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.

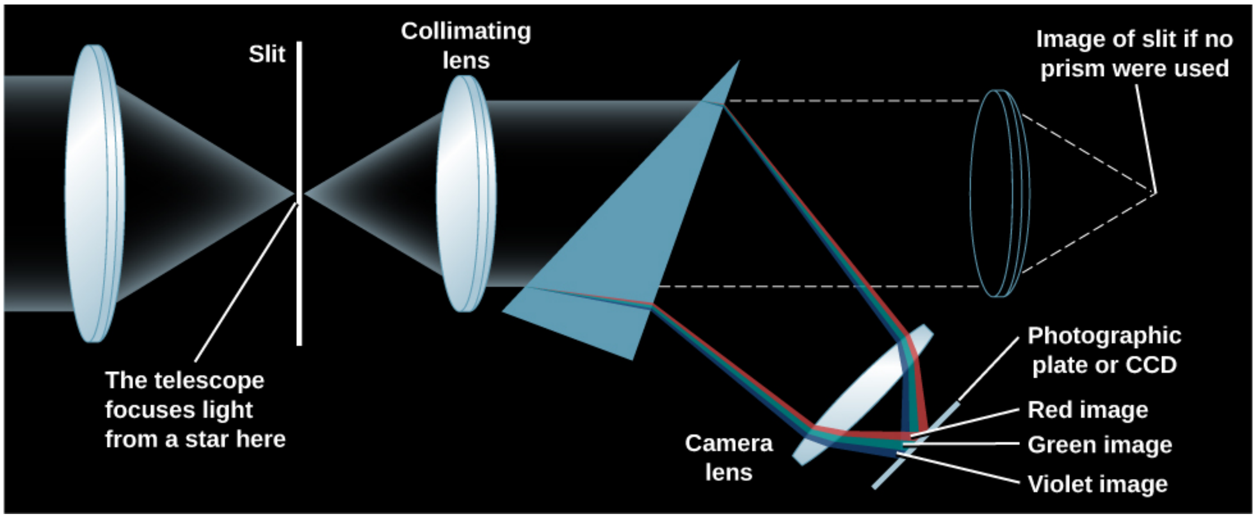

Figure 6.16 Prism Spectrometer. The light from the telescope is focused on a slit. A prism (or grating) disperses the light into a spectrum, which is then photographed or recorded electronically.

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.

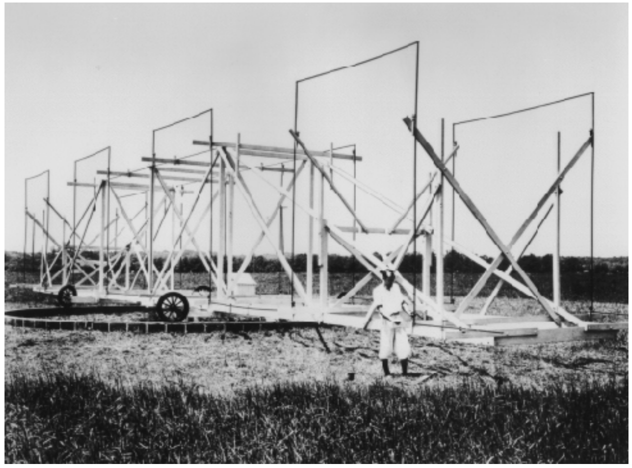

Figure 6.17 First Radio Telescope. This rotating radio antenna was used by Jansky in his serendipitous discovery of radio radiation from the Milky Way.

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.

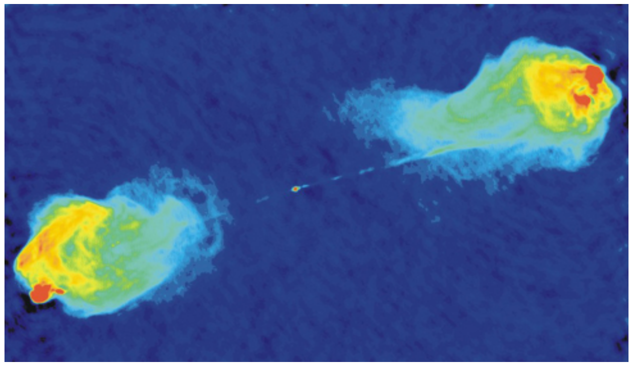

Figure 6.18 Radio Image. This image has been constructed of radio observations at the Very Large Array of a galaxy called Cygnus A. Colors have been added to help the eye sort out regions of different radio intensities. Red regions are the most intense, blue the least. The visible galaxy would be a small 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	fast.bao.ac.cn/en/

Table 6.2

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

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

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.

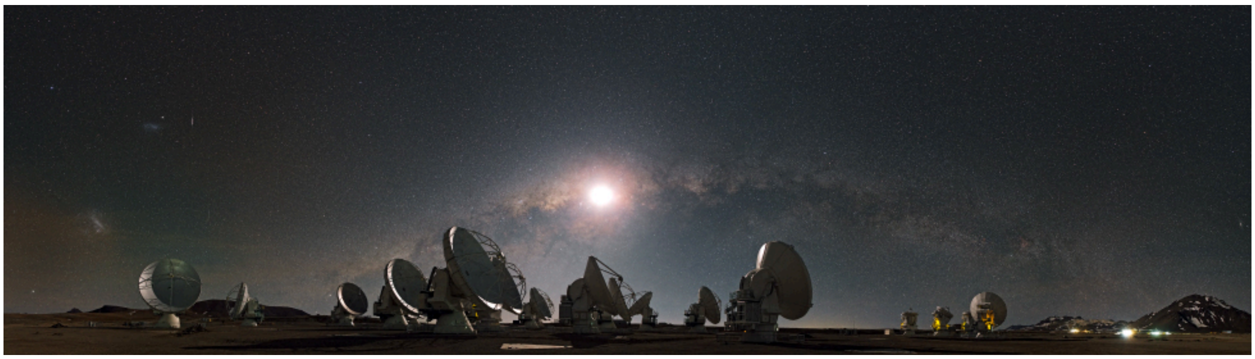

Figure 6.20 Atacama Large Millimeter/Submillimeter Array (ALMA). Located in the Atacama Desert of Northern Chile, ALMA currently provides the highest resolution for radio observations. (credit: ESO/S. Guisard)

LINK TO LEARNING

Watch this documentary (https://openstax.org/l/30ALMAdoc) 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 faculty 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