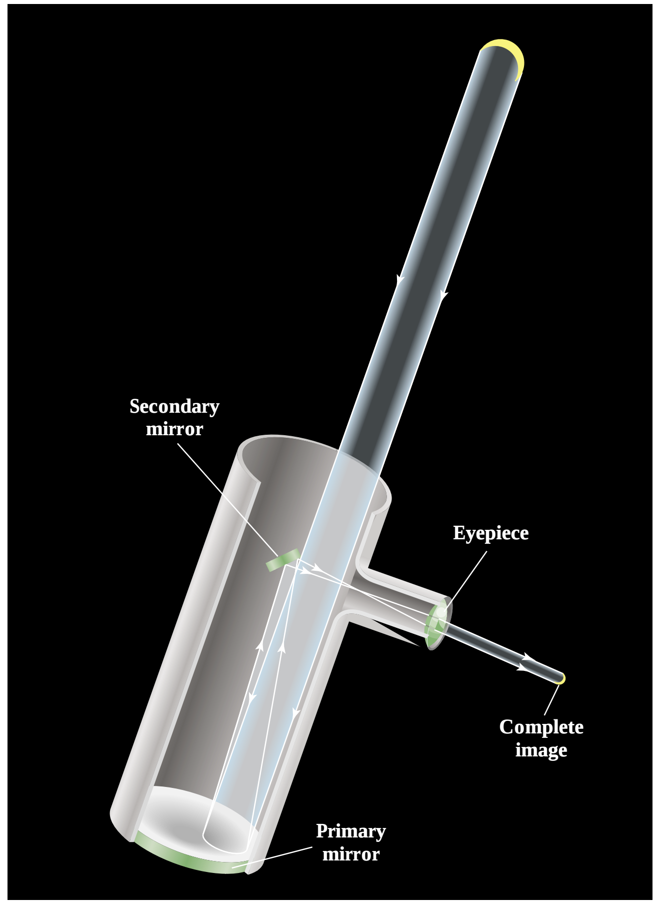
To make a reflector, an optician traditionally grinds and polishes a large slab of glass into a concave spherical surface. However, light entering a spherical telescope mirror at different distances from the mirror's center comes into focus at different focal lengths, as occurs for a spherical lens, and images taken with all such telescopes appear blurry (see Figure 3-18a).

Spherical aberration in reflecting telescopes with spherical primaries may be overcome by including a thin correcting lens, called a **Schmidt corrector plate,** at the top of the telescope (see Figure 3-18c). The light coming into the telescope is refracted by the plate just enough to compensate for spherical aberration and to bring all 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 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. However, the plate does not allow for as much magnification as a telescope with a parabolic mirror.

While parabolic primary mirrors have been meticulously ground over the past century, the advent of computer-controlled grinding and rotating furnaces (Figure 3-21), in which the liquid glass actually spins into a parabolic shape, has now made it economical to cast parabolic mirrors with diameters of several meters.

3-10 Earth's atmosphere hinders astronomical research

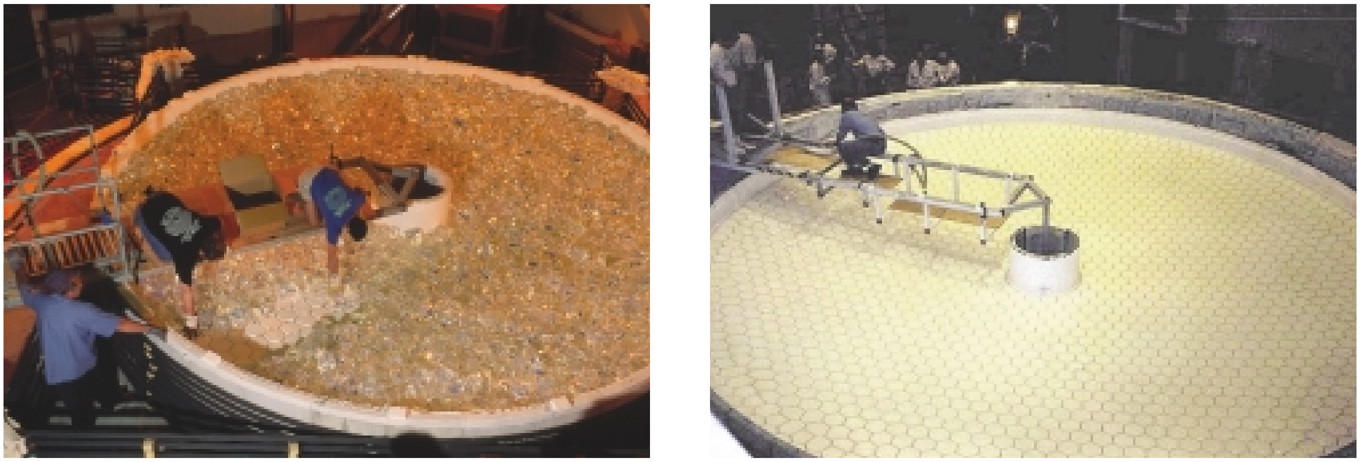
Besides the problems and restrictions inherent in the optics of telescopes, the Earth's atmosphere also introduces difficulties.



IGURE 3-20 The Secondary Mirror Does Not Create a Hole in the Image Because the light rays from distant objects are parallel, light from the entire object reflects off all parts of the mirror. Therefore, every part of the object sends photons to the eyepiece. This figure shows the reconstruction of the entire 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.

The problems arise because the air is turbulent and filled with impurities. 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 the Earth, move upward to create this effect. Light passing through such a blob is refracted, because each hot air mass has a different density than the cooler air around it. Hence, because each blob behaves like a lens, images of objects beyond it appear distorted.

The atmosphere over our heads is similarly moving and 4
changing density, and the starlight passing through it is similarly refracted. Because the 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 through large telescopes,



a

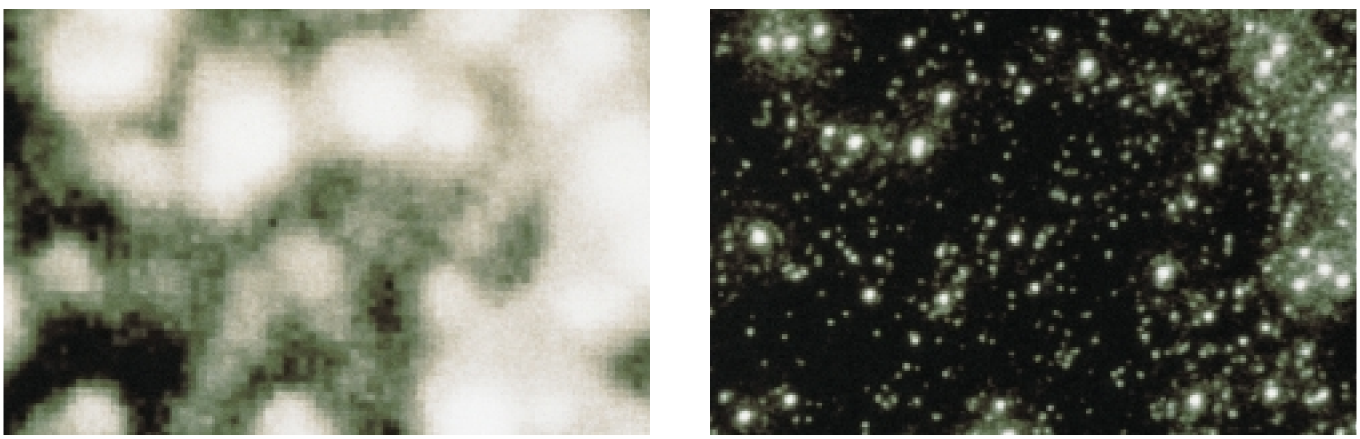
b

IGURE 3-21 Rotating Furnace for Making Parabolic Telescope Mirrors (a) To make each 8.4-meter 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; b: The University of Arizona, Steward Observatory)

twinkling smears out a star's image, causing it to look like a disk rather than a pinpoint of light (Figure 3-22a). Astronomers use the expression *"seeing"* to describe how much twinkling is occurring and, therefore, how smeared out are the images from their telescopes.

The angular diameter of a star's smeared-out image, called the **seeing disk,** is a realistic measure of the best possible resolution. The size of the seeing disk varies from one observatory site to another. At Mount Palomar in California, the seeing disk is roughly one arcsec (1″). The best conditions on Earth, with a seeing disk of 0.2″, have been reported at the observatory on the 14,000-ft summit of Mauna Kea, the tallest volcano on the island of Hawaii (pictured in the photo that opens this chapter).

Without the effects of the Earth's atmosphere, stars do not twinkle. As a result, photographs taken from telescopes in space reveal stars as much finer points (Figure 3-22b) and more detail for extended objects, such as planets and galaxies. The Hubble Space Telescope, as we will see often in this book, achieves magnificent resolution.



a

b

R I V U X G

IGURE 3-22 Effects of Twinkling The same star field photographed with (a) a ground-based telescope, which is subject to twinkling, and (b) the Hubble Space Telescope, which is free from the effects of twinkling. (NASA/ESA)

Insight into Science **Research Requires Patience** Seeing—indeed, most observing in science—is 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. Patience is not a virtue in cutting-edge science; it is a necessity. Next time you visit an observatory, ask astronomers how the seeing has been lately, but be prepared for a series of expletives!

WEB LINK 3.4 Light pollution from cities poses another problem for Earth-based telescopes (Figure 3-23). Keep in mind that the larger the primary mirror, the more light is gathered and therefore the more information astronomers can obtain. The 5-m (200 in.) telescope at the Palomar Observatory between San Diego and Los Angeles, California, was the first truly great large telescope, providing astronomers with invaluable insights into the universe for decades. However, light pollution from the two cities now fills the night sky, seriously reducing the ability of that telescope to collect light from the stars. Not surprisingly, the best observing sites in the world are high on mountaintops—above smog, water vapor, and clouds—and far from city lights.

3-11 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. They could operate 24 hours a day and over a wide range of wavelengths—from the infrared through the visible range and far out into the ultraviolet part of the spectrum. NASA has plans for four such Great Observatories, the first of which is the Hubble Space Telescope (HST), which was carried aloft by the Space Shuttle in April 1990.

Soon after HST was placed in orbit, astronomers discovered that the telescope's 2.4-m primary mirror lacked the proper curvature, which caused its star images to be surrounded by a hazy glow. During a repair mission in December 1993, astronauts installed corrective optics that eliminated the problem (Figure 3-24). It was fully upgraded in 2002. Now HST has a resolution of better than 0.1″, which is better than can be obtained by telescopes on the Earth's surface without the use of advanced technology (see section 3-12).

WEB LINK 3.5 The observations taken by HST have staggered the imaginations of astronomers. It has made new observations related to the planets in our solar system, planetary systems forming around other stars, the distances to other galaxies, black holes, quasars, the formation of the ear-

FIGURE 3-23 Light Pollution These two images of Tucson, Arizona, were taken from the Kitt Peak National Observatory, which is 38 linear miles away. They show the dramatic growth in ground light output between 1959 (top) and 1989 (bottom). Since 1972, light pollution, a problem for many observatories around the world, has been at least partially controlled by a series of local ordinances. (NOAO/AURA/NSF/Galaxy)

IGURE 3-24 The Hubble Space Telescope (HST) This photograph of HST hovering above the Space Shuttle's cargo bay was taken in 1993, at completion of the first servicing mission. During its 20-year lifetime, HST is studying the heavens at wavelengths from the infrared through the ultraviolet. (NASA)

liest galaxies, and the age of the universe, among many other things. This success, coupled with rapidly improving technology, has spurred scientists and engineers to begin developing the Next Generation Space Telescope called NGST to replace Hubble. NGST is scheduled for launch in 2009.

3-12 Advanced technology is spawning a new generation of superb telescopes

The clarity of images taken by the Hubble Space Telescope may suggest that ground-based observational astronomy is a dying practice. However, two exciting ground-based techniques, called active optics and adaptive optics, promise to match the quality of Hubble—or better it!

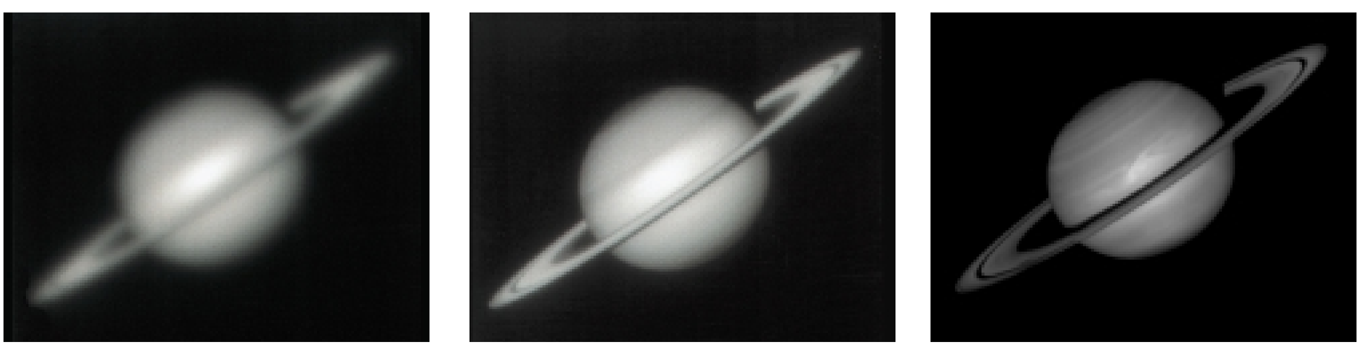
Active optics finds the best orientation for the primary mirror in response to changes in temperature and the shape of the telescope mount. It adjusts the mirror every few seconds to help keep the telescope aimed at its target. With active optics, the New Technology Telescope in Chile and the Keck telescopes in Hawaii routinely achieve resolutions as fine as 0.3″ when the resolution is much worse for telescopes without active optics at the same sites.

WEB LINK 3.6

Adaptive optics uses sensors to determine the amount of twinkling created by atmospheric turbulence. The stellar motion is neutralized by computer-activated, motorized supports that actually reshape either the primary mirror or a smaller mirror installed farther down the optical path of the telescope. Adaptive optics effectively eliminates atmospheric distortion and produces remarkably sharp images (Figure 3-25). Many large ground-based telescopes now use adaptive optics on at least some observations, resulting in images comparable to those from HST.

WEB LINK 3.7

Until the 1980s, telescopes with primary mirrors of between 2 and 6 m were the largest and most powerful in the world. Now, new technologies in mirror building and computer control allow us to construct much larger telescopes. There are at least 49 reflectors around the world today with primary mirrors measuring 2 m or



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IGURE 3-25 Images from Earth and Space (a) Image of Saturn from an Earth-based telescope without adaptive optics. (b) Image of Saturn from an Earth-based telescope with adaptive optics. (c) Image of Saturn from the Hubble Space Telescope, which does not incorporate adaptive optics technology. (a & b: Air Force Research Laboratory, Starfire Optical Range, Kirtland AFB, NM; c: Reta Beebe/New Mexico State University, D. Gilmore, L. Bergeron/STScI, and NASA)

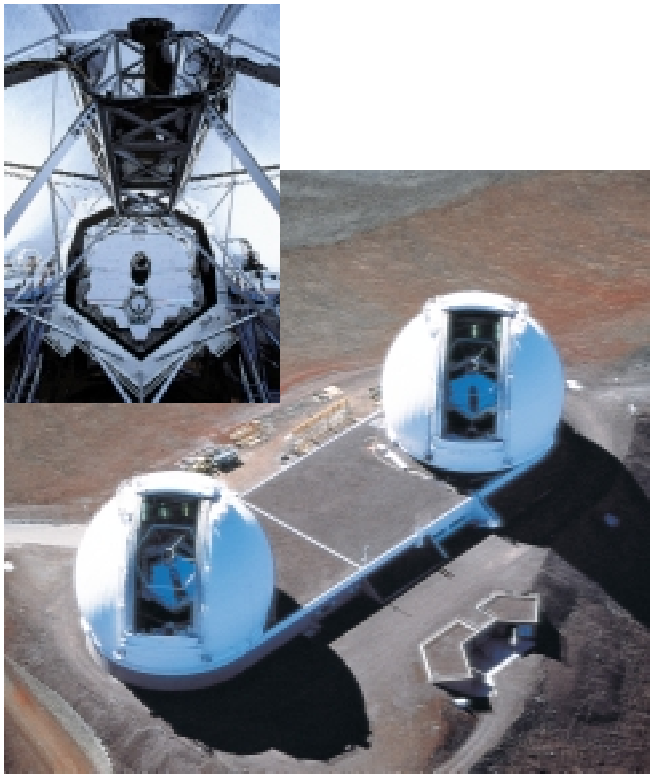


FIGURE 3-26 The 10-m Keck Telescopes Located on the (hopefully) dormant Mauna Kea volcano in Hawaii (see chapter opening photograph), these huge twin telescopes each consist of 36 hexagonal mirrors measuring 1.8 m (5.9 ft) across. Each Keck telescope has the light-gathering, resolving, and magnifying 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. (W. M. Keck Observatory, Courtesy of Richard J. Wainscoat)

more in diameter. This number is up by 11 in only 3 years. Among these are ten with mirrors between 8 and 10 m in diameter, with more than a dozen other very large telescopes under construction.

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-m (400 in.) Keck I and Keck II telescopes on the summit of Mauna Kea in Hawaii. Thirty-six hexagonal mirrors are mounted side by side in each telescope to collect the same amount of light as a single primary mirror 10 m in diameter (Figure 3-26). Another method combines images from different telescopes. For example, used together to observe the same object, the Keck telescopes have the resolving power of a single 85-meter telescope.

3-13 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 point of a telescope, an astronomer could record extremely faint features that could not be seen just by looking through the telescope. The reason is that our eyes clear the images in them several times a second, whereas film adds up the intensity of all the photons affecting its emulsion. Brighter, higher-resolution images therefore reveal greater detail in galaxies, star clusters, and planets than we could otherwise see. Moreover, we can collect even more light by taking long exposures—hour-long exposures are quite routine.

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 a photographic plate triggers a reaction in the photosensitive material of the plate. Thus, roughly 98% of the light falling onto a photographic plate is wasted.

WEB LINK 3.8

Technology has changed all that. We have now replaced photographic film with highly efficient electronic light detectors called **charge-coupled devices (CCDs).** Each CCD is roughly the size of a large postage stamp (Figure 3-27). A CCD is divided into an array

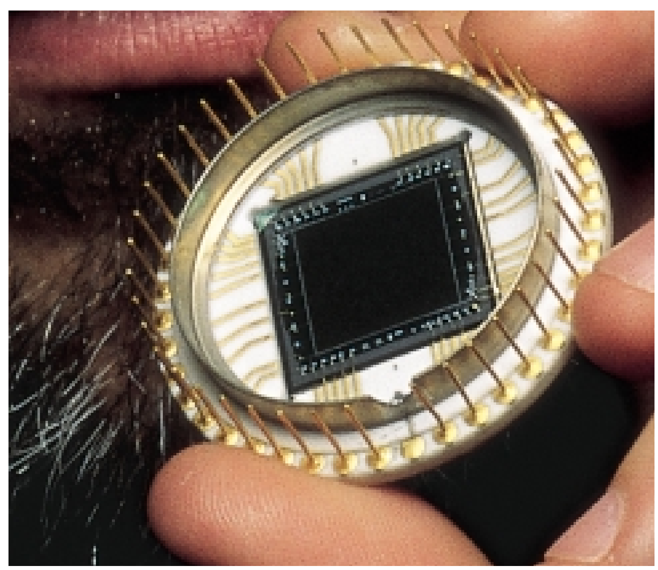
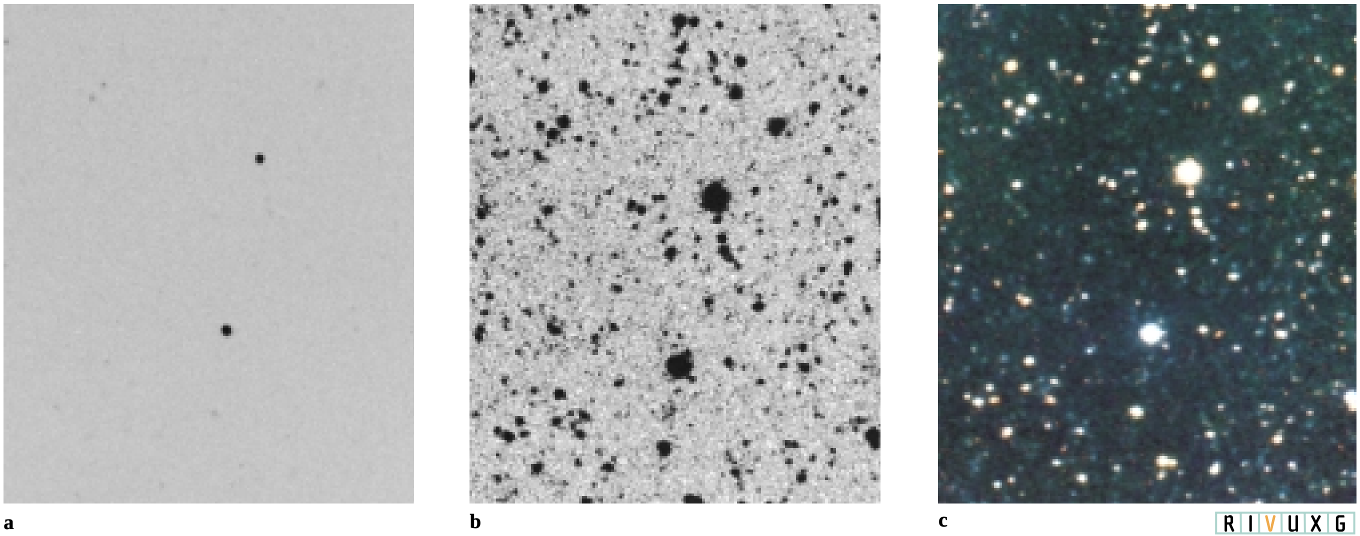


FIGURE 3-27 A Charge-Coupled Device (CCD) This tiny silicon square contains 16,777,216 light-sensitive pixels that store images in a one-piece CCD array. Electronic circuits transfer the data to a waiting computer. (IRFA, University of Hawaii, and Roger Ressmeyer. ©1993 Corbis)



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IGURE 3-28 Ordinary 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 virtually 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)

of small, light-sensitive squares called picture elements or, more commonly, **pixels.** For example, one of the latest CCDs has more than 16 million pixels arranged in 4096 rows by 4096 columns. This is about 1000 times more pixels per square centimeter than in a typical computer screen.

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 falling on that pixel. When the exposure is finished, the charge on each pixel is read into a computer. The computer then transfers the image onto a television monitor. CCDs commonly respond to 70% of the light falling on them; their resolution is better than that of film, and they respond more uniformly to light of different colors. Figure 3-28 shows one photograph and two CCD images of the same region of the sky, all taken with the same telescope. Notice that many details visible in the CCD images are absent in the ordinary photograph.

RADIO ASTRONOMY—AND BEYOND

Until the 1930s, all information that astronomers gathered from the universe was based on visible light. Scientists began to wonder if objects in the universe might also emit radio waves, infrared and ultraviolet radiation, and perhaps even X rays or gamma rays. Little did anyone realize back then the enormous range of objects and activities in the universe that emit one or more of these radiations without giving off any detectable visible light!

3-14 A radio telescope uses a large concave dish to reflect radio waves to a focal point

The first evidence of nonvisible radiation from outer space came from the work of a young radio engineer, Karl Jansky, working at Bell Laboratories. Using long antennas, Jansky was investigating the sources of radio 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 the center of our Galaxy is located in the direction of Sagittarius, Jansky concluded that he was detecting radio waves from elsewhere in the Galaxy.

Insight into Science **Think "Outside the Box"** Observations and experiments often require scientists to make connections between seemingly unrelated concepts. Jansky's proposal that some radio waves originate in space is an example of a scientist connecting apparently disparate scientific fields—astronomy and radio engineering.

Radio telescopes record radio signals from the sky. At first, astronomers were not enthusiastic about detecting radio noise from space, in part because of the poor angular resolution of early radio telescopes. The angular resolution

GUIDED DISCOVERY Buying a Telescope

If you feel elated discovering treasures, you may want to consider viewing the night sky through powerful binoculars or a telescope. Both types of instruments enable you to find many beautiful, exciting objects in space. Binoculars are nice because you can quickly scan the heavens to see craters on the Moon, star clusters, the Great Nebula of Orion, and even the Andromeda galaxy. Telescopes open new vistas and even enable amateur astronomers to discover new comets, among other things, adding to our scientific database and immortalizing the discoverers' names.

There are four basic types of telescope mounts that steer the telescopes around the sky: The Fork Equatorial Mount, the German Equatorial Mount, the Altitude-Azimuth (Alt-Azimuth) Mount, and the Dobsonian Mount (see figure below).

a b c d

Buying a Telescope (a) Fork Equatorial Mount, (b) German Equatorial Mount, (c) Alt-Azimuth Mount, (d) Dobsonian Mount. (a, b, & d: Andy Crawford/Dorling Kindersley; c: Celestron Images)

The table on the next page presents the advantages and disadvantages of each mount.

Reflecting and refracting telescopes both have pros and cons, as discussed in the text. Perhaps the most significant difference is in their lengths. Newtonian reflectors tend to be longer and more bulky than any other type. Nevertheless, Newtonian reflectors are the least expensive and simplest to build. As a result, they are the telescope of choice for the Dobsonian mounts. If you plan to take photographs, a Cassegrain telescope is the best instrument because it remains balanced as the telescope tracks objects across the sky.

If you want to see especially large areas of the sky, you may want to purchase a telescope with a *Schmidt corrector plate.* The most common wide-field telescopes are of the Schmidt-Cassegrain design. These telescopes have a Schmidt corrector plate on top and a Cassegrain mirror on the bottom with their eyepieces located underneath.

If you build or buy a telescope with the eyepiece positioned so that you have to crawl under it or climb a ladder to see through it, you will find the experience less satisfying than if you can observe in a comfortable position. If the eyepiece is not easily accessible, you can buy a *diagonal mirror* (a right-angle mirror that goes between the telescope body and the eyepiece) to help correct this problem.

You will also want to get a few different *eyepieces* (three is a good number to start with), so that you can look at large areas of the sky under low magnification and details of small areas under high magnification. As discussed in the text, the magnification of a telescope depends on the focal lengths of the objective lens and the eyepiece. The objective lens or primary mirror is fixed in the telescope. However, all telescopes come with removable eyepieces. Change the eyepiece to another of different focal length, and you change the telescope's magnification. Keep in mind, however, that increasing the magnification decreases the area of the sky that you see.

Unless your telescope is computerized, it is also essential to have a *finder scope,* which is a small, low-magnification, very-wide-field telescope, with crosshairs, attached directly onto your main telescope. If the finder and your main scope are well aligned, you can quickly zero in on an object.

If you plan to take photographs with a CCD camera or other instrument on your telescope or to show the cosmos to large groups of people, you will need a *tracking motor* to enable the telescope to follow the stars automatically. Tracking motors require their own power from batteries, an adaptor for a car cigarette lighter, or a 110-V outlet. The motor should also be able to run at high speed so you can slew (turn) the telescope rapidly from one object to the next. For photography, you will also need a *camera adapter.*

Viewing the Sun is very exciting, especially when you can observe sunspots. If you want to observe the Sun, it is essential that you buy a good *Sun filter.* **Never, ever look at the Sun directly, either through a telescope or with your naked eye. Doing so for even a second can lead to partial or total blindness!**

Finally, you will need a flashlight with a red plastic film over the lens or one with a red LED light. Because red light does not cause the pupils of your eyes to contract, they will remain dilated (wide open) while you use the red flashlight to inspect your equipment and your star charts.

Telescope Mounts

Type of Telescope	**Pros**	**Cons**
Fork Equatorial	Can track objects in the sky with a clock drive	Eyepiece is in an uncomfortable position near celestial poles
	Useful for taking CCD or film photographs	
	Not too heavy or cumbersome	
German Equatorial	Can track objects in the sky with a clock drive	Hard at first to learn to set up
	Useful for taking CCD or film photographs	Takes a long time to set up
	Easy to change direction telescope points	Very heavy compared to other types of mounts
Alt-Azimuth	Compact—easy to set up, store, and carry	Must be computerized in order to track objects in the sky
	Eyepiece is convenient for viewing	
Dobsonian	Least expensive for a given diameter primary mirror	Eyepiece is often in inconvenient position
	Easy to set up	Cannot track objects in the sky or take photographs without specialized equipment
	Easy to use	

IGURE 3-29 A Radio Telescope Recall that the secondary mirror or prime focus on most telescopes block incoming light or other radiation. This new 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 reflector. By using this new design, there is no such loss of signal. Such configurations are also common on microwave dishes used to receive satellite TV transmissions. (National Radio Astronomy Observatory)

of any telescope decreases as the wavelength increases. In other words, the longer the wavelength, the fuzzier the picture. Because radio radiation has very long wavelengths, astronomers first thought that radio telescopes could only produce blurry, indistinct images.

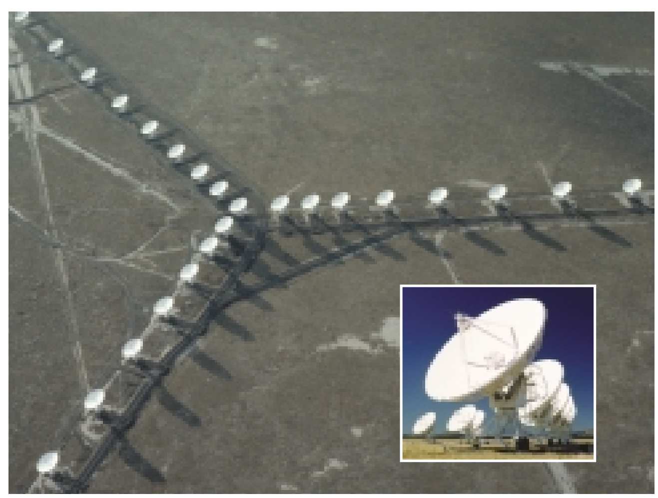
VIDEO 3.1

Radio telescopes each have a large, reflecting, concave dish that acts exactly like a mirror in an optical telescope (Figure 3-29). A small antenna tuned to the desired wavelength is located either at the prime focus or the Cassegrain focus. The incoming signal is relayed to amplifiers and recording instruments. 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 dishes more than 25 m in diameter. Nevertheless, even the largest radio dish in existence (305-m diameter in Arecibo, Puerto Rico) 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 detecting radio waves of 1-mm wavelength.

To overcome the limitation on resolution set by telescope diameter, a clever technique enables radio astronomers to produce radio images often better than those available in the optical part of the spectrum. Called **interferometry,** the idea is to combine the data received simultaneously by two or more telescopes. The telescopes can be kilometers or even continents apart. The radio signals received by all 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 one gigantic dish with a diameter equal to the distance between the farthest-most telescopes in the array.

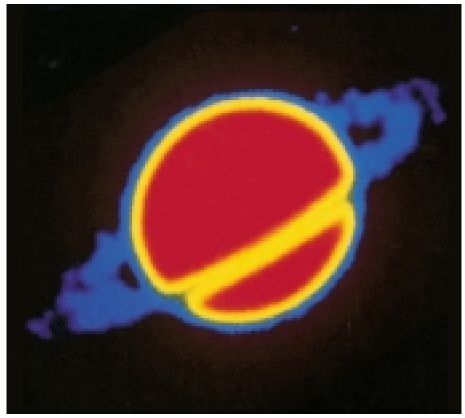
Interferometry, exploited for the first time in the late 1940s, gave astronomers their first detailed views of "radio objects" in the sky. More recently, radio telescopes separated by thousands of kilometers have been linked together in **very-long-baseline interferometry (VLBI),** producing images that are much sharper and clearer than even those from optical telescopes. The best angular resolution on Earth is obtained by combining radio data from telescopes on opposite sides of the Earth. 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 used in even longer-baseline interferometers. Interferometry is so successful that it has recently been applied successfully to optical and infrared telescopes.

One of the most complex systems of radio telescopes began operating in 1980 on the Plains of San Agustin near Socorro, New Mexico. Called the Very Large Array (VLA), it consists of 27 concave dishes, each 26 m (85 ft) in diameter. The 27 telescopes 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. Figure 3-30 shows the VLA. This system produces



IGURE 3-30 The Very Large Array (VLA) The 27 radio telescopes of the VLA system are arranged along the arms of a Y in central New Mexico. The telescopes can be moved 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/Corbis; *inset:* David Nunuk/Science Photo Library/Photo Researchers)

a R I V U X G



b R I V U X G

FIGURE 3-31 Optical 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, shows radio emission from Saturn at a wavelength of 2 cm (a: NASA; b: ©1982 Associated Universities, Inc. under contract with the National Science Foundation/VLA observations by Imke de Pater, J. R. Dickel)

radio views of the sky with resolutions comparable to that of the very best optical telescopes.

To make radio images more comprehensible, radio astronomers often use false colors or gray scales to display their radio views of astronomical objects. An example of the use of false colors is shown in Figure 3-31. 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 working at other nonvisible-wavelength ranges also frequently use false-color techniques to display views obtained from their instruments.

WEB LINK 3.9 The Very Long Baseline Array (VLBA) consists of ten 25-m radio telescopes located across the United States from Hawaii to New Hampshire. With a maximum baseline of 8000 km, VLBA has a resolving power of 0.001″. It is making major contributions to astronomy, such as the discovery in 1994 of a black hole in a nearby galaxy (discussed in Chapter 13). The 1997 addition of a radio telescope in space tripled the maximum baseline for radio telescope arrays.

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

As the success of radio astronomy mounted, astronomers started exploring the possibility of making observations at other nonvisible wavelengths. The next two parts of the spectrum to be explored were infrared and ultraviolet. As with radio telescopes, infrared and ultraviolet telescopes are all reflectors. 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 on Hawaii is exceptionally dry (most of the moisture in the air is below the height of this volcano), and infrared observations are the primary function of NASA's 3-m Infrared Telescope Facility (IRTF) there.

WEB LINK 3.10 The best way of avoiding water vapor is to place a telescope in orbit around the Earth. The 1983 Infrared Astronomical Satellite (IRAS), the HST NICMOS (Near Infrared Camera and Multi-Object Spectrometer), the 1995 Infrared Space Observatory (ISO), and the 2002 Space Infrared Telescope Facility (SIRTF, Figure 3-32) have done much to reveal the full richness and variety of the infrared sky. SIRTF is the infrared equivalent to HST. These are among NASA's Great Observatories. Infrared astronomy has provided astronomers with the ability to take the temperatures of asteroids, see the otherwise invisible surface features on Saturn's cloud-enshrouded moon Titan, the bands of dust in our Galaxy, the dust disks around nearby stars, and the distant galaxies that emit most of their radiation at infrared wavelengths, among many other things. These infrared observatories have located more than a quarter million infrared sources in the sky. Most of these features are invisible to optical telescopes.

The best observations at ultraviolet wavelengths are also made from space, because the Earth's atmosphere absorbs much of this radiation. During the early 1970s, both Apollo and Skylab astronauts used small telescopes above the Earth's atmosphere to give us some of our first views of the ultraviolet sky. Small rockets have also been used to place ultraviolet cameras briefly above the Earth's atmosphere. A typical ultraviolet view is shown in Figure 3-33, along with a corresponding infrared view from IRAS, a view in visible light, and a star chart.

Some of the finest early ultraviolet astronomy was accomplished by the International Ultraviolet Explorer (IUE), which was launched in 1978 and functioned until 1996. The satellite was built around a Cassegrain telescope with a 45-cm (18-in.) mirror and a total focal length of 6.74 m (22 ft). Observations covered the ultraviolet range from 116 to

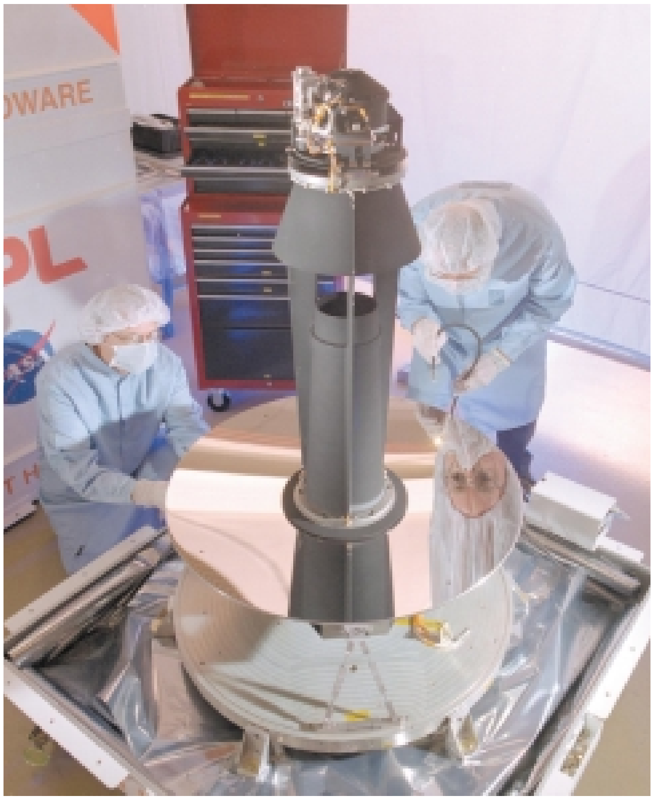


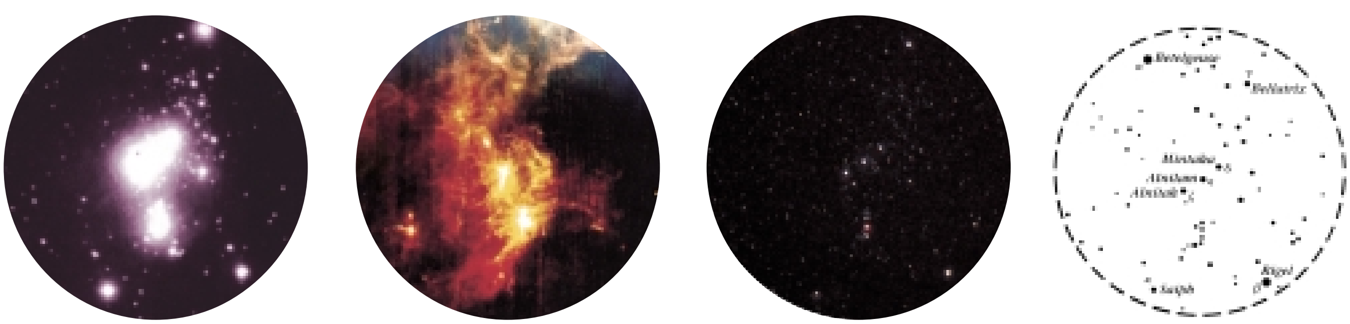
FIGURE 3-32 Mirror Assembly for the Space Infrared Telescope Facility (SIRTF) Launched in 2002, this Great Observatory is scheduled to observe the infrared cosmos for five years. It will take images and spectra of planets, comets, gas, and dust around other stars and in interstellar space, galaxies, and the large-scale distribution of matter in the universe. (Balz/SIRTF Science Center)

320 nm. The Space Shuttle was transformed into an orbiting observatory twice in the 1990s, carrying aloft and then returning to Earth three ultraviolet telescopes. In 1992 the Extreme Ultraviolet Explorer (EUVE) was launched. It is sensitive to photons with wavelengths between 7 and 76 nm, at the short end of the ultraviolet spectrum. 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, astronomers launched the Far Ultraviolet Spectroscopic Explorer (FUSE). It is providing us with information about such things as how much deuterium (hydrogen nuclei with one neutron) was created when the universe formed and the chemical evolution of galaxies.

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

Because neither X rays nor gamma rays penetrate the Earth's atmosphere, observations at these extremely short wavelengths must be made from space. Astronomers got their first look at the X-ray sky during brief rocket flights in the late 1940s. Several small satellites launched during the early 1970s viewed the entire X-ray and gamma-ray sky, revealing hundreds of previously unknown short-wavelength sources, including several black holes (see Chapter 13). X-ray telescopes have also been carried on Space Shuttle missions (see Figure I-4a).

Because of their high energies, X rays penetrate even highly polished surfaces that they meet head on. Therefore,



a R I V U X G   b R I V U X G   c R I V U X G   d

WEB LINK 3.11

FIGURE 3-33 Orion as Seen in Ultraviolet, Infrared, and Visible Wavelengths (a) An ultraviolet view of the constellation Orion obtained during a brief rocket flight on December 5, 1975. The 100-s exposure captured wavelengths ranging from 125 to 200 nm. (b) A false-color view from the Infrared Astronomical Satellite uses color to display specific ranges of infrared wavelengths: red indicates long-wavelength radiation; green, intermediate-wavelength radiation; and blue, short-wavelength radiation. For comparison, (c) an ordinary optical photograph and (d) a star chart are included. (a: G. R. Carruthers, NRL; b: NASA; c: R. C. Mitchell, Central Washington University) normal reflecting mirrors cannot be used to focus them. However, when barely skimming or grazing a surface, X rays can be reflected and thereby focused. Figure 3-34 shows the design of "grazing incidence" X-ray telescopes.

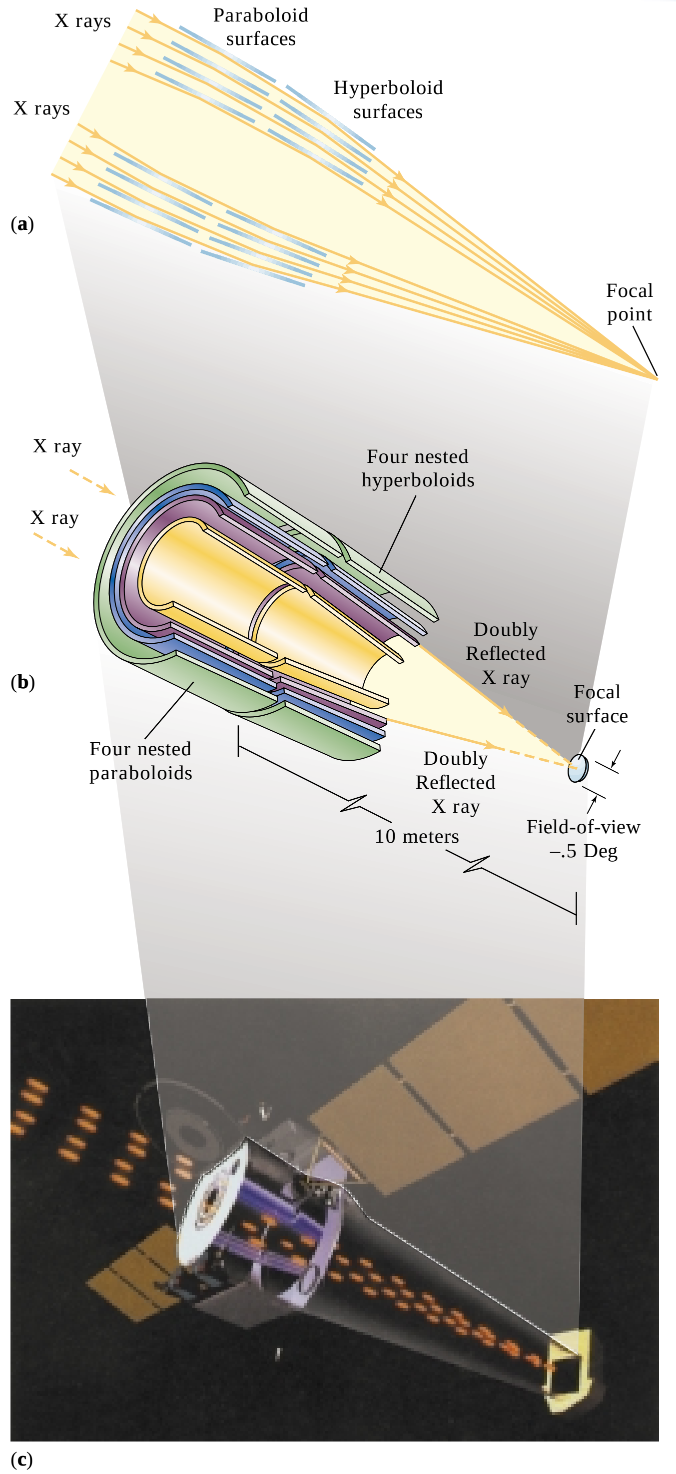
MORE TO KNOW 3.1 Seeing Non-Visible Radiation

The Chandra X-ray Observatory, another NASA Great Observatory, was launched in 1999 and provides astronomers with the highest resolution X-ray images available. To date, thousands of X-ray sources have also been discovered all across the sky. Among these are planetary atmospheres, stars, 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.

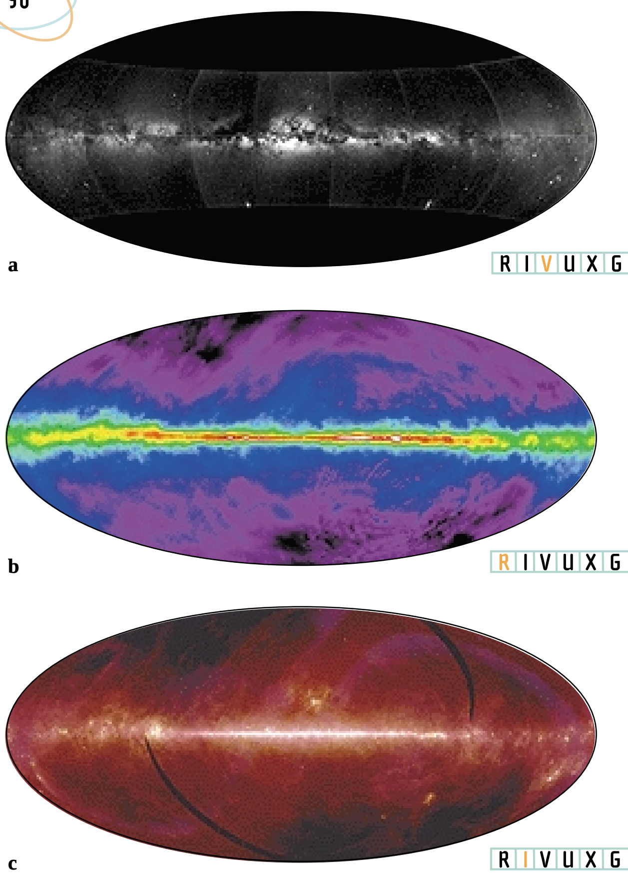
WEB LINK 3.12 The electromagnetic radiation with the shortest wavelengths and the most energy are gamma rays. In 1991 the Compton Gamma Ray Observatory was carried aloft by the Space Shuttle. Named in honor of Arthur Holly Compton, an American physicist who made important discoveries about gamma rays, this orbiting observatory carried four instruments that performed a variety of observations, giving us tantalizing views of the gamma-ray sky. Gamma rays are too powerful even for grazing incidence telescopes. Therefore, astronomers have devised other methods of detecting them and determining where they came from. 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 nowhere near as precise as those used in other parts of the spectrum, and the best resolution gamma ray instruments are only accurate to
5 about 5″. In summary, we can now observe in virtually all parts of the electromagnetic spectrum (Figure 3-35).

3-17 Frontiers yet to be discovered

Before the twentieth century, astronomers were like the blind person trying to describe the elephant. Our ancestors did not have the technology that could enable them to see the big picture of the universe. 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 is so new an activity that we are still making new and often unexpected discoveries almost daily. Perhaps the greatest challenge to observational astronomy is the



IGURE 3-34 **Grazing Incidence X-ray Telescopes** X rays penetrate objects they strike head on. To focus them, they have to be gently nudged by skimming off cylindrical "mirrors." The shapes of the mirrors optimize the focus. The bottom diagram shows how X rays are focused in the Chandra X-ray Telescope. (a & b: NASA/CXC/SAO; c: NASA/Chandra X-ray Observatory Center/Smithsonian Astrophysical Observatory)



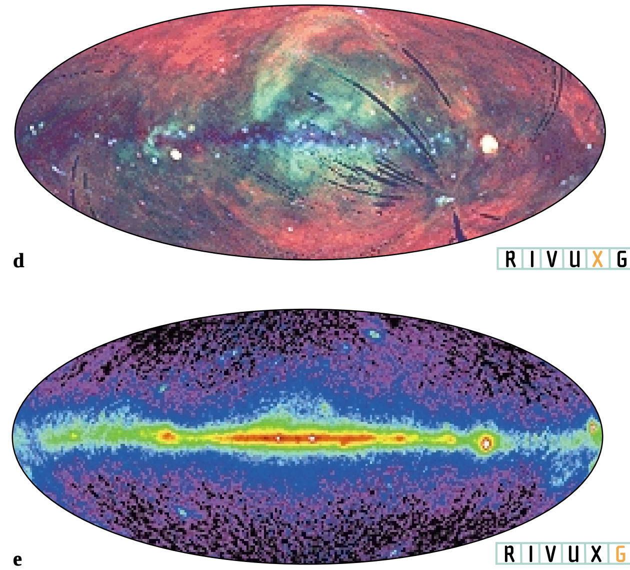


FIGURE 3-35 Survey of the Universe in Various Parts of the Electromagnetic Spectrum Mapping the celestial sphere onto a flat surface (like making a map of the Earth), astronomers can see the overall distribution of strong or nearby energy sources in space. The center of our Galaxy cuts these images horizontally in half. Since most of the emissions shown in these diagrams 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) visible light, (b) radio waves, (c) infrared radiation, (d) X rays, (e) gamma rays. (GFSC/NASA)

fact that when we add up all the currently observable matter in the universe, it only amounts to about 5 percent of all the "stuff" that must exist. We know that there is so much more out there because of its observed gravitational effects. It helps keep galaxies from flying apart, but we cannot yet see it. There is still a lot to discover about the elephant.

Further Reading on These Topics

WHAT DID YOU THINK?

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

2 *What 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 common everyday form of dangerous electromagnetic radiation we 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 stars twinkle?* Rapid changes in the density of the Earth's atmosphere cause passing starlight to change direction, making stars appear to twinkle.

5 *What type(s) of electromagnetic radiation can telescopes currently detect?* Telescopes have been built that can observe the entire electromagnetic spectrum.

KEY WORDS

achromatic lens, 74
active optics, 81
adaptive optics, 81
angular resolution, 72
Cassegrain focus, 77
charge-coupled device (CCD), 82

chromatic aberration, 74
coudé focus, 77
electromagnetic spectrum, 69
eyepiece lens, 71
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spherical aberration, 74
twinkling, 78
ultraviolet (UV) radiation, 69
very-long-baseline interferometry (VLBI), 86
wavelength (λ), 67
X ray, 69

KEY IDEAS

The Nature of Light

• Photons, compact units of vibrating electric and magnetic fields, all carry energy through space at the same speed, "the speed of light" (300,000 km/s in a vacuum, slower in any medium).

• Radio waves, infrared, visible light, ultraviolet radiation, X rays, and gamma rays are all forms of electromagnetic radiation.

• 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.

• Infrared radiation and radio waves have wavelengths longer than those of visible light. Ultraviolet radiation, X rays, and gamma rays have wavelengths that are shorter.

Optics and Telescopes

• A telescope's most important function is to gather as much light as possible. Its second function is to reveal the observed object in as much detail as possible. Often the least important function of a telescope is to magnify objects.

• 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.

• Reflecting telescopes, or reflectors, produce images by reflecting light rays from concave mirrors to a focal point or focal plane. Reflectors are not subject to many of the problems that limit the usefulness of refractors. Telescopes that employ advanced technologies, such as active or adaptive optics, produce extremely sharp images.

• Charge-coupled devices (CCDs) are used at a telescope's focal point to record images.

• Earth-based telescopes are being built with active and adaptive optics. These advanced technologies yield resolving power comparable to the Hubble Space Telescope.

Radio Astronomy—and Beyond

• 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.

• The Earth's atmosphere is transparent to most visible light and radio waves, along with some infrared and ultraviolet, arriving from space, but it absorbs much of the electromagnetic radiation at other wavelengths.

• For observations at other wavelengths, astronomers depend upon telescopes carried above the atmosphere by rockets and satellites. Satellite-based observatories are giving us a wealth of new information about the universe and permit coordinated observation of the sky at all wavelengths.

REVIEW QUESTIONS

The answers to all computational problems, which are preceded by an asterisk (*), appear at the end of the book.

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

2 Give everyday examples of refraction and reflection.

INTERACTIVE EXERCISE 3.1

3 Describe a refracting telescope by doing Interactive Exercise 3-1 and transcribe the drawing and correct labels to paper, if requested.

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

5 With the aid of a diagram, describe a reflecting telescope. Describe four different ways in which an astronomer can access the light collected by reflecting telescopes.

6 Explain some of the advantages of reflecting telescopes over refracting telescopes.

7 What are the three major functions of a telescope?

8 What is meant by the angular resolution of a telescope?

9 What limits the ability of the 5-m telescope on Mount Palomar to collect starlight?

10 Why will many of the very large telescopes of the future make use of multiple mirrors or ultrathin mirrors?

11 What is meant by adaptive optics? What problem does adaptive optics overcome?

12 Compare an optical reflecting telescope and a radio telescope. What do they have in common? How are they different?

13 Why can radio astronomers observe at any time during the day, whereas optical astronomers are mostly limited to observing at night?

14 Why must astronomers use satellites and Earth-orbiting observatories to study the heavens at X-ray or gamma-ray wavelengths?

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

ADVANCED QUESTIONS

16 Advertisements for telescopes frequently give a magnification for the instrument. Is this a good criterion for evaluating telescopes? Explain your answer.

*17 The observing cage in which an astronomer sits at the prime focus of the 5-m telescope on Mount Palomar 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 $\pi \approx 3.14$.

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

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

*20 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 eyepieces whose focal lengths are (a) 9 mm, (b) 20 mm, and (c) 55 mm?

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

DISCUSSION QUESTIONS

22 Discuss the advantages and disadvantages of using a small optical telescope in Earth orbit versus a large optical telescope on a mountaintop.

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

WHAT IF ...

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

25 An observatory were established on the Moon? List the advantages and disadvantages for astronomy.

26 We had eyes sensitive to radio waves? How would we be different and how would our visual perceptions of the world be different?

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

WEB/CD-ROM QUESTIONS

28 Several telescope manufacturers build telescopes with a design called a "Schmidt-Cassegrain." These use a correcting lens in an arrangement like that shown in Figure 3-18c. Consult advertisements on the Web to see the appearance of these telescopes and find out their cost. Why are they very popular among amateur astronomers?

29 Projects are under way to build large optical reflectors in South Africa (SALT, the Southern African Large Telescope) and in the Canary Islands (GTC, the Gran Telescopio Canarias). Search for current information about these telescopes on the Web. What will be the sizes of the primary mirrors? Are the telescopes designed for imaging, for spectroscopy, or both? Will they observe only at visible wavelengths? In what ways do they complement or surpass existing telescopes?

AIMM 3.1

30 Access the Active Integrated Media Module "Telescope Magnification" in Chapter 3 of the *Discovering the Universe* Web site or CD-ROM. A common telescope found in department stores is a 3-inch (76-mm) diameter refractor with a $f_{obj} = 750$ mm that boasts a magnification of 300 times. Use the magnification calculator to determine the magnifications that are achieved by using each of the following commonly found eyepieces on that telescope: Eyepiece A with focal length 40 mm; Eyepiece B with focal length 25 mm; Eyepiece C with focal length 12 mm; and Eyepiece D with focal length 2.5 mm. Which eyepiece was used in the advertisement and why was that one chosen?

OBSERVING PROJECTS

31 During the daytime, obtain a telescope and several eyepieces of differing focal lengths. If you can determine the telescope's focal length (often printed on it), calculate and record the magnifying power of 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 do the field of view and the quality of the image change as you go from low magnification to high magnification?

32 On a dark, clear, moonless night, can you see the Milky Way from where you live? If so, briefly describe its appearance. If not, what is interfering with your ability to see it?

STARRY NIGHT

33 Determine what fraction of stars visible to the naked eye you can see from your location. On the next dark, clear night, observe the night sky and then run *Starry Night Backyard™*. Press the "sky" button on top and then choose and record which of the following most accurately represents your actual night sky: No Sky Pollution/Small City Light Pollution/Large City Light Pollution. Right mouse click and then choose centre/lock with the little hand near the center of the screen. Set the sky pollution to match your sky. If you have used either sky pollution setting, the goal of this project is to estimate what fraction of the visible stars you are not seeing. If you are using the No Sky Pollution setting, the goal is to see what fraction of the stars the inner-city viewers are missing. Using a roughly 3 inch/8 cm-square section of the sky on the screen (about the size of a 1.44 MB floppy disk), count and record the number of stars with your present setting. Now set the sky to either No Sky Pollution in the first case or Large City Light Pollution in the second and count the stars. What fraction of the stars were you seeing in the first case? What fraction of the stars are large city viewers missing in the second case?

34 Observe the stars when the Moon is either full, new, or in a quarter phase. Record the phase of the Moon and note, qualitatively, whether you see many more stars than those just visible in the well-known asterisms such as the Big Dipper or Orion. You are taking this information so you can compare it with observations on a later date. Repeat these observations on a clear night about a week later, again noting the phase of the Moon and the numbers of visible stars. Compare the numbers of stars on the two nights. On which night did you see more stars? Why? During what three phases of the Moon did you expect that astronomers most like to make their observations?

STARRY NIGHT

35 On a clear night, view the Moon, a planet, and a star through a telescope using eyepieces of various focal lengths. (Use your *Starry Night Backyard™* program or consult a source on the Internet or such magazines as *Sky & Telescope* or *Astronomy* to determine the phase of the Moon and the locations of the planets.) How do the images change as you view with increasing magnification? Do they degrade at any point?

36 Many towns and cities have amateur astronomy clubs. Attend a "star party" hosted by your local club. People bring their telescopes to these gatherings and are delighted to show you their instruments and take you on a telescopic tour of the heavens. Such experiences can lead to a very enjoyable, lifelong hobby.

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 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?

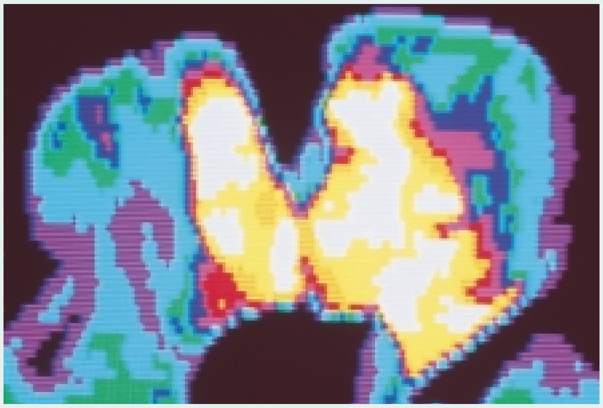
A Darker Vision Gamma rays, X rays, and most ultraviolet radiation do not pass through the Earth's atmosphere, and the world would look dark, indeed, if our eyes were sensitive only to these wavelengths. Radio waves, in contrast, easily pass through our atmosphere. But to see the same detail from radio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

What about infrared radiation? While 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 optical 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. And 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 gives off more infrared (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 the Earth. However, because most infrared radiation passes through these clouds, we would be able, unaided, 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.



R I V U X G

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. (D. Montrose/Custom Medical Stock Photo)