

## 6

## Astronomical Instruments

**Figure 6.1** Hubble Space Telescope (HST). This artist's impression shows the Hubble above Earth, with the rectangular solar panels that provide it with power seen to the left and right.

## Chapter Outline

- 6.1 Telescopes
- 6.2 Telescopes Today
- 6.3 Visible-Light Detectors and Instruments
- 6.4 Radio Telescopes
- 6.5 Observations outside Earth's Atmosphere
- 6.6 The Future of Large Telescopes



## Thinking Ahead

If you look at the sky when you are far away from city lights, there seem to be an overwhelming number of stars up there. In reality, only about 9000 stars are visible to the unaided eye (from both hemispheres of our planet). The light from most stars is so weak that by the time it reaches Earth, it cannot be detected by the human eye. How can we learn about the vast majority of objects in the universe that our unaided eyes simply cannot see?

In this chapter, we describe the tools astronomers use to extend their vision into space. We have learned almost everything we know about the universe from studying electromagnetic radiation, as discussed in the chapter on [Radiation and Spectra](#). In the twentieth century, our exploration of space made it possible to detect electromagnetic radiation at all wavelengths, from gamma rays to radio waves. The different wavelengths carry different kinds of information, and the appearance of any given object often depends on the wavelength at which the observations are made.

## 6.1 Telescopes

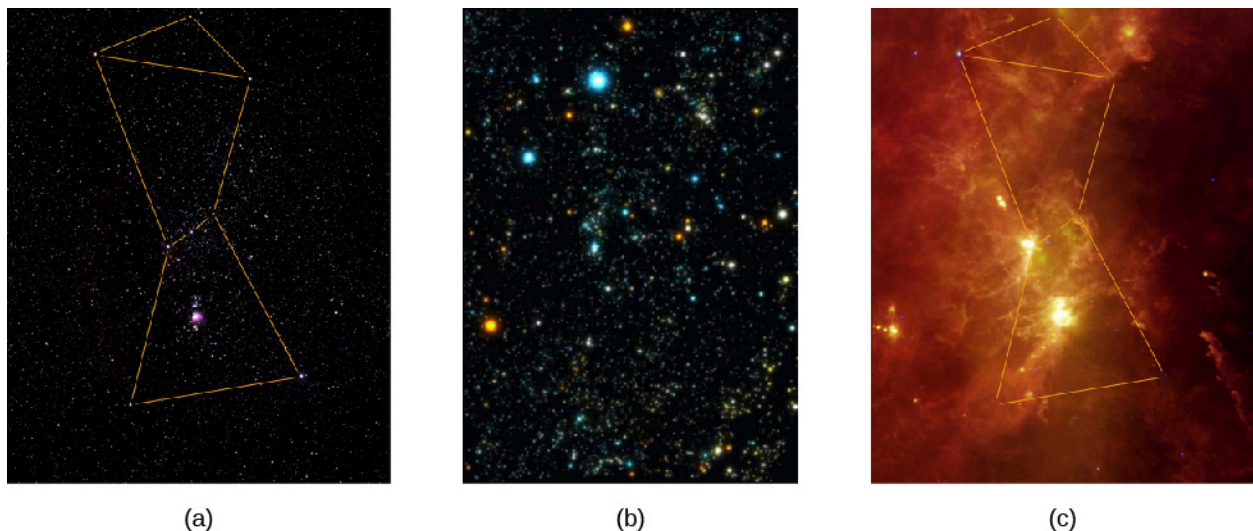
### Learning Objectives

By the end of this section, you will be able to:

- Describe the three basic components of a modern system for measuring astronomical sources
- Describe the main functions of a telescope
- Describe the two basic types of visible-light telescopes and how they form images

### Systems for Measuring Radiation

There are three basic components of a modern system for measuring radiation from astronomical sources. First, there is a **telescope**, which serves as a “bucket” for collecting visible light (or radiation at other wavelengths, as shown in [Figure 6.2](#)). Just as you can catch more rain with a garbage can than with a coffee cup, large telescopes gather much more light than your eye can. Second, there is an instrument attached to the telescope that sorts the incoming radiation by wavelength. Sometimes the sorting is fairly crude. For example, we might simply want to separate blue light from red light so that we can determine the temperature of a star. But at other times, we want to see individual spectral lines to determine what an object is made of, or to measure its speed (as explained in the [Radiation and Spectra](#) chapter). Third, we need some type of **detector**, a device that senses the radiation in the wavelength regions we have chosen and permanently records the observations.



**Figure 6.2 Orion Region at Different Wavelengths.** The same part of the sky looks different when observed with instruments that are sensitive to different bands of the spectrum. (a) Visible light: this shows part of the Orion region as the human eye sees it, with dotted lines added to show the figure of the mythical hunter, Orion. (b) X-rays: here, the view emphasizes the point-like X-ray sources nearby. The colors are artificial, changing from yellow to white to blue with increasing energy of the X-rays. The bright, hot stars in Orion are still seen in this image, but so are many other objects located at very different distances, including other stars, star corpses, and galaxies at the edge of the observable universe. (c) Infrared radiation: here, we mainly see the glowing dust in this region. (credit a: modification of work by Howard McCallon/NASA/IRAS; credit b: modification of work by Howard McCallon/NASA/IRAS; credit c: modification of work by Michael F. Corcoran)

The history of the development of astronomical telescopes is about how new technologies have been applied to improve the efficiency of these three basic components: the telescopes, the wavelength-sorting device, and the detectors. Let’s first look at the development of the telescope.

Many ancient cultures built special sites for observing the sky ([Figure 6.3](#)). At these ancient *observatories*, they could measure the positions of celestial objects, mostly to keep track of time and date. Many of these ancient observatories had religious and ritual functions as well. The eye was the only device available to gather light, all of the colors in the light were observed at once, and the only permanent record of the observations was made by human beings writing down or sketching what they saw.



(a)



(b)

**Figure 6.3 Two Pre-Telescopic Observatories.** (a) Machu Picchu is a fifteenth century Incan site located in Peru. (b) Stonehenge, a prehistoric site (3000–2000 BCE), is located in England. (credit a: modification of work by Allard Schmidt)

While Hans Lippershey, Zaccharias Janssen, and Jacob Metius are all credited with the invention of the telescope around 1608—applying for patents within weeks of each other—it was Galileo who, in 1610, used this simple tube with lenses (which he called a spyglass) to observe the sky and gather more light than his eyes alone could. Even his small telescope—used over many nights—revolutionized ideas about the nature of the planets and the position of Earth.

### How Telescopes Work

Telescopes have come a long way since Galileo’s time. Now they tend to be huge devices; the most expensive cost hundreds of millions to billions of dollars. (To provide some reference point, however, keep in mind that just renovating college football stadiums typically costs hundreds of millions of dollars—with the most expensive recent renovation, at Texas A&M University’s Kyle Field, costing \$450 million.) The reason astronomers keep building bigger and bigger telescopes is that celestial objects—such as planets, stars, and galaxies—send much more light to Earth than any human eye (with its tiny opening) can catch, and bigger telescopes can detect fainter objects. If you have ever watched the stars with a group of friends, you know that there’s plenty of starlight to go around; each of you can see each of the stars. If a thousand more people were watching, each of them would also catch a bit of each star’s light. Yet, as far as you are concerned, the light not shining into your eye is wasted. It would be great if some of this “wasted” light could also be captured and brought to your eye. This is precisely what a telescope does.

The most important functions of a telescope are (1) to *collect* the faint light from an astronomical source and (2) to *focus* all the light into a point or an image. Most objects of interest to astronomers are extremely faint: the more light we can collect, the better we can study such objects. (And remember, even though we are focusing on visible light first, there are many telescopes that collect other kinds of electromagnetic radiation.)

Telescopes that collect visible radiation use a lens or mirror to gather the light. Other types of telescopes may use collecting devices that look very different from the lenses and mirrors with which we are familiar, but they serve the same function. In all types of telescopes, the light-gathering ability is determined by the area of the device acting as the light-gathering “bucket.” Since most telescopes have mirrors or lenses, we can compare their light-gathering power by comparing the **apertures**, or diameters, of the opening through which light travels or reflects.

The amount of light a telescope can collect increases with the size of the aperture. A telescope with a mirror that is 4 meters in diameter can collect 16 times as much light as a telescope that is 1 meter in diameter. (The diameter is squared because the area of a circle equals  $\pi d^2/4$ , where  $d$  is the diameter of the circle.)



## EXAMPLE 6.1

**Calculating the Light-Collecting Area**

What is the area of a 1-m diameter telescope? A 4-m diameter one?

**Solution**

Using the equation for the area of a circle,

$$A = \frac{\pi d^2}{4}$$

the area of a 1-m telescope is

$$\frac{\pi d^2}{4} = \frac{\pi(1 \text{ m})^2}{4} = 0.79 \text{ m}^2$$

and the area of a 4-m telescope is

$$\frac{\pi d^2}{4} = \frac{\pi(4 \text{ m})^2}{4} = 12.6 \text{ m}^2$$

**Check Your Learning**

Show that the ratio of the two areas is 16:1.

**Answer:**

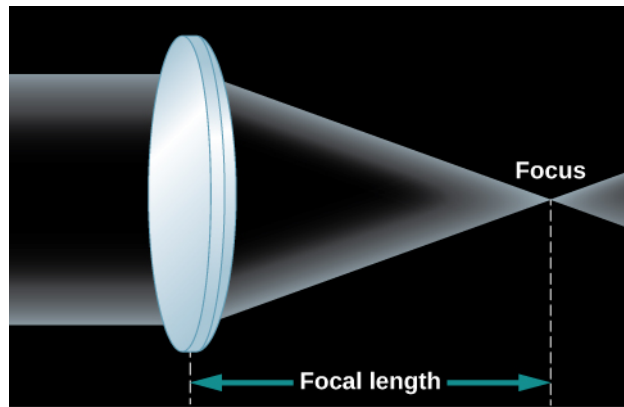
$\frac{12.6 \text{ m}^2}{0.79 \text{ m}^2} = 16$ . Therefore, with 16 times the area, a 4-m telescope collects 16 times the light of a 1-m telescope.

After the telescope forms an image, we need some way to detect and record it so that we can measure, reproduce, and analyze the image in various ways. Before the nineteenth century, astronomers simply viewed images with their eyes and wrote descriptions of what they saw. This was very inefficient and did not lead to a very reliable long-term record; you know from crime shows on television that eyewitness accounts are often inaccurate.

In the nineteenth century, the use of photography became widespread. In those days, photographs were a chemical record of an image on a specially treated glass plate. Today, the image is generally detected with sensors similar to those in digital cameras, recorded electronically, and stored in computers. This permanent record can then be used for detailed and quantitative studies. Professional astronomers rarely look through the large telescopes that they use for their research.

**Formation of an Image by a Lens or a Mirror**

Whether or not you wear glasses, you see the world through lenses; they are key elements of your eyes. A lens is a transparent piece of material that bends the rays of light passing through it. If the light rays are parallel as they enter, the lens brings them together in one place to form an image ([Figure 6.4](#)). If the curvatures of the lens surfaces are just right, all parallel rays of light (say, from a star) are bent, or *refracted*, in such a way that they converge toward a point, called the **focus** of the lens. At the focus, an image of the light source appears. In the case of parallel light rays, the distance from the lens to the location where the light rays focus, or image, behind the lens is called the *focal length* of the lens.

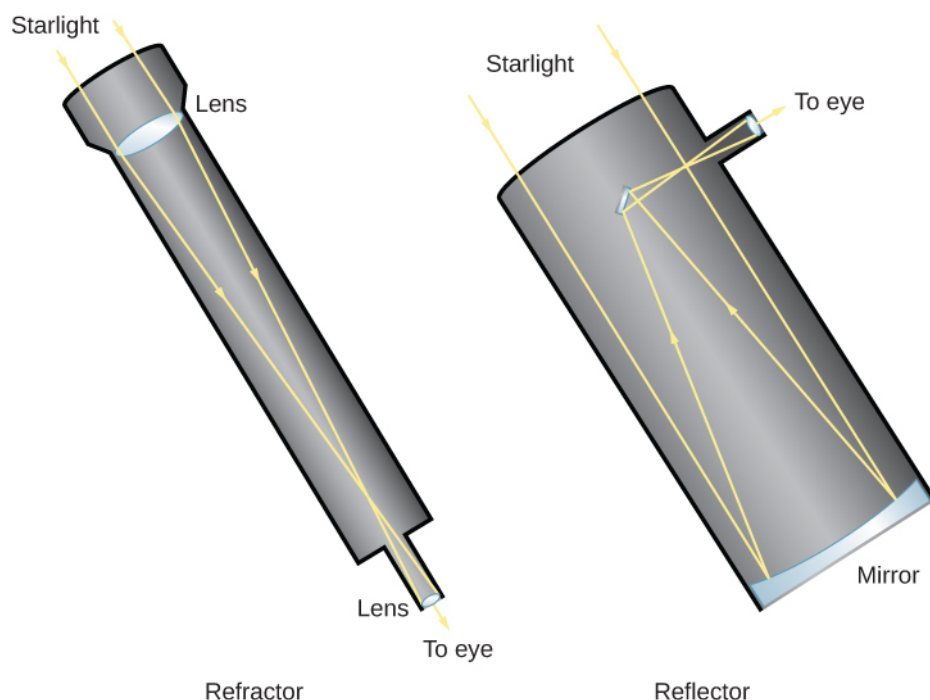


**Figure 6.4 Formation of an Image by a Simple Lens.** Parallel rays from a distant source are bent by the convex lens so that they all come together in a single place (the focus) to form an image.

As you look at [Figure 6.4](#), you may ask why two rays of light from the same star would be parallel to each other. After all, if you draw a picture of star shining in all directions, the rays of light coming from the star don't look parallel at all. But remember that the stars (and other astronomical objects) are all extremely far away. By the time the few rays of light pointed toward us actually arrive at Earth, they are, for all practical purposes, parallel to each other. Put another way, any rays that were *not* parallel to the ones pointed at Earth are now heading in some very different direction in the universe.

To view the image formed by the lens in a telescope, we use an additional lens called an **eyepiece**. The eyepiece focuses the image at a distance that is either directly viewable by a human or at a convenient place for a detector. Using different eyepieces, we can change the *magnification* (or size) of the image and also redirect the light to a more accessible location. Stars look like points of light, and magnifying them makes little difference, but the image of a planet or a galaxy, which has structure, can often benefit from being magnified.

Many people, when thinking of a telescope, picture a long tube with a large glass lens at one end. This design, which uses a lens as its main optical element to form an image, as we have been discussing, is known as a *refractor* ([Figure 6.5](#)), and a telescope based on this design is called a **refracting telescope**. Galileo's telescopes were refractors, as are today's binoculars and field glasses. However, there is a limit to the size of a refracting telescope. The largest one ever built was a 49-inch refractor built for the Paris 1900 Exposition, and it was dismantled after the Exposition. Currently, the largest refracting telescope is the 40-inch refractor at Yerkes Observatory in Wisconsin.



**Figure 6.5 Refracting and Reflecting Telescopes.** Light enters a refracting telescope through a lens at the upper end, which focuses the light near the bottom of the telescope. An eyepiece then magnifies the image so that it can be viewed by the eye, or a detector like a photographic plate can be placed at the focus. The upper end of a reflecting telescope is open, and the light passes through to the mirror located at the bottom of the telescope. The mirror then focuses the light at the top end, where it can be detected. Alternatively, as in this sketch, a second mirror may reflect the light to a position outside the telescope structure, where an observer can have easier access to it. Professional astronomers' telescopes are more complicated than this, but they follow the same principles of reflection and refraction.

One problem with a refracting telescope is that the light must pass *through* the lens of a refractor. That means the glass must be perfect all the way through, and it has proven very difficult to make large pieces of glass without flaws and bubbles in them. Also, optical properties of transparent materials change a little bit with the wavelengths (or colors) of light, so there is some additional distortion, known as **chromatic aberration**. Each wavelength focuses at a slightly different spot, causing the image to appear blurry.

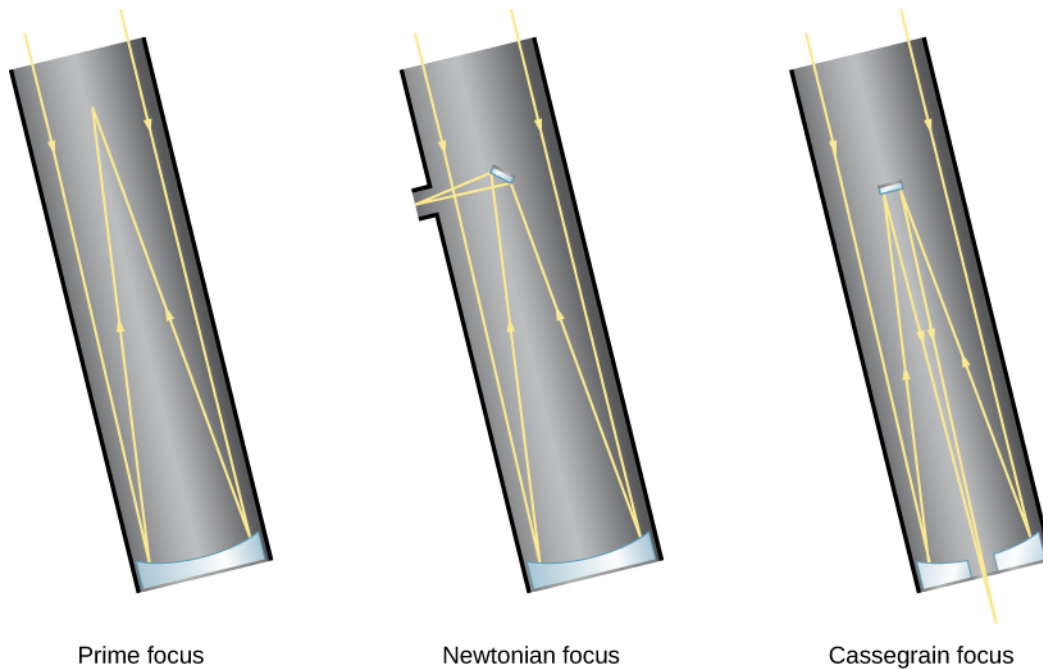
In addition, since the light must pass through the lens, the lens can only be supported around its edges (just like the frames of our eyeglasses). The force of gravity will cause a large lens to sag and distort the path of the light rays as they pass through it. Finally, because the light passes through it, both sides of the lens must be manufactured to precisely the right shape in order to produce a sharp image.

A different type of telescope uses a concave *primary mirror* as its main optical element. The mirror is curved like the inner surface of a sphere, and it reflects light in order to form an image ([Figure 6.5](#)). Telescope mirrors are coated with a shiny metal, usually silver, aluminum, or, occasionally, gold, to make them highly reflective. If the mirror has the correct shape, all parallel rays are reflected back to the same point, the focus of the mirror. Thus, images are produced by a mirror exactly as they are by a lens.

Telescopes designed with mirrors avoid the problems of refracting telescopes. Because the light is reflected from the front surface only, flaws and bubbles within the glass do not affect the path of the light. In a telescope designed with mirrors, only the front surface has to be manufactured to a precise shape, and the mirror can be supported from the back. For these reasons, most astronomical telescopes today (both amateur and professional) use a mirror rather than a lens to form an image; this type of telescope is called a **reflecting telescope**. The first successful reflecting telescope was built by Isaac Newton in 1668.

In a reflecting telescope, the concave mirror is placed at the bottom of a tube or open framework. The mirror reflects the light back up the tube to form an image near the front end at a location called the **prime focus**. The image can be observed at the prime focus, or additional mirrors can intercept the light and redirect it to a

position where the observer can view it more easily (Figure 6.6). Since an astronomer at the prime focus can block much of the light coming to the main mirror, the use of a small *secondary mirror* allows more light to get through the system.



**Figure 6.6 Focus Arrangements for Reflecting Telescopes.** Reflecting telescopes have different options for where the light is brought to a focus. With prime focus, light is detected where it comes to a focus after reflecting from the primary mirror. With Newtonian focus, light is reflected by a small secondary mirror off to one side, where it can be detected (see also Figure 6.5). Most large professional telescopes have a Cassegrain focus in which light is reflected by the secondary mirror down through a hole in the primary mirror to an observing station below the telescope.

## MAKING CONNECTIONS



### Choosing Your Own Telescope

If the astronomy course you are taking whets your appetite for exploring the sky further, you may be thinking about buying your own telescope. Many excellent amateur telescopes are available, and some research is required to find the best model for your needs. Some good sources of information about personal telescopes are the two popular US magazines aimed at amateur astronomers: *Sky & Telescope* and *Astronomy*. Both carry regular articles with advice, reviews, and advertisements from reputable telescope dealers.

Some of the factors that determine which telescope is right for you depend upon your preferences:

- Will you be setting up the telescope in one place and leaving it there, or do you want an instrument that is portable and can come with you on outdoor excursions? How portable should it be, in terms of size and weight?
- Do you want to observe the sky with your eyes only, or do you want to take photographs? (Long-exposure photography, for example, requires a good clock drive to turn your telescope to compensate for Earth's rotation.)
- What types of objects will you be observing? Are you interested primarily in comets, planets, star clusters, or galaxies, or do you want to observe all kinds of celestial sights?

You may not know the answers to some of these questions yet. For this reason, you may want to “test-

drive” some telescopes first. Most communities have amateur astronomy clubs that sponsor star parties open to the public. The members of those clubs often know a lot about telescopes and can share their ideas with you. Your instructor may know where the nearest amateur astronomy club meets; or, to find a club near you, use the websites suggested in [Appendix B](#).

Furthermore, you may already have an instrument like a telescope at home (or have access to one through a relative or friend). Many amateur astronomers recommend starting your survey of the sky with a good pair of binoculars. These are easily carried around and can show you many objects not visible (or clear) to the unaided eye.

When you are ready to purchase a telescope, you might find the following ideas useful:

- The key characteristic of a telescope is the aperture of the main mirror or lens; when someone says they have a 6-inch or 8-inch telescope, they mean the diameter of the collecting surface. The larger the aperture, the more light you can gather, and the fainter the objects you can see or photograph.
- Telescopes of a given aperture that use lenses (refractors) are typically more expensive than those using mirrors (reflectors) because both sides of a lens must be polished to great accuracy. And, because the light passes through it, the lens must be made of high-quality glass throughout. In contrast, only the front surface of a mirror must be accurately polished.
- Magnification is not one of the criteria on which to base your choice of a telescope. As we discussed, the magnification of the image is done by a smaller eyepiece, so the magnification can be adjusted by changing eyepieces. However, a telescope will magnify not only the astronomical object you are viewing but also the turbulence of Earth’s atmosphere. If the magnification is too high, your image will shimmer and shake and be difficult to view. A good telescope will come with a variety of eyepieces that stay within the range of useful magnification.
- The mount of a telescope (the structure on which it rests) is one of its most critical elements. Because a telescope shows a tiny field of view, which is magnified significantly, even the smallest vibration or jarring of the telescope can move the object you are viewing around or out of your field of view. A sturdy and stable mount is essential for serious viewing or photography (although it clearly affects how portable your telescope can be).
- A telescope requires some practice to set up and use effectively. Don’t expect everything to go perfectly on your first try. Take some time to read the instructions. If a local amateur astronomy club is nearby, use it as a resource.

## 6.2 Telescopes Today

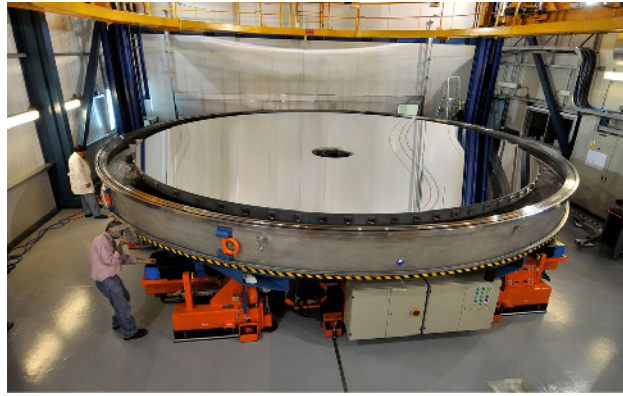
### Learning Objectives

By the end of this section, you will be able to:

- › Recognize the largest visible-light and infrared telescopes in operation today
- › Discuss the factors relevant to choosing an appropriate telescope site
- › Define the technique of adaptive optics and describe the effects of the atmosphere on astronomical observations

Since Newton’s time, when the sizes of the mirrors in telescopes were measured in inches, reflecting telescopes have grown ever larger. In 1948, US astronomers built a telescope with a 5-meter (200-inch) diameter mirror on Palomar Mountain in Southern California. It remained the largest visible-light telescope in the world for several decades. The giants of today, however, have primary mirrors (the largest mirrors in the telescope) that are 8- to 10-meters in diameter, and larger ones are being built ([Figure 6.7](#)).





**Figure 6.7 Large Telescope Mirror.** This image shows one of the primary mirrors of the European Southern Observatory's Very Large Telescope, named Yepun, just after it was recoated with aluminum. The mirror is a little over 8 meters in diameter. (credit: ESO/G. Huedepohl)

### Modern Visible-Light and Infrared Telescopes

The decades starting in 1990 saw telescope building around the globe grow at an unprecedented rate. (See [Table 6.1](#), which also includes websites for each telescope in case you want to visit or learn more about them.) Technological advancements had finally made it possible to build telescopes significantly larger than the 5-meter telescope at Palomar at a reasonable cost. New technologies have also been designed to work well in the infrared, and not just visible, wavelengths.

**Large Single-Dish Visible-Light and Infrared Telescopes**

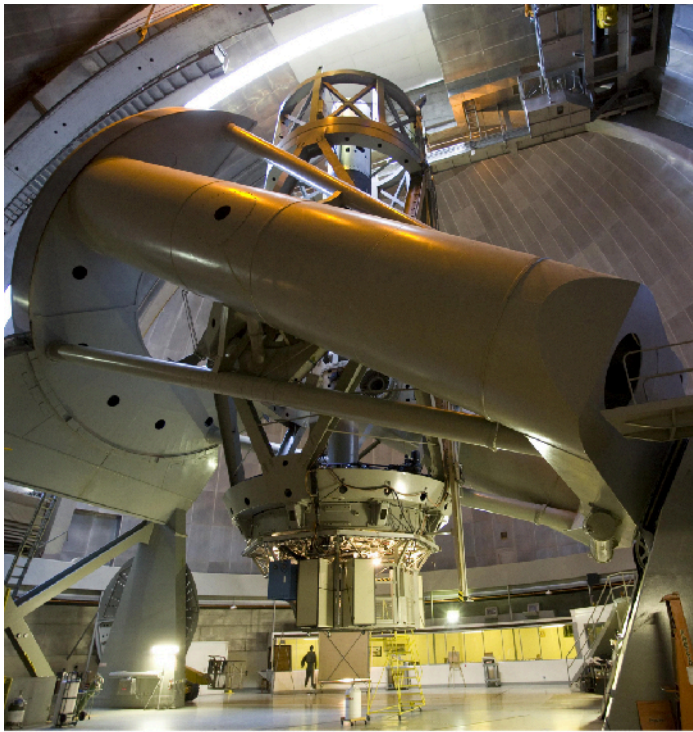
Aperture (m)	Telescope Name	Location	Status	Website
39	European Extremely Large Telescope (E-ELT)	Cerro Armazonas, Chile	First light 2025 (estimated)	<a href="http://www.eso.org/sci/facilities/eelt">www.eso.org/sci/facilities/eelt</a>
30	Thirty-Meter Telescope (TMT)	Maunakea, HI	First light 2025 (estimated)	<a href="http://www.tmt.org">www.tmt.org</a>
24.5	Giant Magellan Telescope (GMT)	Las Campanas Observatory, Chile	First light 2025 (estimated)	<a href="http://www.gmto.org">www.gmto.org</a>
11.1 × 9.9	Southern African Large Telescope (SALT)	Sutherland, South Africa	2005	<a href="http://www.salt.ac.za">www.salt.ac.za</a>
10.4	Gran Telescopio Canarias (GTC)	La Palma, Canary Islands	First light 2007	<a href="http://www.gtc.iac.es">http://www.gtc.iac.es</a>
10.0	Keck I and II (two telescopes)	Maunakea, HI	Completed 1993–96	<a href="http://www.keckobservatory.org">www.keckobservatory.org</a>
9.1	Hobby–Eberly Telescope (HET)	Mount Locke, TX	Completed 1997	<a href="http://www.as.utexas.edu/mcdonald/het">www.as.utexas.edu/mcdonald/het</a>

**Table 6.1**

Aperture (m)	Telescope Name	Location	Status	Website
8.4	Large Binocular Telescope (LBT) (two telescopes)	Mount Graham, AZ	First light 2004	<a href="http://www.lbto.org">www.lbto.org</a>
8.4	Large Synoptic Survey Telescope (Rubin Obs.)	The Cerro Pachón, Chile	First light 2021	<a href="http://www.lsst.org">www.lsst.org</a>
8.3	Subaru Telescope	Maunakea, HI	First light 1998	<a href="http://www.naoj.org">www.naoj.org</a>
8.2	Very Large Telescope (VLT)	Cerro Paranal, Chile	All four telescopes completed 2000	<a href="http://www.eso.org/public/teles-instr/paranal">www.eso.org/public/teles-instr/paranal</a>
8.1	Gemini North and Gemini South	Maunakea, HI (North) and Cerro Pachón, Chile (South)	First light 1999 (North), First light 2000 (South)	<a href="http://www.gemini.edu">www.gemini.edu</a>
6.5	Magellan Telescopes (two telescopes: Baade and Landon Clay)	Las Campanas, Chile	First light 2000 and 2002	<a href="http://obs.carnegiescience.edu/Magellan">obs.carnegiescience.edu/Magellan</a>
6.5	Multi-Mirror Telescope (MMT)	Mount Hopkins, AZ	Completed 1979	<a href="http://www.mmt.org">www.mmt.org</a>
6.0	Big Telescope Altazimuth (BTA-6)	Mount Pastukhov, Russia	Completed 1976	<a href="http://w0.sao.ru/Doc-en/Telescopes/bta/descrip.html">w0.sao.ru/Doc-en/Telescopes/bta/descrip.html</a>
5.1	Hale Telescope	Mount Palomar, CA	Completed 1948	<a href="http://www.astro.caltech.edu/palomar/about/telescopes/hale.html">www.astro.caltech.edu/palomar/about/telescopes/hale.html</a>

Table 6.1

The differences between the Palomar telescope and the modern Gemini North telescope (to take an example) are easily seen in [Figure 6.8](#). The Palomar telescope is a massive steel structure designed to hold the 14.5-ton primary mirror with a 5-meter diameter. Glass tends to sag under its own weight; hence, a huge steel structure is needed to hold the mirror. A mirror 8 meters in diameter, the size of the Gemini North telescope, if it were built using the same technology as the Palomar telescope, would have to weigh at least eight times as much and would require an enormous steel structure to support it.



(a)

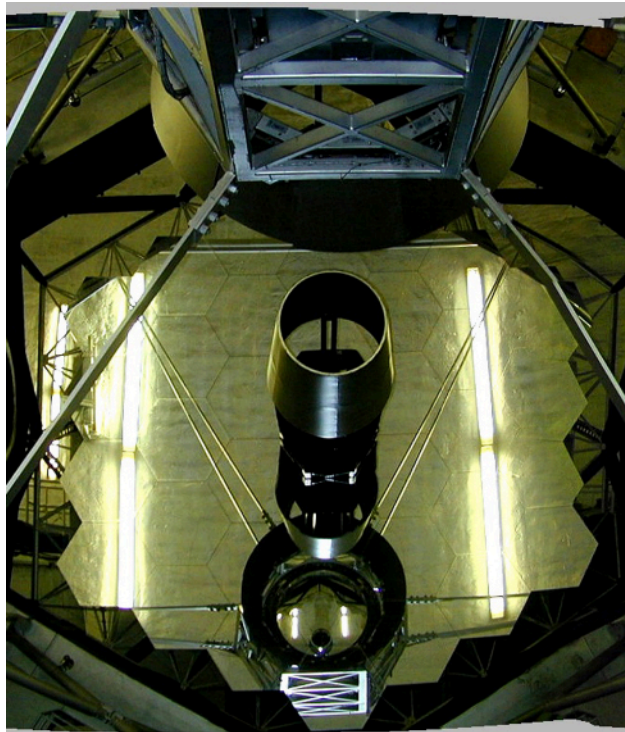


(b)

**Figure 6.8 Modern Reflecting Telescopes.** (a) The Palomar 5-meter reflector: The Hale telescope on Palomar Mountain has a complex mounting structure that enables the telescope (in the open “tube” pointing upward in this photo) to swing easily into any position. (b) The Gemini North 8-meter telescope: The Gemini North mirror has a larger area than the Palomar mirror, but note how much less massive the whole instrument seems. (credit a: modification of work by Caltech/Palomar Observatory; credit b: modification of work by Gemini Observatory/AURA)

The 8-meter Gemini North telescope looks like a featherweight by contrast, and indeed it is. The mirror is only about 8 inches thick and weighs 24.5 tons, less than twice as much as the Palomar mirror. The Gemini North telescope was completed about 50 years after the Palomar telescope. Engineers took advantage of new technologies to build a telescope that is much lighter in weight relative to the size of the primary mirror. The Gemini mirror does sag, but with modern computers, it is possible to measure that sag many times each second and apply forces at 120 different locations to the back of the mirror to correct the sag, a process called *active control*. Seventeen telescopes with mirrors 6.5 meters in diameter and larger have been constructed since 1990.

The twin 10-meter Keck telescopes on Maunakea, which were the first of these new-technology instruments, use precision control in an entirely novel way. Instead of a single primary mirror 10 meters in diameter, each Keck telescope achieves its larger aperture by combining the light from 36 separate hexagonal mirrors, each 1.8 meters wide ([Figure 6.9](#)). Computer-controlled actuators (motors) constantly adjust these 36 mirrors so that the overall reflecting surface acts like a single mirror with just the right shape to collect and focus the light into a sharp image.



**Figure 6.9 Thirty-Six Eyes Are Better Than One.** The mirror of the 10-meter Keck telescope is composed of 36 hexagonal sections. (credit: NASA)

### LINK TO LEARNING



Learn more about the [Keck Observatory on Maunakea \(https://openstax.org/l/30KeckObserv\)](https://openstax.org/l/30KeckObserv) through this History Channel clip on the telescopes and the work that they do.

In addition to holding the mirror, the steel structure of a telescope is designed so that the entire telescope can be pointed quickly toward any object in the sky. Since Earth is rotating, the telescope must have a motorized drive system that moves it very smoothly from east to west at exactly the same rate that Earth is rotating from west to east, so it can continue to point at the object being observed. All this machinery must be housed in a dome to protect the telescope from the elements. The dome has an opening in it that can be positioned in front of the telescope and moved along with it, so that the light from the objects being observed is not blocked.

### VOYAGERS IN ASTRONOMY



#### George Ellery Hale: Master Telescope Builder

George Ellery Hale ([Figure 6.10](#)) was a giant among early telescope builders. Not once, but four times, he initiated projects that led to the construction of what was the world's largest telescope at the time. And he was a master at winning over wealthy benefactors to underwrite the construction of these new instruments.





**Figure 6.10 George Ellery Hale (1868–1938).** Hale’s work led to the construction of several major telescopes, including the 40-inch refracting telescope at Yerkes Observatory, and three reflecting telescopes: the 60-inch Hale and 100-inch Hooker telescopes at Mount Wilson Observatory, and the 200-inch Hale Telescope at Palomar Observatory.

Hale’s training and early research were in solar physics. In 1892, at age 24, he was named associate professor of astral physics and director of the astronomical observatory at the University of Chicago. At the time, the largest telescope in the world was the 36-inch refractor at the Lick Observatory near San Jose, California. Taking advantage of an existing glass blank for a 40-inch telescope, Hale set out to raise money for a larger telescope than the one at Lick. One prospective donor was Charles T. Yerkes, who, among other things, ran the trolley system in Chicago.

Hale wrote to Yerkes, encouraging him to support the construction of the giant telescope by saying that “the donor could have no more enduring monument. It is certain that Mr. Lick’s name would not have been nearly so widely known today were it not for the famous observatory established as a result of his munificence.” Yerkes agreed, and the new telescope was completed in May 1897; it remains the largest refractor in the world ([Figure 6.11](#)).



**Figure 6.11 World's Largest Refractor.** The Yerkes 40-inch (1-meter) telescope.

Even before the completion of the Yerkes refractor, Hale was not only dreaming of building a still larger telescope but was also taking concrete steps to achieve that goal. In the 1890s, there was a major controversy about the relative quality of refracting and reflecting telescopes. Hale realized that 40 inches was close to the maximum feasible aperture for refracting telescopes. If telescopes with significantly larger apertures were to be built, they would have to be reflecting telescopes.

Using funds borrowed from his own family, Hale set out to construct a 60-inch reflector. For a site, he left the Midwest for the much better conditions on Mount Wilson—at the time, a wilderness peak above the small city of Los Angeles. In 1904, at the age of 36, Hale received funds from the Carnegie Foundation to establish the Mount Wilson Observatory. The 60-inch mirror was placed in its mount in December 1908.

Two years earlier, in 1906, Hale had already approached John D. Hooker, who had made his fortune in hardware and steel pipe, with a proposal to build a 100-inch telescope. The technological risks were substantial. The 60-inch telescope was not yet complete, and the usefulness of large reflectors for astronomy had yet to be demonstrated. George Ellery Hale's brother called him "the greatest gambler in the world." Once again, Hale successfully obtained funds, and the 100-inch telescope was completed in November 1917. (It was with this telescope that Edwin Hubble was able to establish that the spiral nebulae were separate islands of stars—or galaxies—quite removed from our own Milky Way.)

Hale was not through dreaming. In 1926, he wrote an article in *Harper's Magazine* about the scientific value of a still larger telescope. This article came to the attention of the Rockefeller Foundation, which granted \$6 million for the construction of a 200-inch telescope. Hale died in 1938, but the 200-inch (5-meter) telescope on Palomar Mountain was dedicated 10 years later and is now named in Hale's honor.

## Picking the Best Observing Sites

A telescope like the Gemini or Keck telescope costs about \$100 million to build. That kind of investment demands that the telescope be placed in the best possible site. Since the end of the nineteenth century, astronomers have realized that the best observatory sites are on mountains, far from the lights and pollution of cities. Although a number of urban observatories remain, especially in the large cities of Europe, they have become administrative centers or museums. The real action takes place far away, often on desert mountains or isolated peaks in the Atlantic and Pacific Oceans, where we find the staff's living quarters, computers, electronic and machine shops, and of course the telescopes themselves. A large observatory today requires a supporting staff of 20 to 100 people in addition to the astronomers.

The performance of a telescope is determined not only by the size of its mirror but also by its location. Earth's atmosphere, so vital to life, presents challenges for the observational astronomer. In at least four ways, our air imposes limitations on the usefulness of telescopes:

1. The most obvious limitation is weather conditions such as clouds, wind, and rain. At the best sites, the weather is clear as much as 75% of the time.
2. Even on a clear night, the atmosphere filters out a certain amount of starlight, especially in the infrared, where the absorption is due primarily to water vapor. Astronomers therefore prefer dry sites, generally found at high altitudes.
3. The sky above the telescope should be dark. Near cities, the air scatters the glare from lights, producing an illumination that hides the faintest stars and limits the distances that can be probed by telescopes. (Astronomers call this effect **light pollution**.) Observatories are best located at least 100 miles from the nearest large city.
4. Finally, the air is often unsteady; light passing through this turbulent air is disturbed, resulting in blurred star images. Astronomers call these effects "bad **seeing**." When seeing is bad, images of celestial objects are distorted by the constant twisting and bending of light rays by turbulent air.

The best observatory sites are therefore high, dark, and dry. The world's largest telescopes are found in such remote mountain locations as the Andes Mountains of Chile ([Figure 6.12](#)), the desert peaks of Arizona, the Canary Islands in the Atlantic Ocean, and Maunakea in Hawaii, a dormant volcano with an altitude of 13,700 feet (4200 meters).

#### LINK TO LEARNING



Light pollution is a problem not just for professional astronomers but for everyone who wants to enjoy the beauty of the night sky. In addition research is now showing that it can disrupt the life cycle of animals with whom we share the urban and suburban landscape. And the light wasted shining into the sky leads to unnecessary municipal expenses and use of fossil fuels. Concerned people have formed an organization, the International Dark-Sky Association, whose [website \(https://openstax.org/l/30IntDSA\)](https://openstax.org/l/30IntDSA) is full of good information. A citizen science project called [Globe at Night \(https://openstax.org/l/30GlbAtNight\)](https://openstax.org/l/30GlbAtNight) allows you to measure the light levels in your community by counting stars and to compare it to others around the world. Recently, a new threat to dark skies has emerged. A number of commercial companies are planning and launching large swarms of satellites into low-Earth orbit to provide internet access around the world. Unfortunately, these satellites reflect sunlight and have already begun to ruin astronomical photographs the world over. See the [Further Exploration](#) section at the end of this chapter for more resources on this topic. If you get interested in this topic and want to do a paper for your astronomy course or another course while you are in college, the [Dark Night Skies guide \(https://openstax.org/l/30DNSGuide\)](https://openstax.org/l/30DNSGuide) can point you to a variety of resources on the topic.



**Figure 6.12 High and Dry Site.** Cerro Paranal, a mountain summit 2.7 kilometers above sea level in Chile’s Atacama Desert, is the site of the European Southern Observatory’s Very Large Telescope. This photograph shows the four 8-meter telescope buildings on the site and vividly illustrates that astronomers prefer high, dry sites for their instruments. The 4.1-meter Visible and Infrared Survey Telescope for Astronomy (VISTA) can be seen in the distance on the next mountain peak. (credit: ESO)

## The Resolution of a Telescope

In addition to gathering as much light as they can, astronomers also want to have the sharpest images possible. **Resolution** refers to the precision of detail present in an image: that is, the smallest features that can be distinguished. Astronomers are always eager to make out more detail in the images they study, whether they are following the weather on Jupiter or trying to peer into the violent heart of a “cannibal galaxy” that recently ate its neighbor for lunch.

One factor that determines how good the resolution will be is the size of the telescope. Larger apertures produce sharper images. Until very recently, however, visible-light and infrared telescopes on Earth’s surface could not produce images as sharp as the theory of light said they should.

The problem—as we saw earlier in this chapter—is our planet’s atmosphere, which is turbulent. It contains many small-scale blobs or cells of gas that range in size from inches to several feet. Each cell has a slightly different temperature from its neighbor, and each cell acts like a lens, bending (refracting) the path of the light by a small amount. This bending slightly changes the position where each light ray finally reaches the detector in a telescope. The cells of air are in motion, constantly being blown through the light path of the telescope by winds, often in different directions at different altitudes. As a result, the path followed by the light is constantly changing.

For an analogy, think about watching a parade from a window high up in a skyscraper. You decide to throw some confetti down toward the marchers. Even if you drop a handful all at the same time and in the same direction, air currents will toss the pieces around, and they will reach the ground at different places. As we described earlier, we can think of the light from the stars as a series of parallel beams, each making its way through the atmosphere. Each path will be slightly different, and each will reach the detector of the telescope at a slightly different place. The result is a blurred image, and because the cells are being blown by the wind, the nature of the blur will change many times each second. You have probably noticed this effect as the “twinkling” of stars seen from Earth. The light beams are bent enough that part of the time they reach your eye, and part of the time some of them miss, thereby making the star seem to vary in brightness. In space, however, the light of the stars is steady.

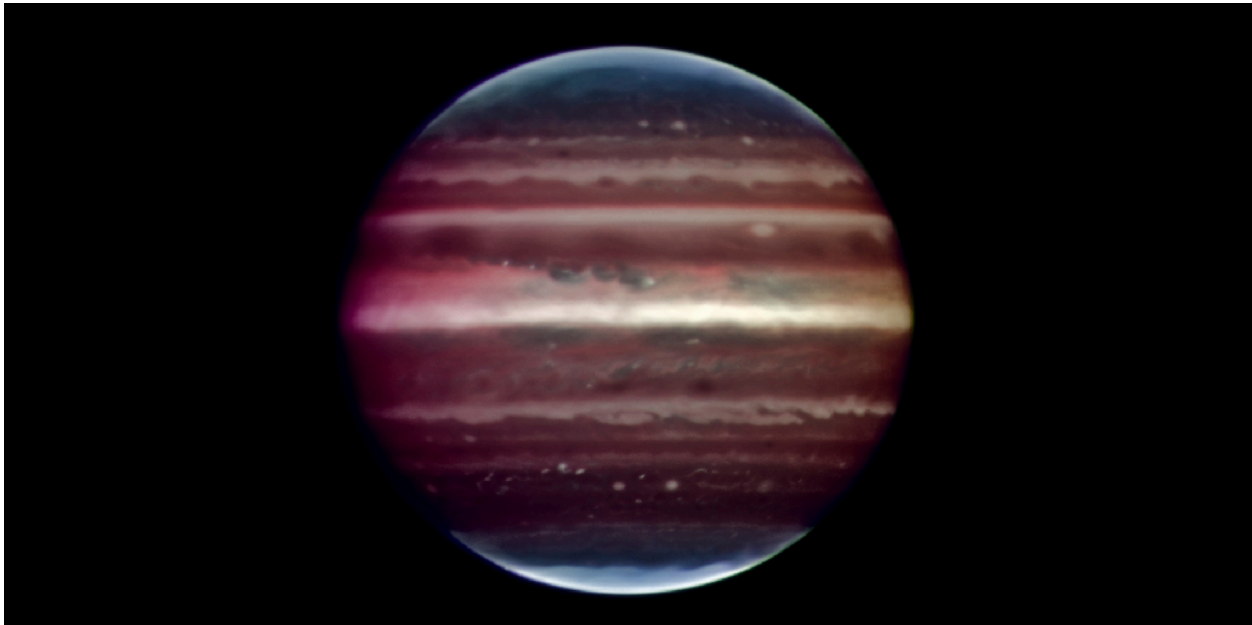
Astronomers search the world for locations where the amount of atmospheric blurring, or turbulence, is as small as possible. It turns out that the best sites are in coastal mountain ranges and on isolated volcanic peaks in the middle of an ocean. Air that has flowed long distances over water before it encounters land is especially stable.

The resolution of an image is measured in units of angle on the sky, typically in units of arcseconds. One arcsecond is  $1/3600$  degree, and there are 360 degrees in a full circle. So we are talking about tiny angles on



the sky. To give you a sense of just how tiny, we might note that 1 arcsecond is how big a quarter would look when seen from a distance of 5 kilometers. The best images obtained from the ground with traditional techniques reveal details as small as several tenths of an arcsecond across. This image size is remarkably good. One of the main reasons for launching the Hubble Space Telescope was to escape Earth's atmosphere and obtain even sharper images.

But since we can't put every telescope into space, astronomers have devised a technique called **adaptive optics** that can beat Earth's atmosphere at its own game of blurring. This technique (which is most effective in the infrared region of the spectrum with our current technology) makes use of a small flexible mirror placed in the beam of a telescope. A sensor measures how much the atmosphere has distorted the image, and as often as 500 times per second, it sends instructions to the flexible mirror on how to change shape in order to compensate for distortions produced by the atmosphere. The light is thus brought back to an almost perfectly sharp focus at the detector. [Figure 6.13](#) shows just how effective this technique is. With adaptive optics, ground-based telescopes can achieve resolutions of 0.1 arcsecond or a little better in the infrared region of the spectrum. This impressive figure is the equivalent of the resolution that the Hubble Space Telescope achieves in the visible-light region of the spectrum.



**Figure 6.13 Power of Adaptive Optics.** One of the clearest pictures of Jupiter ever taken from the ground, this image was produced with adaptive optics using an 8-meter-diameter telescope at the Very Large Telescope in Chile. Adaptive optics uses infrared wavelengths to remove atmospheric blurring, resulting in a much clearer image. (credit: modification of work by ESO, F.Marchis, M.Wong (UC Berkeley); E.Marchetti, P.Amico, S.Tordo (ESO))

## ASTRONOMY BASICS



### How Astronomers Really Use Telescopes

In the popular view (and some bad movies), an astronomer spends most nights in a cold observatory peering through a telescope, but this is not very accurate today. Most astronomers do not live at observatories, but near the universities or laboratories where they work. An astronomer might spend only a week or so each year observing at the telescope and the rest of the time measuring or analyzing the data acquired from large project collaborations and dedicated surveys. Many astronomers use radio telescopes for space experiments, which work just as well during the daylight hours. Still others work at purely theoretical problems using supercomputers and never observe at a telescope of any kind.

Even when astronomers are observing with large telescopes, they seldom peer through them. Electronic detectors permanently record the data for detailed analysis later. At some observatories, observations may be made remotely, with the astronomer sitting at a computer thousands of miles away from the telescope.

Time on major telescopes is at a premium, and an observatory director will typically receive many more requests for telescope time than can be accommodated during the year. Astronomers must therefore write a convincing proposal explaining how they would like to use the telescope and why their observations will be important to the progress of astronomy. A committee of astronomers is then asked to judge and rank the proposals, and time is assigned only to those with the greatest merit. Even if your proposal is among the high-rated ones, you may have to wait many months for your turn. If the skies are cloudy on the nights you have been assigned, it may be more than a year before you get another chance.

Some older astronomers still remember long, cold nights spent alone in an observatory dome, with only music from a tape recorder or an all-night radio station for company. The sight of the stars shining brilliantly hour after hour through the open slit in the observatory dome was unforgettable. So, too, was the relief as the first pale light of dawn announced the end of a 12-hour observation session. Astronomy is much easier today, with teams of observers working together, often at their computers, in a warm room. Those who are more nostalgic, however, might argue that some of the romance has gone from the field, too.

### 6.3 Visible-Light Detectors and Instruments

#### Learning Objectives

By the end of this section, you will be able to:

- Describe the difference between photographic plates and charge-coupled devices
- Describe the unique difficulties associated with infrared observations and their solutions
- Describe how a spectrometer works

After a telescope collects radiation from an astronomical source, the radiation must be *detected* and measured. The first detector used for astronomical observations was the human eye, but it suffers from being connected to an imperfect recording and retrieving device—the human brain. Photography and modern electronic detectors have eliminated the quirks of human memory by making a permanent record of the information from the cosmos.

The eye also suffers from having a very short *integration time*; it takes only a fraction of a second to add light energy together before sending the image to the brain. One important advantage of modern detectors is that the light from astronomical objects can be collected by the detector over longer periods of time; this technique is called “taking a long exposure.” Exposures of several hours are required to detect very faint objects in the cosmos.

Before the light reaches the detector, astronomers today normally use some type of instrument to sort the light according to wavelength. The instrument may be as simple as colored filters, which transmit light within a specified range of wavelengths. A red transparent plastic is an everyday example of a filter that transmits only the red light and blocks the other colors. After the light passes through a filter, it forms an image that astronomers can then use to measure the apparent brightness and color of objects. We will show you many examples of such images in the later chapters of this book, and we will describe what we can learn from them.

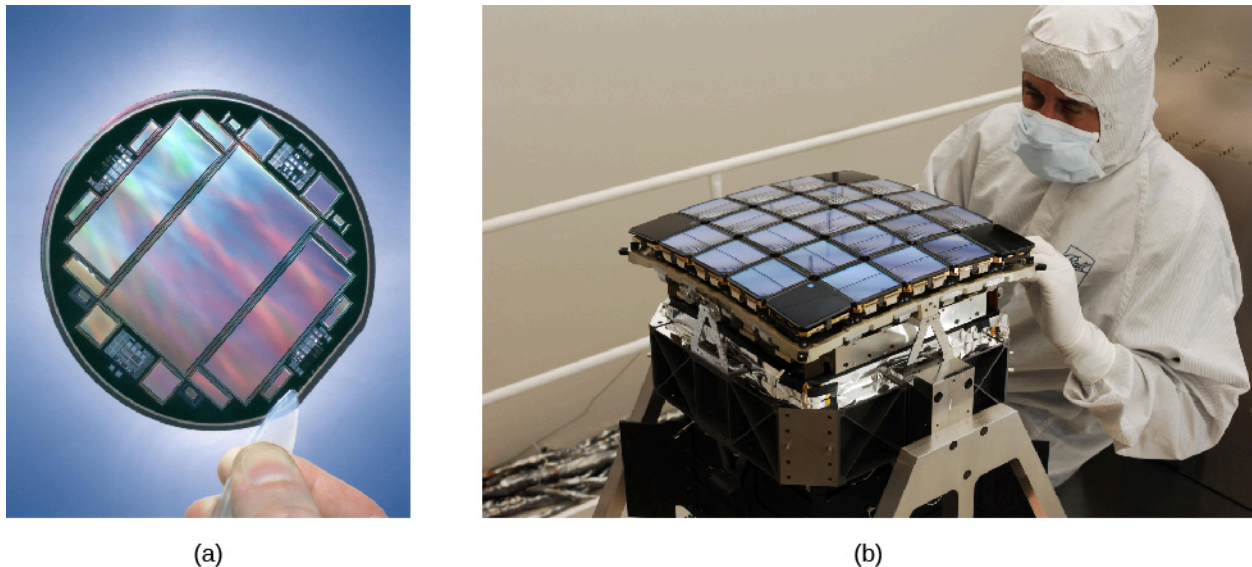
Alternatively, the instrument between telescope and detector may be one of several devices that spread the light out into its full rainbow of colors so that astronomers can measure individual lines in the spectrum. Such an instrument (which you learned about in the chapter on [Radiation and Spectra](#)) is called a *spectrometer* because it allows astronomers to measure (to meter) the spectrum of a source of radiation. Whether a filter or

a spectrometer, both types of wavelength-sorting instruments still have to use detectors to record and measure the properties of light.

### Photographic and Electronic Detectors

Throughout most of the twentieth century, photographic film or *glass plates* served as the prime astronomical detectors, whether for photographing spectra or direct images of celestial objects. In a photographic plate, a light-sensitive chemical coating is applied to a piece of glass that, when developed, provides a lasting record of the image. At observatories around the world, vast collections of photographs preserve what the sky has looked like during the past 100 years. Photography represents a huge improvement over the human eye, but it still has limitations. Photographic films are inefficient: only about 1% of the light that actually falls on the film contributes to the chemical change that makes the image; the rest is wasted.

Astronomers today have much more efficient electronic detectors to record astronomical images. Most often, these are **charge-coupled devices (CCDs)**, which are similar to the detectors used in video camcorders or in digital cameras (like the one more and more students have on their cell phones) (see [Figure 6.14](#)). In a CCD, photons of radiation hitting any part of the detector generate a stream of charged particles (electrons) that are stored and counted at the end of the exposure. Each place where the radiation is counted is called a pixel (picture element), and modern detectors can count the photons in millions of pixels (megapixels, or MPs).



**Figure 6.14 Charge-Coupled Devices (CCDs).** (a) This CCD is a mere 300-micrometers thick (thinner than a human hair) yet holds more than 21 million pixels. (b) This matrix of 42 CCDs served the Kepler telescope. (credit a: modification of work by US Department of Energy; credit b: modification of work by NASA and Ball Aerospace)

Because CCDs typically record as much as 60–70% of all the photons that strike them, and the best silicon and infrared CCDs exceed 90% sensitivity, we can detect much fainter objects. Among these are many small moons around the outer planets, icy dwarf planets beyond Pluto, and dwarf galaxies of stars. CCDs also provide more accurate measurements of the brightness of astronomical objects than photography, and their output is digital—in the form of numbers that can go directly into a computer for analysis.

### Infrared Observations

Observing the universe in the infrared band of the spectrum presents some additional challenges. The infrared region extends from wavelengths near 1 micrometer ( $\mu\text{m}$ ), which is about the long wavelength sensitivity limit of both CCDs and photography, to 100 micrometers or longer. Recall from the discussion on radiation and spectra that infrared is “heat radiation” (given off at temperatures that we humans are comfortable with). The main challenge to astronomers using infrared is to distinguish between the tiny amount of heat radiation that reaches Earth from stars and galaxies, and the much greater heat radiated by

the telescope itself and our planet's atmosphere.

Typical temperatures on Earth's surface are near 300 K, and the atmosphere through which observations are made is only a little cooler. According to Wien's law (from the chapter on [Radiation and Spectra](#)), the telescope, the observatory, and even the sky are radiating infrared energy with a peak wavelength of about 10 micrometers. To infrared eyes, everything on Earth is brightly aglow—including the telescope and camera ([Figure 6.15](#)). The challenge is to detect faint cosmic sources against this sea of infrared light. Another way to look at this is that an astronomer using infrared must always contend with the situation that a visible-light observer would face if working in broad daylight with a telescope and optics lined with bright fluorescent lights.



**Figure 6.15 Infrared Eyes.** Infrared waves can penetrate places in the universe from which light is blocked, as shown in this infrared image where the plastic bag blocks visible light but not infrared. (credit: NASA/JPL-Caltech/R. Hurt (SSC))

To solve this problem, astronomers must protect the infrared detector from nearby radiation, just as you would shield photographic film from bright daylight. Since anything warm radiates infrared energy, the detector must be isolated in very cold surroundings; often, it is held near absolute zero (1 to 3 K) by immersing it in liquid helium. The second step is to reduce the radiation emitted by the telescope structure and optics, and to block this heat from reaching the infrared detector.

#### LINK TO LEARNING



Check out [The Infrared Zoo \(https://openstax.org/l/30IFZoo\)](https://openstax.org/l/30IFZoo) to get a sense of what familiar objects look like with infrared radiation. Slide the slider to change the wavelength of radiation for the picture, and click the arrow to see other animals.

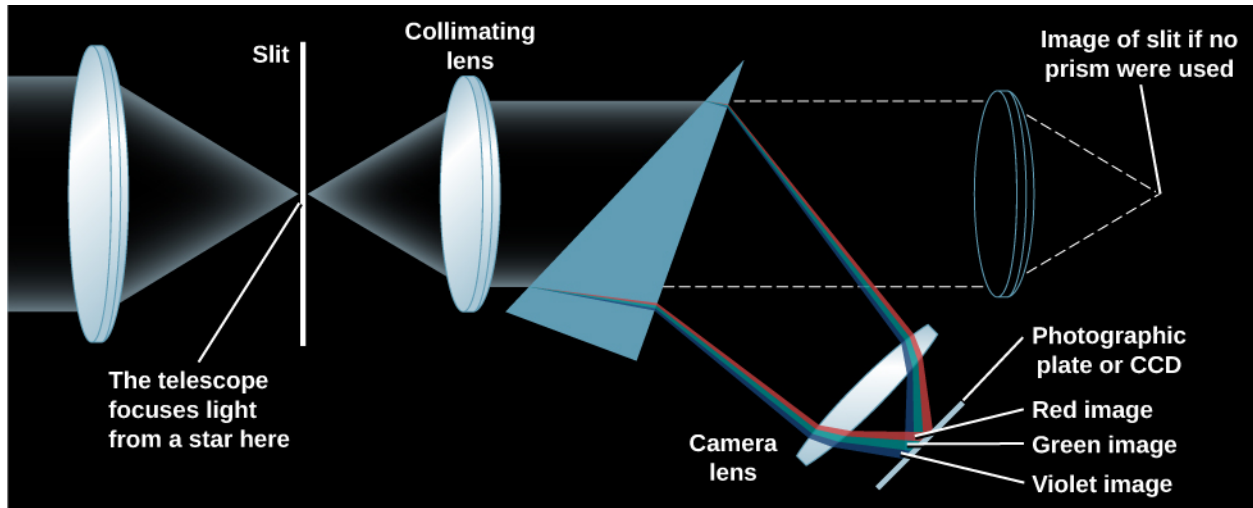
## Spectroscopy

Spectroscopy is one of the astronomer's most powerful tools, providing information about the composition, temperature, motion, and other characteristics of celestial objects. More than half of the time spent on most large telescopes is used for spectroscopy.

The many different wavelengths present in light can be separated by passing them through a spectrometer to form a spectrum. The design of a simple spectrometer is illustrated in [Figure 6.16](#). Light from the source (actually, the image of a source produced by the telescope) enters the instrument through a small hole or



narrow slit, and is collimated (made into a beam of parallel rays) by a lens. The light then passes through a prism, producing a spectrum: different wavelengths leave the prism in different directions because each wavelength is bent by a different amount when it enters and leaves the prism. A second lens placed behind the prism focuses the many different images of the slit or entrance hole onto a CCD or other detecting device. This collection of images (spread out by color) is the spectrum that astronomers can then analyze at a later point. As spectroscopy spreads the light out into more and more collecting bins, fewer photons go into each bin, so either a larger telescope is needed or the integration time must be greatly increased—usually both.



**Figure 6.16 Prism Spectrometer.** The light from the telescope is focused on a slit. A prism (or grating) disperses the light into a spectrum, which is then photographed or recorded electronically.

In practice, astronomers today are more likely to use a different device, called a *grating*, to disperse the spectrum. A grating is a piece of material with thousands of grooves on its surface. While it functions completely differently, a grating, like a prism, also spreads light out into a spectrum.

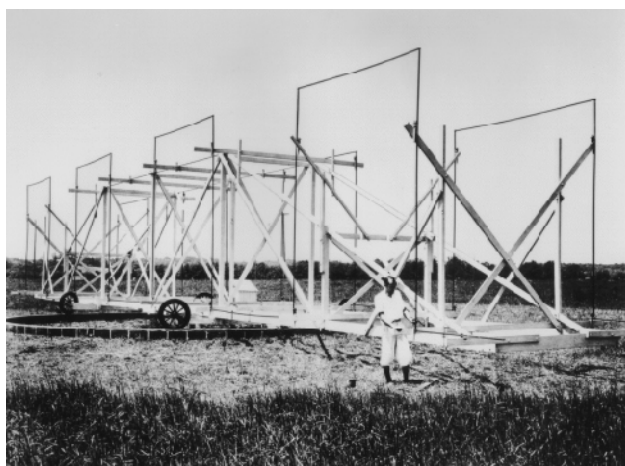
## 6.4 Radio Telescopes

### Learning Objectives

By the end of this section, you will be able to:

- Describe how radio waves from space are detected
- Identify the world's largest radio telescopes
- Define the technique of interferometry and discuss the benefits of interferometers over single-dish telescopes

In addition to visible and infrared radiation, radio waves from astronomical objects can also be detected from the surface of Earth. In the early 1930s, Karl G. Jansky, an engineer at Bell Telephone Laboratories, was experimenting with antennas for long-range radio communication when he encountered some mysterious static—radio radiation coming from an unknown source ([Figure 6.17](#)). He discovered that this radiation came in strongest about four minutes earlier on each successive day and correctly concluded that since Earth's sidereal rotation period (how long it takes us to rotate relative to the stars) is four minutes shorter than a solar day, the radiation must be originating from some region fixed on the celestial sphere. Subsequent investigation showed that the source of this radiation was part of the Milky Way Galaxy; Jansky had discovered the first source of cosmic radio waves.



**Figure 6.17 First Radio Telescope.** This rotating radio antenna was used by Jansky in his serendipitous discovery of radio radiation from the Milky Way.

In 1936, Grote Reber, who was an amateur astronomer interested in radio communications, used galvanized iron and wood to build the first antenna specifically designed to receive cosmic radio waves. Over the years, Reber built several such antennas and used them to carry out pioneering surveys of the sky for celestial radio sources; he remained active in radio astronomy for more than 30 years. During the first decade, he worked practically alone because professional astronomers had not yet recognized the vast potential of radio astronomy.

### Detection of Radio Energy from Space

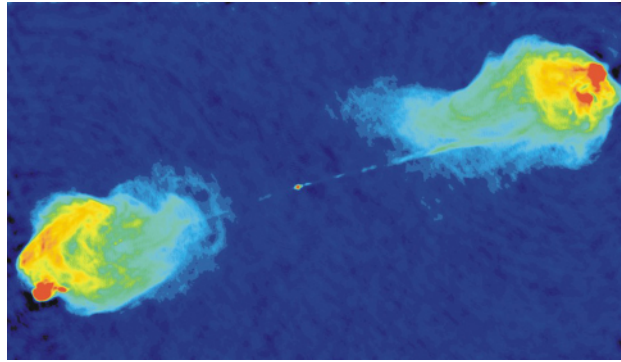
It is important to understand that radio waves cannot be “heard”: they are not the sound waves you hear coming out of the radio receiver in your home or car. Like light, radio waves are a form of electromagnetic radiation, but unlike light, we cannot detect them with our senses—we must rely on electronic equipment to pick them up. In commercial radio broadcasting, we encode sound information (music or a newscaster’s voice) into radio waves. These must be decoded at the other end and then turned back into sound by speakers or headphones.

The radio waves we receive from space do not, of course, have music or other program information encoded in them. If cosmic radio signals were translated into sound, they would sound like the static you hear when scanning between stations. Nevertheless, there is information in the radio waves we receive—information that can tell us about the chemistry and physical conditions of the sources of the waves.

Just as vibrating charged particles can produce electromagnetic waves (see the [Radiation and Spectra](#) chapter), electromagnetic waves can make charged particles move back and forth. Radio waves can produce a current in conductors of electricity such as metals. An antenna is such a conductor: it intercepts radio waves, which create a feeble current in it. The current is then amplified in a radio receiver until it is strong enough to measure or record. Like your television or radio, receivers can be tuned to select a single frequency (channel). In astronomy, however, it is more common to use sophisticated data-processing techniques that allow thousands of separate frequency bands to be detected simultaneously. Thus, the astronomical radio receiver operates much like a spectrometer on a visible-light or infrared telescope, providing information about how much radiation we receive at each wavelength or frequency. After computer processing, the radio signals are recorded on magnetic disks for further analysis.

Radio waves are reflected by conducting surfaces, just as light is reflected from a shiny metallic surface, and according to the same laws of optics. A radio-reflecting telescope consists of a concave metal reflector (called a *dish*), analogous to a telescope mirror. The radio waves collected by the dish are reflected to a focus, where they can then be directed to a receiver and analyzed. Because humans are such visual creatures, radio astronomers often construct a pictorial representation of the radio sources they observe. [Figure 6.18](#) shows

such a radio image of a distant galaxy, where radio telescopes reveal vast jets and complicated regions of radio emissions that are completely invisible in photographs taken with light.



**Figure 6.18 Radio Image.** This image has been constructed of radio observations at the Very Large Array of a galaxy called Cygnus A. Colors have been added to help the eye sort out regions of different radio intensities. Red regions are the most intense, blue the least. The visible galaxy would be a small dot in the center of the image. The radio image reveals jets of expelled material (more than 160,000 light-years long) on either side of the galaxy. (credit: NRAO/AUI)

Radio astronomy is a young field compared with visible-light astronomy, but it has experienced tremendous growth in recent decades. The world's largest radio reflectors that can be pointed to any direction in the sky have apertures of 100 meters. One of these has been built at the US National Radio Astronomy Observatory in West Virginia ([Figure 6.19](#)). [Table 6.2](#) lists some of the major radio telescopes of the world.



**Figure 6.19 Robert C. Byrd Green Bank Telescope.** This fully steerable radio telescope in West Virginia went into operation in August 2000. Its dish is about 100 meters across. (credit: modification of work by “b3nscott”/Flickr)

**Major Radio Observatories of the World**

Observatory	Location	Description	Website
Individual Radio Dishes			
Five-hundred-meter Aperture Spherical radio Telescope (FAST)	Guizhou, China	500-m fixed dish	<a href="http://fast.bao.ac.cn/en/">fast.bao.ac.cn/en/</a>

**Table 6.2**

Observatory	Location	Description	Website
Arecibo Observatory	Arecibo, Puerto Rico	305-m fixed dish	<a href="http://www.naic.edu">www.naic.edu</a>
Green Bank Telescope (GBT)	Green Bank, WV	110 × 100-m steerable dish	<a href="http://www.science.nrao.edu/facilities/gbt">www.science.nrao.edu/facilities/gbt</a>
Effelsberg 100-m Telescope	Bonn, Germany	100-m steerable dish	<a href="http://www.mpifr-bonn.mpg.de/en/effelsberg">www.mpifr-bonn.mpg.de/en/effelsberg</a>
Lovell Telescope	Manchester, England	76-m steerable dish	<a href="http://www.jb.man.ac.uk/aboutus/lovell">www.jb.man.ac.uk/aboutus/lovell</a>
Canberra Deep Space Communication Complex (CDSCC)	Tidbinbilla, Australia	70-m steerable dish	<a href="http://www.cdsc.nasa.gov">www.cdsc.nasa.gov</a>
Goldstone Deep Space Communications Complex (GDSCC)	Barstow, CA	70-m steerable dish	<a href="http://www.gdsc.nasa.gov">www.gdsc.nasa.gov</a>
Parkes Observatory	Parkes, Australia	64-m steerable dish	<a href="http://www.parkes.atnf.csiro.au">www.parkes.atnf.csiro.au</a>
Arrays of Radio Dishes			
Square Kilometre Array (SKA)	South Africa and Western Australia	Thousands of dishes, km <sup>2</sup> collecting area, partial array in 2020	<a href="http://www.skatelescope.org">www.skatelescope.org</a>
Atacama Large Millimeter/submillimeter Array (ALMA)	Atacama desert, Northern Chile	66 7-m and 12-m dishes	<a href="http://www.almaobservatory.org">www.almaobservatory.org</a>
Jansky Very Large Array (VLA)	Socorro, New Mexico	27-element array of 25-m dishes (36-km baseline)	<a href="http://www.science.nrao.edu/facilities/vla">www.science.nrao.edu/facilities/vla</a>
Westerbork Synthesis Radio Telescope (WSRT)	Westerbork, the Netherlands	12-element array of 25-m dishes (1.6-km baseline)	<a href="http://www.astron.nl/radio-observatory/public/public-0">www.astron.nl/radio-observatory/public/public-0</a>
Very Long Baseline Array (VLBA)	Ten US sites, HI to the Virgin Islands	10-element array of 25-m dishes (9000 km baseline)	<a href="http://www.science.nrao.edu/facilities/vlba">www.science.nrao.edu/facilities/vlba</a>

Table 6.2



Observatory	Location	Description	Website
Australia Telescope Compact Array (ATCA)	Several sites in Australia	8-element array (seven 22-m dishes plus Parkes 64 m)	<a href="http://www.narrabri.atnf.csiro.au">www.narrabri.atnf.csiro.au</a>
Multi-Element Radio Linked Interferometer Network (MERLIN)	Cambridge, England, and other British sites	Network of seven dishes (the largest is 32 m)	<a href="http://www.e-merlin.ac.uk">www.e-merlin.ac.uk</a>
Millimeter-wave Telescopes			
IRAM	Granada, Spain	30-m steerable mm-wave dish	<a href="http://www.iram-institute.org">www.iram-institute.org</a>
James Clerk Maxwell Telescope (JCMT)	Maunakea, HI	15-m steerable mm-wave dish	<a href="http://www.eaobservatory.org/jcmt">www.eaobservatory.org/jcmt</a>
Nobeyama Radio Observatory (NRO)	Minamimaki, Japan	6-element array of 10-m wave dishes	<a href="http://www.nro.nao.ac.jp/en">www.nro.nao.ac.jp/en</a>
Hat Creek Radio Observatory (HCRO)	Cassel, CA	6-element array of 5-m wave dishes	<a href="http://www.sri.com/research-development/specialized-facilities/hat-creek-radio-observatory">www.sri.com/research-development/specialized-facilities/hat-creek-radio-observatory</a>

Table 6.2

## Radio Interferometry

As we discussed earlier, a telescope's ability to show us fine detail (its resolution) depends upon its aperture, but it also depends upon the wavelength of the radiation that the telescope is gathering. The longer the waves, the harder it is to resolve fine detail in the images or maps we make. Because radio waves have such long wavelengths, they present tremendous challenges for astronomers who need good resolution. In fact, even the largest radio dishes on Earth, operating alone, cannot make out as much detail as the typical small visible-light telescope used in a college astronomy lab. To overcome this difficulty, radio astronomers have learned to sharpen their images by linking two or more radio telescopes together electronically. Two or more telescopes linked together in this way are called an **interferometer**.

"Interferometer" may seem like a strange term because the telescopes in an interferometer work cooperatively; they don't "interfere" with each other. **Interference**, however, is a technical term for the way that multiple waves interact with each other when they arrive in our instruments, and this interaction allows us to coax more detail out of our observations. The resolution of an interferometer depends upon the separation of the telescopes, not upon their individual apertures. Two telescopes separated by 1 kilometer provide the same resolution as would a single dish 1 kilometer across (although they are not, of course, able to collect as much radiation as a radio-wave bucket that is 1 kilometer across).

To get even better resolution, astronomers combine a large number of radio dishes into an **interferometer array**. In effect, such an array works like a large number of two-dish interferometers, all observing the same

part of the sky together. Computer processing of the results permits the reconstruction of a high-resolution radio image. The most extensive such instrument in the United States is the National Radio Astronomy Observatory's Jansky Very Large Array (VLA) near Socorro, New Mexico. It consists of 27 movable radio telescopes (on railroad tracks), each having an aperture of 25 meters, spread over a total span of about 36 kilometers. By electronically combining the signals from all of its individual telescopes, this array permits the radio astronomer to make pictures of the sky at radio wavelengths comparable to those obtained with a visible-light telescope, with a resolution of about 1 arcsecond.

The Atacama Large Millimeter/submillimeter array (ALMA) in the Atacama Desert of Northern Chile ([Figure 6.20](#)), at an altitude of 16,400 feet, consists of 12 7-meter and 54 12-meter telescopes, and can achieve baselines up to 16 kilometers. Since it became operational in 2013, it has made observations at resolutions down to 6 milliarcseconds (0.006 arcseconds), a remarkable achievement for radio astronomy.



**Figure 6.20 Atacama Large Millimeter/Submillimeter Array (ALMA).** Located in the Atacama Desert of Northern Chile, ALMA currently provides the highest resolution for radio observations. (credit: ESO/S. Guisard)

### LINK TO LEARNING



Watch this [documentary \(https://openstax.org/l/30ALMAdoc\)](https://openstax.org/l/30ALMAdoc) that explains the work that went into designing and building ALMA, discusses some of its first images, and explores its future.

Initially, the size of interferometer arrays was limited by the requirement that all of the dishes be physically wired together. The maximum dimensions of the array were thus only a few tens of kilometers. However, larger interferometer separations can be achieved if the telescopes do not require a physical connection. Astronomers, with the use of current technology and computing power, have learned to time the arrival of electromagnetic waves coming from space very precisely at each telescope and combine the data later. If the telescopes are as far apart as California and Australia, or as West Virginia and Crimea in Ukraine, the resulting resolution far surpasses that of visible-light telescopes.

The United States operates the Very Long Baseline Array (VLBA), made up of 10 individual telescopes stretching from the Virgin Islands to Hawaii ([Figure 6.21](#)). The VLBA, completed in 1993, can form astronomical images with a resolution of 0.0001 arcseconds, permitting features as small as 10 astronomical units (AU) to be distinguished at the center of our Galaxy.



**Figure 6.21 Very Long Baseline Array.** This map shows the distribution of 10 antennas that constitute an array of radio telescopes stretching across the United States and its territories.

Recent advances in technology have also made it possible to do interferometry at visible-light and infrared wavelengths. At the beginning of the twenty-first century, three observatories with multiple telescopes each began using their dishes as interferometers, combining their light to obtain a much greater resolution. In addition, a dedicated interferometric array was built on Mt. Wilson in California. Just as in radio arrays, these observations allow astronomers to make out more detail than a single telescope could provide.

### Visible-Light Interferometers

Longest Baseline (m)	Telescope Name	Location	Mirrors	Status
400	CHARA Array (Center for High Angular Resolution Astronomy)	Mount Wilson, CA	Six 1-m telescopes	Operational since 2004
200	Very Large Telescope	Cerro Paranal, Chile	Four 8.2-m telescopes	Completed 2000
85	Keck I and II telescopes	Maunakea, HI	Two 10-m telescopes	Operated from 2001 to 2012
22.8	Large Binocular Telescope	Mount Graham, AZ	Two 8.4-m telescopes	First light 2004

**Table 6.3**

## Radar Astronomy

**Radar** is the technique of transmitting radio waves to an object in our solar system and then detecting the radio radiation that the object reflects back. The time required for the round trip can be measured electronically with great precision. Because we know the speed at which radio waves travel (the speed of light), we can determine the distance to the object or a particular feature on its surface (such as a mountain).

Radar observations have been used to determine the distances to planets and how fast things are moving in the solar system (using the Doppler effect, discussed in the [Radiation and Spectra](#) chapter). Radar waves have played important roles in navigating spacecraft throughout the solar system. In addition, as will be discussed in later chapters, radar observations have determined the rotation periods of Venus and Mercury, probed tiny Earth-approaching asteroids, and allowed us to investigate the mountains and valleys on the surfaces of Mercury, Venus, Mars, and the large moons of Jupiter.

Any radio dish can be used as a radar telescope if it is equipped with a powerful transmitter as well as a

receiver. For many years, the most spectacular facility in the world for radar astronomy was the 1000-foot (305-meter) telescope at Arecibo in Puerto Rico ([Figure 6.22](#)). The Arecibo telescope was too large to be pointed directly at different parts of the sky. Instead, it was constructed in a huge natural “bowl” (more than a mere dish) formed by several hills, and it was lined with reflecting metal panels. A limited ability to track astronomical sources was achieved by moving the receiver system, which was suspended on cables 100 meters above the surface of the bowl. Unfortunately, the telescope was seriously damaged in the powerful storms of 2020 and had to be decommissioned. An even larger (500-meter) radar telescope has recently gone into operation in China and is called the Five-hundred-meter Aperture Spherical Telescope (FAST).



**Figure 6.22 Largest Radio and Radar Dish.** The Arecibo Observatory in Puerto Rico was the largest and most powerful astronomical radar facility in the world and was often featured in films. In November 2020 it collapsed, damaging the 300-meter diameter “dish” and destroying the radar transmitter and receiver. (credit: National Astronomy and Ionosphere Center, Cornell U., NSF)

## 6.5 Observations outside Earth’s Atmosphere

### Learning Objectives

By the end of this section, you will be able to:

- List the advantages of making astronomical observations from space
- Explain the importance of the Hubble Space Telescope
- Describe some of the major space-based observatories astronomers use

Earth’s atmosphere blocks most radiation at wavelengths shorter than visible light, so we can only make direct ultraviolet, X-ray, and gamma ray observations from space (though indirect gamma ray observations can be made from Earth). Getting above the distorting effects of the atmosphere is also an advantage at visible and infrared wavelengths. The stars don’t “twinkle” in space, so the amount of detail you can observe is limited only by the size of your instrument. On the other hand, it is expensive to place telescopes into space, and repairs can present a major challenge. This is why astronomers continue to build telescopes for use on the ground as well as for launching into space.

### Airborne and Space Infrared Telescopes

Water vapor, the main source of atmospheric interference for making infrared observations, is concentrated in the lower part of Earth’s atmosphere. For this reason, a gain of even a few hundred meters in elevation can make an important difference in the quality of an infrared observatory site. Given the limitations of high mountains, most of which attract clouds and violent storms, and the fact that the ability of humans to perform complex tasks degrades at high altitudes, it was natural for astronomers to investigate the possibility of observing infrared waves from airplanes and ultimately from space.

Infrared observations from airplanes have been made since the 1960s, starting with a 15-centimeter telescope on board a Learjet. From 1974 through 1995, NASA operated a 0.9-meter airborne telescope flying regularly

out of the Ames Research Center south of San Francisco. Observing from an altitude of 12 kilometers, the telescope was above 99% of the atmospheric water vapor. More recently, NASA (in partnership with the German Aerospace Center) has constructed a much larger 2.5-meter telescope, called the Stratospheric Observatory for Infrared Astronomy (SOFIA), which flies in a modified Boeing 747SP ([Figure 6.23](#)).



**Figure 6.23 Stratospheric Observatory for Infrared Astronomy (SOFIA).** SOFIA allows observations to be made above most of Earth's atmospheric water vapor. (credit: NASA)

#### LINK TO LEARNING



To find out more about SOFIA, watch this [video \(https://openstax.org/l/30SOFIAvid\)](https://openstax.org/l/30SOFIAvid) provided by NASA's Armstrong Flight Research Center.

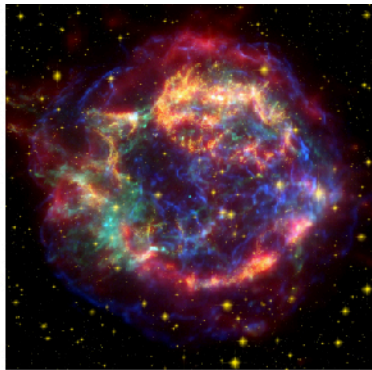
Getting even higher and making observations from space itself have important advantages for infrared astronomy. First is the elimination of all interference from the atmosphere. Equally important is the opportunity to cool the entire optical system of the instrument in order to nearly eliminate infrared radiation from the telescope itself. If we tried to cool a telescope within the atmosphere, it would quickly become coated with condensing water vapor and other gases, making it useless. Only in the vacuum of space can optical elements be cooled to hundreds of degrees below freezing and still remain operational.

The first orbiting infrared observatory, launched in 1983, was the Infrared Astronomical Satellite (IRAS), built as a joint project by the United States, the Netherlands, and Britain. IRAS was equipped with a 0.6-meter telescope cooled to a temperature of less than 10 K. For the first time, the infrared sky could be seen as if it were night, rather than through a bright foreground of atmospheric and telescope emissions. IRAS carried out a rapid but comprehensive survey of the entire infrared sky over a 10-month period, cataloging about 350,000 sources of infrared radiation. Since then, several other infrared telescopes have operated in space with much better sensitivity and resolution due to improvements in infrared detectors. The most powerful of these infrared telescopes is the 0.85-meter Spitzer Space Telescope, which launched in 2003. A few of its observations are shown in [Figure 6.24](#). With infrared observations, astronomers can detect cooler parts of cosmic objects, such as the dust clouds around star nurseries and the remnants of dying stars, that visible-light images don't reveal.





Flame nebula



Cassiopeia A



Helix nebula

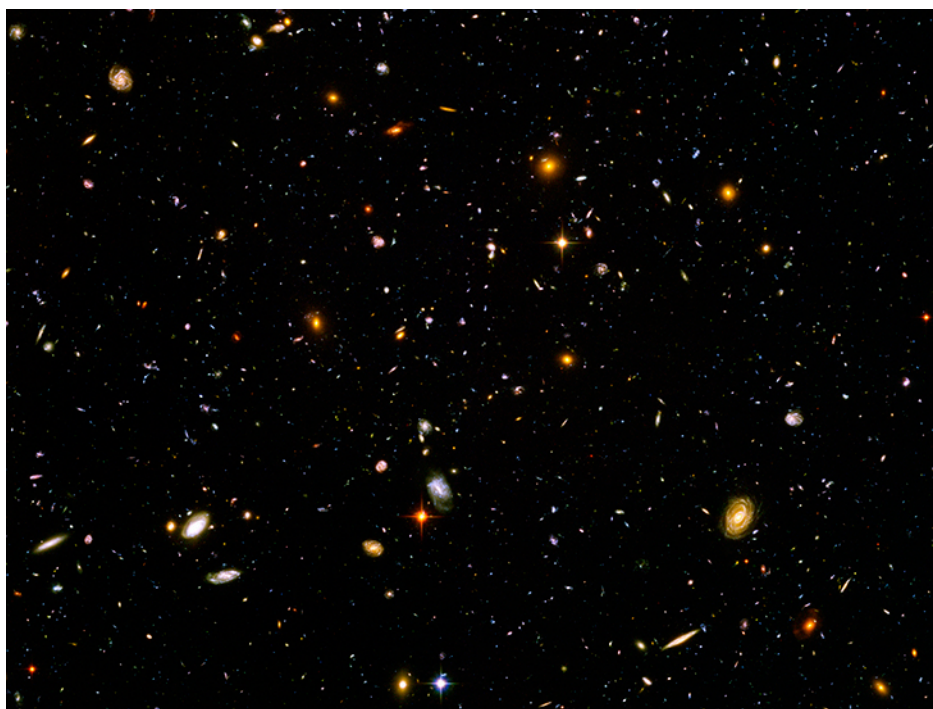
**Figure 6.24 Observations from the Spitzer Space Telescope (SST).** These infrared images—a region of star formation, the remnant of an exploded star, and a region where an old star is losing its outer shell—show just a few of the observations made and transmitted back to Earth from the SST. Since our eyes are not sensitive to infrared rays, we don't perceive colors from them. The colors in these images have been selected by astronomers to highlight details like the composition or temperature in these regions. (credit "Flame nebula": modification of work by NASA (X-ray: NASA/CXC/PSU/K.Getman, E.Feigelson, M.Kuhn & the MYStIX team; Infrared: NASA/JPL-Caltech); credit "Cassiopeia A": modification of work by NASA/JPL-Caltech; credit "Helix nebula": modification of work by NASA/JPL-Caltech)

## Hubble Space Telescope

In April 1990, a great leap forward in astronomy was made with the launch of the Hubble Space Telescope (HST). With an aperture of 2.4 meters, this is the largest telescope put into space so far. (Its aperture was limited by the size of the payload bay in the Space Shuttle that served as its launch vehicle.) It was named for Edwin Hubble, the astronomer who discovered the expansion of the universe in the 1920s (whose work we will discuss in the chapters on [Galaxies](#)).

HST is operated jointly by NASA's Goddard Space Flight Center and the Space Telescope Science Institute in Baltimore. It was the first orbiting observatory designed to be serviced by Shuttle astronauts and, over the years since it was launched, they made several visits to improve or replace its initial instruments and to repair some of the systems that operate the spacecraft ([Figure 6.1](#))—though this repair program has now been discontinued, and no more visits or improvements will be made.

With the Hubble, astronomers have obtained some of the most detailed images of astronomical objects from the solar system outward to the most distant galaxies. Among its many great achievements is the Hubble Ultra-Deep Field, an image of a small region of the sky observed for almost 100 hours. It contains views of about 10,000 galaxies, some of which formed when the universe was just a few percent of its current age ([Figure 6.25](#)).



**Figure 6.25 Hubble Ultra-Deep Field (HUDF).** The Hubble Space Telescope has provided an image of a specific region of space built from data collected between September 24, 2003, and January 16, 2004. These data allow us to search for galaxies that existed approximately 13 billion years ago. (credit: modification of work by NASA)

The HST's mirror was ground and polished to a remarkable degree of accuracy. If we were to scale up its 2.4-meter mirror to the size of the entire continental United States, there would be no hill or valley larger than about 6 centimeters in its smooth surface. Unfortunately, after it was launched, scientists discovered that the primary mirror had a slight error in its *shape*, equal to roughly 1/50 the width of a human hair. Small as that sounds, it was enough to ensure that much of the light entering the telescope did not come to a clear focus and that all the images were blurry. (In a misplaced effort to save money, a complete test of the optical system had not been carried out before launch, so the error was not discovered until HST was in orbit.)

The solution was to do something very similar to what we do for astronomy students with blurry vision: put corrective optics in front of their eyes. In December 1993, in one of the most exciting and difficult space missions ever flown, astronauts captured the orbiting telescope and brought it back into the shuttle payload bay. There they installed a package containing compensating optics as well as a new, improved camera before releasing HST back into orbit. The telescope now works as it was intended to, and further missions to it were able to install even more advanced instruments to take advantage of its capabilities.

### High-Energy Observatories

Ultraviolet, X-ray, and direct gamma-ray (high-energy electromagnetic wave) observations can be made only from space. Such observations first became possible in 1946, with V2 rockets captured from Germany after World War II. The US Naval Research Laboratory put instruments on these rockets for a series of pioneering flights, used initially to detect ultraviolet radiation from the Sun. Since then, many other rockets have been launched to make X-ray and ultraviolet observations of the Sun, and later of other celestial objects.

Beginning in the 1960s, a steady stream of high-energy observatories has been launched into orbit to reveal and explore the universe at short wavelengths. Among recent X-ray telescopes is the Chandra X-ray Observatory, which was launched in 1999 ([Figure 6.26](#)). It is producing X-ray images with unprecedented resolution and sensitivity. Designing instruments that can collect and focus energetic radiation like X-rays and gamma rays is an enormous technological challenge. The 2002 Nobel Prize in physics was awarded to Riccardo Giacconi, a pioneer in the field of building and launching sophisticated X-ray instruments. In 2008, NASA

launched the Fermi Gamma-ray Space Telescope, designed to measure cosmic gamma rays at energies greater than any previous telescope, and thus able to collect radiation from some of the most energetic events in the universe.



**Figure 6.26 Chandra X-Ray Satellite.** Chandra, the world’s most powerful X-ray telescope, was developed by NASA and launched in July 1999. (credit: modification of work by NASA)

One major challenge is to design “mirrors” to reflect such penetrating radiation as X-rays and gamma rays, which normally pass straight through matter. However, although the technical details of design are more complicated, the three basic components of an observing system, as we explained earlier in this chapter, are the same at all wavelengths: a telescope to gather up the radiation, filters or instruments to sort the radiation according to wavelength, and some method of detecting and making a permanent record of the observations. [Table 6.4](#) lists some of the most important active space observatories that humanity has launched.

Gamma-ray detections can also be made from Earth’s surface by using the atmosphere as the primary detector. When a gamma ray hits our atmosphere, it accelerates charged particles (mostly electrons) in the atmosphere. Those energetic particles hit other particles in the atmosphere and give off their own radiation. The effect is a cascade of light and energy that can be detected on the ground. The VERITAS array in Arizona and the H.E.S.S. array in Namibia are two such ground-based gamma-ray observatories.

**Recent Observatories in Space**

Observatory	Date Operation Began	Bands of the Spectrum	Notes	Website
Hubble Space Telescope (HST)	1990	visible, UV, IR	2.4-m mirror; images and spectra	<a href="http://www.hubblesite.org">www.hubblesite.org</a>
Chandra X-Ray Observatory	1999	X-rays	X-ray images and spectra	<a href="http://www.chandra.si.edu">www.chandra.si.edu</a>

**Table 6.4**

Observatory	Date Operation Began	Bands of the Spectrum	Notes	Website
XMM-Newton	1999	X-rays	X-ray spectroscopy	<a href="http://www.cosmos.esa.int/web/xmm-newton">http://www.cosmos.esa.int/web/xmm-newton</a>
International Gamma-Ray Astrophysics Laboratory (INTEGRAL)	2002	X- and gamma-rays	higher resolution gamma-ray images	<a href="http://sci.esa.int/integral/">http://sci.esa.int/integral/</a>
Spitzer Space Telescope	2003	IR	0.85-m telescope	<a href="http://www.spitzer.caltech.edu">www.spitzer.caltech.edu</a>
Fermi Gamma-ray Space Telescope	2008	gamma-rays	first high-energy gamma-ray observations	<a href="http://fermi.gsfc.nasa.gov">fermi.gsfc.nasa.gov</a>
Kepler	2009	visible-light	planet finder	<a href="http://kepler.nasa.gov">http://kepler.nasa.gov</a>
Wide-field Infrared Survey Explorer (WISE)	2009	IR	whole-sky map, asteroid searches	<a href="http://www.nasa.gov/mission_pages/WISE/main">www.nasa.gov/mission_pages/WISE/main</a>
Gaia	2013	visible-light	Precise map of the Milky Way	<a href="http://sci.esa.int/gaia/">http://sci.esa.int/gaia/</a>
Transiting Exoplanet Survey Satellite (TESS)	2018	visible-light	Planet finder	<a href="http://tess.mit.edu">http://tess.mit.edu</a>

Table 6.4

## 6.6 The Future of Large Telescopes

### Learning Objectives

By the end of this section, you will be able to:

- Describe the next generation of ground- and space-based observatories
- Explain some of the challenges involved in building these observatories

If you've ever gone on a hike, you have probably been eager to see what lies just around the next bend in the path. Researchers are no different, and astronomers and engineers are working on the technologies that will allow us to explore even more distant parts of the universe and to see them more clearly.

The premier space facility planned for the next decade is the James Webb Space Telescope ([Figure 6.27](#)), which was launched on December 25, 2021. James Webb was one of the early administrators in NASA. As we write this (in December 2021), the telescope is on its way to a stable orbit point, some 1.5 million kilometers from Earth (where no astronauts can currently travel if the facility needs repair). During its 29-day journey, a number of activities must be successfully executed in order to prepare the JWST to make observations. A solar array will be deployed to provide energy, and a sunshield will be stretched out to protect the telescope from the intense heat of the Sun. The secondary and primary mirrors will then be unfolded. The primary mirror is 6 meters in diameter, made up, like the Keck telescopes, of 36 small hexagons. JWST has been designed to

operate at infrared wavelengths and will have the sensitivity needed to detect the very first generation of stars, formed when the universe was only a few hundred million years old.



**Figure 6.27 James Webb Space Telescope (JWST).** This image shows some of the mirrors of the JWST as they underwent cryogenic testing. The mirrors were exposed to extreme temperatures in order to gather accurate measurements on changes in their shape as they heated and cooled. (credit: NASA/MSFC/David Higginbotham/Emmett Given)

### LINK TO LEARNING



Watch this [video \(https://openstax.org/l/30JWSTvid\)](https://openstax.org/l/30JWSTvid) to learn more about the James Webb Space Telescope and how it will build upon the work that Hubble has allowed us to begin in exploring the universe. Visit [NASA's James Webb Space Telescope site \(https://openstax.org/l/30JWSTtrack\)](https://openstax.org/l/30JWSTtrack) to keep track of how the JWST is doing.

On the ground, astronomers have started building the Vera Rubin Observatory<sup>1</sup>, which has an 8.4-meter telescope with a significantly larger field of view than any existing telescopes. It will rapidly scan the sky to find *transients*, phenomena that change quickly, such as exploding stars and chunks of rock that orbit near Earth. It is expected to see first light in 2022.

The international gamma-ray community is planning the Cherenkov Telescope Array (CTA), two arrays of telescopes, one in each hemisphere, which will indirectly measure gamma rays from the ground. The CTA will measure gamma-ray energies a thousand times as great as the Fermi telescope can detect.

Several groups of astronomers around the globe interested in studying visible light and the infrared are exploring the feasibility of building ground-based telescopes with mirrors larger than 30 meters across. Stop and think what this means: 30 meters is one-third the length of a football field. It is technically impossible to build and transport a single astronomical mirror that is 30 meters or larger in diameter. The primary mirror of these giant telescopes will consist of smaller mirrors, all aligned so that they act as a very large mirror in combination.

The most ambitious of these projects is the European Extremely Large Telescope (ELT) ([Figure 6.28](#)). (Astronomers try to outdo each other not only with the size of these telescopes, but also their names!) The design of the European ELT calls for a 39.3-meter primary mirror, which will follow the Keck design and be made up of 798 hexagonal mirrors, each 1.4 meters in diameter and all held precisely in position so that they form a continuous surface. Construction on the site in the Atacama Desert in Northern Chile started in 2014, and operations are expected to begin in about 2025.

International consortia with major contributions from U.S. astronomers have developed plans for the

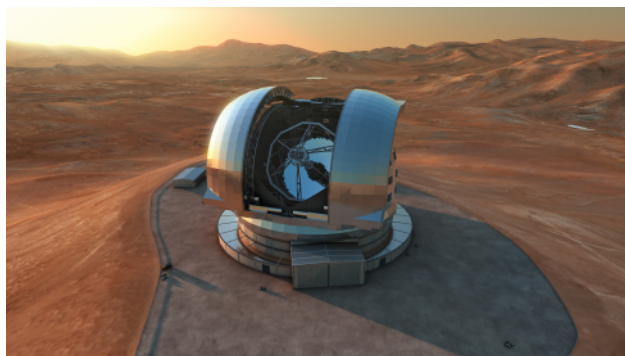
<sup>1</sup> The observatory is named after the American astronomer whose work led us to the understanding that much of the universe is made of a mysterious substance that scientists call dark matter (which we explain in [The Mass of the Galaxy](#)).



construction of two large new telescopes. One is a Thirty-Meter Telescope (TMT) for which the preferred site is Maunakea in Hawaii. The design of this telescope is similar to that of the European ELT and will make use of 492 hexagonal elements. Each segment is about 1.44 meters (56.6 inches) across corners. The segments are closely spaced, with gaps between the segments only 2.5 mm (0.1 inch) wide.

The Giant Magellan Telescope (GMT) is the second ELT project with major participation by U.S. astronomers. The GMT is also a segmented mirror telescope that employs seven stiff monolith 8.4-meter mirrors as segments. Construction has started at the selected site, which is near the Las Campanas Observatory on the southern edge of the Atacama Desert.

These giant telescopes will combine light-gathering power with high-resolution imaging. These powerful new instruments will enable astronomers to tackle many important astronomical problems. As just one example, they provide us images and spectra of planets around other stars and thus, perhaps, give us the first real evidence (from the chemistry of these planets' atmospheres) that life exists elsewhere.



**Figure 6.28 Artist's Conception of the European Extremely Large Telescope.** The primary mirror in this telescope is 39.3 meters across. The telescope is under construction in the Atacama Desert in Northern Chile. (credit: ESO/L. Calçada)

#### LINK TO LEARNING



Check out this [fun diagram \(https://openstax.org/l/30JWSTdiag\)](https://openstax.org/l/30JWSTdiag) comparing the sizes of the largest planned and existing telescopes to a regulation basketball and tennis court.

## Key Terms

**adaptive optics** systems used with telescopes that can compensate for distortions in an image introduced by the atmosphere, thus resulting in sharper images

**aperture** diameter of the primary lens or mirror of a telescope

**charge-coupled device (CCD)** array of high-sensitivity electronic detectors of electromagnetic radiation, used at the focus of a telescope (or camera lens) to record an image or spectrum

**chromatic aberration** distortion that causes an image to appear fuzzy when each wavelength coming into a transparent material focuses at a different spot

**detector** device sensitive to electromagnetic radiation that makes a record of astronomical observations

**eyepiece** magnifying lens used to view the image produced by the objective lens or primary mirror of a telescope

**focus** (of telescope) point where the rays of light converged by a mirror or lens meet

**interference** process in which waves mix together such that their crests and troughs can alternately reinforce and cancel one another

**interferometer** instrument that combines electromagnetic radiation from one or more telescopes to obtain a resolution equivalent to what would be obtained with a single telescope with a diameter equal to the baseline separating the individual separate telescopes

**interferometer array** combination of multiple radio dishes to, in effect, work like a large number of two-dish interferometers

**prime focus** point in a telescope where the objective lens or primary mirror focuses the light

**radar** technique of transmitting radio waves to an object and then detecting the radiation that the object reflects back to the transmitter; used to measure the distance to, and motion of, a target object or to form images of it

**reflecting telescope** telescope in which the principal light collector is a concave mirror

**refracting telescope** telescope in which the principal light collector is a lens or system of lenses

**resolution** detail in an image; specifically, the smallest angular (or linear) features that can be distinguished

**seeing** unsteadiness of Earth's atmosphere, which blurs telescopic images; good seeing means the atmosphere is steady

**telescope** instrument for collecting visible-light or other electromagnetic radiation

## Summary

### 6.1 Telescopes

A telescope collects the faint light from astronomical sources and brings it to a focus, where an instrument can sort the light according to wavelength. Light is then directed to a detector, where a permanent record is made. The light-gathering power of a telescope is determined by the diameter of its aperture, or opening—that is, by the area of its largest or primary lens or mirror. The primary optical element in a telescope is either a convex lens (in a refracting telescope) or a concave mirror (in a reflector) that brings the light to a focus. Most large telescopes are reflectors; it is easier to manufacture and support large mirrors because the light does not have to pass through glass.

### 6.2 Telescopes Today

New technologies for creating and supporting lightweight mirrors have led to the construction of a number of large telescopes since 1990. The site for an astronomical observatory must be carefully chosen for clear weather, dark skies, low water vapor, and excellent atmospheric seeing (low atmospheric turbulence). The resolution of a visible-light or infrared telescope is degraded by turbulence in Earth's atmosphere. The technique of adaptive optics, however, can make corrections for this turbulence in real time and produce exquisitely detailed images.

### 6.3 Visible-Light Detectors and Instruments

Visible-light detectors include the human eye, photographic film, and charge-coupled devices (CCDs). Detectors that are sensitive to infrared radiation must be cooled to very low temperatures since everything in and near the telescope gives off infrared waves. A spectrometer disperses the light into a spectrum to be recorded for detailed analysis.

### 6.4 Radio Telescopes

In the 1930s, radio astronomy was pioneered by Karl G. Jansky and Grote Reber. A radio telescope is basically a radio antenna (often a large, curved dish) connected to a receiver. Significantly enhanced resolution can be obtained with interferometers, including interferometer arrays like the 27-element VLA and the 66-element ALMA. Expanding to very long baseline interferometers, radio astronomers can achieve resolutions as precise as 0.0001 arcsecond. Radar astronomy involves transmitting as well as receiving. The largest radar telescope currently in operation is a 305-meter bowl at Arecibo.

### 6.5 Observations outside Earth's Atmosphere

Infrared observations are made with telescopes aboard aircraft and in space, as well as from ground-based facilities on dry mountain peaks. Ultraviolet, X-ray, and gamma-ray observations must be made from above the atmosphere. Many orbiting observatories have been flown to observe in these bands of the spectrum in the last few decades. The largest-aperture telescope in space is the Hubble Space telescope (HST), the most significant infrared telescope is Spitzer, and Chandra and Fermi are the premier X-ray and gamma-ray observatories, respectively.

### 6.6 The Future of Large Telescopes

New and even larger telescopes are on the drawing boards. The James Webb Space Telescope, a 6-meter successor to Hubble, is currently scheduled for launch in 2021. Gamma-ray astronomers are planning to build the CTA to measure very energetic gamma rays. Astronomers are building the LSST to observe with an unprecedented field of view and a new generation of visible-light/infrared telescopes with apertures of 24.5 to 39 meters in diameter.



#### For Further Exploration

##### Articles

Blades, J. C. "Fixing the Hubble One Last Time." *Sky & Telescope* (October 2008): 26. On the last Shuttle service mission and what the Hubble was then capable of doing.

Brown, A. "How Gaia will Map a Billion Stars." *Astronomy* (December 2014): 32. Nice review of the mission to do photometry and spectroscopy of all stars above a certain brightness.

Irion, R. "Prime Time." *Astronomy* (February 2001): 46. On how time is allotted on the major research telescopes.

Jedicke, Peter & Robert. "The Coming Giant Sky Patrols." *Sky & Telescope* (September 2008): 30. About giant telescopes to survey the sky continuously.

Lazio, Joseph, et al. "Tuning in to the Universe: 21<sup>st</sup> Century Radio Astronomy." *Sky & Telescope* (July 2008): 21. About ALMA and the Square Kilometer Array.

Lowe, Jonathan. "Mirror, Mirror." *Sky & Telescope* (December 2007): 22. On the Large Binocular Telescope in Arizona.

Lowe, Jonathan. "Next Light: Tomorrow's Monster Telescopes." *Sky & Telescope* (April 2008): 20. About plans for extremely large telescopes on the ground.

Mason, Todd & Robin. "Palomar's Big Eye." *Sky & Telescope* (December 2008): 36. On the Hale 200-inch telescope.

Subinsky, Raymond. "Who Really Invented the Telescope." *Astronomy* (August 2008): 84. Brief historical introduction, focusing on Hans Lippershey.

Young, Monica "The New Space Race (and Problem)." *Sky & Telescope* (March 2020): 14. A good discussion of the danger that huge numbers of new reflective satellites (to provide Wi-Fi) poses to the darkness of the night sky for astronomers.

### Websites

Websites for major telescopes are given in [Table 6.1](#), [Table 6.2](#), [Table 6.3](#), and [Table 6.4](#).

Information on Swarms of Satellites on Low-Earth Orbit

- American Astronomical Society page on the issue with updates and links: <https://aas.org/posts/advocacy/2020/12/impacts-large-satellite-constellations-astronomy-live-updates> (<https://aas.org/posts/advocacy/2020/12/impacts-large-satellite-constellations-astronomy-live-updates>)
- Lawler, S. "Space-X's Starlink Satellites are About to Ruin Stargazing Forever" on the *Astronomy* magazine website (November 25, 2020): <https://astronomy.com/news/2020/11/spacexs-starlink-satellites-are-about-to-ruin-stargazing-for-everyone> (<https://astronomy.com/news/2020/11/spacexs-starlink-satellites-are-about-to-ruin-stargazing-for-everyone>)
- Patel, N. "Satellite Mega-constellations Risk Ruining Astronomy Forever" in *Technology Review*, September 2, 2020: <https://www.technologyreview.com/2020/09/02/1007938/satellite-mega-constellations-risk-ruining-astronomy-forever/> (<https://www.technologyreview.com/2020/09/02/1007938/satellite-mega-constellations-risk-ruining-astronomy-forever/>)

### Videos

Astronomy from the Stratosphere: SOFIA: <https://www.youtube.com/watch?v=Nv98BcBBA9c> (<https://www.youtube.com/watch?v=Nv98BcBBA9c>). A talk by Dr. Dana Backman (1:15:32)

Galaxies Viewed in Full Spectrum of Light: <https://www.youtube.com/watch?v=368K0iQv8nE> (<https://www.youtube.com/watch?v=368K0iQv8nE>). Scientists with the Spitzer Observatory show how a galaxy looks different at different wavelengths (6:22)

Lifting the Cosmic Veil: Highlights from a Decade of the Spitzer Space Telescope: <https://www.youtube.com/watch?v=nkrNQcwky78> (<https://www.youtube.com/watch?v=nkrNQcwky78>). A talk by Dr. Michael Bica (1:42:44)

## Collaborative Group Activities

- Most large telescopes get many more proposals for observing projects than there is night observing time available in a year. Suppose your group is the telescope time allocation committee reporting to an observatory director. What criteria would you use in deciding how to give out time on the telescope? What steps could you take to make sure all your colleagues thought the process was fair and people would still talk to you at future astronomy meetings?
- Your group is a committee of nervous astronomers about to make a proposal to the government ministers of your small European country to chip in with other countries to build the world's largest telescope in the high, dry desert of the Chilean Andes Mountains. You expect the government ministers to be very skeptical about supporting this project. What arguments would you make to convince them to participate?
- The same government ministers we met in the previous activity ask you to draw up a list of the pros and

cons of having the world's largest telescope in the mountains of Chile (instead of a mountain in Europe). What would your group list in each column?

- D. Your group should discuss and make a list of all the ways in which an observing session at a large visible-light telescope and a large radio telescope might differ. (Hint: Bear in mind that because the Sun is not especially bright at many radio wavelengths, observations with radio telescopes can often be done during the day.)
- E. Another "environmental threat" to astronomy (besides light pollution) comes from the spilling of terrestrial communications into the "channels"—wavelengths and frequencies—previously reserved for radio astronomy. For example, the demand for cellular phones means that more and more radio channels will be used for this purpose. The faint signals from cosmic radio sources could be drowned in a sea of earthly conversation (translated and sent as radio waves). Assume your group is a congressional committee being lobbied by both radio astronomers, who want to save some clear channels for doing astronomy, and the companies that stand to make a lot of money from expanding cellular phone use. What arguments would sway you to each side?
- F. When the site for the new Thirty-Meter Telescope on Hawaii's Maunakea was dedicated, a group of native Hawaiians announced opposition to the project because astronomers were building too many telescopes on a mountain that native Hawaiians consider a sacred site. You can read more about this controversy at [http://www.nytimes.com/2015/12/04/science/space/hawaii-court-rescinds-permit-to-build-thirty-meter-telescope.html?\\_r=0](http://www.nytimes.com/2015/12/04/science/space/hawaii-court-rescinds-permit-to-build-thirty-meter-telescope.html?_r=0) and at <http://www.nature.com/news/the-mountain-top-battle-over-the-thirty-meter-telescope-1.18446>. Once your group has the facts, discuss the claims of each side in the controversy. How do you think it should be resolved?
- G. If you could propose to use a large modern telescope, what would you want to find out? What telescope would you use and why?
- H. Light pollution (spilled light in the night sky making it difficult to see the planets and stars) used to be an issue that concerned mostly astronomers. Now spilled light at night is also of concern to environmentalists and those worrying about global warming. Can your group come up with some non-astronomical reasons to be opposed to light pollution?



## Exercises

### Review Questions

1. What are the three basic components of a modern astronomical instrument? Describe each in one to two sentences.
2. Name the two spectral windows through which electromagnetic radiation easily reaches the surface of Earth and describe the largest-aperture telescope currently in use for each window.
3. List the largest-aperture single telescope currently in use in each of the following bands of the electromagnetic spectrum: radio, X-ray, gamma ray.
4. When astronomers discuss the apertures of their telescopes, they say bigger is better. Explain why.
5. The Hooker telescope at Palomar Observatory has a diameter of 5 m, and the Keck I telescope has a diameter of 10 m. How much more light can the Keck telescope collect than the Hooker telescope in the same amount of time?
6. What is meant by "reflecting" and "refracting" telescopes?
7. Why are the largest visible-light telescopes in the world made with mirrors rather than lenses?



8. Compare the eye, photographic film, and CCDs as detectors for light. What are the advantages and disadvantages of each?
9. What is a charge-coupled device (CCD), and how is it used in astronomy?
10. Why is it difficult to observe at infrared wavelengths? What do astronomers do to address this difficulty?
11. Radio and radar observations are often made with the same antenna, but otherwise they are very different techniques. Compare and contrast radio and radar astronomy in terms of the equipment needed, the methods used, and the kind of results obtained.
12. Look back at [Figure 6.18](#) of Cygnus A and read its caption again. The material in the giant lobes at the edges of the image had to have been ejected from the center *at least* how many years ago?
13. Why do astronomers place telescopes in Earth's orbit? What are the advantages for the different regions of the spectrum?
14. What was the problem with the Hubble Space Telescope and how was it solved?
15. Describe the techniques radio astronomers use to obtain a resolution comparable to what astronomers working with visible light can achieve.
16. What kind of visible-light and infrared telescopes on the ground are astronomers planning for the future? Why are they building them on the ground and not in space?
17. Describe one visible-light or infrared telescope that astronomers are planning to launch into space in the future.

### Thought Questions

18. What happens to the image produced by a lens if the lens is “stopped down” (the aperture reduced, thereby reducing the amount of light passing through the lens) with an iris diaphragm—a device that covers its periphery?
19. What would be the properties of an ideal astronomical detector? How closely do the actual properties of a CCD approach this ideal?
20. Many decades ago, the astronomers on the staff of Mount Wilson and Palomar Observatories each received about 60 nights per year for their observing programs. Today, an astronomer feels fortunate to get 10 nights per year on a large telescope. Can you suggest some reasons for this change?
21. The largest observatory complex in the world is on Maunakea, the tallest mountain on Earth. What are some factors astronomers consider when selecting an observatory site? Don't forget practical ones. Should astronomers, for example, consider building an observatory on Denali (Mount McKinley) or Mount Everest?
22. Suppose you are looking for sites for a visible-light observatory, an infrared observatory, and a radio observatory. What are the main criteria of excellence for each? What sites are actually considered the best today?
23. Radio astronomy involves wavelengths much longer than those of visible light, and many orbiting observatories have probed the universe for radiation of very short wavelengths. What sorts of objects and physical conditions would you expect to be associated with emission of radiation at very long and very short wavelengths?
24. The dean of a university located near the ocean (who was not a science major in college) proposes building an infrared telescope right on campus and operating it in a nice heated dome so that astronomers will be comfortable on cold winter nights. Criticize this proposal, giving your reasoning.

## Figuring for Yourself

25. What is the area, in square meters, of a 10-m telescope?
26. Approximately 9000 stars are visible to the naked eye in the whole sky (imagine that you could see around the entire globe and both the northern and southern hemispheres), and there are about 41,200 square degrees on the sky. How many stars are visible per square degree? Per square arcsecond?
27. Theoretically (that is, if seeing were not an issue), the resolution of a telescope is inversely proportional to its diameter. How much better is the resolution of the ALMA when operating at its longest baseline than the resolution of the Arecibo telescope?
28. In broad daylight, the size of your pupil is typically 3 mm. In dark situations, it expands to about 7 mm. How much more light can it gather?
29. How much more light can be gathered by a telescope that is 8 m in diameter than by your fully dark-adapted eye at 7 mm?
30. How much more light can the Keck telescope (with its 10-m diameter mirror) gather than an amateur telescope whose mirror is 25 cm (0.25 m) across?
31. People are often bothered when they discover that reflecting telescopes have a second mirror in the middle to bring the light out to an accessible focus where big instruments can be mounted. “Don’t you lose light?” people ask. Well, yes, you do, but there is no better alternative. You can estimate how much light is lost by such an arrangement. The primary mirror (the one at the bottom in [Figure 6.6](#)) of the Gemini North telescope is 8 m in diameter. The secondary mirror at the top is about 1 m in diameter. Use the formula for the area of a circle to estimate what fraction of the light is blocked by the secondary mirror.
32. Telescopes can now be operated remotely from a warm room, but until about 25 years ago, astronomers worked at the telescope to guide it so that it remained pointed in exactly the right place. In a large telescope, like the Palomar 200-inch telescope, astronomers sat in a cage at the top of the telescope, where the secondary mirror is located, as shown in [Figure 6.6](#). Assume for the purpose of your calculation that the diameter of this cage was 40 inches. What fraction of the light is blocked?
33. The HST cost about \$1.7 billion for construction and \$300 million for its shuttle launch, and it costs \$250 million per year to operate. If the telescope lasts for 20 years, what is the total cost per year? Per day? If the telescope can be used just 30% of the time for actual observations, what is the cost per hour and per minute for the astronomer’s observing time on this instrument? What is the cost per person in the United States? Was your investment in the Hubble Space telescope worth it?
34. How much more light can the James Webb Space Telescope (with its 6-m diameter mirror) gather than the Hubble Space Telescope (with a diameter of 2.4 m)?
35. The Palomar telescope’s 5-m mirror weighs 14.5 tons. If a 10-m mirror were constructed of the same thickness as Palomar’s (only bigger), how much would it weigh?

