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Astronomy

17

ANALYZING STARLIGHT

Figure 17.1 Star Colors. This long time exposure shows the colors of the stars. The circular motion of the stars across the image is provided by Earth's rotation. The various colors of the stars are caused by their different temperatures. (credit: modification of work by ESO/A.Santerne)

Chapter Outline

17.1 The Brightness of Stars
17.2 Colors of Stars
17.3 The Spectra of Stars (and Brown Dwarfs)
17.4 Using Spectra to Measure Stellar Radius, Composition, and Motion

Thinking Ahead

Everything we know about stars—how they are born, what they are made of, how far away they are, how long they live, and how they will die—we learn by decoding the messages contained in the light and radiation that reaches Earth. What questions should we ask, and how do we find the answers?

We can begin our voyage to the stars by looking at the night sky. It is obvious that stars do not all appear equally bright, nor are they all the same color. To understand the stars, we must first determine their basic properties, such as what their temperatures are, how much material they contain (their masses), and how much energy they produce. Since our Sun is a star, of course the same techniques, including spectroscopy, used to study the Sun can be used to find out what stars are like. As we learn more about the stars, we will use these characteristics to begin assembling clues to the main problems we are interested in solving: How do stars form? How long do they survive? What is their ultimate fate?

17.1 THE BRIGHTNESS OF STARS

Learning Objectives

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

- Explain the difference between luminosity and apparent brightness

- Understand how astronomers specify brightness with magnitudes

Luminosity

Perhaps the most important characteristic of a star is its **luminosity**—the total amount of energy at all wavelengths that it emits per second. Earlier, we saw that the Sun puts out a tremendous amount of energy every second. (And there are stars far more luminous than the Sun out there.) To make the comparison among stars easy, astronomers express the luminosity of other stars in terms of the Sun's luminosity. For example, the luminosity of Sirius is about 25 times that of the Sun. We use the symbol L_{Sun} to denote the Sun's luminosity; hence, that of Sirius can be written as 25 L_{Sun}. In a later chapter, we will see that if we can measure how much energy a star emits and we also know its mass, then we can calculate how long it can continue to shine before it exhausts its nuclear energy and begins to die.

Apparent Brightness

Astronomers are careful to distinguish between the luminosity of the star (the total energy output) and the amount of energy that happens to reach our eyes or a telescope on Earth. Stars are democratic in how they produce radiation; they emit the same amount of energy in every direction in space. Consequently, only a minuscule fraction of the energy given off by a star actually reaches an observer on Earth. We call the amount of a star's energy that reaches a given area (say, one square meter) each second here on Earth its **apparent brightness**. If you look at the night sky, you see a wide range of apparent brightnesses among the stars. Most stars, in fact, are so dim that you need a telescope to detect them.

If all stars were the same luminosity—if they were like standard bulbs with the same light output—we could use the difference in their apparent brightnesses to tell us something we very much want to know: how far away they are. Imagine you are in a big concert hall or ballroom that is dark except for a few dozen 25-watt bulbs placed in fixtures around the walls. Since they are all 25-watt bulbs, their luminosity (energy output) is the same. But from where you are standing in one corner, they do *not* have the same apparent brightness. Those close to you appear brighter (more of their light reaches your eye), whereas those far away appear dimmer (their light has spread out more before reaching you). In this way, you can tell which bulbs are closest to you. In the same way, if all the stars had the same luminosity, we could immediately infer that the brightest-appearing stars were close by and the dimmest-appearing ones were far away.

To pin down this idea more precisely, recall from the **Radiation and Spectra** chapter that we know exactly how light fades with increasing distance. The energy we receive is inversely proportional to the square of the distance. If, for example, we have two stars of the same luminosity and one is twice as far away as the other, it will look four times dimmer than the closer one. If it is three times farther away, it will look nine (three squared) times dimmer, and so forth.

Alas, the stars do not all have the same luminosity. (Actually, we are pretty glad about that because having many different types of stars makes the universe a much more interesting place.) But this means that if a star looks dim in the sky, we cannot tell whether it appears dim because it has a low luminosity but is relatively nearby, or because it has a high luminosity but is very far away. To measure the luminosities of stars, we must first compensate for the dimming effects of distance on light, and to do that, we must know how far away they are. Distance is among the most difficult of all astronomical measurements. We will return to how it is determined after we have learned more about the stars. For now, we will describe how astronomers specify the apparent brightness of stars.

The Magnitude Scale

The process of measuring the apparent brightness of stars is called *photometry* (from the Greek *photo* meaning

"light" and *–metry* meaning "to measure"). As we saw **Observing the Sky: The Birth of Astronomy**, astronomical photometry began with Hipparchus. Around 150 B.C.E., he erected an observatory on the island of Rhodes in the Mediterranean. There he prepared a catalog of nearly 1000 stars that included not only their positions but also estimates of their apparent brightnesses.

Hipparchus did not have a telescope or any instrument that could measure apparent brightness accurately, so he simply made estimates with his eyes. He sorted the stars into six brightness categories, each of which he called a **magnitude**. He referred to the brightest stars in his catalog as first-magnitudes stars, whereas those so faint he could barely see them were sixth-magnitude stars. During the nineteenth century, astronomers attempted to make the scale more precise by establishing exactly how much the apparent brightness of a sixth-magnitude star differs from that of a first-magnitude star. Measurements showed that we receive about 100 times more light from a first-magnitude star than from a sixth-magnitude star. Based on this measurement, astronomers then defined an accurate magnitude system in which a difference of five magnitudes corresponds exactly to a brightness ratio of 100:1. In addition, the magnitudes of stars are decimalized; for example, a star isn't just a "second-magnitude star," it has a magnitude of 2.0 (or 2.1, 2.3, and so forth). So what number is it that, when multiplied together five times, gives you this factor of 100? Play on your calculator and see if you can get it. The answer turns out to be about 2.5, which is the fifth root of 100. This means that a magnitude 1.0 star and a magnitude 2.0 star differ in brightness by a factor of about 2.5. Likewise, we receive about 2.5 times as much light from a magnitude 2.0 star as from a magnitude 3.0 star. What about the difference between a magnitude 1.0 star and a magnitude 3.0 star? Since the difference is 2.5 times for each "step" of magnitude, the total difference in brightness is 2.5 × 2.5 = 6.25 times.

Here are a few rules of thumb that might help those new to this system. If two stars differ by 0.75 magnitudes, they differ by a factor of about 2 in brightness. If they are 2.5 magnitudes apart, they differ in brightness by a factor of 10, and a 4-magnitude difference corresponds to a difference in brightness of a factor of 40.You might be saying to yourself at this point, "Why do astronomers continue to use this complicated system from more than 2000 years ago?" That's an excellent question and, as we shall discuss, astronomers today can use other ways of expressing how bright a star looks. But because this system is still used in many books, star charts, and computer apps, we felt we had to introduce students to it (even though we were very tempted to leave it out.)

The brightest stars, those that were traditionally referred to as first-magnitude stars, actually turned out (when measured accurately) not to be identical in brightness. For example, the brightest star in the sky, Sirius, sends us about 10 times as much light as the average first-magnitude star. On the modern magnitude scale, Sirius, the star with the brightest apparent magnitude, has been assigned a magnitude of −1.5. Other objects in the sky can appear even brighter. Venus at its brightest is of magnitude −4.4, while the Sun has a magnitude of −26.8. **Figure 17.2** shows the range of observed magnitudes from the brightest to the faintest, along with the actual magnitudes of several well-known objects. The important fact to remember when using magnitude is that the system goes backward: the *larger* the magnitude, the *fainter* the object you are observing.

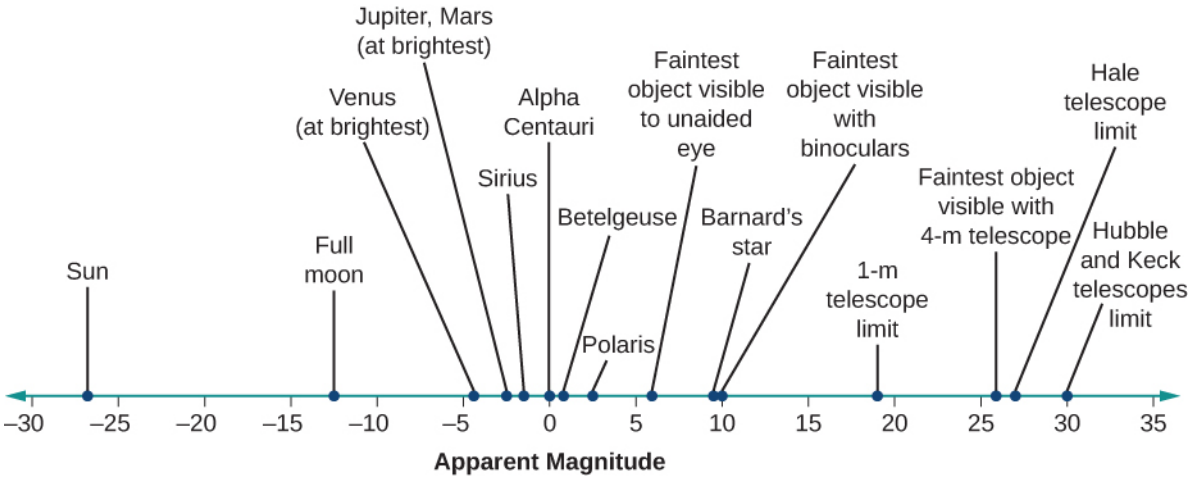


Figure 17.2 Apparent Magnitudes of Well-Known Objects. The faintest magnitudes that can be detected by the unaided eye, binoculars, and large telescopes are also shown.

EXAMPLE 17.1

The Magnitude Equation

Even scientists can't calculate fifth roots in their heads, so astronomers have summarized the above discussion in an equation to help calculate the difference in brightness for stars with different magnitudes. If m_1 and m_2 are the magnitudes of two stars, then we can calculate the ratio of their brightness $\left(\frac{b_2}{b_1}\right)$ using this equation:

$$m_1 - m_2 = 2.5 \log\left(\frac{b_2}{b_1}\right) \qquad \text{or} \qquad \frac{b_2}{b_1} = 2.5^{m_1 - m_2}$$

Here is another way to write this equation:

$$\frac{b_2}{b_1} = \left(100^{0.2}\right)^{m_1 - m_2}$$

Let's do a real example, just to show how this works. Imagine that an astronomer has discovered something special about a dim star (magnitude 8.5), and she wants to tell her students how much dimmer the star is than Sirius. Star 1 in the equation will be our dim star and star 2 will be Sirius.

Solution

Remember, Sirius has a magnitude of −1.5. In that case:

$$\frac{b_2}{b_1} = \left(100^{0.2}\right)^{8.5 - (-1.5)} = \left(100^{0.2}\right)^{10}$$
$$= (100)^2 = 100 \times 100 = 10{,}000$$

Check Your Learning

It is a common misconception that Polaris (magnitude 2.0) is the brightest star in the sky, but, as we saw, that distinction actually belongs to Sirius (magnitude −1.5). How does Sirius' apparent brightness

compare to that of Polaris?

Answer:

$$\frac{b_{\text{Sirius}}}{b_{\text{Polaris}}} = \left(100^{0.2}\right)^{2.0-(-1.5)} = \left(100^{0.2}\right)^{3.5} = 100^{0.7} = 25$$

(Hint: If you only have a basic calculator, you may wonder how to take 100 to the 0.7th power. But this is something you can ask Google to do. Google now accepts mathematical questions and will answer them. So try it for yourself. Ask Google, "What is 100 to the 0.7th power?")

Our calculation shows that Sirius' apparent brightness is 25 times greater than Polaris' apparent brightness.

Other Units of Brightness

Although the magnitude scale is still used for visual astronomy, it is not used at all in newer branches of the field. In radio astronomy, for example, no equivalent of the magnitude system has been defined. Rather, radio astronomers measure the amount of energy being collected each second by each square meter of a radio telescope and express the brightness of each source in terms of, for example, watts per square meter.

Similarly, most researchers in the fields of infrared, X-ray, and gamma-ray astronomy use energy per area per second rather than magnitudes to express the results of their measurements. Nevertheless, astronomers in all fields are careful to distinguish between the *luminosity* of the source (even when that luminosity is all in X-rays) and the amount of energy that happens to reach us on Earth. After all, the luminosity is a really important characteristic that tells us a lot about the object in question, whereas the energy that reaches Earth is an accident of cosmic geography.

To make the comparison among stars easy, in this text, we avoid the use of magnitudes as much as possible and will express the luminosity of other stars in terms of the Sun's luminosity. For example, the luminosity of Sirius is 25 times that of the Sun. We use the symbol L_{Sun} to denote the Sun's luminosity; hence, that of Sirius can be written as 25 L_{Sun}.

17.2 COLORS OF STARS

Learning Objectives

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

- Compare the relative temperatures of stars based on their colors
- Understand how astronomers use color indexes to measure the temperatures of stars

Look at the beautiful picture of the stars in the Sagittarius Star Cloud shown in **Figure 17.3**. The stars show a multitude of colors, including red, orange, yellow, white, and blue. As we have seen, stars are not all the same color because they do not all have identical temperatures. To define *color* precisely, astronomers have devised quantitative methods for characterizing the color of a star and then using those colors to determine stellar temperatures. In the chapters that follow, we will provide the temperature of the stars we are describing, and this section tells you how those temperatures are determined from the colors of light the stars give off.

Figure 17.3 Sagittarius Star Cloud. This image, which was taken by the Hubble Space Telescope, shows stars in the direction toward the center of the Milky Way Galaxy. The bright stars glitter like colored jewels on a black velvet background. The color of a star indicates its temperature. Blue-white stars are much hotter than the Sun, whereas red stars are cooler. On average, the stars in this field are at a distance of about 25,000 light-years (which means it takes light 25,000 years to traverse the distance from them to us) and the width of the field is about 13.3 light-years. (credit: Hubble Heritage Team (AURA/STScI/NASA))

Color and Temperature

As we learned in **The Electromagnetic Spectrum** section, Wien's law relates stellar color to stellar temperature. Blue colors dominate the visible light output of very hot stars (with much additional radiation in the ultraviolet). On the other hand, cool stars emit most of their visible light energy at red wavelengths (with more radiation coming off in the infrared) (**Table 17.1**). The color of a star therefore provides a measure of its intrinsic or true surface temperature (apart from the effects of reddening by interstellar dust, which will be discussed in **Between the Stars: Gas and Dust in Space**). Color does not depend on the distance to the object. This should be familiar to you from everyday experience. The color of a traffic signal, for example, appears the same no matter how far away it is. If we could somehow take a star, observe it, and then move it much farther away, its apparent brightness (magnitude) would change. But this change in brightness is the same for all wavelengths, and so its color would remain the same.

Example Star Colors and Corresponding Approximate Temperatures

Star Color	Approximate Temperature	Example
Blue	25,000 K	Spica
White	10,000 K	Vega
Yellow	6000 K	Sun
Orange	4000 K	Aldebaran

Table 17.1

Example Star Colors and Corresponding Approximate Temperatures

Star Color	Approximate Temperature	Example
Red	3000 K	Betelgeuse

Table 17.1

LINK TO LEARNING

Go to this **interactive simulation from the University of Colorado (https://openstax.org/l/30UofCsimstar)** to see the color of a star changing as the temperature is changed.

The hottest stars have temperatures of over 40,000 K, and the coolest stars have temperatures of about 2000 K. Our Sun's surface temperature is about 6000 K; its peak wavelength color is a slightly greenish-yellow. In space, the Sun would look white, shining with about equal amounts of reddish and bluish wavelengths of light. It looks somewhat yellow as seen from Earth's surface because our planet's nitrogen molecules scatter some of the shorter (i.e., blue) wavelengths out of the beams of sunlight that reach us, leaving more long wavelength light behind. This also explains why the sky is blue: the blue sky is sunlight scattered by Earth's atmosphere.

Color Indices

In order to specify the exact color of a star, astronomers normally measure a star's apparent brightness through filters, each of which transmits only the light from a particular narrow band of wavelengths (colors). A crude example of a filter in everyday life is a green-colored, plastic, soft drink bottle, which, when held in front of your eyes, lets only the green colors of light through.

One commonly used set of filters in astronomy measures stellar brightness at three wavelengths corresponding to ultraviolet, blue, and yellow light. The filters are named: U (ultraviolet), B (blue), and V (visual, for yellow). These filters transmit light near the wavelengths of 360 nanometers (nm), 420 nm, and 540 nm, respectively. The brightness measured through each filter is usually expressed in magnitudes. The difference between any two of these magnitudes—say, between the blue and the visual magnitudes (B–V)—is called a **color index**.

LINK TO LEARNING

Go to this **light and filters simulator (https://openstax.org/l/30lightfiltsim)** for a demonstration of how different light sources and filters can combine to determine the observed spectrum. You can also see how the perceived colors are associated with the spectrum.

By agreement among astronomers, the ultraviolet, blue, and visual magnitudes of the UBV system are adjusted to give a color index of 0 to a star with a surface temperature of about 10,000 K, such as Vega. The B–V color indexes of stars range from −0.4 for the bluest stars, with temperatures of about 40,000 K, to +2.0 for the reddest stars, with temperatures of about 2000 K. The B–V index for the Sun is about +0.65. Note that, by convention,

the B–V index is always the “bluer” minus the “redder” color.

Why use a color index if it ultimately implies temperature? Because the brightness of a star through a filter is what astronomers actually measure, and we are always more comfortable when our statements have to do with measurable quantities.

17.3 THE SPECTRA OF STARS (AND BROWN DWARFS)

Learning Objectives

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

- Describe how astronomers use spectral classes to characterize stars
- Explain the difference between a star and a brown dwarf

Measuring colors is only one way of analyzing starlight. Another way is to use a spectrograph to spread out the light into a spectrum (see the **Radiation and Spectra** and the **Astronomical Instruments** chapters). In 1814, the German physicist Joseph Fraunhofer observed that the spectrum of the Sun shows dark lines crossing a continuous band of colors. In the 1860s, English astronomers Sir William Huggins and Lady Margaret Huggins (**Figure 17.4**) succeeded in identifying some of the lines in stellar spectra as those of known elements on Earth, showing that the same chemical elements found in the Sun and planets exist in the stars. Since then, astronomers have worked hard to perfect experimental techniques for obtaining and measuring spectra, and they have developed a theoretical understanding of what can be learned from spectra. Today, spectroscopic analysis is one of the cornerstones of astronomical research.

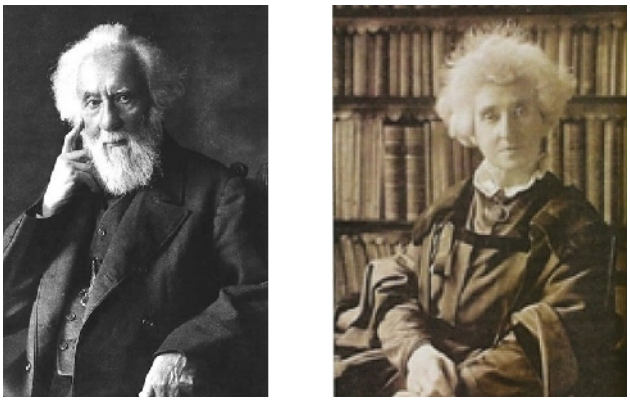


Figure 17.4 William Huggins (1824–1910) and Margaret Huggins (1848–1915). William and Margaret Huggins were the first to identify the lines in the spectrum of a star other than the Sun; they also took the first spectrogram, or photograph of a stellar spectrum.

Formation of Stellar Spectra

When the spectra of different stars were first observed, astronomers found that they were not all identical. Since the dark lines are produced by the chemical elements present in the stars, astronomers first thought that the spectra differ from one another because stars are not all made of the same chemical elements. This hypothesis turned out to be wrong. *The primary reason that stellar spectra look different is because the stars have different temperatures*. Most stars have nearly the same composition as the Sun, with only a few exceptions.

Hydrogen, for example, is by far the most abundant element in most stars. However, lines of hydrogen are not seen in the spectra of the hottest and the coolest stars. In the atmospheres of the hottest stars, hydrogen atoms are completely ionized. Because the electron and the proton are separated, ionized hydrogen cannot produce absorption lines. (Recall from the **Formation of Spectral Lines** section, the lines are the result of electrons in

orbit around a nucleus changing energy levels.)

In the atmospheres of the coolest stars, hydrogen atoms have their electrons attached and can switch energy levels to produce lines. However, practically all of the hydrogen atoms are in the lowest energy state (unexcited) in these stars and thus can absorb only those photons able to lift an electron from that first energy level to a higher level. Photons with enough energy to do this lie in the ultraviolet part of the electromagnetic spectrum, and there are very few ultraviolet photons in the radiation from a cool star. What this means is that if you observe the spectrum of a very hot or very cool star with a typical telescope on the surface of Earth, the most common element in that star, hydrogen, will show very weak spectral lines or none at all.

The hydrogen lines in the visible part of the spectrum (called *Balmer lines*) are strongest in stars with intermediate temperatures—not too hot and not too cold. Calculations show that the optimum temperature for producing visible hydrogen lines is about 10,000 K. At this temperature, an appreciable number of hydrogen atoms are excited to the second energy level. They can then absorb additional photons, rise to still-higher levels of excitation, and produce a dark absorption line. Similarly, every other chemical element, in each of its possible stages of ionization, has a characteristic temperature at which it is most effective in producing absorption lines in any particular part of the spectrum.

Classification of Stellar Spectra

Astronomers use the patterns of lines observed in stellar spectra to sort stars into a **spectral class**. Because a star's temperature determines which absorption lines are present in its spectrum, these spectral classes are a measure of its surface temperature. There are seven standard spectral classes. From hottest to coldest, these seven spectral classes are designated O, B, A, F, G, K, and M. Recently, astronomers have added three additional classes for even cooler objects—L, T, and Y.

At this point, you may be looking at these letters with wonder and asking yourself why astronomers didn't call the spectral types A, B, C, and so on. You will see, as we tell you the history, that it's an instance where tradition won out over common sense.

In the 1880s, Williamina Fleming devised a system to classify stars based on the strength of hydrogen absorption lines. Spectra with the strongest lines were classified as "A" stars, the next strongest "B," and so on down the alphabet to "O" stars, in which the hydrogen lines were very weak. But we saw above that hydrogen lines alone are not a good indicator for classifying stars, since their lines disappear from the visible light spectrum when the stars get too hot or too cold.

In the 1890s, Annie Jump Cannon revised this classification system, focusing on just a few letters from the original system: A, B, F, G, K, M, and O. Instead of starting over, Cannon also rearranged the existing classes—in order of decreasing temperature—into the sequence we have learned: O, B, A, F, G, K, M. As you can read in the feature on **Annie Cannon: Classifier of the Stars** in this chapter, she classified around 500,000 stars over her lifetime, classifying up to three stars per minute by looking at the stellar spectra.

LINK TO LEARNING

For a deep dive into spectral types, explore the interactive project at the **Sloan Digital Sky Survey (https://openstax.org/l/30sloandigsky)** in which you can practice classifying stars yourself.

To help astronomers remember this crazy order of letters, Cannon created a mnemonic, "Oh Be A Fine Girl, Kiss Me." (If you prefer, you can easily substitute "Guy" for "Girl.") Other mnemonics, which we hope will not be

relevant for you, include “Oh Brother, Astronomers Frequently Give Killer Midterms” and “Oh Boy, An F Grade Kills Me!” With the new L, T, and Y spectral classes, the mnemonic might be expanded to “Oh Be A Fine Girl (Guy), Kiss Me Like That, Yo!”

Each of these spectral classes, except possibly for the Y class which is still being defined, is further subdivided into 10 subclasses designated by the numbers 0 through 9. A B0 star is the hottest type of B star; a B9 star is the coolest type of B star and is only slightly hotter than an A0 star.

And just one more item of vocabulary: for historical reasons, astronomers call all the elements heavier than helium *metals*, even though most of them do not show metallic properties. (If you are getting annoyed at the peculiar jargon that astronomers use, just bear in mind that every field of human activity tends to develop its own specialized vocabulary. Just try reading a credit card or social media agreement form these days without training in law!)

Let’s take a look at some of the details of how the spectra of the stars change with temperature. (It is these details that allowed Annie Cannon to identify the spectral types of stars as quickly as three per minute!) As **Figure 17.5** shows, in the hottest O stars (those with temperatures over 28,000 K), only lines of ionized helium and highly ionized atoms of other elements are conspicuous. Hydrogen lines are strongest in A stars with atmospheric temperatures of about 10,000 K. Ionized metals provide the most conspicuous lines in stars with temperatures from 6000 to 7500 K (spectral type F). In the coolest M stars (below 3500 K), absorption bands of titanium oxide and other molecules are very strong. By the way, the spectral class assigned to the Sun is G2. The sequence of spectral classes is summarized in **Table 17.2**.

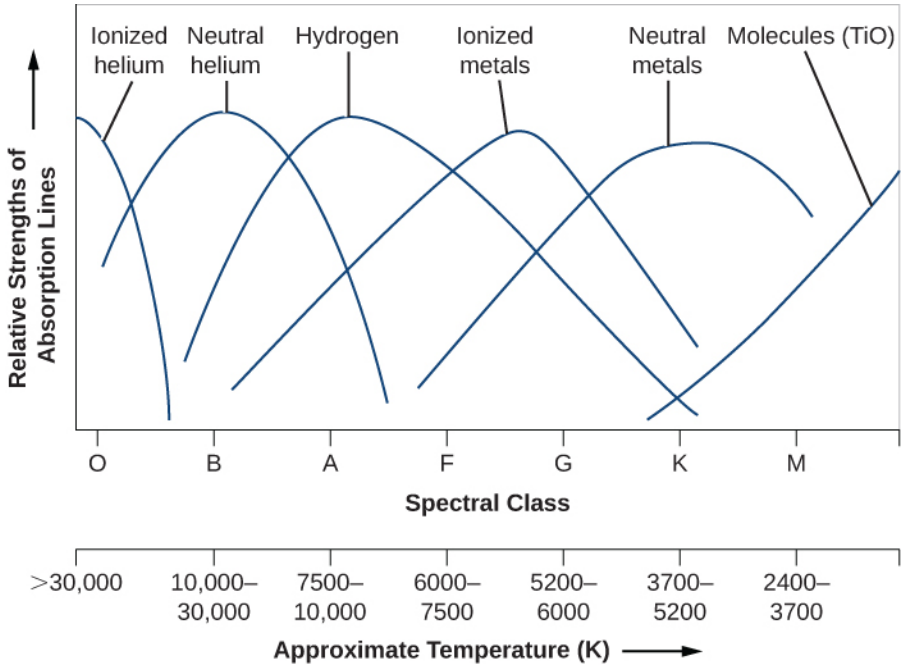


Figure 17.5 Absorption Lines in Stars of Different Temperatures. This graph shows the strengths of absorption lines of different chemical species (atoms, ions, molecules) as we move from hot (left) to cool (right) stars. The sequence of spectral types is also shown.

Spectral Classes for Stars

Spectral Class	Color	Approximate Temperature (K)	Principal Features	Examples
O	Blue	> 30,000	Neutral and ionized helium lines, weak hydrogen lines	10 Lacertae
B	Blue-white	10,000–30,000	Neutral helium lines, strong hydrogen lines	Rigel, Spica
A	White	7500–10,000	Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines	Sirius, Vega
F	Yellow-white	6000–7500	Strong hydrogen lines, strong ionized calcium lines, weak sodium lines, many ionized metal lines	Canopus, Procyon
G	Yellow	5200–6000	Weaker hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of ionized and neutral metals	Sun, Capella
K	Orange	3700–5200	Very weak hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of neutral metals	Arcturus, Aldebaran
M	Red	2400–3700	Strong lines of neutral metals and molecular bands of titanium oxide dominate	Betelgeuse, Antares
L	Red	1300–2400	Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium)	Teide 1
T	Magenta	700–1300	Methane lines	Gliese 229B
Y	Infrared[1]	< 700	Ammonia lines	WISE 1828+2650

Table 17.2

To see how spectral classification works, let's use **Figure 17.5**. Suppose you have a spectrum in which the hydrogen lines are about half as strong as those seen in an A star. Looking at the lines in our figure, you see that the star could be either a B star or a G star. But if the spectrum also contains helium lines, then it is a B star, whereas if it contains lines of ionized iron and other metals, it must be a G star.

If you look at **Figure 17.6**, you can see that you, too, could assign a spectral class to a star whose type was not already known. All you have to do is match the pattern of spectral lines to a standard star (like the ones shown in the figure) whose type has already been determined.

1 Absorption by sodium and potassium atoms makes Y dwarfs appear a bit less red than L dwarfs.

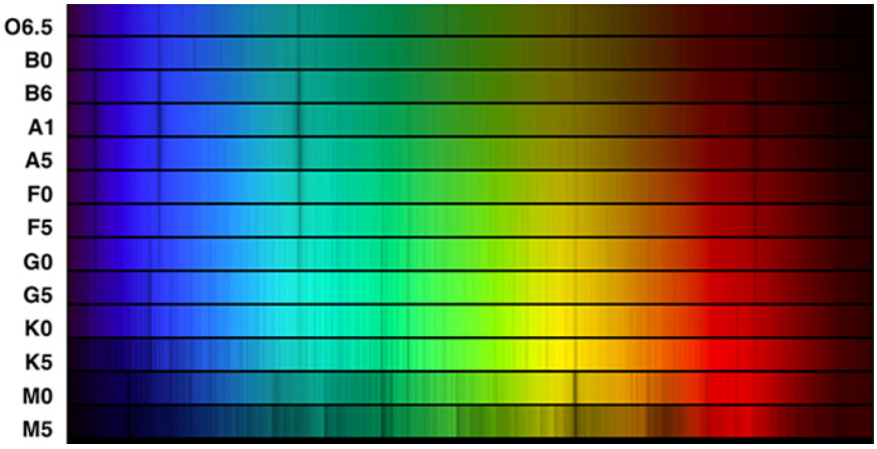


Figure 17.6 Spectra of Stars with Different Spectral Classes. This image compares the spectra of the different spectral classes. The spectral class assigned to each of these stellar spectra is listed at the left of the picture. The strongest four lines seen at spectral type A1 (one in the red, one in the blue-green, and two in the blue) are Balmer lines of hydrogen. Note how these lines weaken at both higher and lower temperatures, as Figure 17.5 also indicates. The strong pair of closely spaced lines in the yellow in the cool stars is due to neutral sodium (one of the neutral metals in Figure 17.5). (Credit: modification of work by NOAO/AURA/NSF)

Both colors and spectral classes can be used to estimate the temperature of a star. Spectra are harder to measure because the light has to be bright enough to be spread out into all colors of the rainbow, and detectors must be sensitive enough to respond to individual wavelengths. In order to measure colors, the detectors need only respond to the many wavelengths that pass simultaneously through the colored filters that have been chosen—that is, to *all* the blue light or *all* the yellow-green light.

VOYAGERS IN ASTRONOMY

Annie Cannon: Classifier of the Stars

Annie Jump Cannon was born in Delaware in 1863 (Figure 17.7). In 1880, she went to Wellesley College, one of the new breed of US colleges opening up to educate young women. Wellesley, only 5 years old at the time, had the second student physics lab in the country and provided excellent training in basic science. After college, Cannon spent a decade with her parents but was very dissatisfied, longing to do scientific work. After her mother's death in 1893, she returned to Wellesley as a teaching assistant and also to take courses at Radcliffe, the women's college associated with Harvard.

Figure 17.7 Annie Jump Cannon (1863–1941). Cannon is well-known for her classifications of stellar spectra. (credit: modification of work by Smithsonian Institution)

In the late 1800s, the director of the Harvard Observatory, Edward C. Pickering, needed lots of help with his ambitious program of classifying stellar spectra. The basis for these studies was a monumental collection of nearly a million photographic spectra of stars, obtained from many years of observations

made at Harvard College Observatory in Massachusetts as well as at its remote observing stations in South America and South Africa. Pickering quickly discovered that educated young women could be hired as assistants for one-third or one-fourth the salary paid to men, and they would often put up with working conditions and repetitive tasks that men with the same education would not tolerate. These women became known as the Harvard Computers. (We should emphasize that astronomers were not alone in reaching such conclusions about the relatively new idea of upper-class, educated women working outside the home: women were exploited and undervalued in many fields. This is a legacy from which our society is just beginning to emerge.)

Cannon was hired by Pickering as one of the "computers" to help with the classification of spectra. She became so good at it that she could visually examine and determine the spectral types of several hundred stars per hour (dictating her conclusions to an assistant). She made many discoveries while investigating the Harvard photographic plates, including 300 variable stars (stars whose luminosity changes periodically). But her main legacy is a marvelous catalog of spectral types for hundreds of thousands of stars, which served as a foundation for much of twentieth-century astronomy.

In 1911, a visiting committee of astronomers reported that "she is the one person in the world who can do this work quickly and accurately" and urged Harvard to give Cannon an official appointment in keeping with her skill and renown. Not until 1938, however, did Harvard appoint her an astronomer at the university; she was then 75 years old.

Cannon received the first honorary degree Oxford awarded to a woman, and she became the first woman to be elected an officer of the American Astronomical Society, the main professional organization of astronomers in the US. She generously donated the money from one of the major prizes she had won to found a special award for women in astronomy, now known as the Annie Jump Cannon Prize. True to form, she continued classifying stellar spectra almost to the very end of her life in 1941.

Spectral Classes L, T, and Y

The scheme devised by Cannon worked well until 1988, when astronomers began to discover objects even cooler than M9-type stars. We use the word *object* because many of the new discoveries are not true stars. A star is defined as an object that during some part of its lifetime derives 100% of its energy from the same process that makes the Sun shine—the fusion of hydrogen nuclei (protons) into helium. Objects with masses less than about 7.5% of the mass of our Sun (about 0.075 M_{Sun}) do not become hot enough for hydrogen fusion to take place. Even before the first such "failed star" was found, this class of objects, with masses intermediate between stars and planets, was given the name **brown dwarfs**.

Brown dwarfs are very difficult to observe because they are extremely faint and cool, and they put out most of their light in the infrared part of the spectrum. It was only after the construction of very large telescopes, like the Keck telescopes in Hawaii, and the development of very sensitive infrared detectors, that the search for brown dwarfs succeeded. The first brown dwarf was discovered in 1988, and, as of the summer of 2015, there are more than 2200 known brown dwarfs.

Initially, brown dwarfs were given spectral classes like $M10^{+}$ or "much cooler than M9," but so many are now known that it is possible to begin assigning spectral types. The hottest brown dwarfs are given types L0–L9 (temperatures in the range 2400–1300 K), whereas still cooler (1300–700 K) objects are given types T0–T9 (see **Figure 17.8**). In class L brown dwarfs, the lines of titanium oxide, which are strong in M stars, have disappeared. This is because the L dwarfs are so cool that atoms and molecules can gather together into dust particles in their atmospheres; the titanium is locked up in the dust grains rather than being available to form molecules of

titanium oxide. Lines of steam (hot water vapor) are present, along with lines of carbon monoxide and neutral sodium, potassium, cesium, and rubidium. Methane (CH_4) lines are strong in class-T brown dwarfs, as methane exists in the atmosphere of the giant planets in our own solar system.

In 2009, astronomers discovered ultra-cool brown dwarfs with temperatures of 500–600 K. These objects exhibited absorption lines due to ammonia (NH_3), which are not seen in T dwarfs. A new spectral class, Y, was created for these objects. As of 2015, over two dozen brown dwarfs belonging to spectral class Y have been discovered, some with temperatures comparable to that of the human body (about 300 K).

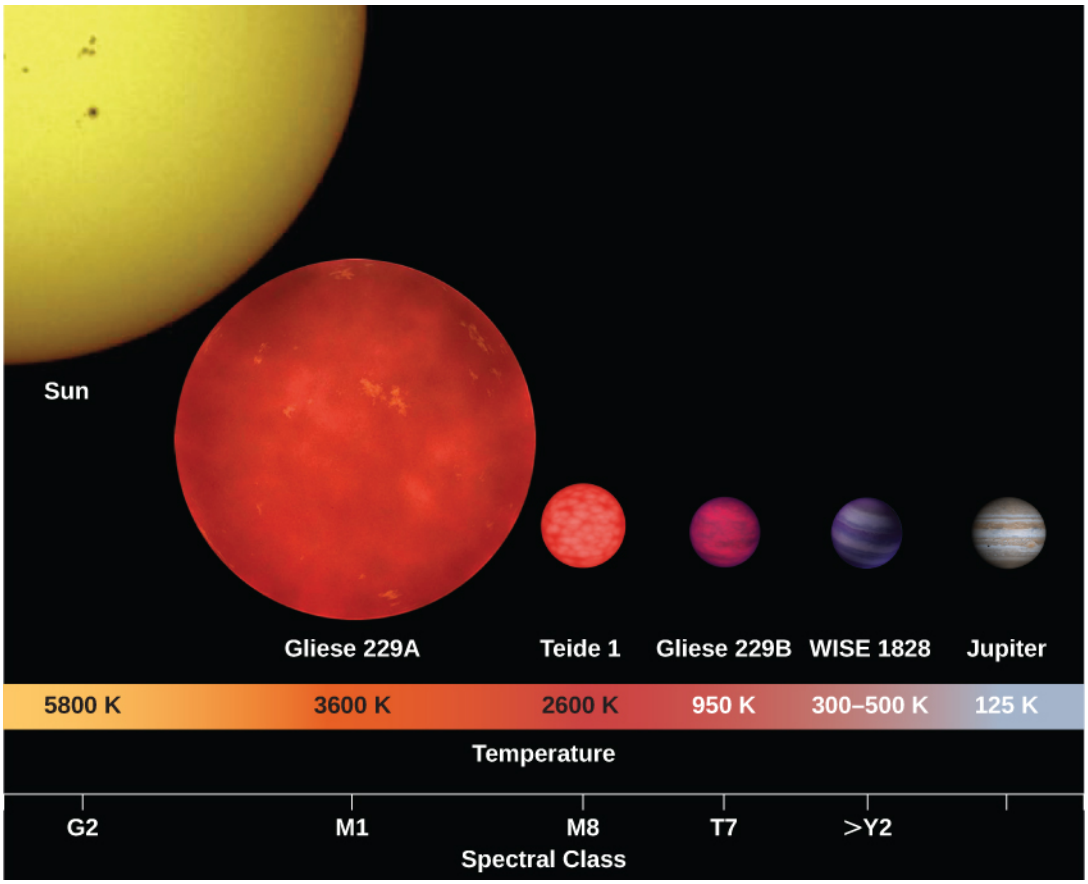


Figure 17.8 Brown Dwarfs. This illustration shows the sizes and surface temperatures of brown dwarfs Teide 1, Gliese 229B, and WISE1828 in relation to the Sun, a red dwarf star (Gliese 229A), and Jupiter. (credit: modification of work by MPIA/V. Joergens)

Most brown dwarfs start out with atmospheric temperatures and spectra like those of true stars with spectral classes of M6.5 and later, even though the brown dwarfs are not hot and dense enough in their interiors to fuse hydrogen. In fact, the spectra of brown dwarfs and true stars are so similar from spectral types late M through L that it is not possible to distinguish the two types of objects based on spectra alone. An independent measure of mass is required to determine whether a specific object is a brown dwarf or a very low mass star. Since brown dwarfs cool steadily throughout their lifetimes, the spectral type of a given brown dwarf changes with time over a billion years or more from late M through L, T, and Y spectral types.

Low-Mass Brown Dwarfs vs. High-Mass Planets

An interesting property of brown dwarfs is that they are all about the same radius as Jupiter, regardless of their masses. Amazingly, this covers a range of masses from about 13 to 80 times the mass of Jupiter (M_J). This can make distinguishing a low-mass brown dwarf from a high-mass planet very difficult.

So, what is the difference between a low-mass brown dwarf and a high-mass planet? The International Astronomical Union considers the distinctive feature to be *deuterium fusion*. Although brown dwarfs do not sustain regular (proton-proton) hydrogen fusion, they are capable of fusing deuterium (a rare form of hydrogen with one proton and one neutron in its nucleus). The fusion of deuterium can happen at a lower temperature than the fusion of hydrogen. If an object has enough mass to fuse deuterium (about 13 M_J or 0.012 M_{Sun}), it is a brown dwarf. Objects with less than 13 M_J do not fuse deuterium and are usually considered planets.

17.4 USING SPECTRA TO MEASURE STELLAR RADIUS, COMPOSITION, AND MOTION

Learning Objectives

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

- Understand how astronomers can learn about a star's radius and composition by studying its spectrum
- Explain how astronomers can measure the motion and rotation of a star using the Doppler effect
- Describe the proper motion of a star and how it relates to a star's space velocity

Analyzing the spectrum of a star can teach us all kinds of things in addition to its temperature. We can measure its detailed chemical composition as well as the pressure in its atmosphere. From the pressure, we get clues about its size. We can also measure its motion toward or away from us and estimate its rotation.

Clues to the Size of a Star

As we shall see in **The Stars: A Celestial Census**, stars come in a wide variety of sizes. At some periods in their lives, stars can expand to enormous dimensions. Stars of such exaggerated size are called **giants**. Luckily for the astronomer, stellar spectra can be used to distinguish giants from run-of-the-mill stars (such as our Sun).

Suppose you want to determine whether a star is a giant. A giant star has a large, extended photosphere. Because it is so large, a giant star's atoms are spread over a great volume, which means that the density of particles in the star's photosphere is low. As a result, the pressure in a giant star's photosphere is also low. This low pressure affects the spectrum in two ways. First, a star with a lower-pressure photosphere shows narrower spectral lines than a star of the same temperature with a higher-pressure photosphere (**Figure 17.9**). The difference is large enough that careful study of spectra can tell which of two stars at the same temperature has a higher pressure (and is thus more compressed) and which has a lower pressure (and thus must be extended). This effect is due to collisions between particles in the star's photosphere—more collisions lead to broader spectral lines. Collisions will, of course, be more frequent in a higher-density environment. Think about it like traffic—collisions are much more likely during rush hour, when the density of cars is high.

Second, more atoms are ionized in a giant star than in a star like the Sun with the same temperature. The ionization of atoms in a star's outer layers is caused mainly by photons, and the amount of energy carried by photons is determined by temperature. But how long atoms *stay* ionized depends in part on pressure. Compared with what happens in the Sun (with its relatively dense photosphere), ionized atoms in a giant star's photosphere are less likely to pass close enough to electrons to interact and combine with one or more of them, thereby becoming neutral again. Ionized atoms, as we discussed earlier, have different spectra from atoms that are neutral.

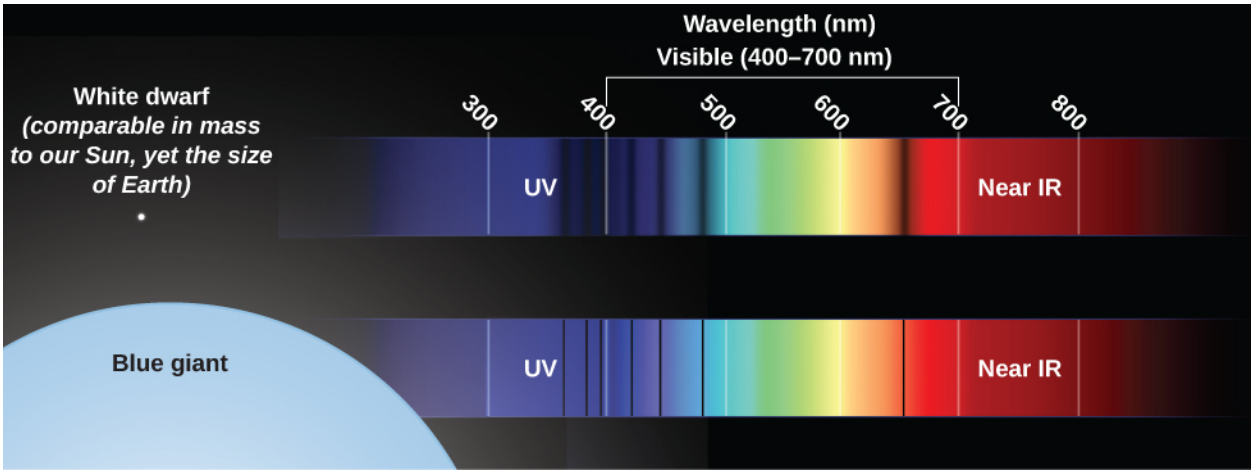


Figure 17.9 Spectral Lines. This figure illustrates one difference in the spectral lines from stars of the same temperature but different pressures. A giant star with a very-low-pressure photosphere shows very narrow spectral lines (bottom), whereas a smaller star with a higher-pressure photosphere shows much broader spectral lines (top). (credit: modification of work by NASA, ESA, A. Field, and J. Kalirai (STScI))

Abundances of the Elements

Absorption lines of a majority of the known chemical elements have now been identified in the spectra of the Sun and stars. If we see lines of iron in a star's spectrum, for example, then we know immediately that the star must contain iron.

Note that the *absence* of an element's spectral lines does not necessarily mean that the element itself is absent. As we saw, the temperature and pressure in a star's atmosphere will determine what types of atoms are able to produce absorption lines. Only if the physical conditions in a star's photosphere are such that lines of an element *should* (according to calculations) be there can we conclude that the absence of observable spectral lines implies low abundance of the element.

Suppose two stars have identical temperatures and pressures, but the lines of, say, sodium are stronger in one than in the other. Stronger lines mean that there are more atoms in the stellar photosphere absorbing light. Therefore, we know immediately that the star with stronger sodium lines contains more sodium. Complex calculations are required to determine exactly how much more, but those calculations can be done for any element observed in any star with any temperature and pressure.

Of course, astronomy textbooks such as ours always make these things sound a bit easier than they really are. If you look at the stellar spectra such as those in **Figure 17.6**, you may get some feeling for how hard it is to decode all of the information contained in the thousands of absorption lines. First of all, it has taken many years of careful laboratory work on Earth to determine the precise wavelengths at which hot gases of each element have their spectral lines. Long books and computer databases have been compiled to show the lines of each element that can be seen at each temperature. Second, stellar spectra usually have many lines from a number of elements, and we must be careful to sort them out correctly. Sometimes nature is unhelpful, and lines of different elements have identical wavelengths, thereby adding to the confusion. And third, as we saw in the chapter on **Radiation and Spectra**, the motion of the star can change the observed wavelength of each of the lines. So, the observed wavelengths may not match laboratory measurements exactly. In practice, analyzing stellar spectra is a demanding, sometimes frustrating task that requires both training and skill.

Studies of stellar spectra have shown that hydrogen makes up about three-quarters of the mass of most stars. Helium is the second-most abundant element, making up almost a quarter of a star's mass. Together, hydrogen and helium make up from 96 to 99% of the mass; in some stars, they amount to more than 99.9%. Among the 4% or less of "heavy elements," oxygen, carbon, neon, iron, nitrogen, silicon, magnesium, and sulfur are among

the most abundant. Generally, but not invariably, the elements of lower atomic weight are more abundant than those of higher atomic weight.

Take a careful look at the list of elements in the preceding paragraph. Two of the most abundant are hydrogen and oxygen (which make up water); add carbon and nitrogen and you are starting to write the prescription for the chemistry of an astronomy student. We are made of elements that are common in the universe—just mixed together in a far more sophisticated form (and a much cooler environment) than in a star.

As we mentioned in **The Spectra of Stars (and Brown Dwarfs)** section, astronomers use the term "metals" to refer to all elements heavier than hydrogen and helium. The fraction of a star's mass that is composed of these elements is referred to as the star's *metallicity*. The metallicity of the Sun, for example, is 0.02, since 2% of the Sun's mass is made of elements heavier than helium.

Appendix K lists how common each element is in the universe (compared to hydrogen); these estimates are based primarily on investigation of the Sun, which is a typical star. Some very rare elements, however, have not been detected in the Sun. Estimates of the amounts of these elements in the universe are based on laboratory measurements of their abundance in primitive meteorites, which are considered representative of unaltered material condensed from the solar nebula (see the **Cosmic Samples and the Origin of the Solar System** chapter).

Radial Velocity

When we measure the spectrum of a star, we determine the wavelength of each of its lines. If the star is not moving with respect to the Sun, then the wavelength corresponding to each element will be the same as those we measure in a laboratory here on Earth. But if stars are moving toward or away from us, we must consider the *Doppler effect* (see **The Doppler Effect** section). We should see all the spectral lines of moving stars shifted toward the red end of the spectrum if the star is moving away from us, or toward the blue (violet) end if it is moving toward us (**Figure 17.10**). The greater the shift, the faster the star is moving. Such motion, along the line of sight between the star and the observer, is called **radial velocity** and is usually measured in kilometers per second.

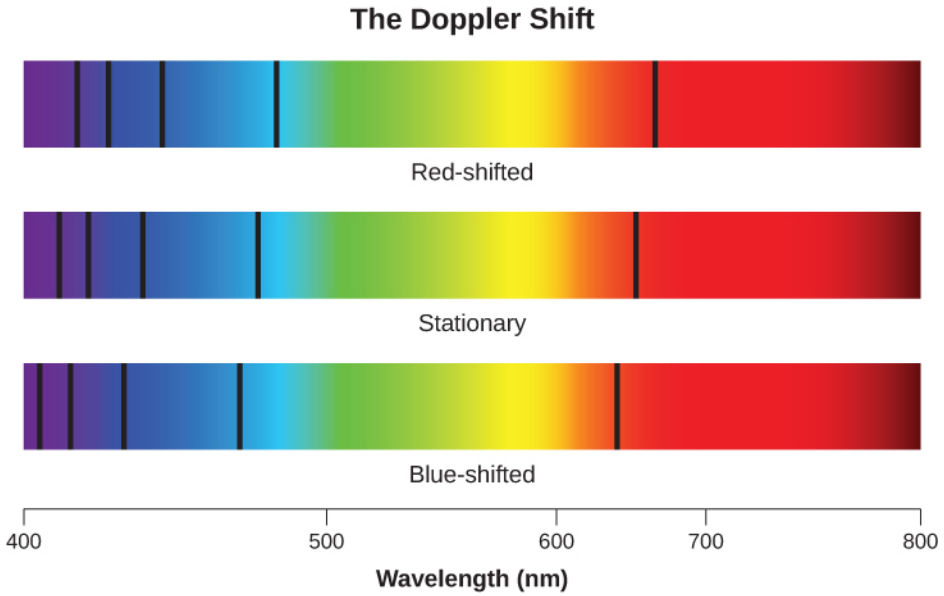


Figure 17.10 Doppler-Shifted Stars. When the spectral lines of a moving star shift toward the red end of the spectrum, we know that the star is moving away from us. If they shift toward the blue end, the star is moving toward us.

William Huggins, pioneering yet again, in 1868 made the first radial velocity determination of a star. He observed the Doppler shift in one of the hydrogen lines in the spectrum of Sirius and found that this star is moving toward the solar system. Today, radial velocity can be measured for any star bright enough for its spectrum to be observed. As we will see in **The Stars: A Celestial Census**, radial velocity measurements of double stars are crucial in deriving stellar masses.

Proper Motion

There is another type of motion stars can have that cannot be detected with stellar spectra. Unlike radial motion, which is along our line of sight (i.e., toward or away from Earth), this motion, called **proper motion**, is *transverse*: that is, across our line of sight. We see it as a change in the relative positions of the stars on the celestial sphere (**Figure 17.11**). These changes are very slow. Even the star with the largest proper motion takes 200 years to change its position in the sky by an amount equal to the width of the full Moon, and the motions of other stars are smaller yet.

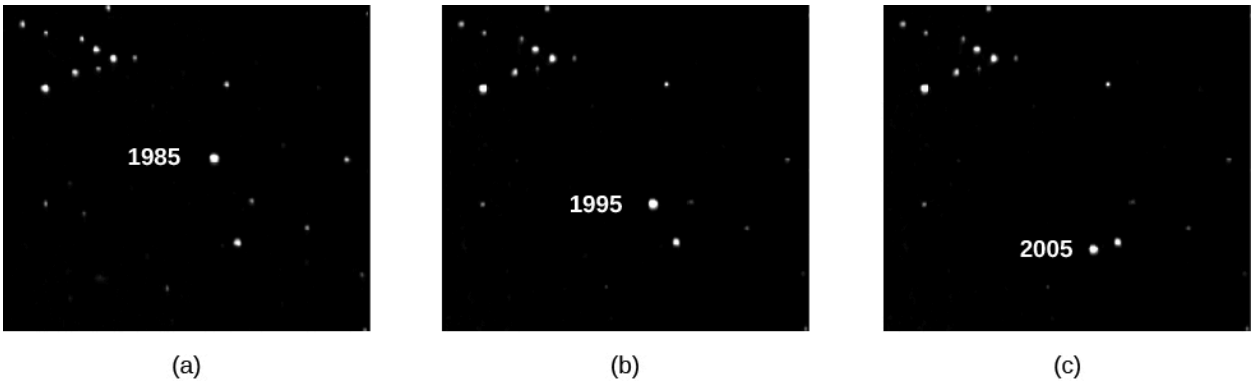


Figure 17.11 Large Proper Motion. Three photographs of Barnard's star, the star with the largest known proper motion, show how this faint star has moved over a period of 20 years. (modification of work by Steve Quirk)

For this reason, with our naked eyes, we do not notice any change in the positions of the bright stars during the course of a human lifetime. If we could live long enough, however, the changes would become obvious. For example, some 50,000 years from now, terrestrial observers will find the handle of the Big Dipper unmistakably more bent than it is now (**Figure 17.12**).

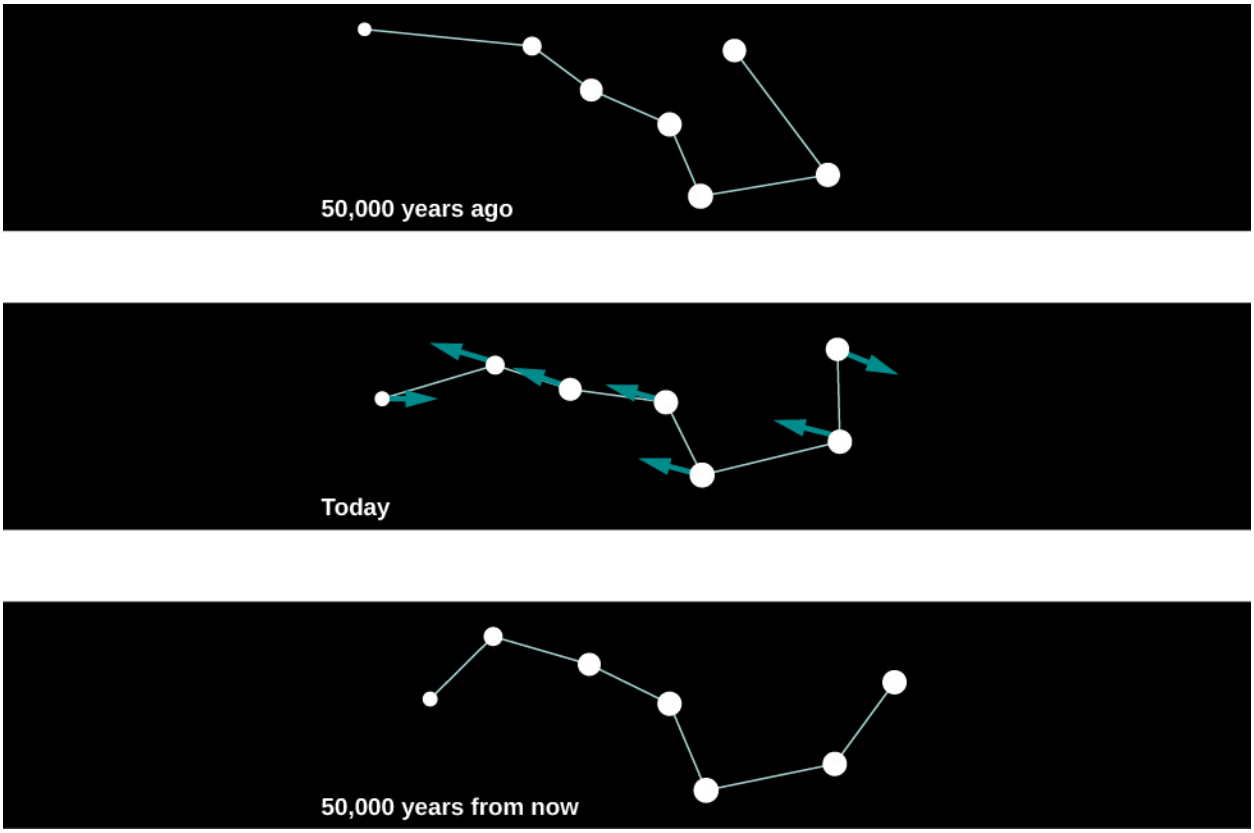


Figure 17.12 Changes in the Big Dipper. This figure shows changes in the appearance of the Big Dipper due to proper motion of the stars over 100,000 years.

We measure the proper motion of a star in arcseconds (1/3600 of a degree) per year. That is, the measurement of proper motion tells us only by how much of an angle a star has changed its position on the celestial sphere. If two stars at different distances are moving at the same velocity perpendicular to our line of sight, the closer one will show a larger shift in its position on the celestial sphere in a year's time. As an analogy, imagine you are standing at the side of a freeway. Cars will appear to whiz past you. If you then watch the traffic from a vantage point half a mile away, the cars will move much more slowly across your field of vision. In order to convert this angular motion to a velocity, we need to know how far away the star is.

To know the true **space velocity** of a star—that is, its total speed and the direction in which it is moving through space relative to the Sun—we must know its radial velocity, proper motion, and distance (Figure 17.13). A star's space velocity can also, over time, cause its distance from the Sun to change significantly. Over several hundred thousand years, these changes can be large enough to affect the apparent brightnesses of nearby stars. Today, Sirius, in the constellation Canis Major (the Big Dog) is the brightest star in the sky, but 100,000 years ago, the star Canopus in the constellation Carina (the Keel) was the brightest one. A little over 200,000 years from now, Sirius will have moved away and faded somewhat, and Vega, the bright blue star in Lyra, will take over its place of honor as the brightest star in Earth's skies.

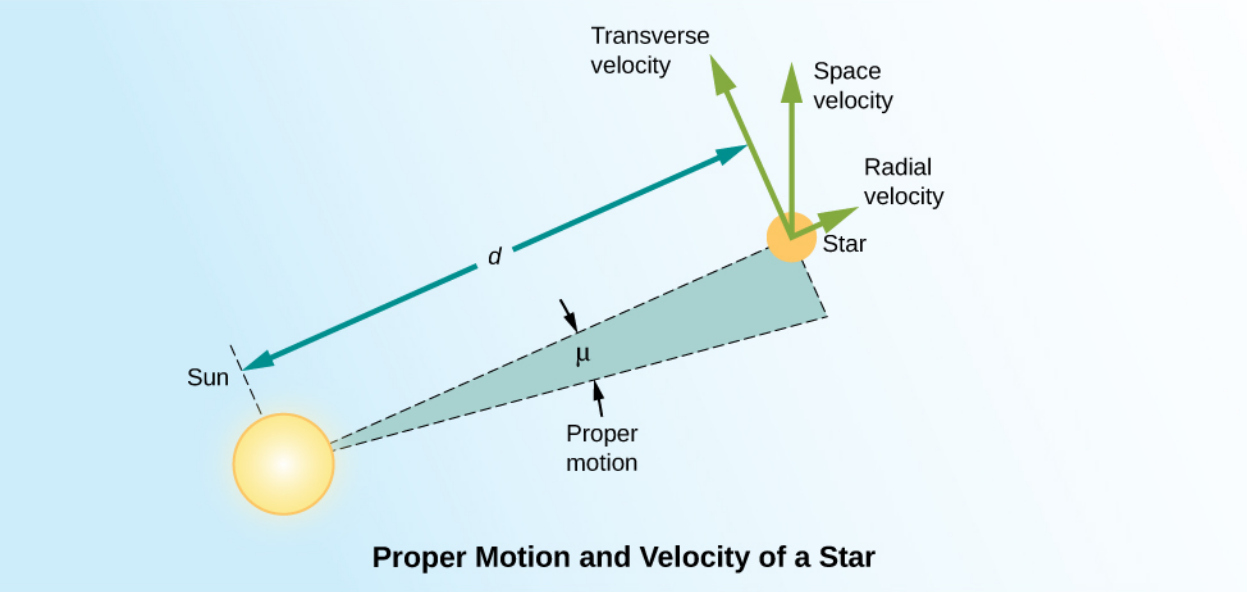


Figure 17.13 Space Velocity and Proper Motion. This figure shows the true space velocity of a star. The radial velocity is the component of the space velocity projected along the line of sight from the Sun to a star. The transverse velocity is a component of the space velocity projected on the sky. What astronomers measure is proper motion (μ), which is the change in the apparent direction on the sky measured in fractions of a degree. To convert this change in direction to a speed in, say, kilometers per second, it is necessary to also know the distance (*d*) from the Sun to the star.

Rotation

We can also use the Doppler effect to measure how fast a star rotates. If an object is rotating, then one of its sides is approaching us while the other is receding (unless its axis of rotation happens to be pointed exactly toward us). This is clearly the case for the Sun or a planet; we can observe the light from either the approaching or receding edge of these nearby objects and directly measure the Doppler shifts that arise from the rotation.

Stars, however, are so far away that they all appear as unresolved points. The best we can do is to analyze the light from the entire star at once. Due to the Doppler effect, the lines in the light that come from the side of the star rotating toward us are shifted to shorter wavelengths and the lines in the light from the opposite edge of the star are shifted to longer wavelengths. You can think of each spectral line that we observe as the sum or composite of spectral lines originating from different speeds with respect to us. Each point on the star has its own Doppler shift, so the absorption line we see from the whole star is actually much wider than it would be if the star were not rotating. If a star is rotating rapidly, there will be a greater spread of Doppler shifts and all its spectral lines should be quite broad. In fact, astronomers call this effect *line broadening*, and the amount of broadening can tell us the speed at which the star rotates (**Figure 17.14**).

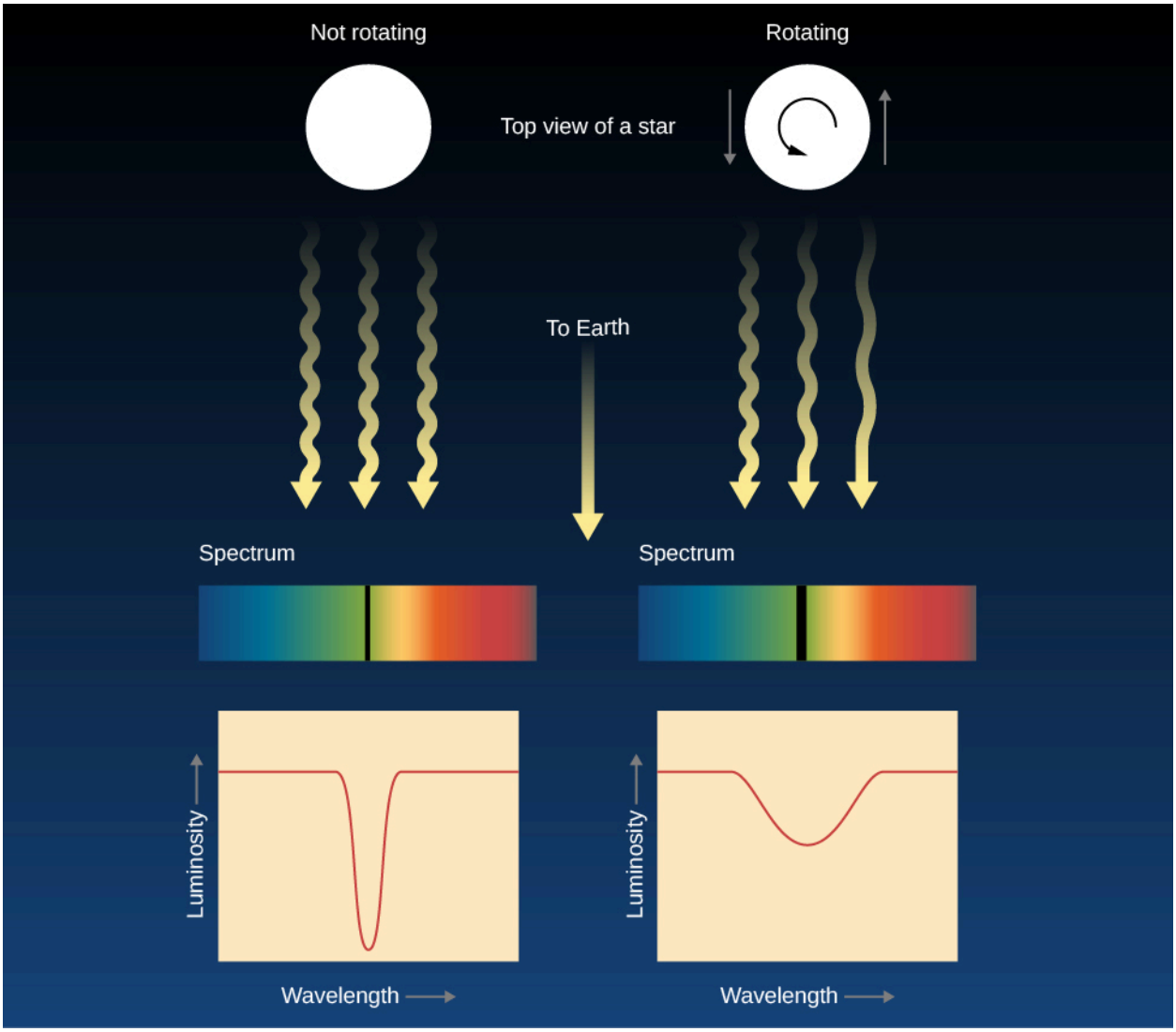


Figure 17.14 Using a Spectrum to Determine Stellar Rotation. A rotating star will show broader spectral lines than a nonrotating star.

Measurements of the widths of spectral lines show that many stars rotate faster than the Sun, some with periods of less than a day! These rapid rotators spin so fast that their shapes are “flattened” into what we call *oblate spheroids*. An example of this is the star Vega, which rotates once every 12.5 hours. Vega’s rotation flattens its shape so much that its diameter at the equator is 23% wider than its diameter at the poles (**Figure 17.15**). The Sun, with its rotation period of about a month, rotates rather slowly. Studies have shown that stars decrease their rotational speed as they age. Young stars rotate very quickly, with rotational periods of days or less. Very old stars can have rotation periods of several months.

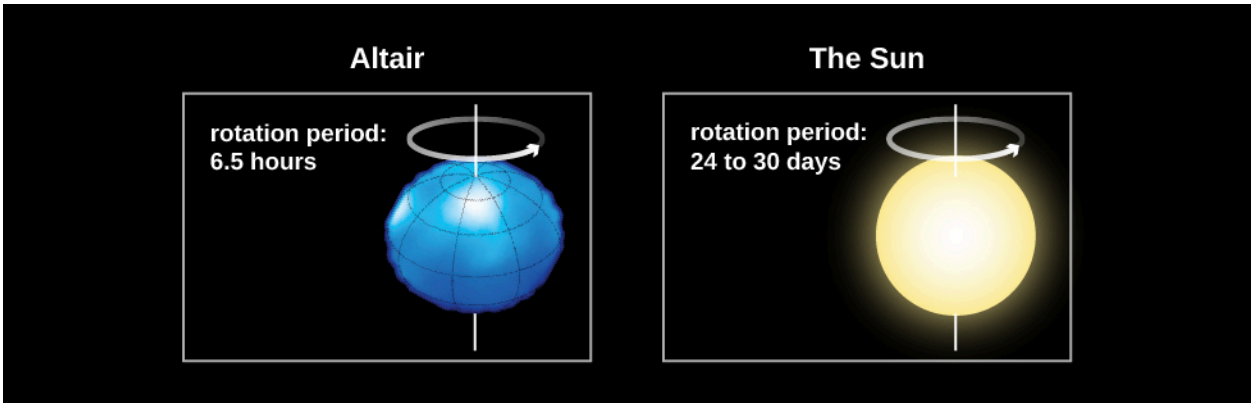


Figure 17.15 Comparison of Rotating Stars. This illustration compares the more rapidly rotating star Altair to the slower rotating Sun.

As you can see, spectroscopy is an extremely powerful technique that helps us learn all kinds of information about stars that we simply could not gather any other way. We will see in later chapters that these same techniques can also teach us about galaxies, which are the most distant objects that can we observe. Without spectroscopy, we would know next to nothing about the universe beyond the solar system.

MAKING CONNECTIONS

Astronomy and Philanthropy

Throughout the history of astronomy, contributions from wealthy patrons of the science have made an enormous difference in building new instruments and carrying out long-term research projects. Edward Pickering's stellar classification project, which was to stretch over several decades, was made possible by major donations from Anna Draper. She was the widow of Henry Draper, a physician who was one of the most accomplished amateur astronomers of the nineteenth century and the first person to successfully photograph the spectrum of a star. Anna Draper gave several hundred thousand dollars to Harvard Observatory. As a result, the great spectroscopic survey is still known as the Henry Draper Memorial, and many stars are still referred to by their "HD" numbers in that catalog (such as HD 209458).

In the 1870s, the eccentric piano builder and real estate magnate James Lick (**Figure 17.16**) decided to leave some of his fortune to build the world's largest telescope. When, in 1887, the pier to house the telescope was finished, Lick's body was entombed in it. Atop the foundation rose a 36-inch refractor, which for many years was the main instrument at the Lick Observatory near San Jose.

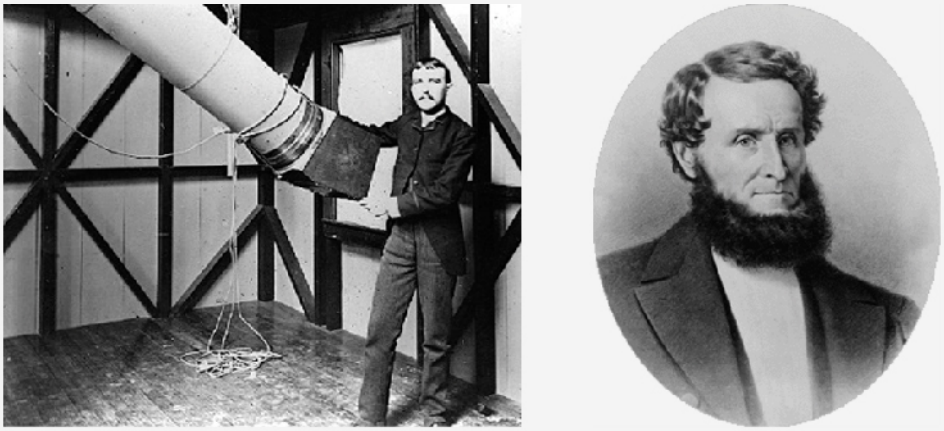


Figure 17.16 Henry Draper (1837–1882) and James Lick (1796–1876). (a) Draper stands next to a telescope used for photography. After his death, his widow funded further astronomy work in his name. (b) Lick was a philanthropist who provided funds to build a 36-inch refractor not only as a memorial to himself but also to aid in further astronomical research.

The Lick telescope remained the largest in the world until 1897, when George Ellery Hale persuaded railroad millionaire Charles Yerkes to finance the construction of a 40-inch telescope near Chicago. More recently, Howard Keck, whose family made its fortune in the oil industry, gave $70 million from his family foundation to the California Institute of Technology to help build the world's largest telescope atop the 14,000-foot peak of Mauna Kea in Hawaii (see the chapter on **Astronomical Instruments** to learn more about these telescopes). The Keck Foundation was so pleased with what is now called the Keck telescope that they gave $74 million more to build Keck II, another 10-meter reflector on the same volcanic peak.

Now, if any of you become millionaires or billionaires, and astronomy has sparked your interest, do keep an astronomical instrument or project in mind as you plan your estate. But frankly, private philanthropy could not possibly support the full enterprise of scientific research in astronomy. Much of our exploration of the universe is financed by federal agencies such as the National Science Foundation and NASA in the United States, and by similar government agencies in the other countries. In this way, all of us, through a very small share of our tax dollars, are philanthropists for astronomy.

CHAPTER 17 REVIEW

KEY TERMS

apparent brightness a measure of the amount of light received by Earth from a star or other object—that is, how bright an object appears in the sky, as contrasted with its luminosity

brown dwarf an object intermediate in size between a planet and a star; the approximate mass range is from about 1/100 of the mass of the Sun up to the lower mass limit for self-sustaining nuclear reactions, which is about 0.075 the mass of the Sun; brown dwarfs are capable of deuterium fusion, but not hydrogen fusion

color index difference between the magnitudes of a star or other object measured in light of two different spectral regions—for example, blue minus visual (B–V) magnitudes

giant a star of exaggerated size with a large, extended photosphere

luminosity the rate at which a star or other object emits electromagnetic energy into space; the total power output of an object

magnitude an older system of measuring the amount of light we receive from a star or other luminous object; the larger the magnitude, the less radiation we receive from the object

proper motion the angular change per year in the direction of a star as seen from the Sun

radial velocity motion toward or away from the observer; the component of relative velocity that lies in the line of sight

space velocity the total (three-dimensional) speed and direction with which an object is moving through space relative to the Sun

spectral class (or spectral type) the classification of stars according to their temperatures using the characteristics of their spectra; the types are O, B, A, F, G, K, and M with L, T, and Y added recently for cooler star-like objects that recent survey have revealed

SUMMARY

17.1 The Brightness of Stars

The total energy emitted per second by a star is called its luminosity. How bright a star looks from the perspective of Earth is its apparent brightness. The apparent brightness of a star depends on both its luminosity and its distance from Earth. Thus, the determination of apparent brightness and measurement of the distance to a star provide enough information to calculate its luminosity. The apparent brightnesses of stars are often expressed in terms of magnitudes, which is an old system based on how human vision interprets relative light intensity.

17.2 Colors of Stars

Stars have different colors, which are indicators of temperature. The hottest stars tend to appear blue or blue-white, whereas the coolest stars are red. A color index of a star is the difference in the magnitudes measured at any two wavelengths and is one way that astronomers measure and express the temperature of stars.

17.3 The Spectra of Stars (and Brown Dwarfs)

The differences in the spectra of stars are principally due to differences in temperature, not composition. The spectra of stars are described in terms of spectral classes. In order of decreasing temperature, these spectral classes are O, B, A, F, G, K, M, L, T, and Y. These are further divided into subclasses numbered from 0 to 9. The classes L, T, and Y have been added recently to describe newly discovered star-like objects—mainly brown dwarfs—that are cooler than M9. Our Sun has spectral type G2.

17.4 Using Spectra to Measure Stellar Radius, Composition, and Motion

Spectra of stars of the same temperature but different atmospheric pressures have subtle differences, so spectra can be used to determine whether a star has a large radius and low atmospheric pressure (a giant star) or a small radius and high atmospheric pressure. Stellar spectra can also be used to determine the chemical composition of stars; hydrogen and helium make up most of the mass of all stars. Measurements of line shifts produced by the Doppler effect indicate the radial velocity of a star. Broadening of spectral lines by the Doppler effect is a measure of rotational velocity. A star can also show proper motion, due to the component of a star's space velocity across the line of sight.

FOR FURTHER EXPLORATION

Articles

Berman, B. "Magnitude Cum Laude." *Astronomy* (December 1998): 92. How we measure the apparent brightnesses of stars is discussed.

Dvorak, J. "The Women Who Created Modern Astronomy [including Annie Cannon]." *Sky & Telescope* (August 2013): 28.

Hearnshaw, J. "Origins of the Stellar Magnitude Scale." *Sky & Telescope* (November 1992): 494. A good history of how we have come to have this cumbersome system is discussed.

Hirshfeld, A. "The Absolute Magnitude of Stars." *Sky & Telescope* (September 1994): 35.

Kaler, J. "Stars in the Cellar: Classes Lost and Found." *Sky & Telescope* (September 2000): 39. An introduction is provided for spectral types and the new classes L and T.

Kaler, J. "Origins of the Spectral Sequence." *Sky & Telescope* (February 1986): 129.

Skrutskie, M. "2MASS: Unveiling the Infrared Universe." *Sky & Telescope* (July 2001): 34. This article focuses on an all-sky survey at 2 microns.

Sneden, C. "Reading the Colors of the Stars." *Astronomy* (April 1989): 36. This article includes a discussion of what we learn from spectroscopy.

Steffey, P. "The Truth about Star Colors." *Sky & Telescope* (September 1992): 266. The color index and how the eye and film "see" colors are discussed.

Tomkins, J. "Once and Future Celestial Kings." *Sky & Telescope* (April 1989): 59. Calculating the motion of stars and determining which stars were, are, and will be brightest in the sky are discussed.

Websites

Discovery of Brown Dwarfs: **http://w.astro.berkeley.edu/~basri/bdwarfs/SciAm-book.pdf (http://w.astro.berkeley.edu/~basri/bdwarfs/SciAm-book.pdf)** .

Listing of Nearby Brown Dwarfs: **http://www.solstation.com/stars/pc10bd.htm**

(http://www.solstation.com/stars/pc10bd.htm) .

Spectral Types of Stars: http://www.skyandtelescope.com/astronomy-equipment/the-spectral-types-of-stars/ (http://www.skyandtelescope.com/astronomy-equipment/the-spectral-types-of-stars/) .

Stellar Velocities https://www.e-education.psu.edu/astro801/content/l4_p7.html (https://www.e-education.psu.edu/astro801/content/l4_p7.html) .

Unheard Voices! The Contributions of Women to Astronomy: A Resource Guide: http://multiverse.ssl.berkeley.edu/women (http://multiverse.ssl.berkeley.edu/women) and http://www.astrosociety.org/education/astronomy-resource-guides/women-in-astronomy-an-introductory-resource-guide/ (http://www.astrosociety.org/education/astronomy-resource-guides/women-in-astronomy-an-introductory-resource-guide/) .

Videos

When You Are Just Too Small to be a Star: https://www.youtube.com/watch?v=zXCDsb4n4KU (https://www.youtube.com/watch?v=zXCDsb4n4KU) . 2013 Public Talk on Brown Dwarfs and Planets by Dr. Gibor Basri of the University of California–Berkeley (1:32:52).

COLLABORATIVE GROUP ACTIVITIES

A. The Voyagers in Astronomy feature on **Annie Cannon: Classifier of the Stars** discusses some of the difficulties women who wanted to do astronomy faced in the first half of the twentieth century. What does your group think about the situation for women today? Do men and women have an equal chance to become scientists? Discuss with your group whether, in your experience, boys and girls were equally encouraged to do science and math where you went to school.

B. In the section on magnitudes in **The Brightness of Stars**, we discussed how this old system of classifying how bright different stars appear to the eye first developed. Your authors complained about the fact that this old system still has to be taught to every generation of new students. Can your group think of any other traditional systems of doing things in science and measurement where tradition rules even though common sense says a better system could certainly be found. Explain. (Hint: Try Daylight Savings Time, or metric versus English units.)

C. Suppose you could observe a star that has only one spectral line. Could you tell what element that spectral line comes from? Make a list of reasons with your group about why you answered yes or no.

D. A wealthy alumnus of your college decides to give $50 million to the astronomy department to build a world-class observatory for learning more about the characteristics of stars. Have your group discuss what kind of equipment they would put in the observatory. Where should this observatory be located? Justify your answers. (You may want to refer back to the **Astronomical Instruments** chapter and to revisit this question as you learn more about the stars and equipment for observing them in future chapters.)

E. For some astronomers, introducing a new spectral type for the stars (like the types L, T, and Y discussed in the text) is similar to introducing a new area code for telephone calls. No one likes to disrupt the old system, but sometimes it is simply necessary. Have your group make a list of steps an astronomer would have to go through to persuade colleagues that a new spectral class is needed.

EXERCISES

Review Questions

1. What two factors determine how bright a star appears to be in the sky?
2. Explain why color is a measure of a star's temperature.
3. What is the main reason that the spectra of all stars are not identical? Explain.
4. What elements are stars mostly made of? How do we know this?
5. What did Annie Cannon contribute to the understanding of stellar spectra?
6. Name five characteristics of a star that can be determined by measuring its spectrum. Explain how you would use a spectrum to determine these characteristics.
7. How do objects of spectral types L, T, and Y differ from those of the other spectral types?
8. Do stars that look brighter in the sky have larger or smaller magnitudes than fainter stars?
9. The star Antares has an apparent magnitude of 1.0, whereas the star Procyon has an apparent magnitude of 0.4. Which star appears brighter in the sky?
10. Based on their colors, which of the following stars is hottest? Which is coolest? Archenar (blue), Betelgeuse (red), Capella (yellow).
11. Order the seven basic spectral types from hottest to coldest.
12. What is the defining difference between a brown dwarf and a true star?

Thought Questions

13. If the star Sirius emits 23 times more energy than the Sun, why does the Sun appear brighter in the sky?
14. How would two stars of equal luminosity—one blue and the other red—appear in an image taken through a filter that passes mainly blue light? How would their appearance change in an image taken through a filter that transmits mainly red light?
15. Table 17.2 lists the temperature ranges that correspond to the different spectral types. What part of the star do these temperatures refer to? Why?
16. Suppose you are given the task of measuring the colors of the brightest stars, listed in Appendix J, through three filters: the first transmits blue light, the second transmits yellow light, and the third transmits red light. If you observe the star Vega, it will appear equally bright through each of the three filters. Which stars will appear brighter through the blue filter than through the red filter? Which stars will appear brighter through the red filter? Which star is likely to have colors most nearly like those of Vega?
17. Star X has lines of ionized helium in its spectrum, and star Y has bands of titanium oxide. Which is hotter? Why? The spectrum of star Z shows lines of ionized helium and also molecular bands of titanium oxide. What is strange about this spectrum? Can you suggest an explanation?
18. The spectrum of the Sun has hundreds of strong lines of nonionized iron but only a few, very weak lines of helium. A star of spectral type B has very strong lines of helium but very weak iron lines. Do these differences mean that the Sun contains more iron and less helium than the B star? Explain.

19. What are the approximate spectral classes of stars with the following characteristics?

A. Balmer lines of hydrogen are very strong; some lines of ionized metals are present.

B. The strongest lines are those of ionized helium.

C. Lines of ionized calcium are the strongest in the spectrum; hydrogen lines show only moderate strength; lines of neutral and metals are present.

D. The strongest lines are those of neutral metals and bands of titanium oxide.

20. Look at the chemical elements in **Appendix K**. Can you identify any relationship between the abundance of an element and its atomic weight? Are there any obvious exceptions to this relationship?

21. **Appendix I** lists some of the nearest stars. Are most of these stars hotter or cooler than the Sun? Do any of them emit more energy than the Sun? If so, which ones?

22. **Appendix J** lists the stars that appear brightest in our sky. Are most of these hotter or cooler than the Sun? Can you suggest a reason for the difference between this answer and the answer to the previous question? (Hint: Look at the luminosities.) Is there any tendency for a correlation between temperature and luminosity? Are there exceptions to the correlation?

23. What star appears the brightest in the sky (other than the Sun)? The second brightest? What color is Betelgeuse? Use **Appendix J** to find the answers.

24. Suppose hominids one million years ago had left behind maps of the night sky. Would these maps represent accurately the sky that we see today? Why or why not?

25. Why can only a lower limit to the rate of stellar rotation be determined from line broadening rather than the actual rotation rate? (Refer to **Figure 17.14**.)

26. Why do you think astronomers have suggested three different spectral types (L, T, and Y) for the brown dwarfs instead of M? Why was one not enough?

27. Sam, a college student, just bought a new car. Sam's friend Adam, a graduate student in astronomy, asks Sam for a ride. In the car, Adam remarks that the colors on the temperature control are wrong. Why did he say that?

Figure 17.17 (credit: modification of work by Michael Sheehan)

28. Would a red star have a smaller or larger magnitude in a red filter than in a blue filter?

29. Two stars have proper motions of one arcsecond per year. Star A is 20 light-years from Earth, and Star B is 10 light-years away from Earth. Which one has the faster velocity in space?

30. Suppose there are three stars in space, each moving at 100 km/s. Star A is moving across (i.e., perpendicular to) our line of sight, Star B is moving directly away from Earth, and Star C is moving away from Earth, but at a 30° angle to the line of sight. From which star will you observe the greatest Doppler shift? From which star will you observe the smallest Doppler shift?

31. What would you say to a friend who made this statement, "The visible-light spectrum of the Sun shows weak hydrogen lines and strong calcium lines. The Sun must therefore contain more calcium than hydrogen."?

Figuring For Yourself

32. In **Appendix J**, how much more luminous is the most luminous of the stars than the least luminous?

For **Exercise 17.33** through **Exercise 17.38**, use the equations relating magnitude and apparent brightness given in the section on the magnitude scale in **The Brightness of Stars** and **Example 17.1**.

33. Verify that if two stars have a difference of five magnitudes, this corresponds to a factor of 100 in the ratio $\left(\frac{b_2}{b_1}\right)$; that 2.5 magnitudes corresponds to a factor of 10; and that 0.75 magnitudes corresponds to a factor of 2.

34. As seen from Earth, the Sun has an apparent magnitude of about −26.7. What is the apparent magnitude of the Sun as seen from Saturn, about 10 AU away? (Remember that one AU is the distance from Earth to the Sun and that the brightness decreases as the inverse square of the distance.) Would the Sun still be the brightest star in the sky?

35. An astronomer is investigating a faint star that has recently been discovered in very sensitive surveys of the sky. The star has a magnitude of 16. How much less bright is it than Antares, a star with magnitude roughly equal to 1?

36. The center of a faint but active galaxy has magnitude 26. How much less bright does it look than the very faintest star that our eyes can see, roughly magnitude 6?

37. You have enough information from this chapter to estimate the distance to Alpha Centauri, the second nearest star, which has an apparent magnitude of 0. Since it is a G2 star, like the Sun, assume it has the same luminosity as the Sun and the difference in magnitudes is a result only of the difference in distance. Estimate how far away Alpha Centauri is. Describe the necessary steps in words and then do the calculation. (As we will learn in the **Celestial Distances** chapter, this method—namely, assuming that stars with identical spectral types emit the same amount of energy—is actually used to estimate distances to stars.) If you assume the distance to the Sun is in AU, your answer will come out in AU.

38. Do the previous problem again, this time using the information that the Sun is 150,000,000 km away. You will get a very large number of km as your answer. To get a better feeling for how the distances compare, try calculating the time it takes light at a speed of 299,338 km/s to travel from the Sun to Earth and from Alpha Centauri to Earth. For Alpha Centauri, figure out how long the trip will take in years as well as in seconds.

39. Star A and Star B have different apparent brightnesses but identical luminosities. If Star A is 20 light-years away from Earth and Star B is 40 light-years away from Earth, which star appears brighter and by what factor?

40. Star A and Star B have different apparent brightnesses but identical luminosities. Star A is 10 light-years away from Earth and appears 36 times brighter than Star B. How far away is Star B?

41. The star Sirius A has an apparent magnitude of −1.5. Sirius A has a dim companion, Sirius B, which is 10,000 times less bright than Sirius A. What is the apparent magnitude of Sirius B? Can Sirius B be seen with the naked eye?

42. Our Sun, a type G star, has a surface temperature of 5800 K. We know, therefore, that it is cooler than a type O star and hotter than a type M star. Given what you learned about the temperature ranges of these types of stars, how many times hotter than our Sun is the hottest type O star? How many times cooler than our Sun is the coolest type M star?

18

THE STARS: A CELESTIAL CENSUS

Figure 18.1 Variety of Stars. Stars come in a variety of sizes, masses, temperatures, and luminosities. This image shows part of a cluster of stars in the Small Magellanic Cloud (catalog number NGC 290). Located about 200,000 light-years away, NGC 290 is about 65 light-years across. Because the stars in this cluster are all at about the same distance from us, the differences in apparent brightness correspond to differences in luminosity; differences in temperature account for the differences in color. The various colors and luminosities of these stars provide clues about their life stories. (credit: modification of work by E. Olszewski (University of Arizona), European Space Agency, NASA)

Chapter Outline

18.1 A Stellar Census
18.2 Measuring Stellar Masses
18.3 Diameters of Stars
18.4 The H–R Diagram

Thinking Ahead

How do stars form? How long do they live? And how do they die? Stop and think how hard it is to answer these questions.

Stars live such a long time that nothing much can be gained from staring at one for a human lifetime. To discover how stars evolve from birth to death, it was necessary to measure the characteristics of many stars (to take a celestial census, in effect) and then determine which characteristics help us understand the stars' life stories. Astronomers tried a variety of hypotheses about stars until they came up with the right approach to understanding their development. But the key was first making a thorough census of the stars around us.

18.1 A STELLAR CENSUS

Learning Objectives

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

- Explain why the stars visible to the unaided eye are not typical
- Describe the distribution of stellar masses found close to the Sun

Before we can make our own survey, we need to agree on a unit of distance appropriate to the objects we are studying. The stars are all so far away that kilometers (and even astronomical units) would be very cumbersome to use; so—as discussed in **Science and the Universe: A Brief Tour**—astronomers use a much larger "measuring stick" called the *light-year*. A light-year is the distance that light (the fastest signal we know) travels in 1 year. Since light covers an astounding 300,000 kilometers per second, and since there are a lot of seconds in 1 year, a light-year is a very large quantity: 9.5 trillion (9.5×10^{12}) kilometers to be exact. (Bear in mind that the light-year is a unit of *distance* even though the term *year* appears in it.) If you drove at the legal US speed limit without stopping for food or rest, you would not arrive at the end of a light-year in space until roughly 12 million years had passed. And the closest star is more than 4 light-years away.

Notice that we have not yet said much about how such enormous distances can be measured. That is a complicated question, to which we will return in **Celestial Distances**. For now, let us assume that distances have been measured for stars in our cosmic vicinity so that we can proceed with our census.

Small Is Beautiful—Or at Least More Common

When we do a census of people in the United States, we count the inhabitants by neighborhood. We can try the same approach for our stellar census and begin with our own immediate neighborhood. As we shall see, we run into two problems—just as we do with a census of human beings. First, it is hard to be sure we have counted *all* the inhabitants; second, our local neighborhood may not contain all possible types of people.

Table 18.1 shows an estimate of the number of stars of each spectral type[1] in our own local neighborhood—within 21 light-years of the Sun. (The Milky Way Galaxy, in which we live, is about 100,000 light-years in diameter, so this figure really applies to a *very* local neighborhood, one that contains a *tiny* fraction of all the billions of stars in the Milky Way.) You can see that there are many more low-luminosity (and hence low mass) stars than high-luminosity ones. Only three of the stars in our local neighborhood (one F type and two A types) are significantly more luminous and more massive than the Sun. This is truly a case where small triumphs over large—at least in terms of numbers. The Sun is more massive than the vast majority of stars in our vicinity.

Stars within 21 Light-Years of the Sun

Spectral Type	Number of Stars
A	2
F	1
G	7
K	17
M	94
White dwarfs	8
Brown dwarfs	33

Table 18.1

1 The spectral types of stars were defined and discussed in Analyzing Starlight.

This table is based on data published through 2015, and it is likely that more faint objects remain to be discovered (see **Figure 18.2**). Along with the L and T brown dwarfs already observed in our neighborhood, astronomers expect to find perhaps hundreds of additional T dwarfs. Many of these are likely to be even cooler than the coolest currently known T dwarf. The reason the lowest-mass dwarfs are so hard to find is that they put out very little light—ten thousand to a million times less light than the Sun. Only recently has our technology progressed to the point that we can detect these dim, cool objects.

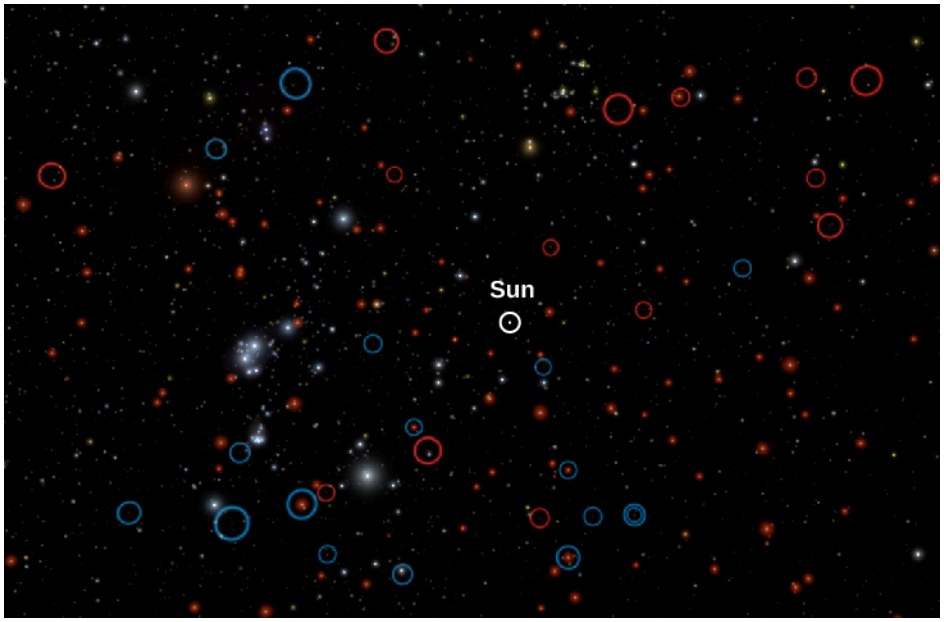


Figure 18.2 Dwarf Simulation. This computer simulation shows the stars in our neighborhood as they would be seen from a distance of 30 light-years away. The Sun is in the center. All the brown dwarfs are circled; those found earlier are circled in blue, the ones found recently with the WISE infrared telescope in space (whose scientists put this diagram together) are circled in red. The common M stars, which are red and faint, are made to look brighter than they really would be so that you can see them in the simulation. Note that luminous hot stars like our Sun are very rare. (credit: modification of work by NASA/ JPL-Caltech)

To put all this in perspective, we note that even though the stars counted in the table are our closest neighbors, you can't just look up at the night sky and see them without a telescope; stars fainter than the Sun cannot be seen with the unaided eye unless they are *very* nearby. For example, stars with luminosities ranging from 1/100 to 1/10,000 the luminosity of the Sun (L_{Sun}) are very common, but a star with a luminosity of 1/100 L_{Sun} would have to be within 5 light-years to be visible to the naked eye—and only three stars (all in one system) are this close to us. The nearest of these three stars, Proxima Centauri, still cannot be seen without a telescope because it has such a low luminosity.

Astronomers are working hard these days to complete the census of our local neighborhood by finding our faintest neighbors. Recent discoveries of nearby stars have relied heavily upon infrared telescopes that are able to find these many cool, low-mass stars. You should expect the number of known stars within 21 light-years of the Sun to keep increasing as more and better surveys are undertaken.

Bright Does Not Necessarily Mean Close

If we confine our census to the local neighborhood, we will miss many of the most interesting kinds of stars. After all, the neighborhood in which you live does not contain all the types of people—distinguished according to age, education, income, race, and so on—that live in the entire country. For example, a few people do live to be over 100 years old, but there may be no such individual within several miles of where you live. In order to sample the full range of the human population, you would have to extend your census to a much larger area. Similarly, some types of stars simply are not found nearby.

A clue that we are missing something in our stellar census comes from the fact that only six of the 20 stars that appear brightest in our sky— Sirius, Vega, Altair, Alpha Centauri, Fomalhaut, and Procyon—are found within 26 light-years of the Sun (**Figure 18.3**). Why are we missing most of the brightest stars when we take our census of the local neighborhood?

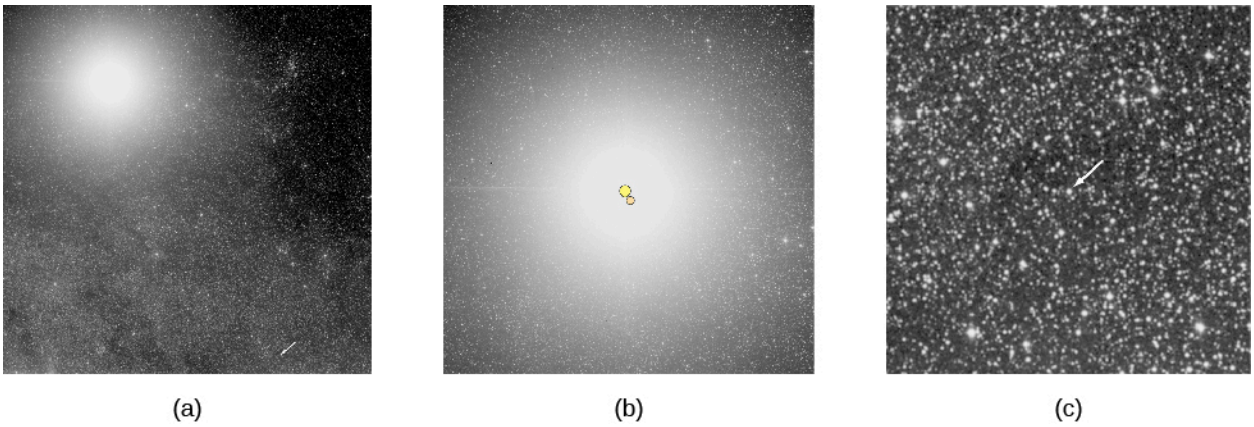


Figure 18.3 The Closest Stars. (a) This image, taken with a wide-angle telescope at the European Southern Observatory in Chile, shows the system of three stars that is our nearest neighbor. (b) Two bright stars that are close to each other (Alpha Centauri A and B) blend their light together. (c) Indicated with an arrow (since you'd hardly notice it otherwise) is the much fainter Proxima Centauri star, which is spectral type M. (credit: modification of work by ESO)

The answer, interestingly enough, is that the stars that appear brightest are *not* the ones closest to us. The brightest stars look the way they do because they emit a very large amount of energy—so much, in fact, that they do not have to be nearby to look brilliant. You can confirm this by looking at **Appendix J**, which gives distances for the 20 stars that appear brightest from Earth. The most distant of these stars is more than *1000 light-years* from us. In fact, it turns out that most of the stars visible without a telescope are hundreds of light-years away and many times more luminous than the Sun. Among the 6000 stars visible to the unaided eye, only about 50 are intrinsically fainter than the Sun. Note also that several of the stars in **Appendix J** are spectral type B, a type that is completely missing from **Table 18.1**.

The most luminous of the bright stars listed in **Appendix J** emit more than 50,000 times more energy than does the Sun. These highly luminous stars are missing from the solar neighborhood because they are very rare. None of them happens to be in the tiny volume of space immediately surrounding the Sun, and only this small volume was surveyed to get the data shown in **Table 18.1**.

For example, let's consider the most luminous stars—those 100 or more times as luminous as the Sun. Although such stars are rare, they are visible to the unaided eye, even when hundreds to thousands of light-years away. A star with a luminosity 10,000 times greater than that of the Sun can be seen without a telescope out to a distance of 5000 light-years. The volume of space included within a distance of 5000 light-years, however, is enormous; so even though highly luminous stars are intrinsically rare, many of them are readily visible to our unaided eye.

The contrast between these two samples of stars, those that are close to us and those that can be seen with the unaided eye, is an example of a **selection effect**. When a population of objects (stars in this example) includes a great variety of different types, we must be careful what conclusions we draw from an examination of any particular subgroup. Certainly we would be fooling ourselves if we assumed that the stars visible to the unaided eye are characteristic of the general stellar population; this subgroup is heavily weighted to the most luminous stars. It requires much more effort to assemble a complete data set for the nearest stars, since most are so faint that they can be observed only with a telescope. However, it is only by doing so that astronomers are able to know about the properties of the vast majority of the stars, which are actually much smaller and fainter than

our own Sun. In the next section, we will look at how we measure some of these properties.

18.2 MEASURING STELLAR MASSES

Learning Objectives

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

- Distinguish the different types of binary star systems
- Understand how we can apply Newton's version of Kepler's third law to derive the sum of star masses in a binary star system
- Apply the relationship between stellar mass and stellar luminosity to determine the physical characteristics of a star

The mass of a star—how much material it contains—is one of its most important characteristics. If we know a star's mass, as we shall see, we can estimate how long it will shine and what its ultimate fate will be. Yet the mass of a star is very difficult to measure directly. Somehow, we need to put a star on the cosmic equivalent of a scale.

Luckily, not all stars live like the Sun, in isolation from other stars. About half the stars are **binary stars**—two stars that orbit each other, bound together by gravity. Masses of binary stars can be calculated from measurements of their orbits, just as the mass of the Sun can be derived by measuring the orbits of the planets around it (see **Orbits and Gravity**).

Binary Stars

Before we discuss in more detail how mass can be measured, we will take a closer look at stars that come in pairs. The first binary star was discovered in 1650, less than half a century after Galileo began to observe the sky with a telescope. John Baptiste Riccioli (1598–1671), an Italian astronomer, noted that the star Mizar, in the middle of the Big Dipper's handle, appeared through his telescope as two stars. Since that discovery, thousands of binary stars have been cataloged. (Astronomers call any pair of stars that appear to be close to each other in the sky *double stars*, but not all of these form a true binary, that is, not all of them are physically associated. Some are just chance alignments of stars that are actually at different distances from us.) Although stars most commonly come in pairs, there are also triple and quadruple systems.

One well-known binary star is Castor, located in the constellation of Gemini. By 1804, astronomer William Herschel, who also discovered the planet Uranus, had noted that the fainter component of Castor had slightly changed its position relative to the brighter component. (We use the term "component" to mean a member of a star system.) Here was evidence that one star was moving around another. It was actually the first evidence that gravitational influences exist outside the solar system. The orbital motion of a binary star is shown in **Figure 18.4**. A binary star system in which both of the stars can be seen with a telescope is called a **visual binary**.

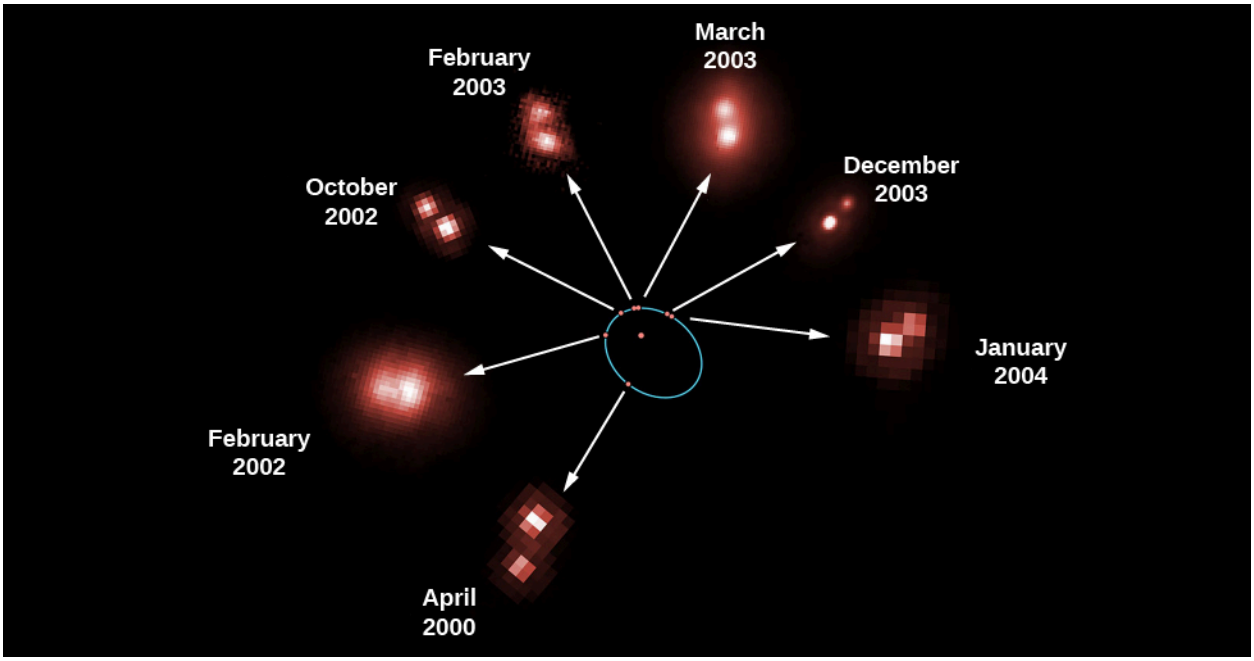


Figure 18.4 Revolution of a Binary Star. This figure shows seven observations of the mutual revolution of two stars, one a brown dwarf and one an ultra-cool L dwarf. Each red dot on the orbit, which is shown by the blue ellipse, corresponds to the position of one of the dwarfs relative to the other. The reason that the pair of stars looks different on the different dates is that some images were taken with the Hubble Space Telescope and others were taken from the ground. The arrows point to the actual observations that correspond to the positions of each red dot. From these observations, an international team of astronomers directly measured the mass of an ultra-cool brown dwarf star for the first time. Barely the size of the planet Jupiter, the dwarf star weighs in at just 8.5% of the mass of our Sun. (credit: modification of work by ESA/NASA and Herve Bouy (Max-Planck-Institut für Extraterrestrische Physik/ESO, Germany))

Edward C. Pickering (1846–1919), at Harvard, discovered a second class of binary stars in 1889—a class in which only one of the stars is actually seen directly. He was examining the spectrum of Mizar and found that the dark absorption lines in the brighter star's spectrum were usually double. Not only were there two lines where astronomers normally saw only one, but the spacing of the lines was constantly changing. At times, the lines even became single. Pickering correctly deduced that the brighter component of Mizar, called Mizar A, is itself really two stars that revolve about each other in a period of 104 days. A star like Mizar A, which appears as a single star when photographed or observed visually through the telescope, but which spectroscopy shows really to be a double star, is called a **spectroscopic binary**.

Mizar, by the way, is a good example of just how complex such star systems can be. Mizar has been known for centuries to have a faint companion called Alcor, which can be seen without a telescope. Mizar and Alcor form an *optical double*—a pair of stars that appear close together in the sky but do not orbit each other. Through a telescope, as Riccioli discovered in 1650, Mizar can be seen to have another, closer companion that does orbit it; Mizar is thus a visual binary. The two components that make up this visual binary, known as Mizar A and Mizar B, are both spectroscopic binaries. So, Mizar is really a quadruple system of stars.

Strictly speaking, it is not correct to describe the motion of a binary star system by saying that one star orbits the other. Gravity is a *mutual* attraction. Each star exerts a gravitational force on the other, with the result that both stars orbit a point between them called the *center of mass*. Imagine that the two stars are seated at either end of a seesaw. The point at which the fulcrum would have to be located in order for the seesaw to balance is the center of mass, and it is always closer to the more massive star (Figure 18.5).

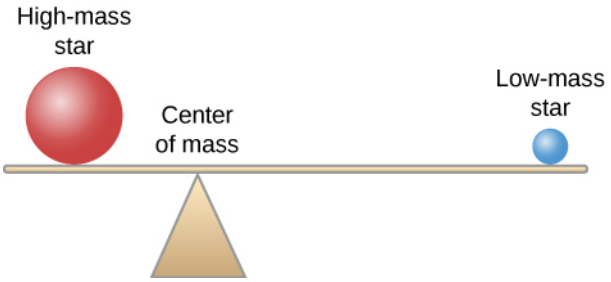


Figure 18.5 Binary Star System. In a binary star system, both stars orbit their center of mass. The image shows the relative positions of two, different-mass stars from their center of mass, similar to how two masses would have to be located on a seesaw in order to keep it level. The star with the higher mass will be found closer to the center of mass, while the star with the lower mass will be farther from it.

Figure 18.6 shows two stars (A and B) moving around their center of mass, along with one line in the spectrum of each star that we observe from the system at different times. When one star is approaching us relative to the center of mass, the other star is receding from us. In the top left illustration, star A is moving toward us, so the line in its spectrum is Doppler-shifted toward the blue end of the spectrum. Star B is moving away from us, so its line shows a redshift. When we observe the composite spectrum of the two stars, the line appears double. When the two stars are both moving across our line of sight (neither away from nor toward us), they both have the same radial velocity (that of the pair's center of mass); hence, the spectral lines of the two stars come together. This is shown in the two bottom illustrations in Figure 18.6.

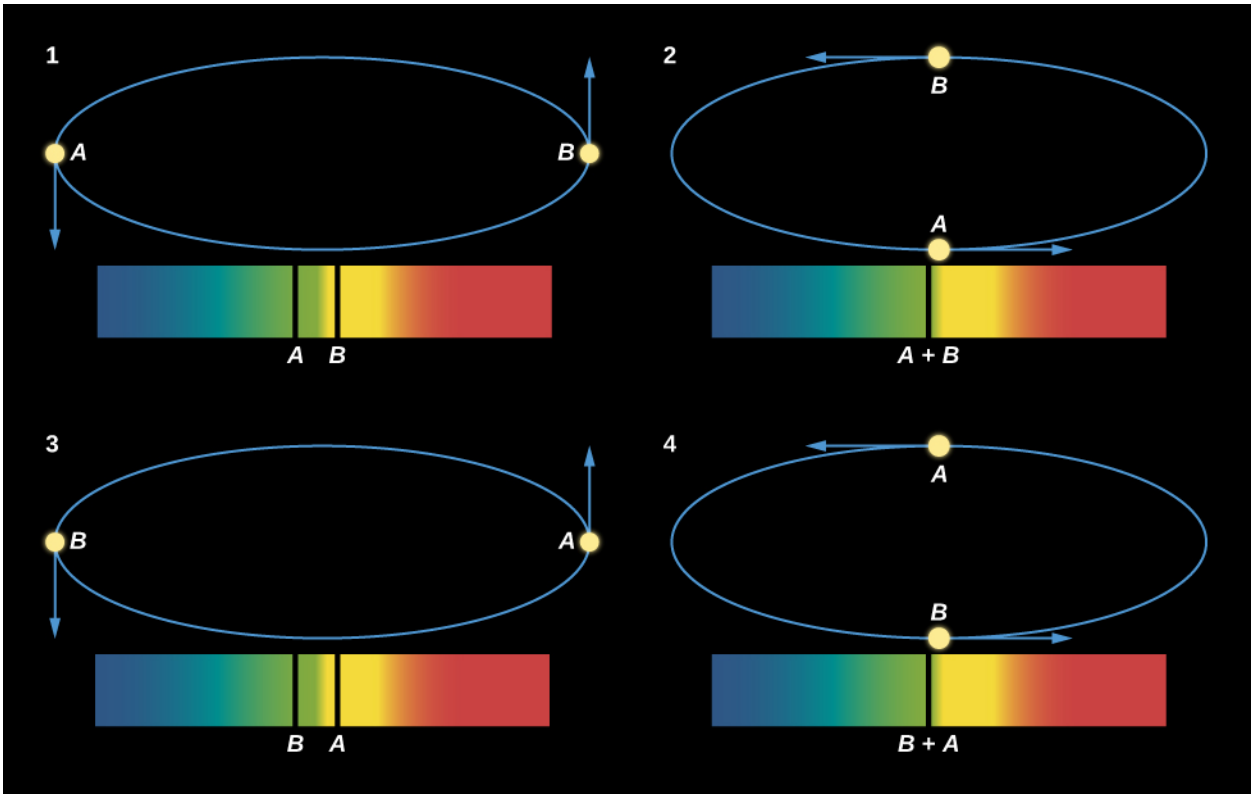


Figure 18.6 Motions of Two Stars Orbiting Each Other and What the Spectrum Shows. We see changes in velocity because when one star is moving toward Earth, the other is moving away; half a cycle later, the situation is reversed. Doppler shifts cause the spectral lines to move back and forth. In diagrams 1 and 3, lines from both stars can be seen well separated from each other. When the two stars are moving perpendicular to our line of sight (that is, they are not moving either toward or away from us), the two lines are exactly superimposed, and so in diagrams 2 and 4, we see only a single spectral line. Note that in the diagrams, the orbit of the star pair is tipped slightly with respect to the viewer (or if the viewer were looking at it in the sky, the orbit would be tilted with respect to the viewer's line of sight). If the orbit were exactly in the plane of the page or screen (or the sky), then it would look nearly circular, but we would see no change in radial velocity (no part of the motion would be toward us or away from us.) If the orbit were perpendicular to the plane of the page or screen, then the stars would appear to move back and forth in a straight line, and we would see the largest-possible radial velocity variations.

A plot showing how the velocities of the stars change with time is called a *radial velocity curve*; the curve for the binary system in Figure 18.6 is shown in Figure 18.7.

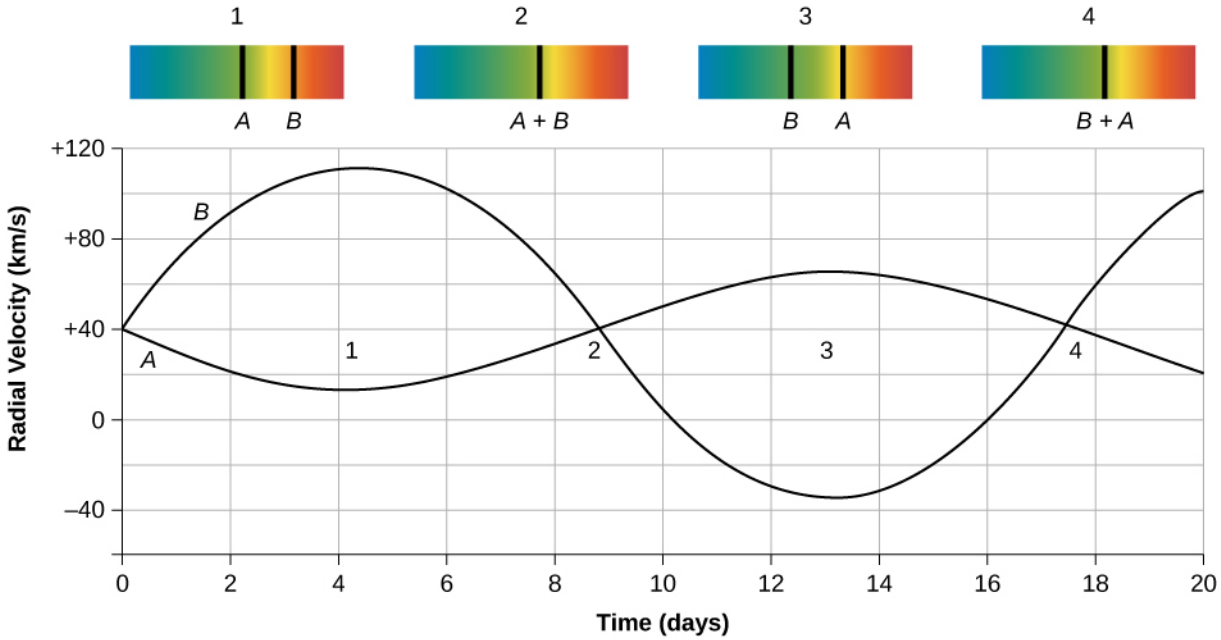


Figure 18.7 Radial Velocities in a Spectroscopic Binary System. These curves plot the radial velocities of two stars in a spectroscopic binary system, showing how the stars alternately approach and recede from Earth. Note that positive velocity means the star is moving away from us relative to the center of mass of the system, which in this case is 40 kilometers per second. Negative velocity means the star is moving toward us relative to the center of mass. The positions on the curve corresponding to the illustrations in Figure 18.6 are marked with the diagram number (1–4).

LINK TO LEARNING

This **animation (https://openstax.org/l/30binstaranim)** lets you follow the orbits of a binary star system in various combinations of the masses of the two stars.

Masses from the Orbits of Binary Stars

We can estimate the masses of binary star systems using Newton's reformulation of Kepler's third law (discussed in **Newton's Universal Law of Gravitation**). Kepler found that the time a planet takes to go around the Sun is related by a specific mathematical formula to its distance from the Sun. In our binary star situation, if two objects are in mutual revolution, then the period (P) with which they go around each other is related to the semimajor axis (D) of the orbit of one with respect to the other, according to this equation

$$D^3 = (M_1 + M_2)P^2$$

where D is in astronomical units, P is measured in years, and $M_1 + M_2$ is the sum of the masses of the two stars in units of the Sun's mass. This is a very useful formula for astronomers; it says that if we can observe the size of the orbit and the period of mutual revolution of the stars in a binary system, we can calculate the sum of their masses.

Most spectroscopic binaries have periods ranging from a few days to a few months, with separations of usually less than 1 AU between their member stars. Recall that an AU is the distance from Earth to the Sun, so this is a

small separation and very hard to see at the distances of stars. This is why many of these systems are known to be double only through careful study of their spectra.

We can analyze a radial velocity curve (such as the one in **Figure 18.7**) to determine the masses of the stars in a spectroscopic binary. This is complex in practice but not hard in principle. We measure the speeds of the stars from the Doppler effect. We then determine the period—how long the stars take to go through an orbital cycle—from the velocity curve. Knowing how fast the stars are moving and how long they take to go around tells us the circumference of the orbit and, hence, the separation of the stars in kilometers or astronomical units. From Kepler's law, the period and the separation allow us to calculate the sum of the stars' masses.

Of course, knowing the sum of the masses is not as useful as knowing the mass of each star separately. But the relative orbital speeds of the two stars can tell us how much of the total mass each star has. As we saw in our seesaw analogy, the more massive star is closer to the center of mass and therefore has a smaller orbit. Therefore, it moves more slowly to get around in the same time compared to the more distant, lower-mass star. If we sort out the speeds relative to each other, we can sort out the masses relative to each other. In practice, we also need to know how the binary system is oriented in the sky to our line of sight, but if we do, and the just-described steps are carried out carefully, the result is a calculation of the masses of each of the two stars in the system.

To summarize, a good measurement of the motion of two stars around a common center of mass, combined with the laws of gravity, allows us to determine the masses of stars in such systems. These mass measurements are absolutely crucial to developing a theory of how stars evolve. One of the best things about this method is that it is independent of the location of the binary system. It works as well for stars 100 light-years away from us as for those in our immediate neighborhood.

To take a specific example, Sirius is one of the few binary stars in **Appendix J** for which we have enough information to apply Kepler's third law:

$$D^3 = (M_1 + M_2)P^2$$

In this case, the two stars, the one we usually call Sirius and its very faint companion, are separated by about 20 AU and have an orbital period of about 50 years. If we place these values in the formula we would have

$$(20)^3 = (M_1 + M_2)(50)^2$$
$$8000 = (M_1 + M_2)(2500)$$

This can be solved for the sum of the masses:

$$M_1 + M_2 = \frac{8000}{2500} = 3.2$$

Therefore, the sum of masses of the two stars in the Sirius binary system is 3.2 times the Sun's mass. In order to determine the individual mass of each star, we would need the velocities of the two stars and the orientation of the orbit relative to our line of sight.

The Range of Stellar Masses

How large can the mass of a star be? Stars more massive than the Sun are rare. None of the stars within 30 light-years of the Sun has a mass greater than four times that of the Sun. Searches at large distances from the Sun have led to the discovery of a few stars with masses up to about 100 times that of the Sun, and a handful of stars (a few out of several billion) may have masses as large as 250 solar masses. However, most stars have less mass than the Sun.

According to theoretical calculations, the smallest mass that a true star can have is about 1/12 that of the Sun. By a "true" star, astronomers mean one that becomes hot enough to fuse protons to form helium (as discussed

in The Sun: A Nuclear Powerhouse). Objects with masses between roughly 1/100 and 1/12 that of the Sun may produce energy for a brief time by means of nuclear reactions involving deuterium, but they do not become hot enough to fuse protons. Such objects are intermediate in mass between stars and planets and have been given the name **brown dwarfs** (Figure 18.8). Brown dwarfs are similar to Jupiter in radius but have masses from approximately 13 to 80 times larger than the mass of Jupiter.[2]

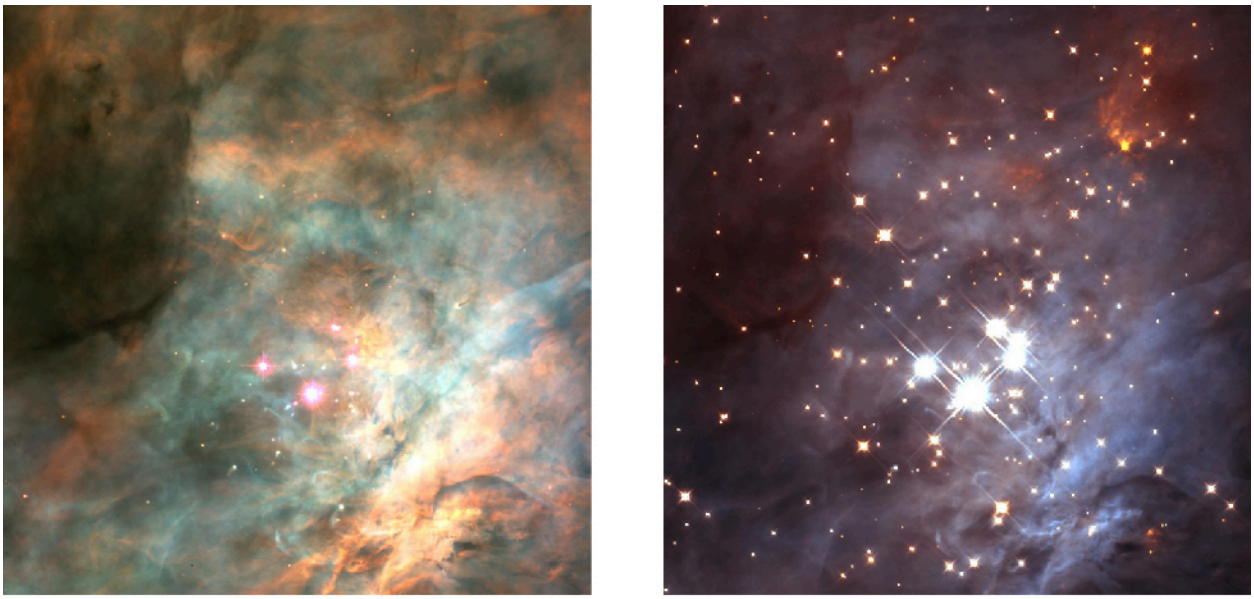


Figure 18.8 Brown Dwarfs in Orion. These images, taken with the Hubble Space Telescope, show the region surrounding the Trapezium star cluster inside the star-forming region called the Orion Nebula. (a) No brown dwarfs are seen in the visible light image, both because they put out very little light in the visible and because they are hidden within the clouds of dust in this region. (b) This image was taken in infrared light, which can make its way to us through the dust. The faintest objects in this image are brown dwarfs with masses between 13 and 80 times the mass of Jupiter. (credit a: NASA, C.R. O'Dell and S.K. Wong (Rice University); credit b: NASA; K.L. Luhman (Harvard-Smithsonian Center for Astrophysics) and G. Schneider, E. Young, G. Rieke, A. Cotera, H. Chen, M. Rieke, R. Thompson (Steward Observatory))

Still-smaller objects with masses less than about 1/100 the mass of the Sun (or 10 Jupiter masses) are called planets. They may radiate energy produced by the radioactive elements that they contain, and they may also radiate heat generated by slowly compressing under their own weight (a process called gravitational contraction). However, their interiors will never reach temperatures high enough for any nuclear reactions, to take place. Jupiter, whose mass is about 1/1000 the mass of the Sun, is unquestionably a planet, for example. Until the 1990s, we could only detect planets in our own solar system, but now we have thousands of them elsewhere as well. (We will discuss these exciting observations in The Birth of Stars and the Discovery of Planets outside the Solar System.)

The Mass-Luminosity Relation

Now that we have measurements of the characteristics of many different types of stars, we can search for relationships among the characteristics. For example, we can ask whether the mass and luminosity of a star are related. It turns out that for most stars, they are: The more massive stars are generally also the more luminous. This relationship, known as the **mass-luminosity relation**, is shown graphically in Figure 18.9. Each point represents a star whose mass and luminosity are both known. The horizontal position on the graph shows

2 Exactly where to put the dividing line between planets and brown dwarfs is a subject of some debate among astronomers as we write this book (as is, in fact, the exact definition of each of these objects). Even those who accept deuterium fusion (see The Birth of Stars and the Discovery of Planets outside the Solar System) as the crucial issue for brown dwarfs concede that, depending on the composition of the star and other factors, the lowest mass for such a dwarf could be anywhere from 11 to 16 Jupiter masses.

the star's mass, given in units of the Sun's mass, and the vertical position shows its luminosity in units of the Sun's luminosity.

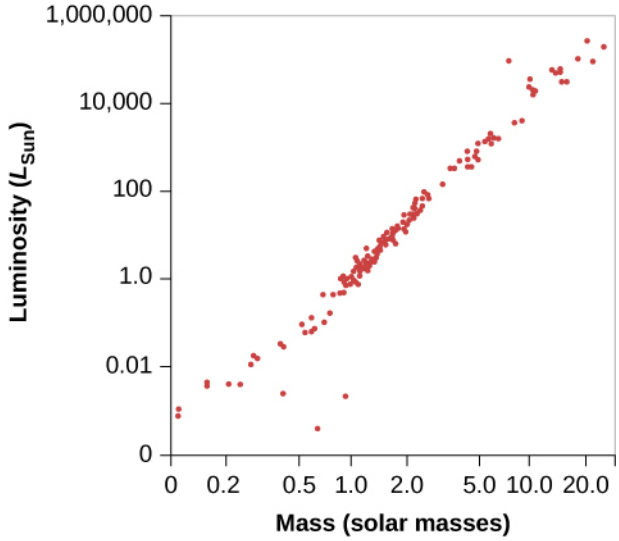


Figure 18.9 Mass-Luminosity Relation. The plotted points show the masses and luminosities of stars. The three points lying below the sequence of points are all white dwarf stars.

We can also say this in mathematical terms.

$$L \sim M^{3.9}$$

It's a reasonably good approximation to say that luminosity (expressed in units of the Sun's luminosity) varies as the fourth power of the mass (in units of the Sun's mass). (The symbol ~ means the two quantities are proportional.) If two stars differ in mass by a factor of 2, then the more massive one will be 2^4, or about 16 times brighter; if one star is 1/3 the mass of another, it will be approximately 81 times less luminous.

EXAMPLE 18.1

Calculating the Mass from the Luminosity of a Star

The mass-luminosity formula can be rewritten so that a value of mass can be determined if the luminosity is known.

Solution

First, we must get our units right by expressing both the mass and the luminosity of a star in units of the Sun's mass and luminosity:

$$L/L_{\text{Sun}} = (M/M_{\text{Sun}})^4$$

Now we can take the 4th root of both sides, which is equivalent to taking both sides to the 1/4 = 0.25 power. The formula in this case would be:

$$M/M_{\text{Sun}} = (L/L_{\text{Sun}})^{0.25} = (L/L_{\text{Sun}})^{0.25}$$

Check Your Learning

In the previous section, we determined the sum of the masses of the two stars in the Sirius binary system (Sirius and its faint companion) using Kepler's third law to be 3.2 solar masses. Using the mass-luminosity relationship, calculate the mass of each individual star.

Answer:

In **Appendix J**, Sirius is listed with a luminosity 23 times that of the Sun. This value can be inserted into the mass-luminosity relationship to get the mass of Sirius:

$M/M_{\text{Sun}} = 23^{0.25} = 2.2$

The mass of the companion star to Sirius is then 3.2 – 2.2 = 1.0 solar mass.

Notice how good this mass-luminosity relationship is. Most stars (see **Figure 18.9**) fall along a line running from the lower-left (low mass, low luminosity) corner of the diagram to the upper-right (high mass, high luminosity) corner. About 90% of all stars obey the mass-luminosity relation. Later, we will explore why such a relationship exists and what we can learn from the roughly 10% of stars that "disobey" it.

18.3 DIAMETERS OF STARS

Learning Objectives

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

- Describe the methods used to determine star diameters
- Identify the parts of an eclipsing binary star light curve that correspond to the diameters of the individual components

It is easy to measure the diameter of the Sun. Its angular diameter—that is, its apparent size on the sky—is about 1/2°. If we know the angle the Sun takes up in the sky and how far away it is, we can calculate its true (linear) diameter, which is 1.39 million kilometers, or about 109 times the diameter of Earth.

Unfortunately, the Sun is the only star whose angular diameter is easily measured. All the other stars are so far away that they look like pinpoints of light through even the largest ground-based telescopes. (They often seem to be bigger, but that is merely distortion introduced by turbulence in Earth's atmosphere.) Luckily, there are several techniques that astronomers can use to estimate the sizes of stars.

Stars Blocked by the Moon

One technique, which gives very precise diameters but can be used for only a few stars, is to observe the dimming of light that occurs when the Moon passes in front of a star. What astronomers measure (with great precision) is the time required for the star's brightness to drop to zero as the edge of the Moon moves across the star's disk. Since we know how rapidly the Moon moves in its orbit around Earth, it is possible to calculate the angular diameter of the star. If the distance to the star is also known, we can calculate its diameter in kilometers. This method works only for fairly bright stars that happen to lie along the zodiac, where the Moon (or, much more rarely, a planet) can pass in front of them as seen from Earth.

Eclipsing Binary Stars

Accurate sizes for a large number of stars come from measurements of **eclipsing binary** star systems, and

so we must make a brief detour from our main story to examine this type of star system. Some binary stars are lined up in such a way that, when viewed from Earth, each star passes in front of the other during every revolution (**Figure 18.10**). When one star blocks the light of the other, preventing it from reaching Earth, the luminosity of the system decreases, and astronomers say that an eclipse has occurred.

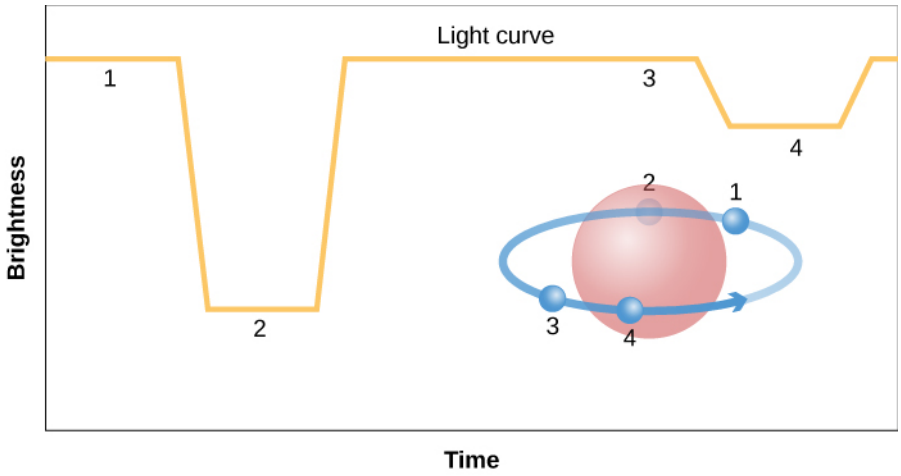


Figure 18.10 Light Curve of an Eclipsing Binary. The light curve of an eclipsing binary star system shows how the combined light from both stars changes due to eclipses over the time span of an orbit. This light curve shows the behavior of a hypothetical eclipsing binary star with total eclipses (one star passes directly in front of and behind the other). The numbers indicate parts of the light curve corresponding to various positions of the smaller star in its orbit. In this diagram, we have assumed that the smaller star is also the hotter one so that it emits more flux (energy per second per square meter) than the larger one. When the smaller, hotter star goes behind the larger one, its light is completely blocked, and so there is a strong dip in the light curve. When the smaller star goes in front of the bigger one, a small amount of light from the bigger star is blocked, so there is a smaller dip in the light curve.

The discovery of the first eclipsing binary helped solve a long-standing puzzle in astronomy. The star Algol, in the constellation of Perseus, changes its brightness in an odd but regular way. Normally, Algol is a fairly bright star, but at intervals of 2 days, 20 hours, 49 minutes, it fades to one-third of its regular brightness. After a few hours, it brightens to normal again. This effect is easily seen, even without a telescope, if you know what to look for.

In 1783, a young English astronomer named John Goodricke (1764–1786) made a careful study of Algol (see the feature on **John Goodricke** for a discussion of his life and work). Even though Goodricke could neither hear nor speak, he made a number of major discoveries in the 21 years of his brief life. He suggested that Algol's unusual brightness variations might be due to an invisible companion that regularly passes in front of the brighter star and blocks its light. Unfortunately, Goodricke had no way to test this idea, since it was not until about a century later that equipment became good enough to measure Algol's spectrum.

In 1889, the German astronomer Hermann Vogel (1841–1907) demonstrated that, like Mizar, Algol is a spectroscopic binary. The spectral lines of Algol were not observed to be double because the fainter star of the pair gives off too-little light compared with the brighter star for its lines to be conspicuous in the composite spectrum. Nevertheless, the periodic shifting back and forth of the brighter star's lines gave evidence that it was revolving about an unseen companion. (The lines of both components need not be visible for a star to be recognized as a spectroscopic binary.)

The discovery that Algol is a spectroscopic binary verified Goodricke's hypothesis. The plane in which the stars revolve is turned nearly edgewise to our line of sight, and each star passes in front of the other during every revolution. (The eclipse of the fainter star in the Algol system is not very noticeable because the part of it that is covered contributes little to the total light of the system. This second eclipse can, however, be detected by careful measurements.)

Any binary star produces eclipses if viewed from the proper direction, near the plane of its orbit, so that one star passes in front of the other (see **Figure 18.10**). But from our vantage point on Earth, only a few binary star systems are oriented in this way.

MAKING CONNECTIONS

Astronomy and Mythology: Algol the Demon Star and Perseus the Hero

The name Algol comes from the Arabic *Ras al Ghul*, meaning "the demon's head."[3] The word "ghoul" in English has the same derivation. As discussed in **Observing the Sky: The Birth of Astronomy**, many of the bright stars have Arabic names because during the long dark ages in medieval Europe, it was Arabic astronomers who preserved and expanded the Greek and Roman knowledge of the skies. The reference to the demon is part of the ancient Greek legend of the hero Perseus, who is commemorated by the constellation in which we find Algol and whose adventures involve many of the characters associated with the northern constellations.

Perseus was one of the many half-god heroes fathered by Zeus (Jupiter in the Roman version), the king of the gods in Greek mythology. Zeus had, to put it delicately, a roving eye and was always fathering somebody or other with a human maiden who caught his fancy. (Perseus derives from *Per Zeus*, meaning "fathered by Zeus.") Set adrift with his mother by an (understandably) upset stepfather, Perseus grew up on an island in the Aegean Sea. The king there, taking an interest in Perseus' mother, tried to get rid of the young man by assigning him an extremely difficult task.

In a moment of overarching pride, a beautiful young woman named Medusa had compared her golden hair to that of the goddess Athena (Minerva for the Romans). The Greek gods did not take kindly to being compared to mere mortals, and Athena turned Medusa into a gorgon: a hideous, evil creature with writhing snakes for hair and a face that turned anyone who looked at it into stone. Perseus was given the task of slaying this demon, which seemed like a pretty sure way to get him out of the way forever.

But because Perseus had a god for a father, some of the other gods gave him tools for the job, including Athena's reflective shield and the winged sandals of Hermes (Mercury in the Roman story). By flying over her and looking only at her reflection, Perseus was able to cut off Medusa's head without ever looking at her directly. Taking her head (which, conveniently, could still turn onlookers to stone even without being attached to her body) with him, Perseus continued on to other adventures.

He next came to a rocky seashore, where boasting had gotten another family into serious trouble with the gods. Queen Cassiopeia had dared to compare her own beauty to that of the Nereids, sea nymphs who were daughters of Poseidon (Neptune in Roman mythology), the god of the sea. Poseidon was so offended that he created a sea-monster named Cetus to devastate the kingdom. King Cepheus, Cassiopeia's beleaguered husband, consulted the oracle, who told him that he must sacrifice his beautiful daughter Andromeda to the monster.

When Perseus came along and found Andromeda chained to a rock near the sea, awaiting her fate, he rescued her by turning the monster to stone. (Scholars of mythology actually trace the essence of this story back to far-older legends from ancient Mesopotamia, in which the god-hero Marduk vanquishes a monster named Tiamat. Symbolically, a hero like Perseus or Marduk is usually associated with the Sun, the monster with the power of night, and the beautiful maiden with the fragile beauty of dawn, which the Sun releases after its nightly struggle with darkness.)

Many of the characters in these Greek legends can be found as constellations in the sky, not necessarily resembling their namesakes but serving as reminders of the story. For example, vain Cassiopeia is sentenced to be very close to the celestial pole, rotating perpetually around the sky and hanging upside down every winter. The ancients imagined Andromeda still chained to her rock (it is much easier to see the chain of stars than to recognize the beautiful maiden in this star grouping). Perseus is next to her with the head of Medusa swinging from his belt. Algol represents this gorgon head and has long been associated with evil and bad fortune in such tales. Some commentators have speculated that the star's change in brightness (which can be observed with the unaided eye) may have contributed to its unpleasant reputation, with the ancients regarding such a change as a sort of evil "wink."

Diameters of Eclipsing Binary Stars

We now turn back to the main thread of our story to discuss how all this can be used to measure the sizes of stars. The technique involves making a light curve of an eclipsing binary, a graph that plots how the brightness changes with time. Let us consider a hypothetical binary system in which the stars are very different in size, like those illustrated in **Figure 18.11**. To make life easy, we will assume that the orbit is viewed exactly edge-on.

Even though we cannot see the two stars separately in such a system, the light curve can tell us what is happening. When the smaller star just starts to pass behind the larger star (a point we call *first contact*), the brightness begins to drop. The eclipse becomes total (the smaller star is completely hidden) at the point called *second contact*. At the end of the total eclipse (*third contact*), the smaller star begins to emerge. When the smaller star has reached *last contact*, the eclipse is completely over.

To see how this allows us to measure diameters, look carefully at **Figure 18.11**. During the time interval between the first and second contacts, the smaller star has moved a distance equal to its own diameter. During the time interval from the first to third contacts, the smaller star has moved a distance equal to the diameter of the larger star. If the spectral lines of both stars are visible in the spectrum of the binary, then the speed of the smaller star with respect to the larger one can be measured from the Doppler shift. But knowing the speed with which the smaller star is moving and how long it took to cover some distance can tell the span of that distance—in this case, the diameters of the stars. The speed multiplied by the time interval from the first to second contact gives the diameter of the smaller star. We multiply the speed by the time between the first and third contacts to get the diameter of the larger star.

3 Fans of Batman comic books and movies will recognize that this name was given to an archvillain in the series.

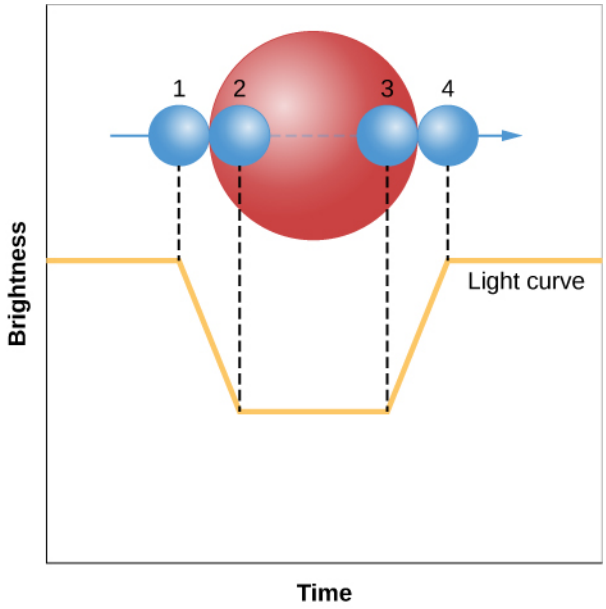


Figure 18.11 Light Curve of an Edge-On Eclipsing Binary. Here we see the light curve of a hypothetical eclipsing binary star whose orbit we view exactly edge-on, in which the two stars fully eclipse each other. From the time intervals between contacts, it is possible to estimate the diameters of the two stars.

In actuality, the situation with eclipsing binaries is often a bit more complicated: orbits are generally not seen exactly edge-on, and the light from each star may be only partially blocked by the other. Furthermore, binary star orbits, just like the orbits of the planets, are ellipses, not circles. However, all these effects can be sorted out from very careful measurements of the light curve.

Using the Radiation Law to Get the Diameter

Another method for measuring star diameters makes use of the Stefan-Boltzmann law for the relationship between energy radiated and temperature (see **Radiation and Spectra**). In this method, the *energy flux* (energy emitted per second per square meter by a blackbody, like the Sun) is given by

$$F = \sigma T^4$$

where σ is a constant and T is the temperature. The surface area of a sphere (like a star) is given by

$$A = 4\pi R^2$$

The luminosity (L) of a star is then given by its surface area in square meters times the energy flux:

$$L = (A \times F)$$

Previously, we determined the masses of the two stars in the Sirius binary system. Sirius gives off 8200 times more energy than its fainter companion star, although both stars have nearly identical temperatures. The extremely large difference in luminosity is due to the difference in radius, since the temperatures and hence the energy fluxes for the two stars are nearly the same. To determine the relative sizes of the two stars, we take the ratio of the corresponding luminosities:

$$\frac{L_{\text{Sirius}}}{L_{\text{companion}}} = \frac{(A_{\text{Sirius}} \times F_{\text{Sirius}})}{(A_{\text{companion}} \times F_{\text{companion}})}$$
$$= \frac{A_{\text{Sirius}}}{A_{\text{companion}}} = \frac{4\pi R^2{}_{\text{Sirius}}}{4\pi R^2{}_{\text{companion}}} = \frac{R^2{}_{\text{Sirius}}}{R^2{}_{\text{companion}}}$$

$$\frac{L_{\text{Sirius}}}{L_{\text{companion}}} = 8200 = \frac{R^2{}_{\text{Sirius}}}{R^2{}_{\text{companion}}}$$

Therefore, the relative sizes of the two stars can be found by taking the square root of the relative luminosity. Since $\sqrt{8200} = 91$, the radius of Sirius is 91 times larger than the radium of its faint companion.

The method for determining the radius shown here requires both stars be visible, which is not always the case.

Stellar Diameters

The results of many stellar size measurements over the years have shown that most nearby stars are roughly the size of the Sun, with typical diameters of a million kilometers or so. Faint stars, as we might have expected, are generally smaller than more luminous stars. However, there are some dramatic exceptions to this simple generalization.

A few of the very luminous stars, those that are also red (indicating relatively low surface temperatures), turn out to be truly enormous. These stars are called, appropriately enough, giant stars or supergiant stars. An example is Betelgeuse, the second brightest star in the constellation of Orion and one of the dozen brightest stars in our sky. Its diameter, remarkably, is greater than 10 AU (1.5 *billion* kilometers!), large enough to fill the entire inner solar system almost as far out as Jupiter. In **Stars from Adolescence to Old Age**, we will look in detail at the evolutionary process that leads to the formation of such giant and supergiant stars.

LINK TO LEARNING

Watch this **star size comparison video (https://openstax.org/l/30starsizecomp)** for a striking visual that highlights the size of stars versus planets and the range of sizes among stars.

18.4 THE H–R DIAGRAM

Learning Objectives

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

- Identify the physical characteristics of stars that are used to create an H–R diagram, and describe how those characteristics vary among groups of stars
- Discuss the physical properties of most stars found at different locations on the H–R diagram, such as radius, and for main sequence stars, mass

In this chapter and **Analyzing Starlight**, we described some of the characteristics by which we might classify stars and how those are measured. These ideas are summarized in **Table 18.2**. We have also given an example of a relationship between two of these characteristics in the mass-luminosity relation. When the characteristics

of large numbers of stars were measured at the beginning of the twentieth century, astronomers were able to begin a deeper search for patterns and relationships in these data.

Measuring the Characteristics of Stars

Characteristic	Technique
Surface temperature	1. Determine the color (very rough). 2. Measure the spectrum and get the spectral type.
Chemical composition	Determine which lines are present in the spectrum.
Luminosity	Measure the apparent brightness and compensate for distance.
Radial velocity	Measure the Doppler shift in the spectrum.
Rotation	Measure the width of spectral lines.
Mass	Measure the period and radial velocity curves of spectroscopic binary stars.
Diameter	1. Measure the way a star's light is blocked by the Moon. 2. Measure the light curves and Doppler shifts for eclipsing binary stars.

Table 18.2

To help understand what sorts of relationships might be found, let's look briefly at a range of data about human beings. If you want to understand humans by comparing and contrasting their characteristics—without assuming any previous knowledge of these strange creatures—you could try to determine which characteristics lead you in a fruitful direction. For example, you might plot the heights of a large sample of humans against their weights (which is a measure of their mass). Such a plot is shown in **Figure 18.12** and it has some interesting features. In the way we have chosen to present our data, height increases upward, whereas weight increases to the left. Notice that humans are not randomly distributed in the graph. Most points fall along a sequence that goes from the upper left to the lower right.

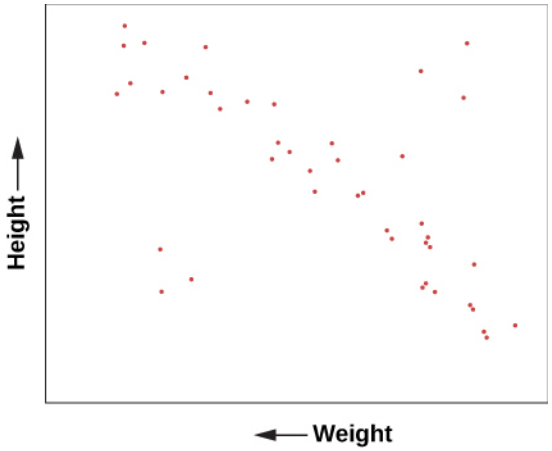


Figure 18.12 Height versus Weight. The plot of the heights and weights of a representative group of human beings. Most points lie along a "main sequence" representing most people, but there are a few exceptions.

We can conclude from this graph that human height and weight are related. Generally speaking, taller human beings weigh more, whereas shorter ones weigh less. This makes sense if you are familiar with the structure of human beings. Typically, if we have bigger bones, we have more flesh to fill out our larger frame. It's not mathematically exact—there is a wide range of variation—but it's not a bad overall rule. And, of course, there are some dramatic exceptions. You occasionally see a short human who is very overweight and would thus be more to the bottom left of our diagram than the average sequence of people. Or you might have a very tall, skinny fashion model with great height but relatively small weight, who would be found near the upper right.

A similar diagram has been found extremely useful for understanding the lives of stars. In 1913, American astronomer Henry Norris Russell plotted the luminosities of stars against their spectral classes (a way of denoting their surface temperatures). This investigation, and a similar independent study in 1911 by Danish astronomer Ejnar Hertzsprung, led to the extremely important discovery that the temperature and luminosity of stars are related (**Figure 18.13**).

Figure 18.13 Hertzsprung (1873–1967) and Russell (1877–1957). (a) Ejnar Hertzsprung and (b) Henry Norris Russell independently discovered the relationship between the luminosity and surface temperature of stars that is summarized in what is now called the H–R diagram.

VOYAGERS IN ASTRONOMY

Henry Norris Russell

When Henry Norris Russell graduated from Princeton University, his work had been so brilliant that the faculty decided to create a new level of honors degree beyond "summa cum laude" for him. His students later remembered him as a man whose thinking was three times faster than just about anybody else's. His memory was so phenomenal, he could correctly quote an enormous number of poems and limericks, the entire Bible, tables of mathematical functions, and almost anything he had learned about astronomy. He was nervous, active, competitive, critical, and very articulate; he tended to dominate every meeting he attended. In outward appearance, he was an old-fashioned product of the nineteenth century who wore high-top black shoes and high starched collars, and carried an umbrella every day of his life. His 264 papers were enormously influential in many areas of astronomy.

Born in 1877, the son of a Presbyterian minister, Russell showed early promise. When he was 12, his family sent him to live with an aunt in Princeton so he could attend a top preparatory school. He lived in the same house in that town until his death in 1957 (interrupted only by a brief stay in Europe for graduate work). He was fond of recounting that both his mother and his maternal grandmother had won prizes in mathematics, and that he probably inherited his talents in that field from their side of the family.

Before Russell, American astronomers devoted themselves mainly to surveying the stars and making impressive catalogs of their properties, especially their spectra (as described in **Analyzing Starlight**. Russell began to see that interpreting the spectra of stars required a much more sophisticated understanding of the physics of the atom, a subject that was being developed by European physicists in the 1910s and 1920s. Russell embarked on a lifelong quest to ascertain the physical conditions inside stars from the clues in their spectra; his work inspired, and was continued by, a generation of astronomers, many trained by Russell and his collaborators.

Russell also made important contributions in the study of binary stars and the measurement of star masses, the origin of the solar system, the atmospheres of planets, and the measurement of distances in astronomy, among other fields. He was an influential teacher and popularizer of astronomy, writing a column on astronomical topics for *Scientific American* magazine for more than 40 years. He and two colleagues wrote a textbook for college astronomy classes that helped train astronomers and astronomy enthusiasts over several decades. That book set the scene for the kind of textbook you are now reading, which not only lays out the facts of astronomy but also explains how they fit together. Russell gave lectures around the country, often emphasizing the importance of understanding modern physics in order to grasp what was happening in astronomy.

Harlow Shapley, director of the Harvard College Observatory, called Russell "the dean of American astronomers." Russell was certainly regarded as the leader of the field for many years and was consulted on many astronomical problems by colleagues from around the world. Today, one of the highest recognitions that an astronomer can receive is an award from the American Astronomical Society called the Russell Prize, set up in his memory.

Features of the H–R Diagram

Following Hertzsprung and Russell, let us plot the temperature (or spectral class) of a selected group of nearby stars against their luminosity and see what we find (**Figure 18.14**). Such a plot is frequently called

the *Hertzsprung–Russell diagram*, abbreviated **H–R diagram**. It is one of the most important and widely used diagrams in astronomy, with applications that extend far beyond the purposes for which it was originally developed more than a century ago.

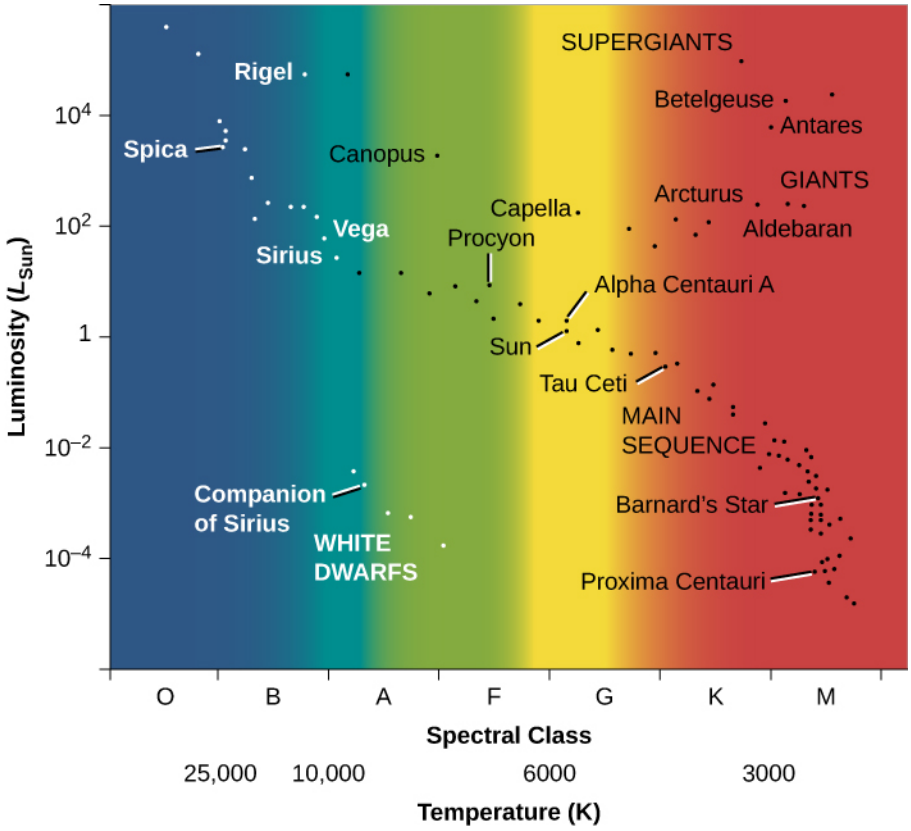


Figure 18.14 H–R Diagram for a Selected Sample of Stars. In such diagrams, luminosity is plotted along the vertical axis. Along the horizontal axis, we can plot either temperature or spectral type (also sometimes called spectral class). Several of the brightest stars are identified by name. Most stars fall on the main sequence.

It is customary to plot H–R diagrams in such a way that temperature increases toward the left and luminosity toward the top. Notice the similarity to our plot of height and weight for people (Figure 18.12). Stars, like people, are not distributed over the diagram at random, as they would be if they exhibited all combinations of luminosity and temperature. Instead, we see that the stars cluster into certain parts of the H–R diagram. The great majority are aligned along a narrow sequence running from the upper left (hot, highly luminous) to the lower right (cool, less luminous). This band of points is called the **main sequence**. It represents a relationship between *temperature* and *luminosity* that is followed by most stars. We can summarize this relationship by saying that hotter stars are more luminous than cooler ones.

A number of stars, however, lie above the main sequence on the H–R diagram, in the upper-right region, where stars have low temperature and high luminosity. How can a star be at once cool, meaning each square meter on the star does not put out all that much energy, and yet very luminous? The only way is for the star to be enormous—to have so many square meters on its surface that the *total* energy output is still large. These stars must be *giants* or *supergiants*, the stars of huge diameter we discussed earlier.

There are also some stars in the lower-left corner of the diagram, which have high temperature and low luminosity. If they have high surface temperatures, each square meter on that star puts out a lot of energy. How then can the overall star be dim? It must be that it has a very small total surface area; such stars are known as **white dwarfs** (white because, at these high temperatures, the colors of the electromagnetic radiation that

they emit blend together to make them look bluish-white). We will say more about these puzzling objects in a moment. **Figure 18.15** is a schematic H–R diagram for a large sample of stars, drawn to make the different types more apparent.

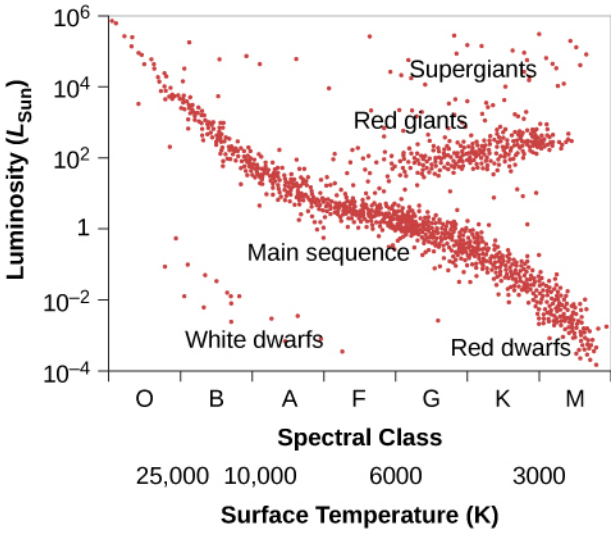


Figure 18.15 Schematic H–R Diagram for Many Stars. Ninety percent of all stars on such a diagram fall along a narrow band called the main sequence. A minority of stars are found in the upper right; they are both cool (and hence red) and bright, and must be giants. Some stars fall in the lower left of the diagram; they are both hot and dim, and must be white dwarfs.

Now, think back to our discussion of star surveys. It is difficult to plot an H–R diagram that is truly representative of all stars because most stars are so faint that we cannot see those outside our immediate neighborhood. The stars plotted in **Figure 18.14** were selected because their distances are known. This sample omits many intrinsically faint stars that are nearby but have not had their distances measured, so it shows fewer faint main-sequence stars than a "fair" diagram would. To be truly representative of the stellar population, an H–R diagram should be plotted for all stars within a certain distance. Unfortunately, our knowledge is reasonably complete only for stars within 10 to 20 light-years of the Sun, among which there are no giants or supergiants. Still, from many surveys (and more can now be done with new, more powerful telescopes), we estimate that about 90% of the true stars overall (excluding brown dwarfs) in our part of space are main-sequence stars, about 10% are white dwarfs, and fewer than 1% are giants or supergiants.

These estimates can be used directly to understand the lives of stars. Permit us another quick analogy with people. Suppose we survey people just like astronomers survey stars, but we want to focus our attention on the location of young people, ages 6 to 18 years. Survey teams fan out and take data about where such youngsters are found at all times during a 24-hour day. Some are found in the local pizza parlor, others are asleep at home, some are at the movies, and many are in school. After surveying a very large number of young people, one of the things that the teams determine is that, averaged over the course of the 24 hours, one-third of all youngsters are found in school.

How can they interpret this result? Does it mean that two-thirds of students are truants and the remaining one-third spend all their time in school? No, we must bear in mind that the survey teams counted youngsters throughout the full 24-hour day. Some survey teams worked at night, when most youngsters were at home asleep, and others worked in the late afternoon, when most youngsters were on their way home from school (and more likely to be enjoying a pizza). If the survey was truly representative, we *can* conclude, however, that if an average of one-third of all youngsters are found in school, then humans ages 6 to 18 years must spend about one-third of *their time* in school.

We can do something similar for stars. We find that, on average, 90% of all stars are located on the main sequence of the H–R diagram. If we can identify some activity or life stage with the main sequence, then it follows that stars must spend 90% of their lives in that activity or life stage.

Understanding the Main Sequence

In **The Sun: A Nuclear Powerhouse**, we discussed the Sun as a representative star. We saw that what stars such as the Sun "do for a living" is to convert protons into helium deep in their interiors via the process of nuclear fusion, thus producing energy. The fusion of protons to helium is an excellent, long-lasting source of energy for a star because the bulk of every star consists of hydrogen atoms, whose nuclei are protons.

Our computer models of how stars evolve over time show us that a typical star will spend about 90% of its life fusing the abundant hydrogen in its core into helium. This then is a good explanation of why 90% of all stars are found on the main sequence in the H–R diagram. But if all the stars on the main sequence are doing the same thing (fusing hydrogen), why are they distributed along a sequence of points? That is, why do they differ in luminosity and surface temperature (which is what we are plotting on the H–R diagram)?

To help us understand how main-sequence stars differ, we can use one of the most important results from our studies of model stars. Astrophysicists have been able to show that the structure of stars that are in equilibrium and derive all their energy from nuclear fusion is completely and uniquely determined by just two quantities: the *total mass* and the *composition* of the star. This fact provides an interpretation of many features of the H–R diagram.

Imagine a cluster of stars forming from a cloud of interstellar "raw material" whose chemical composition is similar to the Sun's. (We'll describe this process in more detail in **The Birth of Stars and Discovery of Planets outside the Solar System**, but for now, the details will not concern us.) In such a cloud, all the clumps of gas and dust that become stars begin with the same chemical composition and differ from one another only in mass. Now suppose that we compute a model of each of these stars for the time at which it becomes stable and derives its energy from nuclear reactions, but before it has time to alter its composition appreciably as a result of these reactions.

The models calculated for these stars allow us to determine their luminosities, temperatures, and sizes. If we plot the results from the models—one point for each model star—on the H–R diagram, we get something that looks just like the main sequence we saw for real stars.

And here is what we find when we do this. The model stars with the largest masses are the hottest and most luminous, and they are located at the upper left of the diagram.

The least-massive model stars are the coolest and least luminous, and they are placed at the lower right of the plot. The other model stars all lie along a line running diagonally across the diagram. In other words, *the main sequence turns out to be a sequence of stellar masses*.

This makes sense if you think about it. The most massive stars have the most gravity and can thus compress their centers to the greatest degree. This means they are the hottest inside and the best at generating energy from nuclear reactions deep within. As a result, they shine with the greatest luminosity and have the hottest surface temperatures. The stars with lowest mass, in turn, are the coolest inside and least effective in generating energy. Thus, they are the least luminous and wind up being the coolest on the surface. Our Sun lies somewhere in the middle of these extremes (as you can see in **Figure 18.14**). The characteristics of representative main-sequence stars (excluding brown dwarfs, which are not true stars) are listed in **Table 18.3**.

Characteristics of Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Temperature	Radius (Sun = 1)
O5	40	7×10^5	40,000 K	18
B0	16	2.7×10^5	28,000 K	7
A0	3.3	55	10,000 K	2.5
F0	1.7	5	7500 K	1.4
G0	1.1	1.4	6000 K	1.1
K0	0.8	0.35	5000 K	0.8
M0	0.4	0.05	3500 K	0.6

Table 18.3

Note that we've seen this 90% figure come up before. This is exactly what we found earlier when we examined the mass-luminosity relation (**Figure 18.9**). We observed that 90% of all stars seem to follow the relationship; these are the 90% of all stars that lie on the main sequence in our H–R diagram. Our models and our observations agree.

What about the other stars on the H–R diagram—the giants and supergiants, and the white dwarfs? As we will see in the next few chapters, these are what main-sequence stars turn into as they age: They are the later stages in a star's life. As a star consumes its nuclear fuel, its source of energy changes, as do its chemical composition and interior structure. These changes cause the star to alter its luminosity and surface temperature so that it no longer lies on the main sequence on our diagram. Because stars spend much less time in these later stages of their lives, we see fewer stars in those regions of the H–R diagram.

Extremes of Stellar Luminosities, Diameters, and Densities

We can use the H–R diagram to explore the extremes in size, luminosity, and density found among the stars. Such extreme stars are not only interesting to fans of the *Guinness Book of World Records*; they can teach us a lot about how stars work. For example, we saw that the most massive main-sequence stars are the most luminous ones. We know of a few extreme stars that are a million times more luminous than the Sun, with masses that exceed 100 times the Sun's mass. These superluminous stars, which are at the upper left of the H–R diagram, are exceedingly hot, very blue stars of spectral type O. These are the stars that would be the most conspicuous at vast distances in space.

The cool supergiants in the upper corner of the H–R diagram are as much as 10,000 times as luminous as the Sun. In addition, these stars have diameters very much larger than that of the Sun. As discussed above, some supergiants are so large that if the solar system could be centered in one, the star's surface would lie beyond the orbit of Mars (see **Figure 18.16**). We will have to ask, in coming chapters, what process can make a star swell up to such an enormous size, and how long these "swollen" stars can last in their distended state.

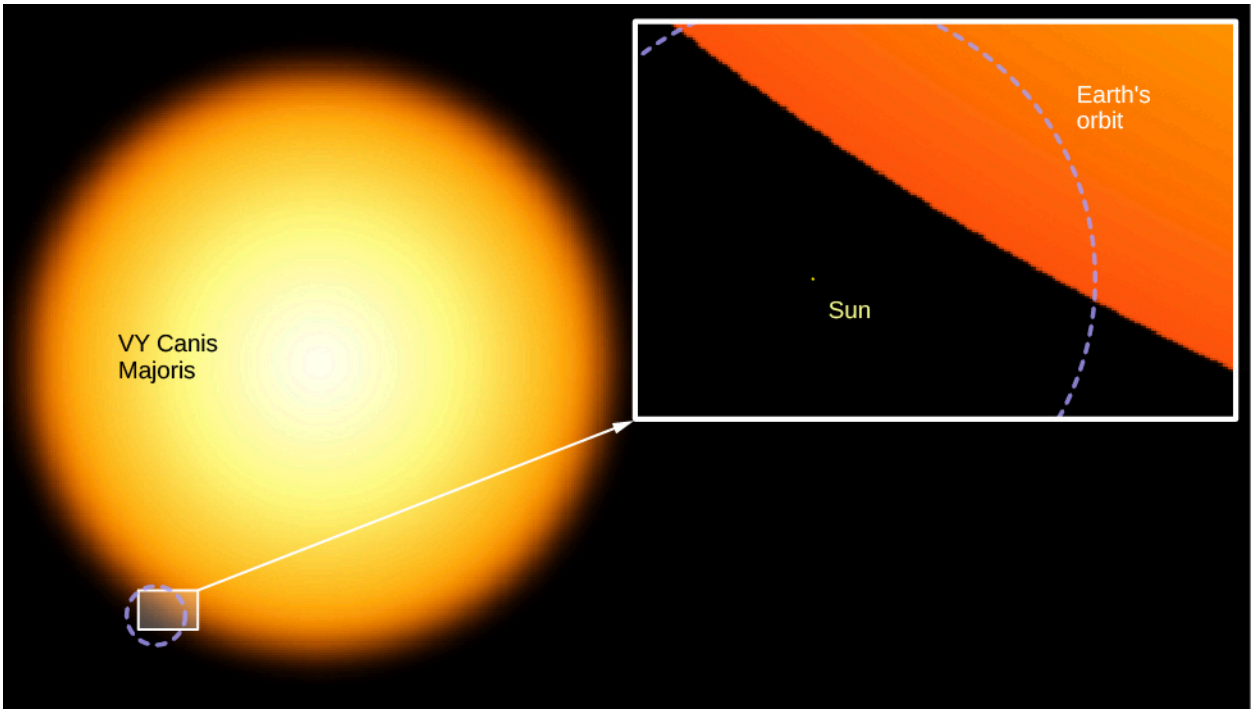


Figure 18.16 The Sun and a Supergiant. Here you see how small the Sun looks in comparison to one of the largest known stars: VY Canis Majoris, a supergiant.

In contrast, the very common red, cool, low-luminosity stars at the lower end of the main sequence are much smaller and more compact than the Sun. An example of such a red dwarf is Ross 614B, with a surface temperature of 2700 K and only 1/2000 of the Sun's luminosity. We call such a star a dwarf because its diameter is only 1/10 that of the Sun. A star with such a low luminosity also has a low mass (about 1/12 that of the Sun). This combination of mass and diameter means that it is so compressed that the star has an average density about 80 times that of the Sun. Its density must be higher, in fact, than that of any known solid found on the surface of Earth. (Despite this, the star is made of gas throughout because its center is so hot.)

The faint, red, main-sequence stars are not the stars of the most extreme densities, however. The white dwarfs, at the lower-left corner of the H–R diagram, have densities many times greater still.

The White Dwarfs

The first white dwarf star was detected in 1862. Called Sirius B, it forms a binary system with Sirius A, the brightest-appearing star in the sky. It eluded discovery and analysis for a long time because its faint light tends to be lost in the glare of nearby Sirius A (Figure 18.17). (Since Sirius is often called the Dog Star—being the brightest star in the constellation of Canis Major, the big dog—Sirius B is sometimes nicknamed the Pup.)

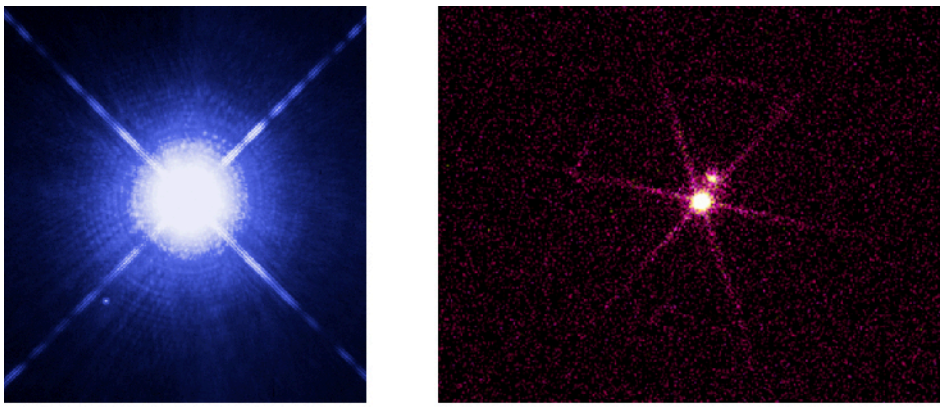


Figure 18.17 Two Views of Sirius and Its White Dwarf Companion. (a) The (visible light) image, taken with the Hubble Space Telescope, shows bright Sirius A, and, below it and off to its left, faint Sirius B. (b) This image of the Sirius star system was taken with the Chandra X-Ray Telescope. Now, the bright object is the white dwarf companion, Sirius B. Sirius A is the faint object above it; what we are seeing from Sirius is probably not actually X-ray radiation but rather ultraviolet light that has leaked into the detector. Note that the ultraviolet intensities of these two objects are completely reversed from the situation in visible light because Sirius B is hotter and emits more higher-frequency radiation. (credit a: modification of work by NASA, H.E. Bond and E. Nelan (Space Telescope Science Institute), M. Barstow and M. Burleigh (University of Leicester) and J.B. Holberg (University of Arizona); credit b: modification of work by NASA/SAO/CXC)

We have now found thousands of white dwarfs. **Table 18.1** shows that about 7% of the true stars (spectral types O–M) in our local neighborhood are white dwarfs. A good example of a typical white dwarf is the nearby star 40 Eridani B. Its surface temperature is a relatively hot 12,000 K, but its luminosity is only 1/275 L_{Sun}. Calculations show that its radius is only 1.4% of the Sun's, or about the same as that of Earth, and its volume is 2.5×10^{-6} that of the Sun. Its mass, however, is 0.57 times the Sun's mass, just a little more than half. To fit such a substantial mass into so tiny a volume, the star's density must be about 210,000 times the density of the Sun, or more than 300,000 g/cm^3. A teaspoonful of this material would have a mass of some 1.6 tons! At such enormous densities, matter cannot exist in its usual state; we will examine the particular behavior of this type of matter in **The Death of Stars**. For now, we just note that white dwarfs are dying stars, reaching the end of their productive lives and ready for their stories to be over.

The British astrophysicist (and science popularizer) Arthur Eddington (1882–1944) described the first known white dwarf this way:

> The message of the companion of Sirius, when decoded, ran: "I am composed of material three thousand times denser than anything you've ever come across. A ton of my material would be a little nugget you could put in a matchbox." What reply could one make to something like that? Well, the reply most of us made in 1914 was, "Shut up; don't talk nonsense."

Today, however, astronomers not only accept that stars as dense as white dwarfs exist but (as we will see) have found even denser and stranger objects in their quest to understand the evolution of different types of stars.

CHAPTER 18 REVIEW

KEY TERMS

binary stars two stars that revolve about each other

brown dwarf an object intermediate in size between a planet and a star; the approximate mass range is from about 1/100 of the mass of the Sun up to the lower mass limit for self-sustaining nuclear reactions, which is about 1/12 the mass of the Sun

eclipsing binary a binary star in which the plane of revolution of the two stars is nearly edge-on to our line of sight, so that the light of one star is periodically diminished by the other passing in front of it

H–R diagram (Hertzsprung–Russell diagram) a plot of luminosity against surface temperature (or spectral type) for a group of stars

main sequence a sequence of stars on the Hertzsprung–Russell diagram, containing the majority of stars, that runs diagonally from the upper left to the lower right

mass-luminosity relation the observed relation between the masses and luminosities of many (90% of all) stars

selection effect the selection of sample data in a nonrandom way, causing the sample data to be unrepresentative of the entire data set

spectroscopic binary a binary star in which the components are not resolved but whose binary nature is indicated by periodic variations in radial velocity, indicating orbital motion

visual binary a binary star in which the two components are telescopically resolved

white dwarf a low-mass star that has exhausted most or all of its nuclear fuel and has collapsed to a very small size; such a star is near its final state of life

SUMMARY

18.1 A Stellar Census

To understand the properties of stars, we must make wide-ranging surveys. We find the stars that appear brightest to our eyes are bright primarily because they are intrinsically very luminous, not because they are the closest to us. Most of the nearest stars are intrinsically so faint that they can be seen only with the aid of a telescope. Stars with low mass and low luminosity are much more common than stars with high mass and high luminosity. Most of the brown dwarfs in the local neighborhood have not yet been discovered.

18.2 Measuring Stellar Masses

The masses of stars can be determined by analysis of the orbit of binary stars—two stars that orbit a common center of mass. In visual binaries, the two stars can be seen separately in a telescope, whereas in a spectroscopic binary, only the spectrum reveals the presence of two stars. Stellar masses range from about 1/12 to more than 100 times the mass of the Sun (in rare cases, going to 250 times the Sun's mass). Objects with masses between 1/12 and 1/100 that of the Sun are called brown dwarfs. Objects in which no nuclear reactions can take place are planets. The most massive stars are, in most cases, also the most luminous, and this correlation is known as the mass-luminosity relation.

18.3 Diameters of Stars

The diameters of stars can be determined by measuring the time it takes an object (the Moon, a planet, or a companion star) to pass in front of it and block its light. Diameters of members of eclipsing binary systems (where the stars pass in front of each other) can be determined through analysis of their orbital motions.

18.4 The H–R Diagram

The Hertzsprung–Russell diagram, or H–R diagram, is a plot of stellar luminosity against surface temperature. Most stars lie on the main sequence, which extends diagonally across the H–R diagram from high temperature and high luminosity to low temperature and low luminosity. The position of a star along the main sequence is determined by its mass. High-mass stars emit more energy and are hotter than low-mass stars on the main sequence. Main-sequence stars derive their energy from the fusion of protons to helium. About 90% of the stars lie on the main sequence. Only about 10% of the stars are white dwarfs, and fewer than 1% are giants or supergiants.

FOR FURTHER EXPLORATION

Articles

Croswell, K. “The Periodic Table of the Cosmos.” *Scientific American* (July 2011):45–49. A brief introduction to the history and uses of the H–R diagram.

Davis, J. “Measuring the Stars.” *Sky & Telescope* (October 1991): 361. The article explains direct measurements of stellar diameters.

DeVorkin, D. “Henry Norris Russell.” *Scientific American* (May 1989): 126.

Kaler, J. “Journeys on the H–R Diagram.” *Sky & Telescope* (May 1988): 483.

McAllister, H. “Twenty Years of Seeing Double.” *Sky & Telescope* (November 1996): 28. An update on modern studies of binary stars.

Parker, B. “Those Amazing White Dwarfs.” *Astronomy* (July 1984): 15. The article focuses on the history of their discovery.

Pasachoff, J. “The H–R Diagram’s 100th Anniversary.” *Sky & Telescope* (June 2014): 32.

Roth, J., and Sinnott, R. “Our Studies of Celestial Neighbors.” *Sky & Telescope* (October 1996): 32. A discussion is provided on finding the nearest stars.

Websites

Eclipsing Binary Stars: **http://www.midnightkite.com/index.aspx?URL=Binary (http://www.midnightkite.com/index.aspx?URL=Binary)** . Dan Bruton at Austin State University has created this collection of animations, articles, and links showing how astronomers use eclipsing binary light curves.

Henry Norris Russell: **http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/russell-henry-n.pdf (http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/russell-henry-n.pdf)** . A biographic memoir by Harlow Shapley.

Henry Norris Russell: **http://www.phys-astro.sonoma.edu/brucemedalists/russell/RussellBio.pdf (http://www.phys-astro.sonoma.edu/brucemedalists/russell/RussellBio.pdf)** . A Bruce Medal profile of Russell.

Hertzsprung–Russell Diagram: **http://skyserver.sdss.org/dr1/en/proj/advanced/hr/**

(http://skyserver.sdss.org/dr1/en/proj/advanced/hr/) . This site from the Sloan Digital Sky Survey introduces the H–R diagram and gives you information for making your own. You can go step by step by using the menu at the left. Note that in the project instructions, the word "here" is a link and takes you to the data you need.

Stars of the Week: http://stars.astro.illinois.edu/sow/sowlist.html (http://stars.astro.illinois.edu/sow/sowlist.html) . Astronomer James Kaler does "biographical summaries" of famous stars—not the Hollywood type, but ones in the real sky.

Videos

WISE Mission Surveys Nearby Stars: http://www.jpl.nasa.gov/video/details.php?id=1089 (http://www.jpl.nasa.gov/video/details.php?id=1089) . Short video about the WISE telescope survey of brown dwarfs and M dwarfs in our immediate neighborhood (1:21).

COLLABORATIVE GROUP ACTIVITIES

A. Two stars are seen close together in the sky, and your group is given the task of determining whether they are a visual binary or whether they just happen to be seen in nearly the same direction. You have access to a good observatory. Make a list of the types of measurements you would make to determine whether they orbit each other.

B. Your group is given information about five main sequence stars that are among the brightest-appearing stars in the sky and yet are pretty far away. Where would these stars be on the H–R diagram and why? Next, your group is given information about five main-sequence stars that are typical of the stars closest to us. Where would these stars be on the H–R diagram and why?

C. A very wealthy (but eccentric) alumnus of your college donates a lot of money for a fund that will help in the search for more brown dwarfs. Your group is the committee in charge of this fund. How would you spend the money? (Be as specific as you can, listing instruments and observing programs.)

D. Use the internet to search for information about the stars with the largest known diameter. What star is considered the record holder (this changes as new measurements are made)? Read about some of the largest stars on the web. Can your group list some reasons why it might be hard to know which star is the largest?

E. Use the internet to search for information about stars with the largest mass. What star is the current "mass champion" among stars? Try to research how the mass of one or more of the most massive stars was measured, and report to the group or the whole class.

EXERCISES

Review Questions

1. How does the mass of the Sun compare with that of other stars in our local neighborhood?

2. Name and describe the three types of binary systems.

3. Describe two ways of determining the diameter of a star.

4. What are the largest- and smallest-known values of the mass, luminosity, surface temperature, and diameter of stars (roughly)?

5. You are able to take spectra of both stars in an eclipsing binary system. List all properties of the stars that can be measured from their spectra and light curves.

6. Sketch an H–R diagram. Label the axes. Show where cool supergiants, white dwarfs, the Sun, and main-sequence stars are found.

7. Describe what a typical star in the Galaxy would be like compared to the Sun.

8. How do we distinguish stars from brown dwarfs? How do we distinguish brown dwarfs from planets?

9. Describe how the mass, luminosity, surface temperature, and radius of main-sequence stars change in value going from the "bottom" to the "top" of the main sequence.

10. One method to measure the diameter of a star is to use an object like the Moon or a planet to block out its light and to measure the time it takes to cover up the object. Why is this method used more often with the Moon rather than the planets, even though there are more planets?

11. We discussed in the chapter that about half of stars come in pairs, or multiple star systems, yet the first eclipsing binary was not discovered until the eighteenth century. Why?

Thought Questions

12. Is the Sun an average star? Why or why not?

13. Suppose you want to determine the average educational level of people throughout the nation. Since it would be a great deal of work to survey every citizen, you decide to make your task easier by asking only the people on your campus. Will you get an accurate answer? Will your survey be distorted by a selection effect? Explain.

14. Why do most known visual binaries have relatively long periods and most spectroscopic binaries have relatively short periods?

15. **Figure 18.11** shows the light curve of a hypothetical eclipsing binary star in which the light of one star is completely blocked by another. What would the light curve look like for a system in which the light of the smaller star is only partially blocked by the larger one? Assume the smaller star is the hotter one. Sketch the relative positions of the two stars that correspond to various portions of the light curve.

16. There are fewer eclipsing binaries than spectroscopic binaries. Explain why.

17. Within 50 light-years of the Sun, visual binaries outnumber eclipsing binaries. Why?

18. Which is easier to observe at large distances—a spectroscopic binary or a visual binary?

19. The eclipsing binary Algol drops from maximum to minimum brightness in about 4 hours, remains at minimum brightness for 20 minutes, and then takes another 4 hours to return to maximum brightness. Assume that we view this system exactly edge-on, so that one star crosses directly in front of the other. Is one star much larger than the other, or are they fairly similar in size? (Hint: Refer to the diagrams of eclipsing binary light curves.)

20. Review this spectral data for five stars.

Table A

Star	Spectrum
1	G, main sequence
2	K, giant
3	K, main sequence
4	O, main sequence
5	M, main sequence

Which is the hottest? Coolest? Most luminous? Least luminous? In each case, give your reasoning.

21. Which changes by the largest factor along the main sequence from spectral types O to M—mass or luminosity?

22. Suppose you want to search for brown dwarfs using a space telescope. Will you design your telescope to detect light in the ultraviolet or the infrared part of the spectrum? Why?

23. An astronomer discovers a type-M star with a large luminosity. How is this possible? What kind of star is it?

24. Approximately 6000 stars are bright enough to be seen without a telescope. Are any of these white dwarfs? Use the information given in this chapter to explain your reasoning.

25. Use the data in **Appendix J** to plot an H–R diagram for the brightest stars. Use the data from **Table 18.3** to show where the main sequence lies. Do 90% of the brightest stars lie on or near the main sequence? Explain why or why not.

26. Use the diagram you have drawn for **Exercise 18.25** to answer the following questions: Which star is more massive—Sirius or Alpha Centauri? Rigel and Regulus have nearly the same spectral type. Which is larger? Rigel and Betelgeuse have nearly the same luminosity. Which is larger? Which is redder?

27. Use the data in **Appendix I** to plot an H–R diagram for this sample of nearby stars. How does this plot differ from the one for the brightest stars in **Exercise 18.25**? Why?

28. If a visual binary system were to have two equal-mass stars, how would they be located relative to the center of the mass of the system? What would you observe as you watched these stars as they orbited the center of mass, assuming very circular orbits, and assuming the orbit was face on to your view?

29. Two stars are in a visual binary star system that we see face on. One star is very massive whereas the other is much less massive. Assuming circular orbits, describe their relative orbits in terms of orbit size, period, and orbital velocity.

30. Describe the spectra for a spectroscopic binary for a system comprised of an F-type and L-type star. Assume that the system is too far away to be able to easily observe the L-type star.

31. **Figure 18.7** shows the velocity of two stars in a spectroscopic binary system. Which star is the most massive? Explain your reasoning.

32. You go out stargazing one night, and someone asks you how far away the brightest stars we see in the sky without a telescope are. What would be a good, general response? (Use **Appendix J** for more information.)

33. If you were to compare three stars with the same surface temperature, with one star being a giant, another a supergiant, and the third a main-sequence star, how would their radii compare to one another?

34. Are supergiant stars also extremely massive? Explain the reasoning behind your answer.

35. Consider the following data on four stars:

Table B

Star	Luminosity (in L_{Sun})	Type
1	100	B, main sequence
2	1/100	B, white dwarf
3	1/100	M, main sequence
4	100	M, giant

Which star would have the largest radius? Which star would have the smallest radius? Which star is the most common in our area of the Galaxy? Which star is the least common?

Figuring For Yourself

36. If two stars are in a binary system with a combined mass of 5.5 solar masses and an orbital period of 12 years, what is the average distance between the two stars?

37. It is possible that stars as much as 200 times the Sun's mass or more exist. What is the luminosity of such a star based upon the mass-luminosity relation?

38. The lowest mass for a true star is 1/12 the mass of the Sun. What is the luminosity of such a star based upon the mass-luminosity relationship?

39. Spectral types are an indicator of temperature. For the first 10 stars in **Appendix J**, the list of the brightest stars in our skies, estimate their temperatures from their spectral types. Use information in the figures and/or tables in this chapter and describe how you made the estimates.

40. We can estimate the masses of most of the stars in **Appendix J** from the mass-luminosity relationship in **Figure 18.9**. However, remember this relationship works only for main sequence stars. Determine which of the first 10 stars in **Appendix J** are main sequence stars. Use one of the figures in this chapter. Make a table of stars' masses.

41. In **Diameters of Stars**, the relative diameters of the two stars in the Sirius system were determined. Let's use this value to explore other aspects of this system. This will be done through several steps, each in its own exercise. Assume the temperature of the Sun is 5800 K, and the temperature of Sirius A, the larger star of the binary, is
10,000 K. The luminosity of Sirius A can be found in **Appendix J**, and is given as about 23 times that of the Sun. Using the values provided, calculate the radius of Sirius A relative to that of the Sun.

42. Now calculate the radius of Sirius' white dwarf companion, Sirius B, to the Sun.

43. How does this radius of Sirius B compare with that of Earth?

44. From the previous calculations and the results from **Diameters of Stars**, it is possible to calculate the density of Sirius B relative to the Sun. It is worth noting that the radius of the companion is very similar to that of Earth, whereas the mass is very similar to the Sun's. How does the companion's density compare to that of the Sun? Recall that density = mass/volume, and the volume of a sphere = $(4/3)\pi R^3$. How does this density compare with that of water and other materials discussed in this text? Can you see why astronomers were so surprised and puzzled when they first determined the orbit of the companion to Sirius?

45. How much would you weigh if you were suddenly transported to the white dwarf Sirius B? You may use your own weight (or if don't want to own up to what it is, assume you weigh 70 kg or 150 lb). In this case, assume that the companion to Sirius has a mass equal to that of the Sun and a radius equal to that of Earth. Remember Newton's law of gravity:

$$F = GM_1M_2/R^2$$

and that your weight is proportional to the force that you feel. What kind of star should you travel to if you want to *lose* weight (and not gain it)?

46. The star Betelgeuse has a temperature of 3400 K and a luminosity of 13,200 L_{Sun}. Calculate the radius of Betelgeuse relative to the Sun.

47. Using the information provided in **Table 18.1**, what is the average stellar density in our part of the Galaxy? Use only the true stars (types O–M) and assume a spherical distribution with radius of 26 light-years.

48. Confirm that the angular diameter of the Sun of 1/2° corresponds to a linear diameter of 1.39 million km. Use the average distance of the Sun and Earth to derive the answer. (Hint: This can be solved using a trigonometric function.)

49. An eclipsing binary star system is observed with the following contact times for the main eclipse:

Table C

Contact	Time	Date
First contact	12:00 p.m.	March 12
Second contact	4:00 p.m.	March 13
Third contact	9:00 a.m.	March 18
Fourth contact	1:00 p.m.	March 19

The orbital velocity of the smaller star relative to the larger is 62,000 km/h. Determine the diameters for each star in the system.

50. If a 100 solar mass star were to have a luminosity of 10^7 times the Sun's luminosity, how would such a star's density compare when it is on the main sequence as an O-type star, and when it is a cool supergiant (M-type)? Use values of temperature from **Figure 18.14** or **Figure 18.15** and the relationship between luminosity, radius, and temperature as given in **Exercise 18.47**.

51. If Betelgeuse had a mass that was 25 times that of the Sun, how would its average density compare to that of the Sun? Use the definition of $\text{density} = \frac{\text{mass}}{\text{volume}}$, where the volume is that of a sphere.

19

CELESTIAL DISTANCES

Figure 19.1 Globular Cluster M80. This beautiful image shows a giant cluster of stars called Messier 80, located about 28,000 light-years from Earth. Such crowded groups, which astronomers call globular clusters, contain hundreds of thousands of stars, including some of the RR Lyrae variables discussed in this chapter. Especially obvious in this picture are the bright red giants, which are stars similar to the Sun in mass that are nearing the ends of their lives. (credit: modification of work by The Hubble Heritage Team (AURA/ STScI/ NASA))

Chapter Outline

19.1 Fundamental Units of Distance
19.2 Surveying the Stars
19.3 Variable Stars: One Key to Cosmic Distances
19.4 The H–R Diagram and Cosmic Distances

Thinking Ahead

How large is the universe? What is the most distant object we can see? These are among the most fundamental questions astronomers can ask. But just as babies must crawl before they can take their first halting steps, so too must we start with a more modest question: How far away are the stars? And even this question proves to be very hard to answer. After all, stars are mere points of light. Suppose you see a point of light in the darkness when you are driving on a country road late at night. How can you tell whether it is a nearby firefly, an oncoming motorcycle some distance away, or the porchlight of a house much farther down the road? It's not so easy, is it? Astronomers faced an even more difficult problem when they tried to estimate how far away the stars are.

In this chapter, we begin with the fundamental definitions of distances on Earth and then extend our reach outward to the stars. We will also examine the newest satellites that are surveying the night sky and discuss the special types of stars that can be used as trail markers to distant galaxies.

19.1 FUNDAMENTAL UNITS OF DISTANCE

Learning Objectives

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

- Understand the importance of defining a standard distance unit
- Explain how the meter was originally defined and how it has changed over time
- Discuss how radar is used to measure distances to the other members of the solar system

The first measures of distances were based on human dimensions—the inch as the distance between knuckles on the finger, or the yard as the span from the extended index finger to the nose of the British king. Later, the requirements of commerce led to some standardization of such units, but each nation tended to set up its own definitions. It was not until the middle of the eighteenth century that any real efforts were made to establish a uniform, international set of standards.

The Metric System

One of the enduring legacies of the era of the French emperor Napoleon is the establishment of the *metric system* of units, officially adopted in France in 1799 and now used in most countries around the world. The fundamental metric unit of length is the *meter*, originally defined as one ten-millionth of the distance along Earth's surface from the equator to the pole. French astronomers of the seventeenth and eighteenth centuries were pioneers in determining the dimensions of Earth, so it was logical to use their information as the foundation of the new system.

Practical problems exist with a definition expressed in terms of the size of Earth, since anyone wishing to determine the distance from one place to another can hardly be expected to go out and re-measure the planet. Therefore, an intermediate standard meter consisting of a bar of platinum-iridium metal was set up in Paris. In 1889, by international agreement, this bar was defined to be exactly one meter in length, and precise copies of the original meter bar were made to serve as standards for other nations.

Other units of length are derived from the meter. Thus, 1 kilometer (km) equals 1000 meters, 1 centimeter (cm) equals 1/100 meter, and so on. Even the old British and American units, such as the inch and the mile, are now defined in terms of the metric system.

Modern Redefinitions of the Meter

In 1960, the official definition of the meter was changed again. As a result of improved technology for generating spectral lines of precisely known wavelengths (see the chapter on **Radiation and Spectra**), the meter was redefined to equal 1,650,763.73 wavelengths of a particular atomic transition in the element krypton-86. The advantage of this redefinition is that anyone with a suitably equipped laboratory can reproduce a standard meter, without reference to any particular metal bar.

In 1983, the meter was defined once more, this time in terms of the velocity of light. Light in a vacuum can travel a distance of one meter in 1/299,792,458.6 second. Today, therefore, light travel time provides our basic unit of length. Put another way, a distance of *one light-second* (the amount of space light covers in one second) is defined to be 299,792,458.6 meters. That's almost 300 million meters that light covers in just one second; light really is *very* fast! We could just as well use the light-second as the fundamental unit of length, but for practical reasons (and to respect tradition), we have defined the meter as a small fraction of the light-second.

Distance within the Solar System

The work of Copernicus and Kepler established the *relative* distances of the planets—that is, how far from the Sun one planet is compared to another (see **Observing the Sky: The Birth of Astronomy** and **Orbits and Gravity**). But their work could not establish the *absolute* distances (in light-seconds or meters or other standard units of length). This is like knowing the height of all the students in your class only as compared to the height of your astronomy instructor, but not in inches or centimeters. Somebody's height has to be measured directly.

Similarly, to establish absolute distances, astronomers had to measure one distance in the solar system directly. Generally, the closer to us the object is, the easier such a measurement would be. Estimates of the distance to Venus were made as Venus crossed the face of the Sun in 1761 and 1769, and an international campaign was organized to estimate the distance to the asteroid Eros in the early 1930s, when its orbit brought it close to Earth. More recently, Venus crossed (or *transited*) the surface of the Sun in 2004 and 2012, and allowed us to make a modern distance estimate, although, as we will see below, by then it wasn't needed (**Figure 19.2**).

LINK TO LEARNING

If you would like more information on just how the motion of Venus across the Sun helped us pin down distances in the solar system, you can turn to a **nice explanation (https://openstaxcollege.org/l/30VenusandSun)** by a NASA astronomer.

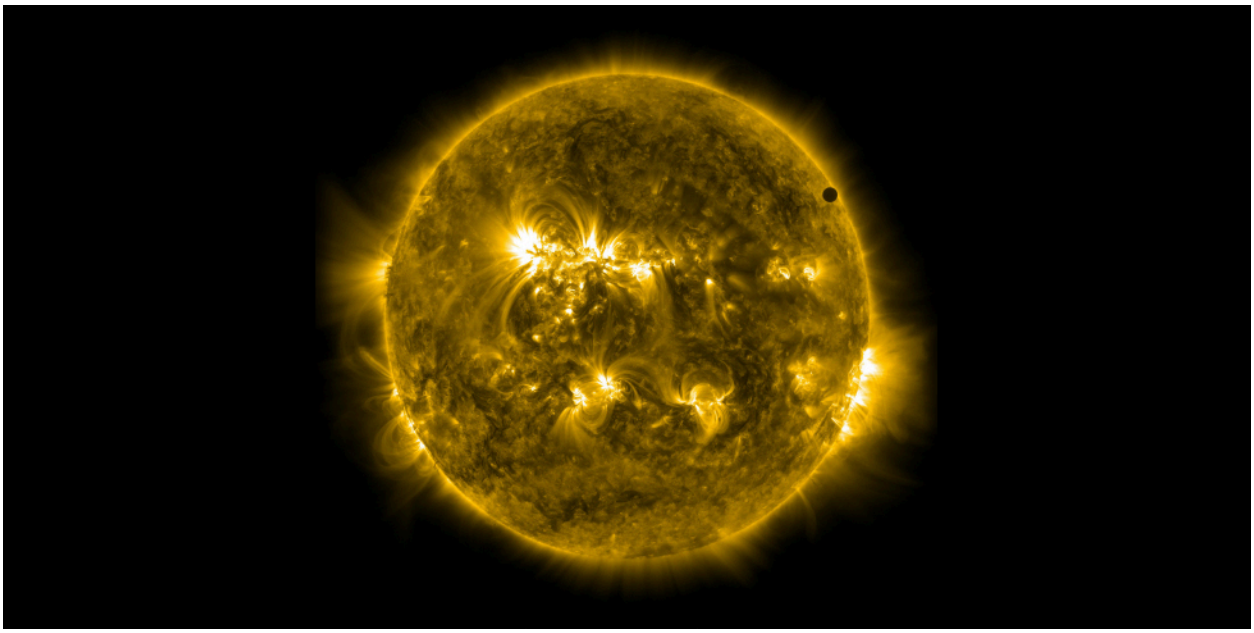


Figure 19.2 Venus Transits the Sun, 2012. This striking "picture" of Venus crossing the face of the Sun (it's the black dot at about 2 o'clock) is more than just an impressive image. Taken with the Solar Dynamics Observatory spacecraft and special filters, it shows a modern transit of Venus. Such events allowed astronomers in the 1800s to estimate the distance to Venus. They measured the time it took Venus to cross the face of the Sun from different latitudes on Earth. The differences in times can be used to estimate the distance to the planet. Today, radar is used for much more precise distance estimates. (credit: modification of work by NASA/SDO, AIA)

The key to our modern determination of solar system dimensions is radar, a type of radio wave that can bounce off solid objects (**Figure 19.3**). As discussed in several earlier chapters, by timing how long a radar beam (traveling at the speed of light) takes to reach another world and return, we can measure the distance involved very accurately. In 1961, radar signals were bounced off Venus for the first time, providing a direct measurement of the distance from Earth to Venus in terms of light-seconds (from the roundtrip travel time of the radar signal).

Subsequently, radar has been used to determine the distances to Mercury, Mars, the satellites of Jupiter, the rings of Saturn, and several asteroids. Note, by the way, that it is not possible to use radar to measure the distance to the Sun directly because the Sun does not reflect radar very efficiently. But we can measure the distance to many other solar system objects and use Kepler's laws to give us the distance to the Sun.

Figure 19.3 Radar Telescope. This dish-shaped antenna, part of the NASA Deep Space Network in California's Mojave Desert, is 70 meters wide. Nicknamed the "Mars antenna," this radar telescope can send and receive radar waves, and thus measure the distances to planets, satellites, and asteroids. (credit: NASA/JPL-Caltech)

From the various (related) solar system distances, astronomers selected the average distance from Earth to the Sun as our standard "measuring stick" within the solar system. When Earth and the Sun are closest, they are about 147.1 million kilometers apart; when Earth and the Sun are farthest, they are about 152.1 million kilometers apart. The average of these two distances is called the astronomical unit (AU). We then express all the other distances in the solar system in terms of the AU. Years of painstaking analyses of radar measurements have led to a determination of the length of the AU to a precision of about one part in a billion. The length of 1 AU can be expressed in light travel time as 499.004854 light-seconds, or about 8.3 light-minutes. If we use the definition of the meter given previously, this is equivalent to 1 AU = 149,597,870,700 meters.

These distances are, of course, given here to a much higher level of precision than is normally needed. In this text, we are usually content to express numbers to a couple of significant places and leave it at that. For our purposes, it will be sufficient to round off these numbers:

$$\text{speed of light: } c = 3 \times 10^8 \text{ m/s} = 3 \times 10^5 \text{ km/s}$$
$$\text{length of light-second: ls} = 3 \times 10^8 \text{ m} = 3 \times 10^5 \text{ km}$$
$$\text{astronomical unit: AU} = 1.50 \times 10^{11} \text{ m} = 1.50 \times 10^8 \text{ km} = 500 \text{ light-seconds}$$

We now know the absolute distance scale within our own solar system with fantastic accuracy. This is the first link in the chain of cosmic distances.

LINK TO LEARNING

The distances between the celestial bodies in our solar system are sometimes difficult to grasp or put into perspective. This **interactive website (https://openstaxcollege.org/l/30DistanceScale)** provides a "map" that shows the distances by using a scale at the bottom of the screen and allows you to scroll

(using your arrow keys) through screens of "empty space" to get to the next planet—all while your current distance from the Sun is visible on the scale.

19.2 SURVEYING THE STARS

Learning Objectives

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

- Understand the concept of triangulating distances to distant objects, including stars
- Explain why space-based satellites deliver more precise distances than ground-based methods
- Discuss astronomers' efforts to study the stars closest to the Sun

It is an enormous step to go from the planets to the stars. For example, our Voyager 1 probe, which was launched in 1977, has now traveled farther from Earth than any other spacecraft. As this is written in 2016, Voyager 1 is 134 AU from the Sun.[1] The nearest star, however, is hundreds of thousands of AU from Earth. Even so, we can, in principle, survey distances to the stars using the same technique that a civil engineer employs to survey the distance to an inaccessible mountain or tree—the method of *triangulation*.

Triangulation in Space

A practical example of triangulation is your own depth perception. As you are pleased to discover every morning when you look in the mirror, your two eyes are located some distance apart. You therefore view the world from two different vantage points, and it is this dual perspective that allows you to get a general sense of how far away objects are.

To see what we mean, take a pen and hold it a few inches in front of your face. Look at it first with one eye (closing the other) and then switch eyes. Note how the pen seems to shift relative to objects across the room. Now hold the pen at arm's length: the shift is less. If you play with moving the pen for a while, you will notice that the farther away you hold it, the less it seems to shift. Your brain automatically performs such comparisons and gives you a pretty good sense of how far away things in your immediate neighborhood are.

If your arms were made of rubber, you could stretch the pen far enough away from your eyes that the shift would become imperceptible. This is because our depth perception fails for objects more than a few tens of meters away. In order to see the shift of an object a city block or more from you, your eyes would need to be spread apart a lot farther.

Let's see how surveyors take advantage of the same idea. Suppose you are trying to measure the distance to a tree across a deep river (**Figure 19.4**). You set up two observing stations some distance apart. That distance (line AB in **Figure 19.4**) is called the *baseline*. Now the direction to the tree (C in the figure) in relation to the baseline is observed from each station. Note that C appears in different directions from the two stations. This apparent change in direction of the remote object due to a change in vantage point of the observer is called **parallax**.

1 To have some basis for comparison, the dwarf planet Pluto orbits at an average distance of 40 AU from the Sun, and the dwarf planet Eris is currently roughly 96 AU from the Sun.

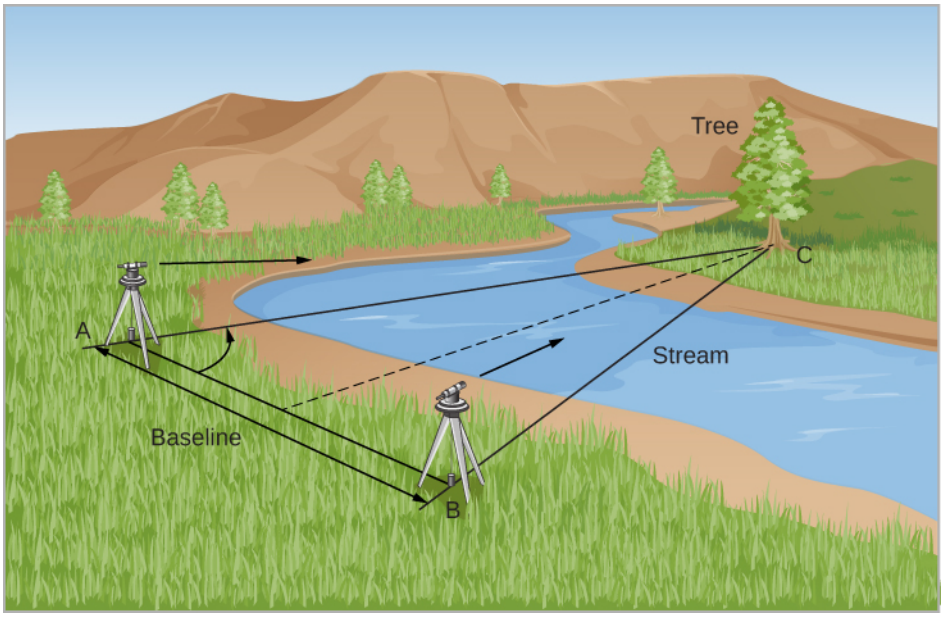


Figure 19.4 Triangulation. Triangulation allows us to measure distances to inaccessible objects. By getting the angle to a tree from two different vantage points, we can calculate the properties of the triangle they make and thus the distance to the tree.

The parallax is also the angle that lines AC and BC make—in mathematical terms, the angle subtended by the baseline. A knowledge of the angles at A and B and the length of the baseline, AB, allows the triangle ABC to be solved for any of its dimensions—say, the distance AC or BC. The solution could be reached by constructing a scale drawing or by using trigonometry to make a numerical calculation. If the tree were farther away, the whole triangle would be longer and skinnier, and the parallax angle would be smaller. Thus, we have the general rule that the smaller the parallax, the more distant the object we are measuring must be.

In practice, the kinds of baselines surveyors use for measuring distances on Earth are completely useless when we try to gauge distances in space. The farther away an astronomical object lies, the longer the baseline has to be to give us a reasonable chance of making a measurement. Unfortunately, nearly all astronomical objects are very far away. To measure their distances requires a very large baseline and highly precise angular measurements. The Moon is the only object near enough that its distance can be found fairly accurately with measurements made without a telescope. Ptolemy determined the distance to the Moon correctly to within a few percent. He used the turning Earth itself as a baseline, measuring the position of the Moon relative to the stars at two different times of night.

With the aid of telescopes, later astronomers were able to measure the distances to the nearer planets and asteroids using Earth's diameter as a baseline. This is how the AU was first established. To reach for the stars, however, requires a much longer baseline for triangulation and extremely sensitive measurements. Such a baseline is provided by Earth's annual trip around the Sun.

Distances to Stars

As Earth travels from one side of its orbit to the other, it graciously provides us with a baseline of 2 AU, or about 300 million kilometers. Although this is a much bigger baseline than the diameter of Earth, the stars are *so far away* that the resulting parallax shift is *still* not visible to the naked eye—not even for the closest stars.

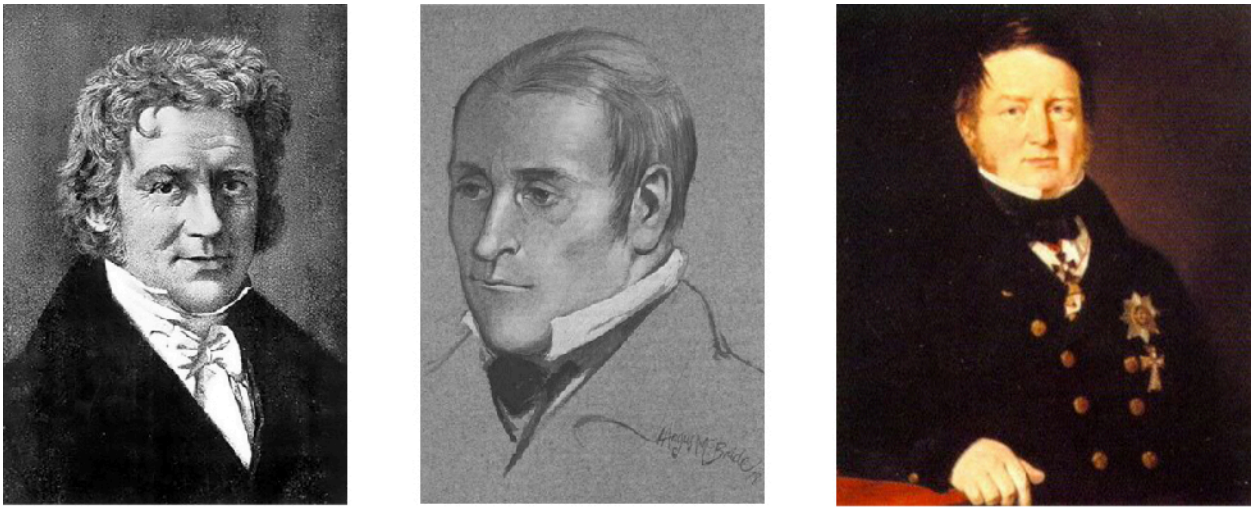
In the chapter on **Observing the Sky: The Birth of Astronomy**, we discussed how this dilemma perplexed the ancient Greeks, some of whom had actually suggested that the Sun might be the center of the solar system, with Earth in motion around it. Aristotle and others argued, however, that Earth could not be revolving about

the Sun. If it were, they said, we would surely observe the parallax of the nearer stars against the background of more distant objects as we viewed the sky from different parts of Earth's orbit (Figure 19.6). Tycho Brahe (1546–1601) advanced the same faulty argument nearly 2000 years later, when his careful measurements of stellar positions with the unaided eye revealed no such shift.

These early observers did not realize how truly distant the stars were and how small the change in their positions therefore was, even with the entire orbit of Earth as a baseline. The problem was that they did not have tools to measure parallax shifts too small to be seen with the human eye. By the eighteenth century, when there was no longer serious doubt about Earth's revolution, it became clear that the stars must be extremely distant. Astronomers equipped with telescopes began to devise instruments capable of measuring the tiny shifts of nearby stars relative to the background of more distant (and thus unshifting) celestial objects.

This was a significant technical challenge, since, even for the nearest stars, parallax angles are usually only a fraction of a second of arc. Recall that one second of arc (arcsec) is an angle of only 1/3600 of a degree. A coin the size of a US quarter would appear to have a diameter of 1 arcsecond if you were viewing it from a distance of about 5 kilometers (3 miles). Think about how small an angle that is. No wonder it took astronomers a long time before they could measure such tiny shifts.

The first successful detections of stellar parallax were in the year 1838, when Friedrich Bessel in Germany (Figure 19.5), Thomas Henderson, a Scottish astronomer working at the Cape of Good Hope, and Friedrich Struve in Russia independently measured the parallaxes of the stars 61 Cygni, Alpha Centauri, and Vega, respectively. Even the closest star, Alpha Centauri, showed a total displacement of only about 1.5 arcseconds during the course of a year.



(a) (b) (c)

Figure 19.5 Friedrich Wilhelm Bessel (1784–1846), Thomas J. Henderson (1798–1844), and Friedrich Struve (1793–1864). (a) Bessel made the first authenticated measurement of the distance to a star (61 Cygni) in 1838, a feat that had eluded many dedicated astronomers for almost a century. But two others, (b) Scottish astronomer Thomas J. Henderson and (c) Friedrich Struve, in Russia, were close on his heels.

Figure 19.6 shows how such measurements work. Seen from opposite sides of Earth's orbit, a nearby star shifts position when compared to a pattern of more distant stars. Astronomers actually define parallax to be *one-half* the angle that a star shifts when seen from opposite sides of Earth's orbit (the angle labeled *P* in Figure 19.6). The reason for this definition is just that they prefer to deal with a baseline of 1 AU instead of 2 AU.

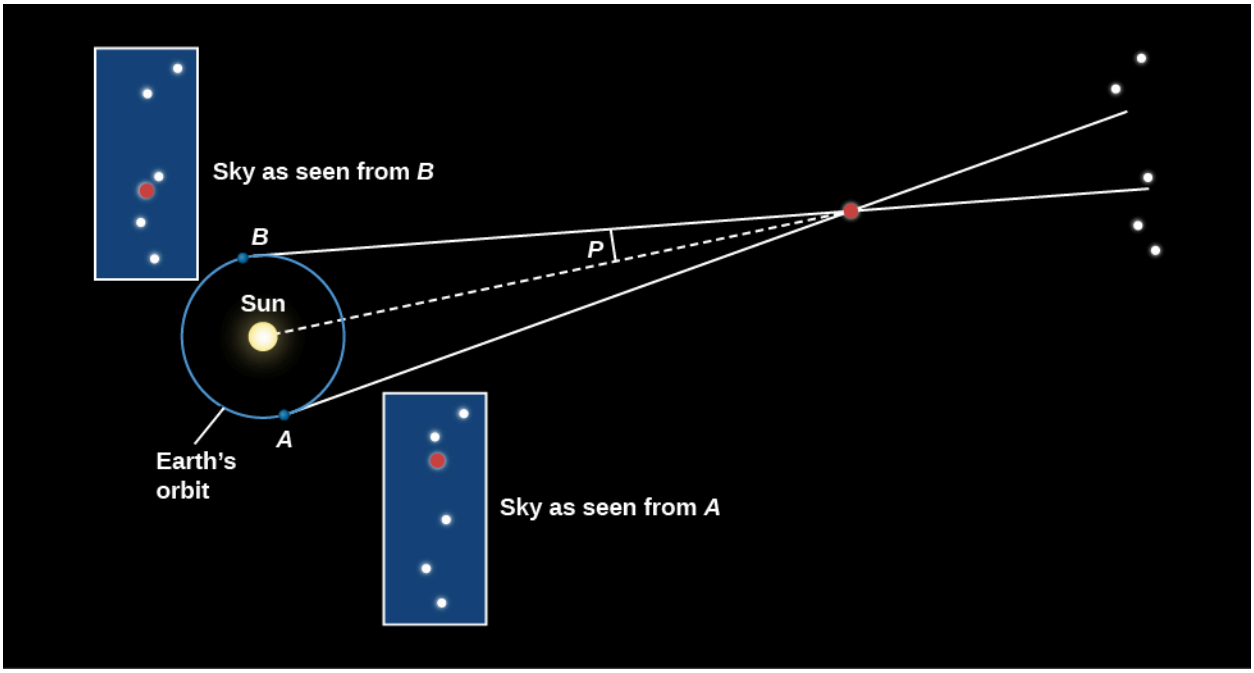


Figure 19.6 Parallax. As Earth revolves around the Sun, the direction in which we see a nearby star varies with respect to distant stars. We define the parallax of the nearby star to be one half of the total change in direction, and we usually measure it in arcseconds.

Units of Stellar Distance

With a baseline of one AU, how far away would a star have to be to have a parallax of 1 arcsecond? The answer turns out to be 206,265 AU, or 3.26 light-years. This is equal to 3.1×10^{13} kilometers (in other words, 31 trillion kilometers). We give this unit a special name, the **parsec** (pc)—derived from "the distance at which we have a *par*allax of one *sec*ond." The distance (D) of a star in parsecs is just the reciprocal of its parallax (p) in arcseconds; that is,

$$D = \frac{1}{p}$$

Thus, a star with a parallax of 0.1 arcsecond would be found at a distance of 10 parsecs, and one with a parallax of 0.05 arcsecond would be 20 parsecs away.

Back in the days when most of our distances came from parallax measurements, a parsec was a useful unit of distance, but it is not as intuitive as the light-year. One advantage of the light-year as a unit is that it emphasizes the fact that, as we look out into space, we are also looking back into time. The light that we see from a star 100 light-years away left that star 100 years ago. What we study is not the star as it is now, but rather as it was in the past. The light that reaches our telescopes today from distant galaxies left them before Earth even existed.

In this text, we will use light-years as our unit of distance, but many astronomers still use parsecs when they write technical papers or talk with each other at meetings. To convert between the two distance units, just bear in mind: 1 parsec = 3.26 light-year, and 1 light-year = 0.31 parsec.

EXAMPLE 19.1

How Far Is a Light-Year?

A light-year is the distance light travels in 1 year. Given that light travels at a speed of 300,000 km/s, how many kilometers are there in a light-year?

Solution

We learned earlier that speed = distance/time. We can rearrange this equation so that distance = velocity × time. Now, we need to determine the number of seconds in a year.

There are approximately 365 days in 1 year. To determine the number of seconds, we must estimate the number of seconds in 1 day.

We can change units as follows (notice how the units of time cancel out):

$$1 \text{ day} \times 24 \text{ hr/day} \times 60 \text{ min/hr} \times 60 \text{ s/min} = 86{,}400 \text{ s/day}$$

Next, to get the number of seconds per year:

$$365 \text{ days/year} \times 86{,}400 \text{ s/day} = 31{,}536{,}000 \text{ s/year}$$

Now we can multiply the speed of light by the number of seconds per year to get the distance traveled by light in 1 year:

$$\begin{aligned} \text{distance} &= \text{velocity} \times \text{time} \\ &= 300{,}000 \text{ km/s} \times 31{,}536{,}000 \text{ s} \\ &= 9.46 \times 10^{12} \text{ km} \end{aligned}$$

That's almost 10,000,000,000,000 km that light covers in a year. To help you imagine how long this distance is, we'll mention that a string 1 light-year long could fit around the circumference of Earth 236 million times.

Check Your Learning

The number above is really large. What happens if we put it in terms that might be a little more understandable, like the diameter of Earth? Earth's diameter is about 12,700 km.

Answer:

$$\begin{aligned} 1 \text{ light-year} &= 9.46 \times 10^{12} \text{ km} \\ &= 9.46 \times 10^{12} \text{ km} \times \frac{1 \text{ Earth diameter}}{12{,}700 \text{ km}} \\ &= 7.45 \times 10^{8} \text{ Earth diameters} \end{aligned}$$

That means that 1 light-year is about 745 million times the diameter of Earth.

ASTRONOMY BASICS

Naming Stars

You may be wondering why stars have such a confusing assortment of names. Just look at the first three stars to have their parallaxes measured: 61 Cygni, Alpha Centauri, and Vega. Each of these names comes from a different tradition of designating stars.

The brightest stars have names that derive from the ancients. Some are from the Greek, such as Sirius, which means "the scorched one"—a reference to its brilliance. A few are from Latin, but many of the best-known names are from Arabic because, as discussed in **Observing the Sky: The Birth of Astronomy**, much of Greek and Roman astronomy was "rediscovered" in Europe after the Dark Ages by means of Arabic translations. Vega, for example, means "swooping Eagle," and Betelgeuse (pronounced "Beetle-juice") means "right hand of the central one."

In 1603, German astronomer Johann Bayer (1572–1625) introduced a more systematic approach to naming stars. For each constellation, he assigned a Greek letter to the brightest stars, roughly in order of brightness. In the constellation of Orion, for example, Betelgeuse is the brightest star, so it got the first letter in the Greek alphabet—alpha—and is known as Alpha Orionis. ("Orionis" is the possessive form of Orion, so Alpha Orionis means "the first of Orion.") A star called Rigel, being the second brightest in that constellation, is called Beta Orionis (**Figure 19.7**). Since there are 24 letters in the Greek alphabet, this system allows the labeling of 24 stars in each constellation, but constellations have many more stars than that.

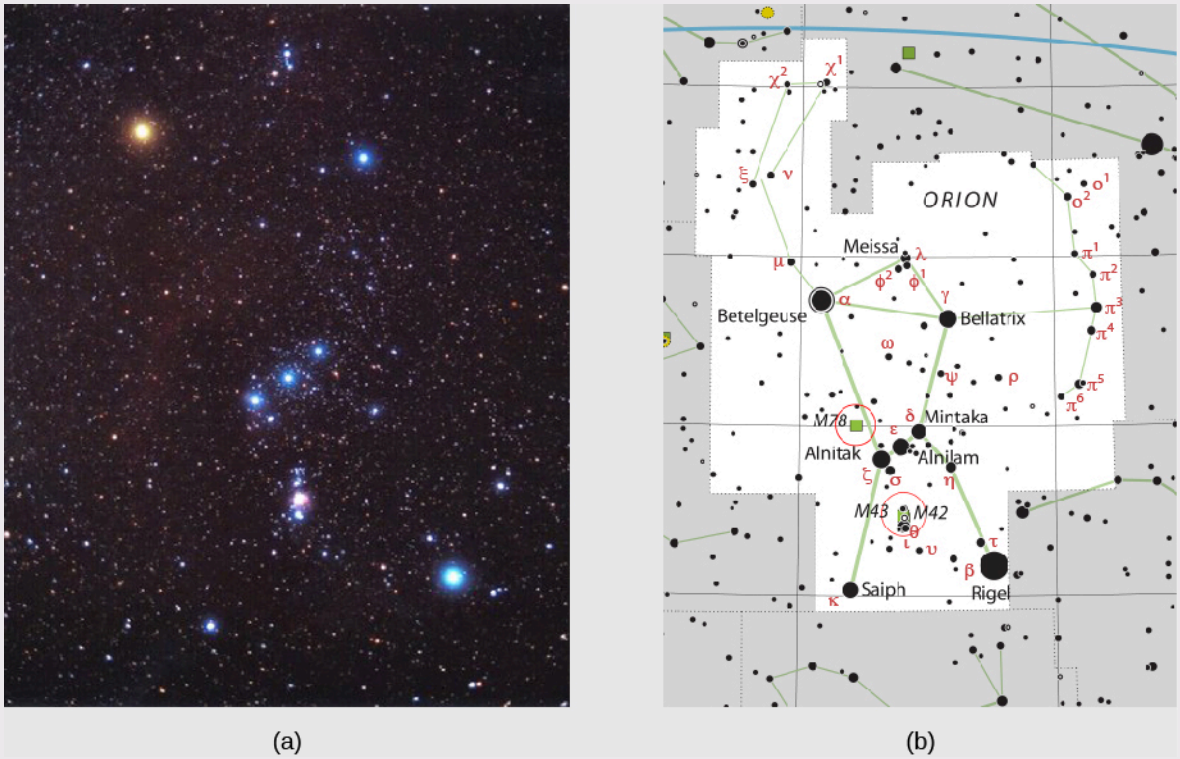


Figure 19.7 Objects in Orion. (a) This image shows the brightest objects in or near the star pattern of Orion, the hunter (of Greek mythology), in the constellation of Orion. (b) Note the Greek letters of Bayer's system in this diagram of the Orion constellation. The objects denoted M42, M43, and M78 are not stars but nebulae—clouds of gas and dust; these numbers come from a list of "fuzzy objects" made by Charles Messier in 1781. (credit a: modification of work by Matthew Spinelli; credit b: modification of work by ESO, IAU and *Sky & Telescope*)

In 1725, the English Astronomer Royal John Flamsteed introduced yet another system, in which the brighter stars eventually got a number in each constellation in order of their location in the sky or, more precisely, their right ascension. (The system of sky coordinates that includes right ascension was discussed in **Earth, Moon, and Sky**.) In this system, Betelgeuse is called 58 Orionis and 61 Cygni is the 61st star in the constellation of Cygnus, the swan.

It gets worse. As astronomers began to understand more and more about stars, they drew up a series of

specialized star catalogs, and fans of those catalogs began calling stars by their catalog numbers. If you look at **Appendix I**—our list of the nearest stars (many of which are much too faint to get an ancient name, Bayer letter, or Flamsteed number)—you will see references to some of these catalogs. An example is a set of stars labeled with a BD number, for "Bonner Durchmusterung." This was a mammoth catalog of over 324,000 stars in a series of zones in the sky, organized at the Bonn Observatory in the 1850s and 1860s. Keep in mind that this catalog was made before photography or computers came into use, so the position of each star had to be measured (at least twice) by eye, a daunting undertaking.

There is also a completely different system for keeping track of stars whose luminosity varies, and another for stars that brighten explosively at unpredictable times. Astronomers have gotten used to the many different star-naming systems, but students often find them bewildering and wish astronomers would settle on one. Don't hold your breath: in astronomy, as in many fields of human thought, tradition holds a powerful attraction. Still, with high-speed computer databases to aid human memory, names may become less and less necessary. Today's astronomers often refer to stars by their precise locations in the sky rather than by their names or various catalog numbers.

The Nearest Stars

No known star (other than the Sun) is within 1 light-year or even 1 parsec of Earth. The stellar neighbors nearest the Sun are three stars in the constellation of Centaurus. To the unaided eye, the brightest of these three stars is Alpha Centauri, which is only 30° from the south celestial pole and hence not visible from the mainland United States. Alpha Centauri itself is a binary star—two stars in mutual revolution—too close together to be distinguished without a telescope. These two stars are 4.4 light-years from us. Nearby is a third faint star, known as Proxima Centauri. Proxima, with a distance of 4.3 light-years, is slightly closer to us than the other two stars. If Proxima Centauri is part of a triple star system with the binary Alpha Centauri, as seems likely, then its orbital period may be longer than 500,000 years.

Proxima Centauri is an example of the most common type of star, and our most common type of stellar neighbor (as we saw in Stars: A Celestial Census.) Low-mass red M dwarfs make up about 70% of all stars and dominate the census of stars within 10 parsecs (33 light-years) of the Sun. For example, a recent survey of the solar neighborhood counted 357 stars and brown dwarfs within 10 parsecs, and 248 of these are red dwarfs. Yet, if you wanted to see an M dwarf with your naked eye, you would be out of luck. These stars only produce a fraction of the Sun's light, and nearly all of them require a telescope to be detected.

The nearest star visible without a telescope from most of the United States is the brightest appearing of all the stars, Sirius, which has a distance of a little more than 8 light-years. It too is a binary system, composed of a faint white dwarf orbiting a bluish-white, main-sequence star. It is an interesting coincidence of numbers that light reaches us from the Sun in about 8 minutes and from the next brightest star in the sky in about 8 years.

EXAMPLE 19.2

Calculating the Diameter of the Sun

For nearby stars, we can measure the apparent shift in their positions as Earth orbits the Sun. We wrote earlier that an object must be 206,265 AU distant to have a parallax of one second of arc. This must seem

like a very strange number, but you can figure out why this is the right value. We will start by estimating the diameter of the Sun and then apply the same idea to a star with a parallax of 1 arcsecond. Make a sketch that has a round circle to represent the Sun, place Earth some distance away, and put an observer on it. Draw two lines from the point where the observer is standing, one to each side of the Sun. Sketch a circle centered at Earth with its circumference passing through the center of the Sun. Now think about proportions. The Sun spans about half a degree on the sky. A full circle has 360°. The circumference of the circle centered on Earth and passing through the Sun is given by:

$$\text{circumference} = 2\pi \times 93{,}000{,}000 \text{ miles}$$

Then, the following two ratios are equal:

$$\frac{0.5^\circ}{360^\circ} = \frac{\text{diameter of Sun}}{2\pi \times 93{,}000{,}000}$$

Calculate the diameter of the Sun. How does your answer compare to the actual diameter?

Solution

To solve for the diameter of the Sun, we can evaluate the expression above.

$$\begin{aligned}\text{diameter of the sun} &= \frac{0.5^\circ}{360^\circ} \times 2\pi \times 93{,}000{,}000 \text{ miles} \\ &= 811{,}577 \text{ miles}\end{aligned}$$

This is very close to the true value of about 848,000 miles.

Check Your Learning

Now apply this idea to calculating the distance to a star that has a parallax of 1 arcsec. Draw a picture similar to the one we suggested above and calculate the distance in AU. (Hint: Remember that the parallax angle is defined by 1 AU, not 2 AU, and that 3600 arcseconds = 1 degree.)

Answer:

206,265 AU

Measuring Parallaxes in Space

The measurements of stellar parallax were revolutionized by the launch of the spacecraft Hipparcos in 1989, which measured distances for thousands of stars out to about 300 light-years with an accuracy of 10 to 20% (see **Figure 19.8** and the feature on **Parallax and Space Astronomy**). However, even 300 light-years are less than 1% the size of our Galaxy's main disk.

In December 2013, the successor to Hipparcos, named *Gaia*, was launched by the European Space Agency. *Gaia* is expected to measure the position and distances to almost one billion stars with an accuracy of a few ten-millionths of an arcsecond. *Gaia's* distance limit will extend well beyond Hipparcos, studying stars out to 30,000 light-years (100 times farther than Hipparcos, covering nearly 1/3 of the galactic disk). *Gaia* will also be able to measure proper motions[2] for thousands of stars in the halo of the Milky Way—something that can only be done for the brightest stars right now. At the end of *Gaia's* mission, we will not only have a three-dimensional map of a large fraction of our own Milky Way Galaxy, but we will also have a strong link in the chain of cosmic distances that we are discussing in this chapter. Yet, to extend this chain beyond *Gaia's* reach and explore

2 Proper motion (as discussed in Analyzing Starlight, is the motion of a star across the sky (perpendicular to our line of sight.)

distances to nearby galaxies, we need some completely new techniques.

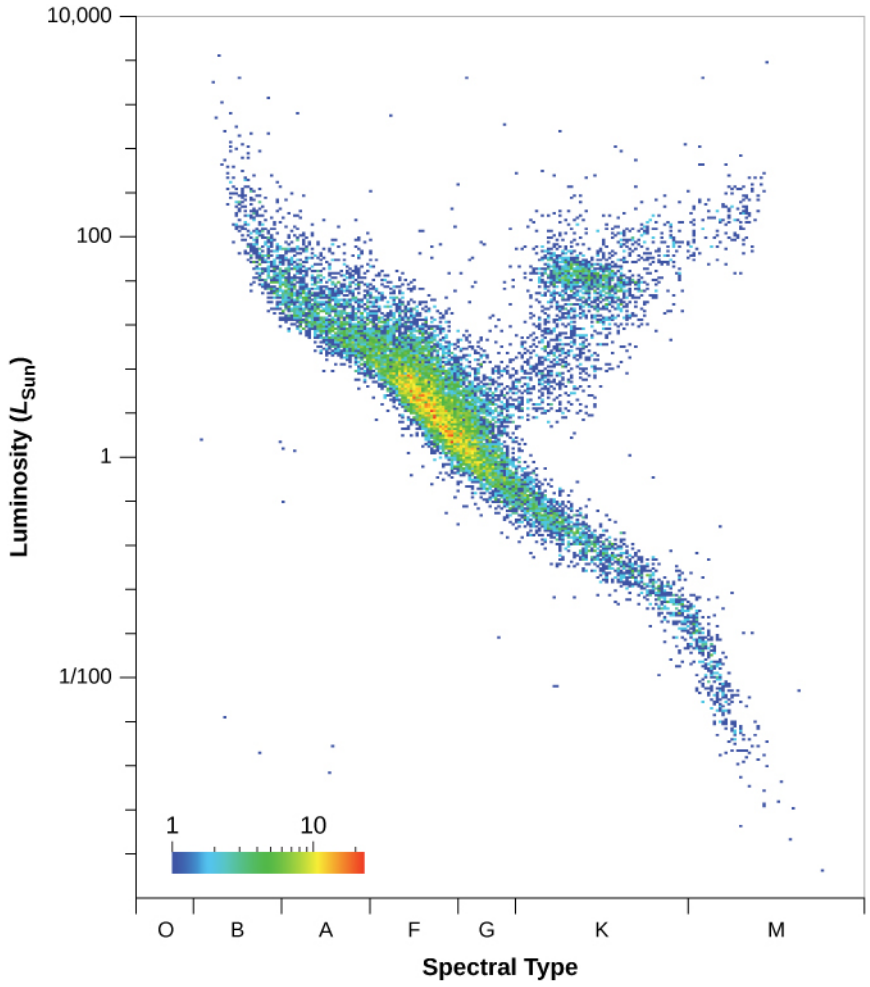


Figure 19.8 H–R Diagram of Stars Measured by Gaia and Hipparcos. This plot includes 16,631 stars for which the parallaxes have an accuracy of 10% or better. The colors indicate the numbers of stars at each point of the diagram, with red corresponding to the largest number and blue to the lowest. Luminosity is plotted along the vertical axis, with luminosity increasing upward. An infrared color is plotted as a proxy for temperature, with temperature decreasing to the right. Most of the data points are distributed along the diagonal running from the top left corner (high luminosity, high temperature) to the bottom right (low temperature, low luminosity). These are main sequence stars. The large clump of data points above the main sequence on the right side of the diagram is composed of red giant stars. (credit: modification of work by the European Space Agency)

MAKING CONNECTIONS

Parallax and Space Astronomy

One of the most difficult things about precisely measuring the tiny angles of parallax shifts from Earth is that you have to observe the stars through our planet's atmosphere. As we saw in **Astronomical Instruments**, the effect of the atmosphere is to spread out the points of starlight into fuzzy disks, making exact measurements of their positions more difficult. Astronomers had long dreamed of being able to measure parallaxes from space, and two orbiting observatories have now turned this dream into reality.

The name of the Hipparcos satellite, launched in 1989 by the European Space Agency, is both an

abbreviation for High Precision Parallax Collecting Satellite and a tribute to Hipparchus, the pioneering Greek astronomer whose work we discussed in the **Observing the Sky: The Birth of Astronomy**. The satellite was designed to make the most accurate parallax measurements in history, from 36,000 kilometers above Earth. However, its onboard rocket motor failed to fire, which meant it did not get the needed boost to reach the desired altitude. Hipparcos ended up spending its 4-year life in an elliptical orbit that varied from 500 to 36,000 kilometers high. In this orbit, the satellite plunged into Earth's radiation belts every 5 hours or so, which finally took its toll on the solar panels that provided energy to power the instruments.

Nevertheless, the mission was successful, resulting in two catalogs. One gives positions of 120,000 stars to an accuracy of one-thousandth of an arcsecond—about the diameter of a golf ball in New York as viewed from Europe. The second catalog contains information for more than a million stars, whose positions have been measured to thirty-thousandths of an arcsecond. We now have accurate parallax measurements of stars out to distances of about 300 light-years. (With ground-based telescopes, accurate measurements were feasible out to only about 60 light-years.)

In order to build on the success of Hipparcos, in 2013, the European Space Agency launched a new satellite called *Gaia*. The Gaia mission is scheduled to last for 5 years. Because *Gaia* carries larger telescopes than Hipparcos, it can observe fainter stars and measure their positions 200 times more accurately. The main goal of the Gaia mission is to make an accurate three-dimensional map of that portion of the Galaxy within about 30,000 light-years by observing 1 billion stars 70 times each, measuring their positions and hence their parallaxes as well as their brightnesses.

For a long time, the measurement of parallaxes and accurate stellar positions was a backwater of astronomical research—mainly because the accuracy of measurements did not improve much for about 100 years. However, the ability to make measurements from space has revolutionized this field of astronomy and will continue to provide a critical link in our chain of cosmic distances.

LINK TO LEARNING

The European Space Agency (ESA) maintains a **Gaia mission website (https://openstaxcollege.org/l/30GaiaMission)** where you can learn more about the Gaia mission and to get the latest news on *Gaia* observations.

To learn more about Hipparcos, explore this **European Space Agency webpage (https://openstaxcollege.org/l/30Hipparcos)** with an ESA vodcast *Charting the Galaxy—from Hipparcos to Gaia*.

19.3 VARIABLE STARS: ONE KEY TO COSMIC DISTANCES

Learning Objectives

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

- Describe how some stars vary their light output and why such stars are important

- Explain the importance of pulsating variable stars, such as cepheids and RR Lyrae-type stars, to our study of the universe

Let's briefly review the key reasons that measuring distances to the stars is such a struggle. As discussed in **The Brightness of Stars**, our problem is that stars come in a bewildering variety of intrinsic luminosities. (If stars were light bulbs, we'd say they come in a wide range of wattages.) Suppose, instead, that all stars had the same "wattage" or luminosity. In that case, the more distant ones would always look dimmer, and we could tell how far away a star is simply by how dim it appeared. In the real universe, however, when we look at a star in our sky (with eye or telescope) and measure its apparent brightness, we cannot know whether it looks dim because it's a low-wattage bulb or because it is far away, or perhaps some of each.

Astronomers need to discover something else about the star that allows us to "read off" its intrinsic luminosity—in effect, to know what the star's true wattage is. With this information, we can then attribute how dim it looks from Earth to its distance. Recall that the apparent brightness of an object decreases with the square of the distance to that object. If two objects have the same luminosity but one is three times farther than the other, the more distant one will look nine times fainter. Therefore, if we know the luminosity of a star and its apparent brightness, we can calculate how far away it is. Astronomers have long searched for techniques that would somehow allow us to determine the luminosity of a star—and it is to these techniques that we turn next.

Variable Stars

The breakthrough in measuring distances to remote parts of our Galaxy, and to other galaxies as well, came from the study of variable stars. Most stars are constant in their luminosity, at least to within a percent or two. Like the Sun, they generate a steady flow of energy from their interiors. However, some stars are seen to vary in brightness and, for this reason, are called *variable stars*. Many such stars vary on a regular cycle, like the flashing bulbs that decorate stores and homes during the winter holidays.

Let's define some tools to help us keep track of how a star varies. A graph that shows how the brightness of a variable star changes with time is called a **light curve** (**Figure 19.9**). The *maximum* is the point of the light curve where the star has its greatest brightness; the *minimum* is the point where it is faintest. If the light variations repeat themselves periodically, the interval between the two maxima is called the *period* of the star. (If this kind of graph looks familiar, it is because we introduced it in **Diameters of Stars**.)

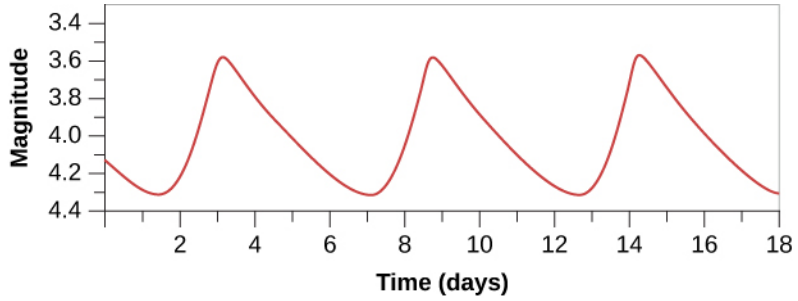


Figure 19.9 Cepheid Light Curve. This light curve shows how the brightness changes with time for a typical cepheid variable, with a period of about 6 days.

Pulsating Variables

There are two special types of variable stars for which—as we will see—measurements of the light curve give us accurate distances. These are called **cepheid** and **RR Lyrae** variables, both of which are **pulsating variable stars**. Such a star actually changes its diameter with time—periodically expanding and contracting, as your chest does when you breathe. We now understand that these stars are going through a brief unstable stage

late in their lives.

The expansion and contraction of pulsating variables can be measured by using the Doppler effect. The lines in the spectrum shift toward the blue as the surface of the star moves toward us and then shift to the red as the surface shrinks back. As the star pulsates, it also changes its overall color, indicating that its temperature is also varying. And, most important for our purposes, the luminosity of the pulsating variable also changes in a regular way as it expands and contracts.

Cepheid Variables

Cepheids are large, yellow, pulsating stars named for the first-known star of the group, Delta Cephei. This, by the way, is another example of how confusing naming conventions get in astronomy; here, a whole class of stars is named after the constellation in which the first one happened to be found. (We textbook authors can only apologize to our students for the whole mess!)

The variability of Delta Cephei was discovered in 1784 by the young English astronomer John Goodricke (see **John Goodricke**). The star rises rather rapidly to maximum light and then falls more slowly to minimum light, taking a total of 5.4 days for one cycle. The curve in **Figure 19.9** represents a simplified version of the light curve of Delta Cephei.

Several hundred cepheid variables are known in our Galaxy. Most cepheids have periods in the range of 3 to 50 days and luminosities that are about 1000 to 10,000 times greater than that of the Sun. Their variations in luminosity range from a few percent to a factor of 10.

Polaris, the North Star, is a cepheid variable that, for a long time, varied by one tenth of a magnitude, or by about 10% in visual luminosity, in a period of just under 4 days. Recent measurements indicate that the amount by which the brightness of Polaris changes is decreasing and that, sometime in the future, this star will no longer be a pulsating variable. This is just one more piece of evidence that stars really do evolve and change in fundamental ways as they age, and that being a cepheid variable represents a stage in the life of the star.

The Period-Luminosity Relation

The importance of cepheid variables lies in the fact that their periods and average luminosities turn out to be directly related. The longer the period (the longer the star takes to vary), the greater the luminosity. This **period-luminosity relation** was a remarkable discovery, one for which astronomers still (pardon the expression) thank their lucky stars. The period of such a star is easy to measure: a good telescope and a good clock are all you need. Once you have the period, the relationship (which can be put into precise mathematical terms) will give you the luminosity of the star.

Let's be clear on what that means. The relation allows you to essentially "read off" how bright the star really is (how much energy it puts out). Astronomers can then compare this intrinsic brightness with the apparent brightness of the star. As we saw, the difference between the two allows them to calculate the distance.

The relation between period and luminosity was discovered in 1908 by Henrietta Leavitt (**Figure 19.10**), a staff member at the Harvard College Observatory (and one of a number of women working for low wages assisting Edward Pickering, the observatory's director; see **Annie Cannon: Classifier of the Stars**). Leavitt discovered hundreds of variable stars in the Large Magellanic Cloud and Small Magellanic Cloud, two great star systems that are actually neighboring galaxies (although they were not known to be galaxies then). A small fraction of these variables were cepheids (**Figure 19.11**).

Figure 19.10 Henrietta Swan Leavitt (1868–1921). Leavitt worked as an astronomer at the Harvard College Observatory. While studying photographs of the Magellanic Clouds, she found over 1700 variable stars, including 20 cepheids. Since all the cepheids in these systems were at roughly the same distance, she was able to compare their luminosities and periods of variation. She thus discovered a fundamental relationship between these characteristics that led to a new and much better way of estimating cosmic distances. (credit: modification of work by AIP)

These systems presented a wonderful opportunity to study the behavior of variable stars independent of their distance. For all practical purposes, the Magellanic Clouds are so far away that astronomers can assume that all the stars in them are at roughly the same distance from us. (In the same way, all the suburbs of Los Angeles are roughly the same distance from New York City. Of course, if you are *in* Los Angeles, you will notice annoying distances between the suburbs, but compared to how far away New York City is, the differences seem small.) If all the variable stars in the Magellanic Clouds are at roughly the same distance, then any difference in their apparent brightnesses must be caused by differences in their intrinsic luminosities.

Figure 19.11 Large Magellanic Cloud. The Large Magellanic Cloud (so named because Magellan's crew were the first Europeans to record it) is a small, irregularly shaped galaxy near our own Milky Way. It was in this galaxy that Henrietta Leavitt discovered the cepheid period-luminosity relation. (credit: ESO)

Leavitt found that the brighter-appearing cepheids always have the longer periods of light variation. Thus, she reasoned, the period must be related to the luminosity of the stars. When Leavitt did this work, the distance to the Magellanic Clouds was not known, so she was only able to show that luminosity was related to period. She could not determine exactly what the relationship is.

To define the period-luminosity relation with actual numbers (to *calibrate* it), astronomers first had to measure the actual distances to a few nearby cepheids in another way. (This was accomplished by finding cepheids associated in clusters with other stars whose distances could be estimated from their spectra, as discussed in the next section of this chapter.) But once the relation was thus defined, it could give us the distance to any cepheid, wherever it might be located (**Figure 19.12**).

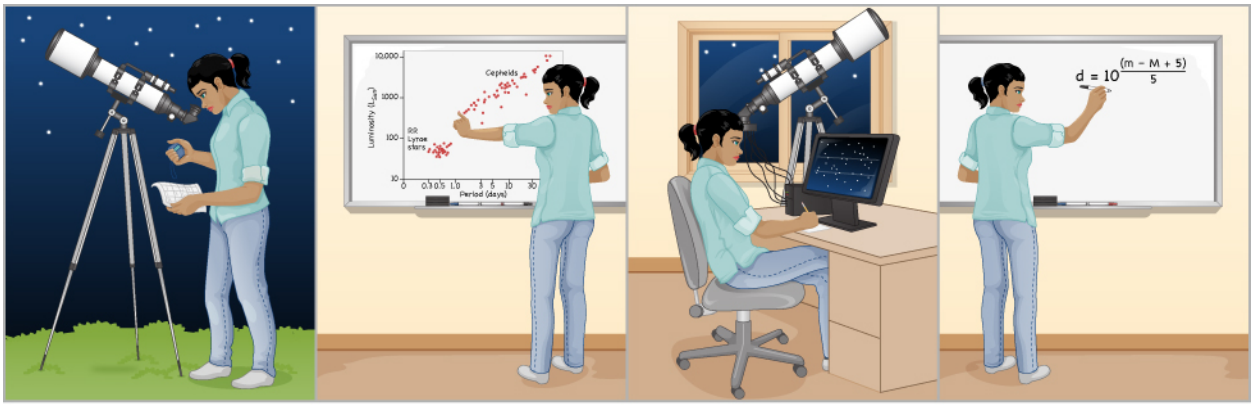


Figure 19.12 How to Use a Cepheid to Measure Distance. (a) Find a cepheid variable star and measure its period. (b) Use the period-luminosity relation to calculate the star's luminosity. (c) Measure the star's apparent brightness. (d) Compare the luminosity with the apparent brightness to calculate the distance.

Here at last was the technique astronomers had been searching for to break the confines of distance that parallax imposed on them. Cepheids can be observed and monitored, it turns out, in many parts of our own Galaxy and in other nearby galaxies as well. Astronomers, including Ejnar Hertzsprung and Harvard's Harlow Shapley, immediately saw the potential of the new technique; they and many others set to work exploring more distant reaches of space using cepheids as signposts. In the 1920s, Edwin Hubble made one of the most significant astronomical discoveries of all time using cepheids, when he observed them in nearby galaxies and discovered the expansion of the universe. As we will see, this work still continues, as the Hubble Space Telescope and other modern instruments try to identify and measure individual cepheids in galaxies farther and farther away. The most distant known variable stars are all cepheids, with some about 60 million light-years away.

VOYAGERS IN ASTRONOMY

John Goodricke

The brief life of John Goodricke (Figure 19.13) is a testament to the human spirit under adversity. Born deaf and unable to speak, Goodricke nevertheless made a number of pioneering discoveries in astronomy through patient and careful observations of the heavens.

Figure 19.13 John Goodricke (1764–1786). This portrait of Goodricke by artist J. Scouler hangs in the Royal Astronomical Society in London. There is some controversy about whether this is actually what Goodricke looked like or whether the painting was much retouched to please his family. (credit: James Scouler)

Born in Holland, where his father was on a diplomatic mission, Goodricke was sent back to England at age eight to study at a special school for the deaf. He did sufficiently well to enter Warrington Academy, a secondary school that offered no special assistance for students with handicaps. His mathematics teacher there inspired an interest in astronomy, and in 1781, at age 17, Goodricke began observing the sky at his family home in York, England. Within a year, he had discovered the brightness variations of the star Algol (discussed in **The Stars: A Celestial Census**) and suggested that an unseen companion star was causing the changes, a theory that waited over 100 years for proof. His paper on the subject was read before the Royal Society (the main British group of scientists) in 1783 and won him a medal from that distinguished group.

In the meantime, Goodricke had discovered two other stars that varied regularly, Beta Lyrae and Delta Cephei, both of which continued to interest astronomers for years to come. Goodricke shared his interest in observing with his older cousin, Edward Pigott, who went on to discover other variable stars during his much longer life. But Goodricke's time was quickly drawing to a close; at age 21, only 2 weeks after he was elected to the Royal Society, he caught a cold while making astronomical observations and never recovered.

Today, the University of York has a building named Goodricke Hall and a plaque that honors his contributions to science. Yet if you go to the churchyard cemetery where he is buried, an overgrown tombstone has only the initials "J. G." to show where he lies. Astronomer Zdenek Kopal, who looked carefully into Goodricke's life, speculated on why the marker is so modest: perhaps the rather staid Goodricke relatives were ashamed of having a "deaf-mute" in the family and could not sufficiently appreciate how much a man who could not hear could nevertheless see.

RR Lyrae Stars

A related group of stars, whose nature was understood somewhat later than that of the cepheids, are called RR Lyrae variables, named for the star RR Lyrae, the best-known member of the group. More common than the cepheids, but less luminous, thousands of these pulsating variables are known in our Galaxy. The periods of RR Lyrae stars are always less than 1 day, and their changes in brightness are typically less than about a factor of two.

Astronomers have observed that the RR Lyrae stars occurring in any particular cluster all have about the same apparent brightness. Since stars in a cluster are all at approximately the same distance, it follows that RR Lyrae variables must all have nearly the same intrinsic luminosity, which turns out to be about 50 L_{Sun}. In this sense, RR Lyrae stars are a little bit like standard light bulbs and can also be used to obtain distances, particularly within our Galaxy. Figure 19.14 displays the ranges of periods and luminosities for both the cepheids and the RR Lyrae stars.

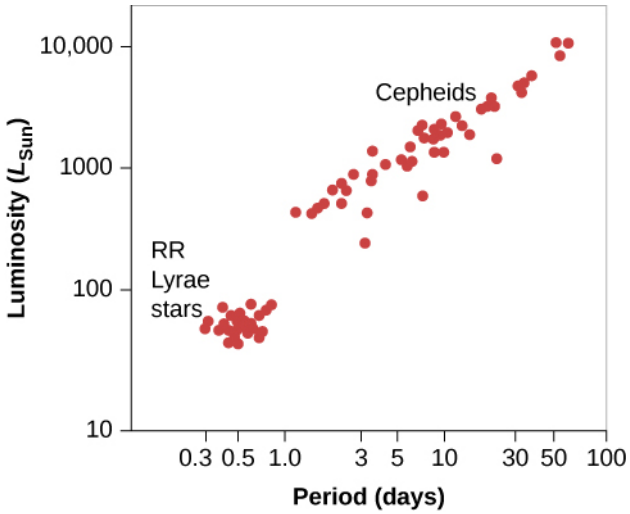


Figure 19.14 Period-Luminosity Relation for Cepheid Variables. In this class of variable stars, the time the star takes to go through a cycle of luminosity changes is related to the average luminosity of the star. Also shown are the period and luminosity for RR Lyrae stars.

19.4 THE H–R DIAGRAM AND COSMIC DISTANCES

Learning Objectives

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

- Understand how spectral types are used to estimate stellar luminosities
- Examine how these techniques are used by astronomers today

Variable stars are not the only way that we can estimate the luminosity of stars. Another way involves the H–R diagram, which shows that the intrinsic brightness of a star can be estimated if we know its spectral type.

Distances from Spectral Types

As satisfying and productive as variable stars have been for distance measurement, these stars are rare and are not found near all the objects to which we wish to measure distances. Suppose, for example, we need the distance to a star that is not varying, or to a group of stars, none of which is a variable. In this case, it turns out the H–R diagram can come to our rescue.

If we can observe the spectrum of a star, we can estimate its distance from our understanding of the H–R diagram. As discussed in Analyzing Starlight, a detailed examination of a stellar spectrum allows astronomers to classify the star into one of the *spectral types* indicating surface temperature. (The types are O, B, A, F, G, K, M, L, T, and Y; each of these can be divided into numbered subgroups.) In general, however, the spectral type alone is not enough to allow us to estimate luminosity. Look again at Figure 18.15. A G2 star could be a main-sequence star with a luminosity of 1 L_{Sun}, or it could be a giant with a luminosity of 100 L_{Sun}, or even a supergiant with a still higher luminosity.

We can learn more from a star's spectrum, however, than just its temperature. Remember, for example, that we can detect pressure differences in stars from the details of the spectrum. This knowledge is very useful because giant stars are larger (and have lower pressures) than main-sequence stars, and supergiants are still larger than giants. If we look in detail at the spectrum of a star, we can determine whether it is a main-sequence star, a giant, or a supergiant.

Suppose, to start with the simplest example, that the spectrum, color, and other properties of a distant G2 star match those of the Sun exactly. It is then reasonable to conclude that this distant star is likely to be a main-sequence star just like the Sun and to have the same luminosity as the Sun. But if there are subtle differences between the solar spectrum and the spectrum of the distant star, then the distant star may be a giant or even a supergiant.

The most widely used system of star classification divides stars of a given spectral class into six categories called **luminosity classes**. These luminosity classes are denoted by Roman numbers as follows:

- Ia: Brightest supergiants
- Ib: Less luminous supergiants
- II: Bright giants
- III: Giants
- IV: Subgiants (intermediate between giants and main-sequence stars)
- V: Main-sequence stars

The full spectral specification of a star includes its luminosity class. For example, a main-sequence star with spectral class F3 is written as F3 V. The specification for an M2 giant is M2 III. Figure 19.15 illustrates the approximate position of stars of various luminosity classes on the H–R diagram. The dashed portions of the lines represent regions with very few or no stars.

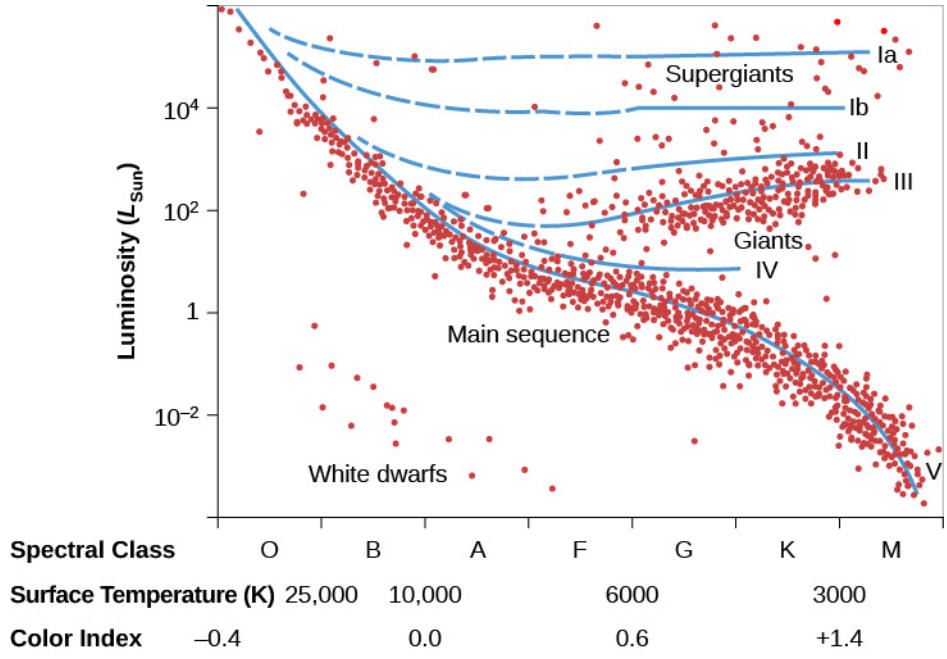


Figure 19.15 Luminosity Classes. Stars of the same temperature (or spectral class) can fall into different luminosity classes on the Hertzsprung-Russell diagram. By studying details of the spectrum for each star, astronomers can determine which luminosity class they fall in (whether they are main-sequence stars, giant stars, or supergiant stars).

With both its spectral and luminosity classes known, a star's position on the H–R diagram is uniquely

determined. Since the diagram plots luminosity versus temperature, this means we can now read off the star's luminosity (once its spectrum has helped us place it on the diagram). As before, if we know how luminous the star really is and see how dim it looks, the difference allows us to calculate its distance. (For historical reasons, astronomers sometimes call this method of distance determination *spectroscopic parallax*, even though the method has nothing to do with parallax.)

The H–R diagram method allows astronomers to estimate distances to nearby stars, as well as some of the most distant stars in our Galaxy, but it is anchored by measurements of parallax. The distances measured using parallax are the gold standard for distances: they rely on no assumptions, only geometry. Once astronomers take a spectrum of a nearby star for which we also know the parallax, we know the luminosity that corresponds to that spectral type. Nearby stars thus serve as benchmarks for more distant stars because we can assume that two stars with identical spectra have the same intrinsic luminosity.

A Few Words about the Real World

Introductory textbooks such as ours work hard to present the material in a straightforward and simplified way. In doing so, we sometimes do our students a disservice by making scientific techniques seem too clean and painless. In the real world, the techniques we have just described turn out to be messy and difficult, and often give astronomers headaches that last long into the day.

For example, the relationships we have described such as the period-luminosity relation for certain variable stars aren't exactly straight lines on a graph. The points representing many stars scatter widely when plotted, and thus, the distances derived from them also have a certain built-in scatter or uncertainty.

The distances we measure with the methods we have discussed are therefore only accurate to within a certain percentage of error—sometimes 10%, sometimes 25%, sometimes as much as 50% or more. A 25% error for a star estimated to be 10,000 light-years away means it could be anywhere from 7500 to 12,500 light-years away. This would be an unacceptable uncertainty if you were loading fuel into a spaceship for a trip to the star, but it is not a bad first figure to work with if you are an astronomer stuck on planet Earth.

Nor is the construction of H–R diagrams as easy as you might think at first. To make a good diagram, one needs to measure the characteristics and distances of many stars, which can be a time-consuming task. Since our own solar neighborhood is already well mapped, the stars astronomers most want to study to advance our knowledge are likely to be far away and faint. It may take hours of observing to obtain a single spectrum. Observers may have to spend many nights at the telescope (and many days back home working with their data) before they get their distance measurement. Fortunately, this is changing because surveys like Gaia will study billions of stars, producing public datasets that all astronomers can use.

Despite these difficulties, the tools we have been discussing allow us to measure a remarkable range of distances—parallaxes for the nearest stars, RR Lyrae variable stars; the H–R diagram for clusters of stars in our own and nearby galaxies; and cepheids out to distances of 60 million light-years. **Table 19.1** describes the distance limits and overlap of each method.

Each technique described in this chapter builds on at least one other method, forming what many call the *cosmic distance ladder*. Parallaxes are the foundation of all stellar distance estimates, spectroscopic methods use nearby stars to calibrate their H–R diagrams, and RR Lyrae and cepheid distance estimates are grounded in H–R diagram distance estimates (and even in a parallax measurement to a nearby cepheid, Delta Cephei).

This chain of methods allows astronomers to push the limits when looking for even more distant stars. Recent work, for example, has used RR Lyrae stars to identify dim companion galaxies to our own Milky Way out at distances of 300,000 light-years. The H–R diagram method was recently used to identify the two most distant

stars in the Galaxy: red giant stars way out in the halo of the Milky Way with distances of almost 1 million light-years.

We can combine the distances we find for stars with measurements of their composition, luminosity, and temperature—made with the techniques described in **Analyzing Starlight** and **The Stars: A Celestial Census**. Together, these make up the arsenal of information we need to trace the evolution of stars from birth to death, the subject to which we turn in the chapters that follow.

Distance Range of Celestial Measurement Methods

Method	Distance Range
Trigonometric parallax	4–30,000 light-years when the Gaia mission is complete
RR Lyrae stars	Out to 300,000 light-years
H–R diagram and spectroscopic distances	Out to 1,200,000 light-years
Cepheid stars	Out to 60,000,000 light-years

Table 19.1

CHAPTER 19 REVIEW

KEY TERMS

cepheid a star that belongs to a class of yellow supergiant pulsating stars; these stars vary periodically in brightness, and the relationship between their periods and luminosities is useful in deriving distances to them

light curve a graph that displays the time variation of the light from a variable or eclipsing binary star or, more generally, from any other object whose radiation output changes with time

luminosity class a classification of a star according to its luminosity within a given spectral class; our Sun, a G2V star, has luminosity class V, for example

parallax an apparent displacement of a nearby star that results from the motion of Earth around the Sun

parsec a unit of distance in astronomy, equal to 3.26 light-years; at a distance of 1 parsec, a star has a parallax of 1 arcsecond

period-luminosity relation an empirical relation between the periods and luminosities of certain variable stars

pulsating variable star a variable star that pulsates in size and luminosity

RR Lyrae one of a class of giant pulsating stars with periods shorter than 1 day, useful for finding distances

SUMMARY

19.1 Fundamental Units of Distance

Early measurements of length were based on human dimensions, but today, we use worldwide standards that specify lengths in units such as the meter. Distances within the solar system are now determined by timing how long it takes radar signals to travel from Earth to the surface of a planet or other body and then return.

19.2 Surveying the Stars

For stars that are relatively nearby, we can "triangulate" the distances from a baseline created by Earth's annual motion around the Sun. Half the shift in a nearby star's position relative to very distant background stars, as viewed from opposite sides of Earth's orbit, is called the parallax of that star and is a measure of its distance. The units used to measure stellar distance are the light-year, the distance light travels in 1 year, and the parsec (pc), the distance of a star with a parallax of 1 arcsecond (1 parsec = 3.26 light-years). The closest star, a red dwarf, is over 1 parsec away. The first successful measurements of stellar parallaxes were reported in 1838. Parallax measurements are a fundamental link in the chain of cosmic distances. The Hipparcos satellite has allowed us to measure accurate parallaxes for stars out to about 300 light-years, and the Gaia mission will result in parallaxes out to 30,000 light-years.

19.3 Variable Stars: One Key to Cosmic Distances

Cepheids and RR Lyrae stars are two types of pulsating variable stars. Light curves of these stars show that their luminosities vary with a regularly repeating period. RR Lyrae stars can be used as standard bulbs, and cepheid variables obey a period-luminosity relation, so measuring their periods can tell us their luminosities. Then, we can calculate their distances by comparing their luminosities with their apparent brightnesses, and this can allow us to measure distances to these stars out to over 60 million light-years.

19.4 The H–R Diagram and Cosmic Distances

Stars with identical temperatures but different pressures (and diameters) have somewhat different spectra. Spectral classification can therefore be used to estimate the luminosity class of a star as well as its temperature. As a result, a spectrum can allow us to pinpoint where the star is located on an H–R diagram and establish its luminosity. This, with the star's apparent brightness, again yields its distance. The various distance methods can be used to check one against another and thus make a kind of distance ladder which allows us to find even larger distances.

FOR FURTHER EXPLORATION

Articles

Adams, A. "The Triumph of Hipparcos." *Astronomy* (December 1997): 60. Brief introduction.

Dambeck, T. "Gaia's Mission to the Milky Way." *Sky & Telescope* (March 2008): 36–39. An introduction to the mission to measure distances and positions of stars with unprecedented accuracy.

Hirshfeld, A. "The Absolute Magnitude of Stars." *Sky & Telescope* (September 1994): 35. Good review of how we measure luminosity, with charts.

Hirshfeld, A. "The Race to Measure the Cosmos." *Sky & Telescope* (November 2001): 38. On parallax.

Trefil, J. Puzzling Out Parallax." *Astronomy* (September 1998): 46. On the concept and history of parallax.

Turon, C. "Measuring the Universe." *Sky & Telescope* (July 1997): 28. On the Hipparcos mission and its results.

Zimmerman, R. "Polaris: The Code-Blue Star." *Astronomy* (March 1995): 45. On the famous cepheid variable and how it is changing.

Websites

ABCs of Distance: **http://www.astro.ucla.edu/~wright/distance.htm (http://www.astro.ucla.edu/~wright/distance.htm)** . Astronomer Ned Wright (UCLA) gives a concise primer on many different methods of obtaining distances. This site is at a higher level than our textbook, but is an excellent review for those with some background in astronomy.

American Association of Variable Star Observers (AAVSO): **https://www.aavso.org/ (https://www.aavso.org/)** . This organization of amateur astronomers helps to keep track of variable stars; its site has some background material, observing instructions, and links.

Friedrich Wilhelm Bessel: **http://messier.seds.org/xtra/Bios/bessel.html (http://messier.seds.org/xtra/Bios/bessel.html)** . A brief site about the first person to detect stellar parallax, with references and links.

Gaia: **http://sci.esa.int/gaia/ (http://sci.esa.int/gaia/)** . News from the Gaia mission, including images and a blog of the latest findings.

Hipparchos: **http://sci.esa.int/hipparcos/ (http://sci.esa.int/hipparcos/)** . Background, results, catalogs of data, and educational resources from the Hipparchos mission to observe parallaxes from space. Some sections are technical, but others are accessible to students.

John Goodricke: The Deaf Astronomer: **http://www.bbc.com/news/magazine-20725639 (http://www.bbc.com/news/magazine-20725639)** . A biographical article from the BBC.

Women in Astronomy: **http://www.astrosociety.org/education/astronomy-resource-guides/women-in-astronomy-an-introductory-resource-guide/ (http://www.astrosociety.org/education/astronomy-**

resource-guides/women-in-astronomy-an-introductory-resource-guide/) . More about Henrietta Leavitt's and other women's contributions to astronomy and the obstacles they faced.

Videos

Gaia's Mission: Solving the Celestial Puzzle: https://www.youtube.com/watch?v=oGri4YNggoc (https://www.youtube.com/watch?v=oGri4YNggoc) . Describes the Gaia mission and what scientists hope to learn, from Cambridge University (19:58).

Hipparcos: Route Map to the Stars: http://www.esa.int/spaceinvideos/Videos/1997/05/Hipparcos_Route_Maps_to_the_Stars_May_97 (http://www.esa.int/spaceinvideos/Videos/1997/05/Hipparcos_Route_Maps_to_the_Stars_May_97) . This ESA video describes the mission to measure parallax and its results (14:32)

How Big Is the Universe: https://www.youtube.com/watch?v=K_xZuopg4Sk (https://www.youtube.com/watch?v=K_xZuopg4Sk) . Astronomer Pete Edwards from the British Institute of Physics discusses the size of the universe and gives a step-by-step introduction to the concepts of distances (6:22)

Search for Miss Leavitt: http://perimeterinstitute.ca/videos/search-miss-leavitt (http://perimeterinstitute.ca/videos/search-miss-leavitt) . Video of talk by George Johnson on his search for Miss Leavitt (55:09).

Women in Astronomy: http://www.youtube.com/watch?v=5vMR7su4fi8 (http://www.youtube.com/watch?v=5vMR7su4fi8) . Emily Rice (CUNY) gives a talk on the contributions of women to astronomy, with many historical and contemporary examples, and an analysis of modern trends (52:54).

COLLABORATIVE GROUP ACTIVITIES

A. In this chapter, we explain the various measurements that have been used to establish the size of a standard meter. Your group should discuss why we have changed the definitions of our standard unit of measurement in science from time to time. What factors in our modern society contribute to the growth of technology? Does technology "drive" science, or does science "drive" technology? Or do you think the two are so intertwined that it's impossible to say which is the driver?

B. Cepheids are scattered throughout our own Milky Way Galaxy, but the period-luminosity relation was discovered from observations of the Magellanic Clouds, a satellite galaxy now known to be about 160,000 light-years away. What reasons can you give to explain why the relation was not discovered from observations of cepheids in our own Galaxy? Would your answer change if there were a small cluster in our own Galaxy that contained 20 cepheids? Why or why not?

C. You want to write a proposal to use the Hubble Space Telescope to look for the brightest cepheids in galaxy M100 and estimate their luminosities. What observations would you need to make? Make a list of all the reasons such observations are harder than it first might appear.

D. Why does your group think so many different ways of naming stars developed through history? (Think back to the days before everyone connected online.) Are there other fields where things are named confusingly and arbitrarily? How do stars differ from other phenomena that science and other professions tend to catalog?

E. Although cepheids and RR Lyrae variable stars tend to change their brightness pretty regularly (while they are in that stage of their lives), some variable stars are unpredictable or change their their behavior even during the course of a single human lifetime. Amateur astronomers all over the world follow such variable stars patiently and persistently, sending their nightly observations to huge databases that are being kept on the behavior of many thousands of stars. None of the hobbyists who do this get paid for making such painstaking observations. Have your group discuss why they do it. Would you ever consider a hobby that involves so much work, long into the night, often on work nights? If observing variable stars doesn't pique your interest, is there something you think you could do as a volunteer after college that does excite you? Why?

F. In **Figure 19.8**, the highest concentration of stars occurs in the middle of the main sequence. Can your group give reasons why this might be so? Why are there fewer very hot stars and fewer very cool stars on this diagram?

G. In this chapter, we discuss two astronomers who were differently abled than their colleagues. John Goodricke could neither hear nor speak, and Henrietta Leavitt struggled with hearing impairment for all of her adult life. Yet they each made fundamental contributions to our understanding of the universe. Does your group know people who are handling a disability? What obstacles would people with different disabilities face in trying to do astronomy and what could be done to ease their way? For a set of resources in this area, see http://astronomerswithoutborders.org/gam2013/programs/1319-people-with-disabilities-astronomy-resources.html.

EXERCISES

Review Questions

1. Explain how parallax measurements can be used to determine distances to stars. Why can we not make accurate measurements of parallax beyond a certain distance?

2. Suppose you have discovered a new cepheid variable star. What steps would you take to determine its distance?

3. Explain how you would use the spectrum of a star to estimate its distance.

4. Which method would you use to obtain the distance to each of the following?

A. An asteroid crossing Earth's orbit

B. A star astronomers believe to be no more than 50 light-years from the Sun

C. A tight group of stars in the Milky Way Galaxy that includes a significant number of variable stars

D. A star that is not variable but for which you can obtain a clearly defined spectrum

5. What are the luminosity class and spectral type of a star with an effective temperature of 5000 K and a luminosity of 100 L_{Sun}?

Thought Questions

6. The meter was redefined as a reference to Earth, then to krypton, and finally to the speed of light. Why do you think the reference point for a meter continued to change?

7. While a meter is the fundamental unit of length, most distances traveled by humans are measured in miles or kilometers. Why do you think this is?

8. Most distances in the Galaxy are measured in light-years instead of meters. Why do you think this is the case?

9. The AU is defined as the *average* distance between Earth and the Sun, not the distance between Earth and the Sun. Why does this need to be the case?

10. What would be the advantage of making parallax measurements from Pluto rather than from Earth? Would there be a disadvantage?

11. Parallaxes are measured in fractions of an arcsecond. One arcsecond equals 1/60 arcmin; an arcminute is, in turn, 1/60th of a degree (°). To get some idea of how big 1° is, go outside at night and find the Big Dipper. The two pointer stars at the ends of the bowl are 5.5° apart. The two stars across the top of the bowl are 10° apart. (Ten degrees is also about the width of your fist when held at arm's length and projected against the sky.) Mizar, the second star from the end of the Big Dipper's handle, appears double. The fainter star, Alcor, is about 12 arcmin from Mizar. For comparison, the diameter of the full moon is about 30 arcmin. The belt of Orion is about 3° long. Keeping all this in mind, why did it take until 1838 to make parallax measurements for even the nearest stars?

12. For centuries, astronomers wondered whether comets were true celestial objects, like the planets and stars, or a phenomenon that occurred in the atmosphere of Earth. Describe an experiment to determine which of these two possibilities is correct.

13. The Sun is much closer to Earth than are the nearest stars, yet it is not possible to measure accurately the diurnal parallax of the Sun relative to the stars by measuring its position relative to background objects in the sky directly. Explain why.

14. Parallaxes of stars are sometimes measured relative to the positions of galaxies or distant objects called quasars. Why is this a good technique?

15. Estimating the luminosity class of an M star is much more important than measuring it for an O star if you are determining the distance to that star. Why is that the case?

16. **Figure 19.9** is the light curve for the prototype cepheid variable Delta Cephei. How does the luminosity of this star compare with that of the Sun?

17. Which of the following can you determine about a star without knowing its distance, and which can you not determine: radial velocity, temperature, apparent brightness, or luminosity? Explain.

18. A G2 star has a luminosity 100 times that of the Sun. What kind of star is it? How does its radius compare with that of the Sun?

19. A star has a temperature of 10,000 K and a luminosity of $10^{-2}\ L_{Sun}$. What kind of star is it?

20. What is the advantage of measuring a parallax distance to a star as compared to our other distance measuring methods?

21. What is the disadvantage of the parallax method, especially for studying distant parts of the Galaxy?

22. Luhman 16 and WISE 0720 are brown dwarfs, also known as failed stars, and are some of the new closest neighbors to Earth, but were only discovered in the last decade. Why do you think they took so long to be discovered?

23. Most stars close to the Sun are red dwarfs. What does this tell us about the average star formation event in our Galaxy?

24. Why would it be easier to measure the characteristics of intrinsically less luminous cepheids than more luminous ones?

25. When Henrietta Leavitt discovered the period-luminosity relationship, she used cepheid stars that were all located in the Small Magellanic Cloud. Why did she need to use stars in another galaxy and not cepheids located in the Milky Way?

Figuring For Yourself

26. A radar astronomer who is new at the job claims she beamed radio waves to Jupiter and received an echo exactly 48 min later. Should you believe her? Why or why not?

27. The New Horizons probe flew past Pluto in July 2015. At the time, Pluto was about 32 AU from Earth. How long did it take for communication from the probe to reach Earth, given that the speed of light in km/hr is 1.08×10^9?

28. Estimate the maximum and minimum time it takes a radar signal to make the round trip between Earth and Venus, which has a semimajor axis of 0.72 AU.

29. The Apollo program (not the lunar missions with astronauts) being conducted at the Apache Point Observatory uses a 3.5-m telescope to direct lasers at retro-reflectors left on the Moon by the Apollo astronauts. If the Moon is 384,472 km away, approximately how long do the operators need to wait to see the laser light return to Earth?

30. In 1974, the Arecibo Radio telescope in Puerto Rico was used to transmit a signal to M13, a star cluster about 25,000 light-years away. How long will it take the message to reach M13, and how far has the message travelled so far (in light-years)?

31. Demonstrate that 1 pc equals 3.09×10^{13} km and that it also equals 3.26 light-years. Show your calculations.

32. The best parallaxes obtained with Hipparcos have an accuracy of 0.001 arcsec. If you want to measure the distance to a star with an accuracy of 10%, its parallax must be 10 times larger than the typical error. How far away can you obtain a distance that is accurate to 10% with Hipparcos data? The disk of our Galaxy is 100,000 light-years in diameter. What fraction of the diameter of the Galaxy's disk is the distance for which we can measure accurate parallaxes?

33. Astronomers are always making comparisons between measurements in astronomy and something that might be more familiar. For example, the Hipparcos web pages tell us that the measurement accuracy of 0.001 arcsec is equivalent to the angle made by a golf ball viewed from across the Atlantic Ocean, or to the angle made by the height of a person on the Moon as viewed from Earth, or to the length of growth of a human hair in 10 sec as seen from 10 meters away. Use the ideas in **Example 19.2** to verify one of the first two comparisons.

34. *Gaia* will have greatly improved precision over the measurements of Hipparcos. The average uncertainty for most *Gaia* parallaxes will be about 50 microarcsec, or 0.00005 arcsec. How many times better than Hipparcos (see **Exercise 19.32**) is this precision?

35. Using the same techniques as used in **Exercise 19.32**, how far away can *Gaia* be used to measure distances with an uncertainty of 10%? What fraction of the Galactic disk does this correspond to?

36. The human eye is capable of an angular resolution of about one arcminute, and the average distance between eyes is approximately 2 in. If you blinked and saw something move about one arcmin across, how far away from you is it? (Hint: You can use the setup in **Example 19.2** as a guide.)

37. How much better is the resolution of the *Gaia* spacecraft compared to the human eye (which can resolve about 1 arcmin)?

38. The most recently discovered system close to Earth is a pair of brown dwarfs known as Luhman 16. It has a distance of 6.5 light-years. How many parsecs is this?

39. What would the parallax of Luhman 16 (see **Exercise 19.38**) be as measured from Earth?

40. The New Horizons probe that passed by Pluto during July 2015 is one of the fastest spacecraft ever assembled. It was moving at about 14 km/s when it went by Pluto. If it maintained this speed, how long would it take New Horizons to reach the nearest star, Proxima Centauri, which is about 4.3 light-years away? (Note: It isn't headed in that direction, but you can pretend that it is.)

41. What physical properties are different for an M giant with a luminosity of 1000 L_{Sun} and an M dwarf with a luminosity of 0.5 L_{Sun}? What physical properties are the same?

20

BETWEEN THE STARS: GAS AND DUST IN SPACE

Figure 20.1 NGC 3603 and Its Parent Cloud. This image, taken by the Hubble Space Telescope, shows the young star cluster NGC 3603 interacting with the cloud of gas from which it recently formed. The bright blue stars of the cluster have blown a bubble in the gas cloud. The remains of this cloud can be seen in the lower right part of the frame, glowing in response to the starlight illuminating it. In its darker parts, shielded from the harsh light of NGC 3603, new stars continue to form. Although the stars of NGC 3603 formed only recently, the most massive of them are already dying and ejecting their mass, producing the blue ring and streak features visible in the upper left part of the image. Thus, this image shows the full life cycle of stars, from formation out of interstellar gas, through life on the main sequence, to death and the return of stellar matter to interstellar space. (credit: modification of work by NASA, Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois Urbana-Champaign))

Chapter Outline

20.1 The Interstellar Medium
20.2 Interstellar Gas
20.3 Cosmic Dust
20.4 Cosmic Rays
20.5 The Life Cycle of Cosmic Material
20.6 Interstellar Matter around the Sun

Thinking Ahead

Where do stars come from? We already know from earlier chapters that stars must die because ultimately they exhaust their nuclear fuel. We might hypothesize that new stars come into existence to replace the ones that die. In order to form new stars, however, we need the raw material to make them. It also turns out that stars eject mass throughout their lives (a kind of wind blows from their surface layers) and that material must go somewhere. What does this "raw material" of stars look like? How would you detect it, especially if it is not yet in the form of stars and cannot generate its own energy?

One of the most exciting discoveries of twentieth-century astronomy was that our Galaxy contains vast quantities of this "raw material"—atoms or molecules of gas and tiny solid dust particles found between the stars. Studying this diffuse matter between the stars helps us understand how new stars form and gives us important clues about our own origins billions of years ago.

20.1 THE INTERSTELLAR MEDIUM

Learning Objectives

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

- Explain how much interstellar matter there is in the Milky Way, and what its typical density is
- Describe how the interstellar medium is divided into gaseous and solid components

Astronomers refer to all the material between stars as *interstellar* matter; the entire collection of interstellar matter is called the **interstellar medium (ISM)**. Some interstellar material is concentrated into giant clouds, each of which is known as a **nebula** (plural "nebulae," Latin for "clouds"). The best-known nebulae are the ones that we can see glowing or reflecting visible light; there are many pictures of these in this chapter.

Interstellar clouds do not last for the lifetime of the universe. Instead, they are like clouds on Earth, constantly shifting, merging with each other, growing, or dispersing. Some become dense and massive enough to collapse under their own gravity, forming new stars. When stars die, they, in turn, eject some of their material into interstellar space. This material can then form new clouds and begin the cycle over again.

About 99% of the material between the stars is in the form of a *gas*—that is, it consists of individual atoms or molecules. The most abundant elements in this gas are hydrogen and helium (which we saw are also the most abundant elements in the stars), but the gas also includes other elements. Some of the gas is in the form of molecules—combinations of atoms. The remaining 1% of the interstellar material is solid—frozen particles consisting of many atoms and molecules that are called *interstellar grains* or **interstellar dust** (Figure 20.2). A typical dust grain consists of a core of rocklike material (silicates) or graphite surrounded by a mantle of ices; water, methane, and ammonia are probably the most abundant ices.

Figure 20.2 Various Types of Interstellar Matter. The reddish nebulae in this spectacular photograph glow with light emitted by hydrogen atoms. The darkest areas are clouds of dust that block the light from stars behind them. The upper part of the picture is filled with the bluish glow of light reflected from hot stars embedded in the outskirts of a huge, cool cloud of dust and gas. The cool supergiant star Antares can be seen as a big, reddish patch in the lower-left part of the picture. The star is shedding some of its outer atmosphere and is surrounded by a cloud of its own making that reflects the red light of the star. The red nebula in the middle right partially surrounds the star Sigma Scorpii. (To the right of Antares, you can see M4, a much more distant cluster of extremely old stars.) (credit: modification of work by ESO/Digitized Sky Survey 2)

If all the interstellar gas within the Galaxy were spread out smoothly, there would be only about one atom of gas per cm^3 in interstellar space. (In contrast, the air in the room where you are reading this book has roughly 10^{19} atoms per cm^3.) The dust grains are even scarcer. A km^3 of space would contain only a few hundred to a few thousand tiny grains, each typically less than one ten-thousandth of a millimeter in diameter. These numbers are just averages, however, because the gas and dust are distributed in a patchy and irregular way, much as water vapor in Earth's atmosphere is often concentrated into clouds.

In some interstellar clouds, the density of gas and dust may exceed the average by as much as a thousand times or more, but even this density is more nearly a vacuum than any we can make on Earth. To show what we mean, let's imagine a vertical tube of air reaching from the ground to the top of Earth's atmosphere with a cross-section of 1 square meter. Now let us extend the same-size tube from the top of the atmosphere all the way to the edge of the observable universe—over 10 billion light-years away. Long though it is, the second tube would still contain fewer atoms than the one in our planet's atmosphere.

While the *density* of interstellar matter is very low, the volume of space in which such matter is found is huge, and so its *total mass* is substantial. To see why, we must bear in mind that stars occupy only a tiny fraction of the volume of the Milky Way Galaxy. For example, it takes light only about four seconds to travel a distance equal to the diameter of the Sun, but more than four *years* to travel from the Sun to the nearest star. Even though the spaces among the stars are sparsely populated, there's a lot of space out there!

Astronomers estimate that the total mass of gas and dust in the Milky Way Galaxy is equal to about 15% of the mass contained in stars. This means that the mass of the interstellar matter in our Galaxy amounts to about 10

billion times the mass of the Sun. There is plenty of raw material in the Galaxy to make generations of new stars and planets (and perhaps even astronomy students).

EXAMPLE 20.1

Estimating Interstellar Mass

You can make a rough estimate of how much interstellar mass our Galaxy contains and also how many new stars could be made from this interstellar matter. All you need to know is how big the Galaxy is and the average density using this formula:

$$\text{total mass} = \text{volume} \times \text{density of atoms} \times \text{mass per atom}$$

You have to remember to use consistent units—such as meters and kilograms. We will assume that our Galaxy is shaped like a cylinder; the volume of a cylinder equals the area of its base times its height

$$V = \pi R^2 \, h$$

where R is the radius of the cylinder and h is its height.

Suppose that the average density of hydrogen gas in our Galaxy is one atom per cm^3. Each hydrogen atom has a mass of 1.7×10^{-27} kg. If the Galaxy is a cylinder with a diameter of 100,000 light-years and a height of 300 light-years, what is the mass of this gas? How many solar-mass stars (2.0×10^{30} kg) could be produced from this mass of gas if it were all turned into stars?

Solution

If the diameter of the Galaxy is 100,000 light-years, then the radius is 50,000 light-years. Recall that 1 light-year = 9.5×10^{12} km = 9.5×10^{17} cm, so the volume of the Galaxy is

$$V = \pi R^2 \, h = \pi(50{,}000 \times 9.5 \times 10^{17} \text{ cm})^2 \, (300 \times 9.5 \times 10^{17} \text{ cm}) = 2.0 \times 10^{66} \text{ cm}^3$$

The total mass is therefore

$$M = V \times \text{density of atoms} \times \text{mass per atom}$$

$$2.0 \times 10^{66} \text{ cm}^3 \times (1 \text{ atom/cm}^3) \times 1.7 \times 10^{-27} \text{ kg} = 3.5 \times 10^{39} \text{ kg}$$

This is sufficient to make

$$N = \frac{M}{(2.0 \times 10^{30} \text{ kg})} = 1.75 \times 10^9$$

stars equal in mass to the Sun. That's roughly 2 billion stars.

Check Your Learning

You can use the same method to estimate the mass of interstellar gas around the Sun. The distance from the Sun to the nearest other star, Proxima Centauri, is 4.2 light-years. We will see in **Interstellar Matter around the Sun** that the gas in the immediate vicinity of the Sun is less dense than average, about 0.1 atoms per cm^3. What is the total mass of interstellar hydrogen in a sphere centered on the Sun and extending out to Proxima Centauri? How does this compare to the mass of the Sun? It is helpful to remember that the volume of a sphere is related to its radius:

$$V = (4/3)\pi R^3$$

Answer:

The volume of a sphere stretching from the Sun to Proxima Centauri is:

$$V = (4/3)\pi R^3 = (4/3)\pi\left(4.2 \times 9.5 \times 10^{17}\ \text{cm}\right)^3 = 2.7 \times 10^{56}\ \text{cm}^3$$

Therefore, the mass of hydrogen in this sphere is:

$$M = V \times \left(0.1\ \text{atom/cm}^3\right) \times 1.7 \times 10^{-27}\ \text{kg} = 4.5 \times 10^{28}\ \text{kg}$$

This is only (4.5 × 10^{28} kg)/(2.0 × 10^{30} kg) = 2.2% the mass of the Sun.

ASTRONOMY BASICS

Naming the Nebulae

As you look at the captions for some of the spectacular photographs in this chapter and **The Birth of Stars and the Discovery of Planets outside the Solar System**, you will notice the variety of names given to the nebulae. A few, which in small telescopes look like something recognizable, are sometimes named after the creatures or objects they resemble. Examples include the Crab, Tarantula, and Keyhole Nebulae. But most have only numbers that are entries in a catalog of astronomical objects.

Perhaps the best-known catalog of nebulae (as well as star clusters and galaxies) was compiled by the French astronomer Charles Messier (1730–1817). Messier's passion was discovering comets, and his devotion to this cause earned him the nickname "The Comet Ferret" from King Louis XV. When comets are first seen coming toward the Sun, they look like little fuzzy patches of light; in small telescopes, they are easy to confuse with nebulae or with groupings of many stars so far away that their light is all blended together. Time and again, Messier's heart leapt as he thought he had discovered one of his treasured comets, only to find that he had "merely" observed a nebula or cluster.

In frustration, Messier set out to catalog the position and appearance of over 100 objects that could be mistaken for comets. For him, this list was merely a tool in the far more important work of comet hunting. He would be very surprised if he returned today to discover that no one recalls his comets anymore, but his catalog of "fuzzy things that are not comets" is still widely used. When **Figure 20.2** refers to M4, it denotes the fourth entry in Messier's list.

A far more extensive listing was compiled under the title of the *New General Catalog* (*NGC*) *of Nebulae and Star Clusters* in 1888 by John Dreyer, working at the observatory in Armagh, Ireland. He based his compilation on the work of William Herschel and his son John, plus many other observers who followed them. With the addition of two further listings (called the *Index Catalogs*), Dreyer's compilation eventually included 13,000 objects. Astronomers today still use his NGC numbers when referring to most nebulae and star groups.

20.2 INTERSTELLAR GAS

Learning Objectives

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

- Name the major types of interstellar gas
- Discuss how we can observe each type
- Describe the temperature and other major properties of each type

Interstellar gas, depending on where it is located, can be as cold as a few degrees above absolute zero or as hot as a million degrees or more. We will begin our voyage through the interstellar medium by exploring the different conditions under which we find gas.

Ionized Hydrogen (H II) Regions—Gas Near Hot Stars

Some of the most spectacular astronomical photographs show interstellar gas located near hot stars (**Figure 20.3**). The strongest line in the visible region of the hydrogen spectrum is the red line in the Balmer series[1] (as explained in the chapter on **Radiation and Spectra**); this emission line accounts for the characteristic red glow in images like **Figure 20.3**.

Figure 20.3 Orion Nebula. The red glow that pervades the great Orion Nebula is produced by the first line in the Balmer series of hydrogen. Hydrogen emission indicates that there are hot young stars nearby that ionize these clouds of gas. When electrons then recombine with protons and move back down into lower energy orbits, emission lines are produced. The blue color seen at the edges of some of the clouds is produced by small particles of dust that scatter the light from the hot stars. Dust can also be seen silhouetted against the glowing gas. (credit: NASA,ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team)

Hot stars are able to heat nearby gas to temperatures close to 10,000 K. The ultraviolet radiation from the stars also ionizes the hydrogen (remember that during ionization, the electron is stripped completely away from the proton). Such a detached proton won't remain alone forever when attractive electrons are around; it will capture a free electron, becoming a neutral hydrogen once more. However, such a neutral atom can then absorb ultraviolet radiation again and start the cycle over. At a typical moment, most of the atoms near a hot

1 Scientists also call this red Balmer line the H-alpha line, with alpha meaning it is the first spectral line in the Balmer series.

star are in the ionized state.

Since hydrogen is the main constituent of interstellar gas, we often characterize a region of space according to whether its hydrogen is neutral or ionized. A cloud of ionized hydrogen is called an **H II region**. (Scientists who work with spectra use the Roman numeral I to indicate that an atom is neutral; successively higher Roman numerals are used for each higher stage of ionization. H II thus refers to hydrogen that has lost its one electron; Fe III is iron with two electrons missing.)

The electrons that are captured by the hydrogen nuclei cascade down through the various energy levels of the hydrogen atoms on their way to the lowest level, or ground state. During each transition downward, they give up energy in the form of light. The process of converting ultraviolet radiation into visible light is called *fluorescence*. Interstellar gas contains other elements besides hydrogen. Many of them are also ionized in the vicinity of hot stars; they then capture electrons and emit light, just as hydrogen does, allowing them to be observed by astronomers. But generally, the red hydrogen line is the strongest, and that is why H II regions look red.

A fluorescent light on Earth works using the same principles as a fluorescent H II region. When you turn on the current, electrons collide with atoms of mercury vapor in the tube. The mercury is excited to a high-energy state because of these collisions. When the electrons in the mercury atoms return to lower-energy levels, some of the energy they emit is in the form of ultraviolet photons. These, in turn, strike a phosphor-coated screen on the inner wall of the light tube. The atoms in the screen absorb the ultraviolet photons and emit visible light as they cascade downward among the energy levels. (The difference is that these atoms give off a wider range of light colors, which mix to give the characteristic white glow of fluorescent lights, whereas the hydrogen atoms in an H II region give off a more limited set of colors.)

Neutral Hydrogen Clouds

The very hot stars required to produce H II regions are rare, and only a small fraction of interstellar matter is close enough to such hot stars to be ionized by them. Most of the volume of the interstellar medium is filled with neutral (nonionized) hydrogen. How do we go about looking for it?

Unfortunately, neutral hydrogen atoms at temperatures typical of the gas in interstellar space neither emit nor absorb light in the visible part of the spectrum. Nor, for the most part, do the other trace elements that are mixed with the interstellar hydrogen. However, some of these other elements can *absorb* visible light even at typical interstellar temperatures. This means that when we observe a bright source such as a hot star or a galaxy, we can sometimes see additional lines in its spectrum produced when interstellar gas absorbs light at particular frequencies (see **Figure 20.4**). Some of the strongest interstellar absorption lines are produced by calcium and sodium, but many other elements can be detected as well in sufficiently sensitive observations (as discussed in **Radiation and Spectra**).

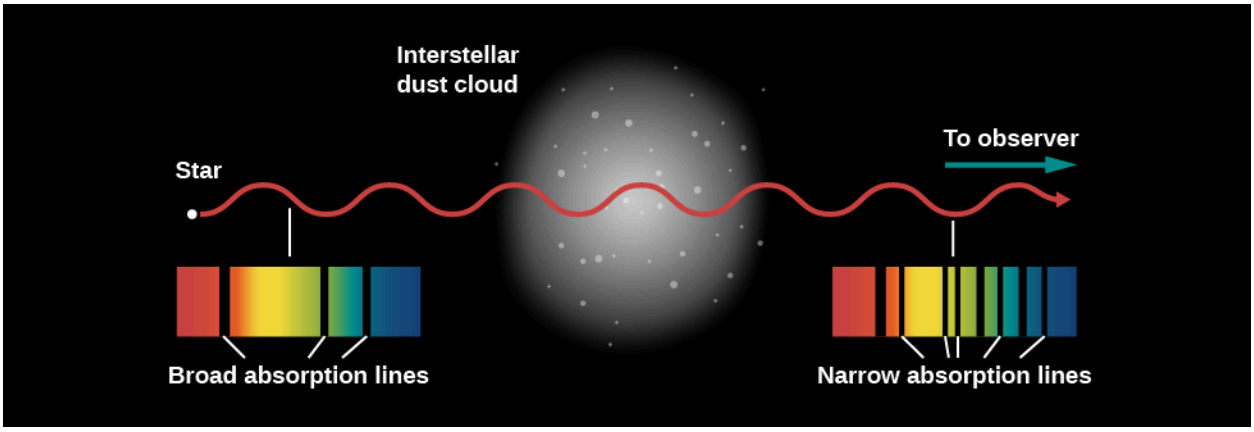


Figure 20.4 Absorption Lines though an Interstellar Dust Cloud. When there is a significant amount of cool interstellar matter between us and a star, we can see the absorption lines of the gas in the star's spectrum. We can distinguish the two kinds of lines because, whereas the star's lines are broad, the lines from the gas are narrower.

The first evidence for absorption by interstellar clouds came from the analysis of a spectroscopic binary star (see **The Stars: A Celestial Census**), published in 1904. While most of the lines in the spectrum of this binary shifted alternately from longer to shorter wavelengths and back again, as we would expect from the Doppler effect for stars in orbit around each other, a few lines in the spectrum remained fixed in wavelength. Since both stars are moving in a binary system, lines that showed no motion puzzled astronomers. The lines were also peculiar in that they were much, much narrower than the rest of the lines, indicating that the gas producing them was at a very low pressure. Subsequent work demonstrated that these lines were not formed in the star's atmosphere at all, but rather in a cold cloud of gas located between Earth and the binary star.

While these and similar observations proved there was interstellar gas, they could not yet detect hydrogen, the most common element, due to its lack of spectral features in the visible part of the spectrum. (The Balmer line of hydrogen is in the visible range, but only excited hydrogen atoms produce it. In the cold interstellar medium, the hydrogen atoms are all in the ground state and no electrons are in the higher-energy levels required to produce either emission or absorption lines in the Balmer series.) Direct detection of hydrogen had to await the development of telescopes capable of seeing very-low-energy changes in hydrogen atoms in other parts of the spectrum. The first such observations were made using radio telescopes, and radio emission and absorption by interstellar hydrogen remains one of our main tools for studying the vast amounts of cold hydrogen in the universe to this day.

In 1944, while he was still a student, the Dutch astronomer Hendrik van de Hulst predicted that hydrogen would produce a strong line at a wavelength of 21 centimeters. That's quite a long wavelength, implying that the wave has such a low frequency and low energy that it cannot come from electrons jumping between energy levels (as we discussed in **Radiation and Spectra**). Instead, energy is emitted when the electron does a flip, something like an acrobat in a circus flipping upright after standing on his head.

The flip works like this: a hydrogen atom consists of a proton and an electron bound together. Both the proton and the electron act is if they were spinning like tops, and spin axes of the two tops can either be pointed in the same direction (aligned) or in opposite directions (anti-aligned). If the proton and electron were spinning in opposite directions, the atom as a whole would have a very slightly lower energy than if the two spins were aligned (**Figure 20.5**). If an atom in the lower-energy state (spins opposed) acquired a small amount of energy, then the spins of the proton and electron could be aligned, leaving the atom in a slightly *excited state*. If the atom then lost that same amount of energy again, it would return to its ground state. The amount of energy involved corresponds to a wave with a wavelength of 21 centimeters; hence, it is known as the *21-centimeter line*.

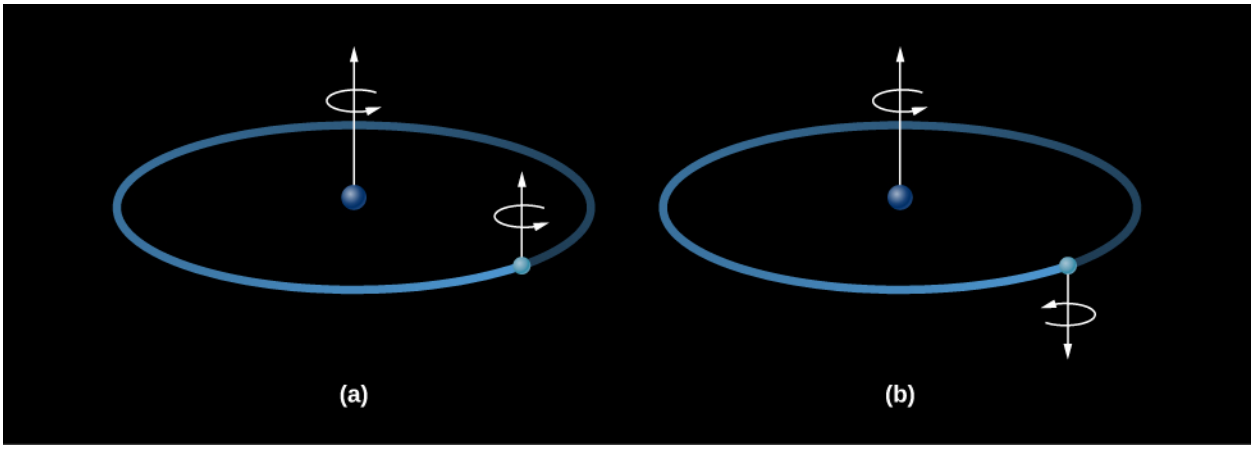


Figure 20.5 Formation of the 21-Centimeter Line. When the electron in a hydrogen atom is in the orbit closest to the nucleus, the proton and the electron may be spinning either (a) in the same direction or (b) in opposite directions. When the electron flips over, the atom gains or loses a tiny bit of energy by either absorbing or emitting electromagnetic energy with a wavelength of 21 centimeters.

Neutral hydrogen atoms can acquire small amounts of energy through collisions with other hydrogen atoms or with free electrons. Such collisions are extremely rare in the sparse gases of interstellar space. An individual atom may wait centuries before such an encounter aligns the spins of its proton and electron. Nevertheless, over many millions of years, a significant fraction of the hydrogen atoms are excited by a collision. (Out there in cold space, that's about as much excitement as an atom typically experiences.)

An excited atom can later lose its excess energy either by colliding with another particle or by giving off a radio wave with a wavelength of 21 centimeters. If there are no collisions, an excited hydrogen atom will wait an average of about 10 million years before emitting a photon and returning to its state of lowest energy. Even though the probability that any single atom will emit a photon is low, there are so many hydrogen atoms in a typical gas cloud that collectively they will produce an observable line at 21 centimeters.

Equipment sensitive enough to detect the 21-cm line of neutral hydrogen became available in 1951. Dutch astronomers had built an instrument to detect the 21-cm waves that they had predicted, but a fire destroyed it. As a result, two Harvard physicists, Harold Ewen and Edward Purcell, made the first detection (**Figure 20.6**), soon followed by confirmations from the Dutch and a group in Australia. Since the detection of the 21-cm line, many other radio lines produced by both atoms and molecules have been discovered (as we will discuss in a moment), and these have allowed astronomers to map out the neutral gas throughout our home Galaxy. Astronomers have also detected neutral interstellar gas, including hydrogen, at many other wavelengths from the infrared to the ultraviolet.

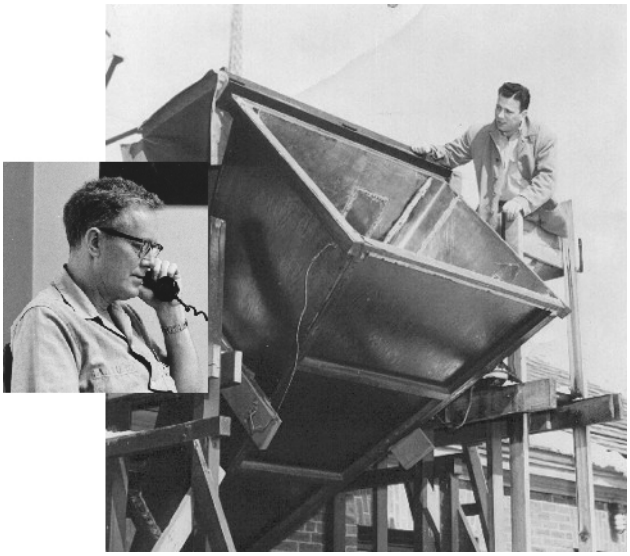


Figure 20.6 Harold Ewen (1922–2015) and Edward Purcell (1912–1997). We see Harold Ewen in 1952 working with the horn antenna (atop the physics laboratory at Harvard) that made the first detection of interstellar 21-cm radiation. The inset shows Edward Purcell, the winner of the 1952 Nobel Prize in physics, a few years later. (credit: modification of work by NRAO)

Modern radio observations show that most of the neutral hydrogen in our Galaxy is confined to an extremely flat layer, less than 300 light-years thick, that extends throughout the disk of the Milky Way Galaxy. This gas has densities ranging from about 0.1 to about 100 atoms per cm^3, and it exists at a wide range of temperatures, from as low as about 100 K (–173 °C) to as high as about 8000 K. These regions of warm and cold gas are interspersed with each other, and the density and temperature at any particular point in space are constantly changing.

Ultra-Hot Interstellar Gas

While the temperatures of 10,000 K found in H II regions might seem warm, they are not the hottest phase of the interstellar medium. Some of the interstellar gas is at a temperature of a *million* degrees, even though there is no visible source of heat nearby. The discovery of this ultra-hot interstellar gas was a big surprise. Before the launch of astronomical observatories into space, which could see radiation in the ultraviolet and X-ray parts of the spectrum, astronomers assumed that most of the region between stars was filled with hydrogen at temperatures no warmer than those found in H II regions. But telescopes launched above Earth's atmosphere obtained ultraviolet spectra that contained interstellar lines produced by oxygen atoms that have been ionized five times. To strip five electrons from their orbits around an oxygen nucleus requires a lot of energy. Subsequent observations with orbiting X-ray telescopes revealed that the Galaxy is filled with numerous bubbles of X-ray-emitting gas. To emit X-rays, and to contain oxygen atoms that have been ionized five times, gas must be heated to temperatures of a million degrees or more.

Theorists have now shown that the source of energy producing these remarkable temperatures is the explosion of massive stars at the ends of their lives (**Figure 20.7**). Such explosions, called *supernovae*, will be discussed in detail in the chapter on **The Death of Stars**. For now, we'll just say that some stars, nearing the ends of their lives, become unstable and literally explode. These explosions launch gas into interstellar space at velocities of tens of thousands of kilometers per second (up to about 30% the speed of light). When this ejected gas collides with interstellar gas, it produces shocks that heat the gas to millions or tens of millions of degrees.

Figure 20.7 Vela Supernova Remnant. About 11,000 years ago, a dying star in the constellation of Vela exploded, becoming as bright as the full moon in Earth's skies. You can see the faint rounded filaments from that explosion in the center of this colorful image. The edges of the remnant are colliding with the interstellar medium, heating the gas they plow through to temperatures of millions of K. Telescopes in space also reveal a glowing sphere of X-ray radiation from the remnant. (credit: Digitized Sky Survey, ESA/ESO/NASA FITS Liberator, Davide De Martin)

Astronomers estimate that one supernova explodes roughly every 100 years somewhere in the Galaxy. On average, shocks launched by supernovae sweep through any given point in the Galaxy about once every few million years. These shocks keep some interstellar space filled with gas at temperatures of millions of degrees, and they continually disturb the colder gas, keeping it in constant, turbulent motion.

Molecular Clouds

A few simple molecules out in space, such as CN and CH, were discovered decades ago because they produce absorption lines in the visible-light spectra of stars behind them. When more sophisticated equipment for obtaining spectra in radio and infrared wavelengths became available, astronomers—to their surprise—found much more complex molecules in interstellar clouds as well.

Just as atoms leave their "fingerprints" in the spectrum of visible light, so the vibration and rotation of atoms within molecules can leave spectral fingerprints in radio and infrared waves. If we spread out the radiation at such longer wavelengths, we can detect emission or absorption lines in the spectra that are characteristic of specific molecules. Over the years, experiments in our laboratories have shown us the exact wavelengths associated with changes in the rotation and vibration of many common molecules, giving us a template of possible lines against which we can now compare our observations of interstellar matter.

The discovery of complex molecules in space came as a surprise because most of interstellar space is filled with ultraviolet light from stars, and this light is capable of *dissociating* molecules (breaking them apart into individual atoms). In retrospect, however, the presence of molecules is not surprising. As we will discuss further in the next section, and have already seen above, interstellar space also contains significant amounts of dust capable of blocking out starlight. When this dust accumulates in a single location, the result is a dark cloud where ultraviolet starlight is blocked and molecules can survive. The largest of these structures are created where gravity pulls interstellar gas together to form giant **molecular clouds**, structures as massive as a million times the mass of the Sun. Within these, most of the interstellar hydrogen has formed the molecule H_2 (molecular hydrogen). Other, more complex molecules are also present in much smaller quantities.

Giant molecular clouds have densities of hundreds to thousands of atoms per cm^3, much denser than

interstellar space is on average. As a result, though they account for a very small fraction of the volume of interstellar space, they contain a significant fraction—20–30%—of the total mass of the Milky Way's gas. Because of their high density, molecular clouds block ultraviolet starlight, the main agent for heating most interstellar gas. As a result, they tend to be extremely cold, with typical temperatures near 10 K (−263 °C). Giant molecular clouds are also the sites where new stars form, as we will discuss below.

It is in these dark regions of space, protected from starlight, that molecules can form. Chemical reactions occurring both in the gas and on the surface of dust grains lead to much more complex compounds, hundreds of which have been identified in interstellar space. Among the simplest of these are water (H_2O), carbon monoxide (CO), which is produced by fires on Earth, and ammonia (NH_3), whose smell you recognize in strong home cleaning products. Carbon monoxide is particularly abundant in interstellar space and is the primary tool that astronomers use to study giant molecular clouds. Unfortunately, the most abundant molecule, H_2, is particularly difficult to observe directly because in most giant molecular clouds, it is too cold to emit even at radio wavelengths. CO, which tends to be present wherever H_2 is found, is a much better emitter and is often used by astronomers to trace molecular hydrogen.

The more complex molecules astronomers have found are mostly combinations of hydrogen, oxygen, carbon, nitrogen, and sulfur atoms. Many of these molecules are *organic* (those that contain carbon and are associated with the carbon chemistry of life on Earth.) They include formaldehyde (used to preserve living tissues), alcohol (see the feature box on **Cocktails in Space**), and antifreeze.

In 1996, astronomers discovered acetic acid (the prime ingredient of vinegar) in a cloud lying in the direction of the constellation of Sagittarius. To balance the sour with the sweet, a simple sugar (glycolaldehyde) has also been found. The largest compounds yet discovered in interstellar space are *fullerenes*, molecules in which 60 or 70 carbon atoms are arranged in a cage-like configuration (see **Figure 20.8**). See **Table 20.1** for a list of a few of the more interesting interstellar molecules that have been found so far.

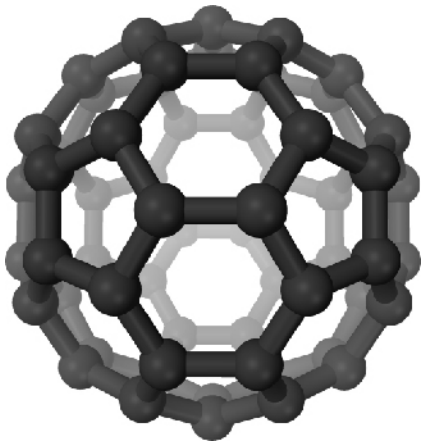


Figure 20.8 Fullerene C60. This three-dimensional perspective shows the characteristic cage-like arrangement of the 60 carbon atoms in a molecule of fullerene C60. Fullerene C60 is also known as a "buckyball," or as its full name, buckminsterfullerene, because of its similarity to the multisided architectural domes designed by American inventor R. Buckminster Fuller.

Some Interesting Interstellar Molecules

Name	Chemical Formula	Use on Earth
Ammonia	NH_3	Household cleansers

Table 20.1

Some Interesting Interstellar Molecules

Name	Chemical Formula	Use on Earth
Formaldehyde	H_2CO	Embalming fluid
Acetylene	HC_2H	Fuel for a welding torch
Acetic acid	$C_2H_2O_4$	The essence of vinegar
Ethyl alcohol	CH_3CH_2OH	End-of-semester parties
Ethylene glycol	$HOCH_2CH_2OH$	Antifreeze ingredient
Benzene	C_6H_6	Carbon ring, ingredient in varnishes and dyes

Table 20.1

The cold interstellar clouds also contain cyanoacetylene (HC_3N) and acetaldehyde (CH_3CHO), generally regarded as starting points for *amino acid* formation. These are building blocks of proteins, which are among the fundamental chemicals from which living organisms on Earth are constructed. The presence of these organic molecules does not imply that life exists in space, but it does show that the chemical building blocks of life can form under a wide range of conditions in the universe. As we learn more about how complex molecules are produced in interstellar clouds, we gain an increased understanding of the kinds of processes that preceded the beginnings of life on Earth billions of years ago.

LINK TO LEARNING

Interested in learning more about fullerenes, buckyballs, or buckminsterfullerenes (as they're called)? Watch a brief video from **NASA's Jet Propulsion Laboratory (https://openstax.org/l/30NASAjetprop)** that explains what they are and illustrates how they were discovered in space.

MAKING CONNECTIONS

Cocktails in Space

Among the molecules astronomers have identified in interstellar clouds is alcohol, which comes in two varieties: methyl (or wood) alcohol and ethyl alcohol (the kind you find in cocktails). Ethyl alcohol is a pretty complex molecule, written by chemists as C_2H_5OH. It is quite plentiful in space (relatively speaking). In clouds where it has been identified, we detect up to one molecule for every m^3. The largest of the clouds (which can be several hundred light-years across) have enough ethyl alcohol to make 10^{28} fifths of liquor.

We need not fear, however, that future interstellar astronauts will become interstellar alcoholics. Even if a

spaceship were equipped with a giant funnel 1 kilometer across and could scoop it through such a cloud at the speed of light, it would take about a thousand years to gather up enough alcohol for one standard martini.

Furthermore, the very same clouds also contain water (H_2O) molecules. Your scoop would gather them up as well, and there are a lot more of them because they are simpler and thus easier to form. For the fun of it, one astronomical paper actually calculated the proof of a typical cloud. *Proof* is the ratio of alcohol to water in a drink, where 0 proof means all water, 100 proof means half alcohol and half water, and 200 proof means all alcohol. The proof of the interstellar cloud was only 0.2, not enough to qualify as a stiff drink

20.3 COSMIC DUST

Learning Objectives

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

- Describe how we can detect interstellar dust
- Understand the role and importance of infrared observations in studying dust
- Explain the terms extinction and interstellar reddening

Figure 20.9 shows a striking example of what is actually a common sight through large telescopes: a dark region on the sky that appears to be nearly empty of stars. For a long time, astronomers debated whether these dark regions were empty "tunnels" through which we looked beyond the stars of the Milky Way Galaxy into intergalactic space, or clouds of some dark material that blocked the light of the stars beyond. The astronomer William Herschel (discoverer of the planet Uranus) thought it was the former, once remarking after seeing one, "Here truly is a hole in heaven!" However, American astronomer E. E. Barnard is generally credited with showing from his extensive series of nebula photographs that the latter interpretation is the correct one (see the feature box on **Edward Emerson Barnard**).

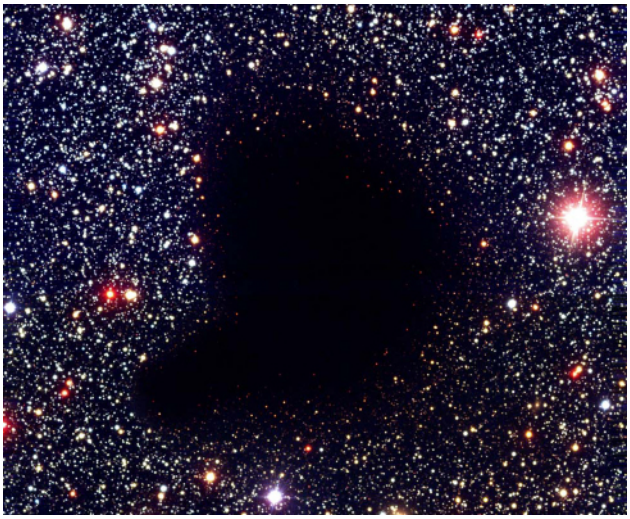


Figure 20.9 Barnard 68. This object, first catalogued by E. E. Barnard, is a dark interstellar cloud. Its striking appearance is due to the fact that, since it is relatively close to Earth, there are no bright stars between us and it, and its dust obscures the light from the stars behind it. (It looks a little bit like a sideways heart; one astronomers sent a photo of this object to his sweetheart as a valentine.) (credit: modification of work by ESO)

Dusty clouds in space betray their presence in several ways: by blocking the light from distant stars, by emitting energy in the infrared part of the spectrum, by reflecting the light from nearby stars, and by making distant stars look redder than they really are.

VOYAGERS IN ASTRONOMY

Edward Emerson Barnard

Born in 1857 in Nashville, Tennessee, two months after his father died, Edward Barnard (Figure 20.10) grew up in such poor circumstances that he had to drop out of school at age nine to help support his ailing mother. He soon became an assistant to a local photographer, where he learned to love both photography and astronomy, destined to become the dual passions of his life. He worked as a photographer's aide for 17 years, studying astronomy on his own. In 1883, he obtained a job as an assistant at the Vanderbilt University Observatory, which enabled him at last to take some astronomy courses.

Married in 1881, Barnard built a house for his family that he could ill afford. But as it happened, a patent medicine manufacturer offered a $200 prize (a lot of money in those days) for the discovery of any new comet. With the determination that became characteristic of him, Barnard spent every clear night searching for comets. He discovered seven of them between 1881 and 1887, earning enough money to make the payments on his home; this "Comet House" later became a local attraction. (By the end of his life, Barnard had found 17 comets through diligent observation.)

In 1887, Barnard got a position at the newly founded Lick Observatory, where he soon locked horns with the director, Edward Holden, a blustering administrator who made Barnard's life miserable. (To be fair, Barnard soon tried to do the same for him.) Despite being denied the telescope time that he needed for his photographic work, in 1892, Barnard managed to discover the first new moon found around Jupiter since Galileo's day, a stunning observational feat that earned him world renown. Now in a position to

demand more telescope time, he perfected his photographic techniques and soon began to publish the best images of the Milky Way taken up to that time. It was during the course of this work that he began to examine the dark regions among the crowded star lanes of the Galaxy and to realize that they must be vast clouds of obscuring material (rather than "holes" in the distribution of stars).

Astronomer-historian Donald Osterbrock has called Barnard an "observaholic:" his daily mood seemed to depend entirely on how clear the sky promised to be for his night of observing. He was a driven, neurotic man, concerned about his lack of formal training, fearful of being scorned, and afraid that he might somehow slip back into the poverty of his younger days. He had difficulty taking vacations and lived for his work: only serious illness could deter him from making astronomical observations.

In 1895, Barnard, having had enough of the political battles at Lick, accepted a job at the Yerkes Observatory near Chicago, where he remained until his death in 1923. He continued his photographic work, publishing compilations of his images that became classic photographic atlases, and investigating the varieties of nebulae revealed in his photographs. He also made measurements of the sizes and features of planets, participated in observations of solar eclipses, and carefully cataloged dark nebulae (see **Figure 20.9**). In 1916, he discovered the star with the largest proper motion, the second-closest star system to our own (see **Analyzing Starlight**). It is now called Barnard's Star in his honor.

Figure 20.10 Edward Emerson Barnard (1857–1923). Barnard's observations provided information that furthered many astronomical explorations. (credit: The Lick Observatory)

Detecting Dust

The dark cloud seen in **Figure 20.9** blocks the light of the many stars that lie behind it; note how the regions in other parts of the photograph are crowded with stars. Barnard 68 is an example of a relatively dense cloud or *dark nebula* containing tiny, solid dust grains. Such opaque clouds are conspicuous on any photograph of the Milky Way, the galaxy in which the Sun is located (see the figures in **The Milky Way Galaxy**). The "dark rift," which runs lengthwise down a long part of the Milky Way in our sky and appears to split it in two, is produced by a collection of such obscuring clouds.

While dust clouds are too cold to radiate a measurable amount of energy in the visible part of the spectrum, they glow brightly in the infrared (**Figure 20.11**). The reason is that small dust grains absorb visible light and ultraviolet radiation very efficiently. The grains are heated by the absorbed radiation, typically to temperatures

from 10 to about 500 K, and re-radiate this heat at infrared wavelengths.

Figure 20.11 Visible and Infrared Images of the Horsehead Nebula in Orion. This dark cloud is one of the best-known images in astronomy, probably because it really does resemble a horse's head. The horse-head shape is an extension of a large cloud of dust that fills the lower part of the picture. (a) Seen in visible light, the dust clouds are especially easy to see against the bright background. (b) This infrared radiation image from the region of the horse head was recorded by NASA's Wide-Field Infrared Survey Explorer. Note how the regions that appear dark in visible light appear bright in the infrared. The dust is heated by nearby stars and re-radiates this heat in the infrared. Only the top of the horse's head is visible in the infrared image. Bright dots seen in the nebula below and to the left and at the top of the horse head are young, newly formed stars. The insets show the horse head and the bright nebula in more detail. (credit a: modification of work by ESO and Digitized Sky Survey; credit b: modification of work by NASA/JPL-Caltech)

Thanks to their small sizes and low temperatures, interstellar grains radiate most of their energy at infrared to microwave frequencies, with wavelengths of tens to hundreds of microns. Earth's atmosphere is opaque to radiation at these wavelengths, so emission by interstellar dust is best measured from space. Observations from above Earth's atmosphere show that dust clouds are present throughout the plane of the Milky Way (Figure 20.12).

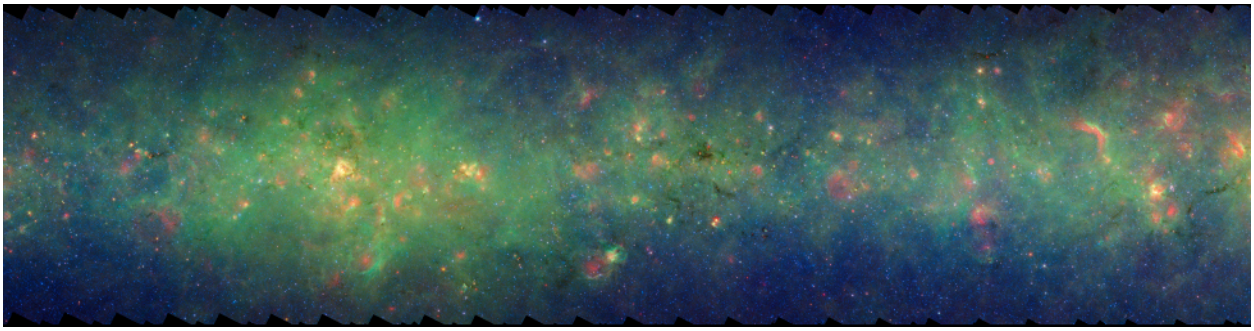


Figure 20.12 Infrared Emission from the Plane of the Milky Way. This infrared image taken by the Spitzer Space Telescope shows a field in the plane of the Milky Way Galaxy. (Our Galaxy is in the shape of a frisbee; the plane of the Milky Way is the flat disk of that frisbee. Since the Sun, Earth, and solar system are located in the plane of the Milky Way and at a large distance from its center, we view the Galaxy edge on, much as we might look at a glass plate from its edge.) This emission is produced by tiny dust grains, which emit at 3.6 microns (blue in this image), 8.0 microns (green), and 24 microns (red). The densest regions of dust are so cold and opaque that they appear as dark clouds even at these infrared wavelengths. The red bubbles visible throughout indicate regions where the dust has been warmed up by young stars. This heating increases the emission at 24 microns, leading to the redder color in this image. (credit: modification of work by NASA/JPL-Caltech/University of Wisconsin)

Some dense clouds of dust are close to luminous stars and scatter enough starlight to become visible. Such a cloud of dust, illuminated by starlight, is called a *reflection nebula*, since the light we see is starlight reflected off

the grains of dust. One of the best-known examples is the nebulosity around each of the brightest stars in the Pleiades cluster (see Figure 20.1). The dust grains are small, and such small particles turn out to scatter light with blue wavelengths more efficiently than light at red wavelengths. A reflection nebula, therefore, usually appears bluer than its illuminating star (Figure 20.13).

Figure 20.13 Pleiades Star Cluster. The bluish light surrounding the stars in this image is an example of a reflection nebula. Like fog around a street lamp, a reflection nebula shines only because the dust within it scatters light from a nearby bright source. The Pleiades cluster is currently passing through an interstellar cloud that contains dust grains, which scatter the light from the hot blue stars in the cluster. The Pleiades cluster is about 400 light-years from the Sun. (credit: NASA, ESA and AURA/Caltech)

Gas and dust are generally intermixed in space, although the proportions are not exactly the same everywhere. The presence of dust is apparent in many photographs of *emission nebulae* in the constellation of Sagittarius, where we see an H II region surrounded by a blue reflection nebula. Which type of nebula appears brighter depends on the kinds of stars that cause the gas and dust to glow. Stars cooler than about 25,000 K have so little ultraviolet radiation of wavelengths shorter than 91.2 nanometers—which is the wavelength required to ionize hydrogen—that the reflection nebulae around such stars outshine the emission nebulae. Stars hotter than 25,000 K emit enough ultraviolet energy that the emission nebulae produced around them generally outshine the reflection nebulae.

Interstellar Reddening

The tiny interstellar dust grains absorb some of the starlight they intercept. But at least half of the starlight that interacts with a grain is merely scattered, that is, it is redirected rather than absorbed. Since neither the absorbed nor the scattered starlight reaches us directly, both absorption and scattering make stars look dimmer. The effects of both processes are called **interstellar extinction** (Figure 20.14).

Astronomers first came to understand interstellar extinction around the early 1930s, as the explanation of a puzzling observation. In the early part of the twentieth century, astronomers discovered that some stars look red even though their spectral lines indicate that they must be extremely hot (and thus should look blue). The solution to this seeming contradiction turned out to be that the light from these hot stars is not only dimmed but also reddened by interstellar dust, a phenomenon known as interstellar **reddening**.

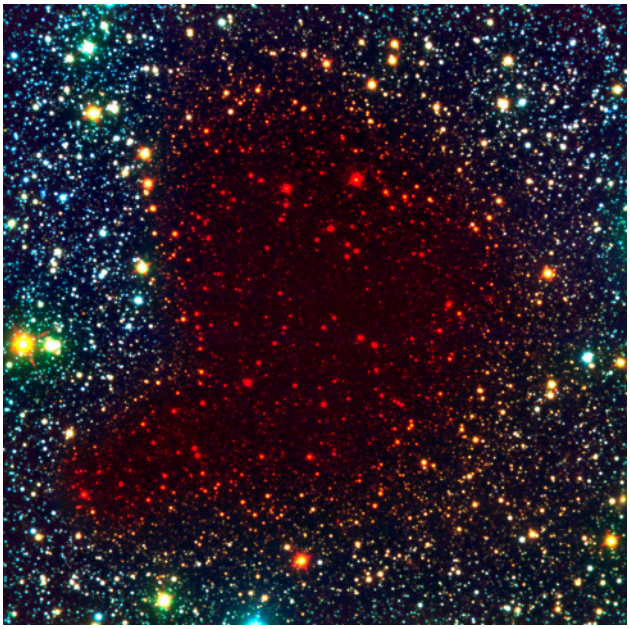


Figure 20.14 Barnard 68 in Infrared. In this image, we see Barnard 68, the same object shown in Figure 20.9. The difference is that, in the previous image, the blue, green, and red channels showed light in the visible (or very nearly visible) part of the spectrum. In this image, the red color shows radiation emitted in the infrared at a wavelength of 2.2 microns. Interstellar extinction is much smaller at infrared than at visible wavelengths, so the stars behind the cloud become visible in the infrared channel. (credit: ESO)

Dust does not interact with all the colors of light the same way. Much of the violet, blue, and green light from these stars has been scattered or absorbed by dust, so it does not reach Earth. Some of their orange and red light, with longer wavelengths, on the other hand, more easily penetrates the intervening dust and completes its long journey through space to enter Earth-based telescopes (Figure 20.15). Thus, the star looks redder from Earth than it would if you could see it from nearby. (Strictly speaking, *reddening* is not the most accurate term for this process, since no red color is added; instead, blues and related colors are subtracted, so it should more properly be called "deblueing.") In the most extreme cases, stars can be so reddened that they are entirely undetectable at visible wavelengths and can be seen only at infrared or longer wavelengths (Figure 20.14).

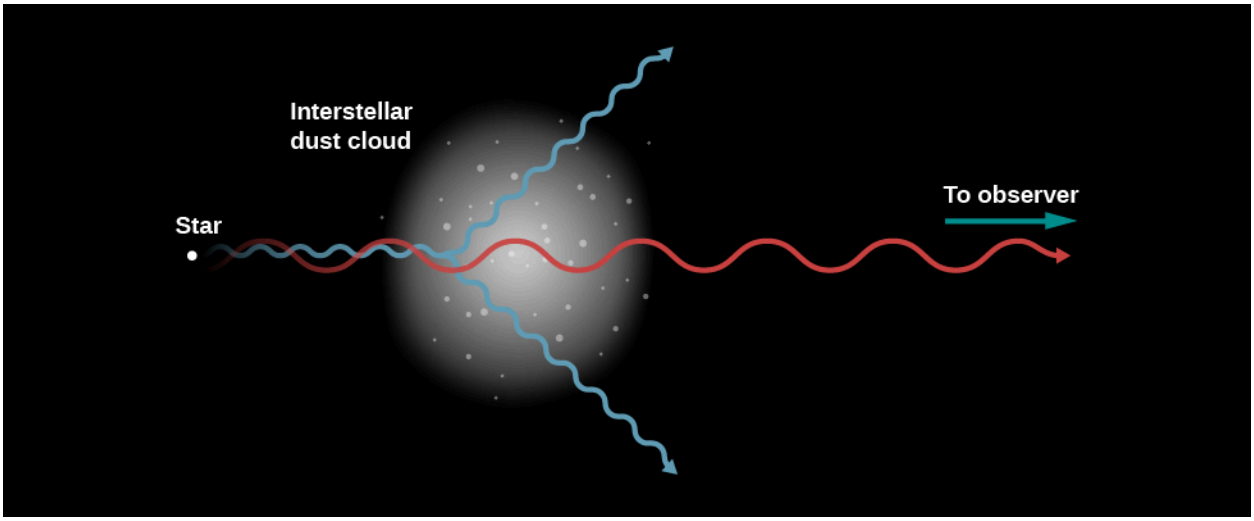


Figure 20.15 Scattering of Light by Dust. Interstellar dust scatters blue light more efficiently than red light, thereby making distant stars appear redder and giving clouds of dust near stars a bluish hue. Here, a red ray of light from a star comes straight through to the observer, whereas a blue ray is shown scattering. A similar scattering process makes Earth's sky look blue.

We have all seen an example of reddening on Earth. The Sun appears much redder at sunset than it does at noon. The lower the Sun is in the sky, the longer the path its light must travel through the atmosphere. Over this greater distance, there is a greater chance that sunlight will be scattered. Since red light is less likely to be scattered than blue light, the Sun appears more and more red as it approaches the horizon.

By the way, scattering of sunlight is also what causes our sky to look blue, even though the gases that make up Earth's atmosphere are transparent. As sunlight comes in, it scatters from the molecules of air. The small size of the molecules means that the blue colors scatter much more efficiently than the greens, yellows, and reds. Thus, the blue in sunlight is scattered out of the beam and all over the sky. The light from the Sun that comes to your eye, on the other hand, is missing some of its blue, so the Sun looks a bit yellower, even when it is high in the sky, than it would from space.

The fact that starlight is reddened by interstellar dust means that long-wavelength radiation is transmitted through the Galaxy more efficiently than short-wavelength radiation. Consequently, if we wish to see farther in a direction with considerable interstellar material, we should look at long wavelengths. This simple fact provides one of the motivations for the development of infrared astronomy. In the infrared region at 2 microns (2000 nanometers), for example, the obscuration is only one-sixth as great as in the visible region (500 nanometers), and we can therefore study stars that are more than twice as distant before their light is blocked by interstellar dust. This ability to see farther by observing in the infrared portion of the spectrum represents a major gain for astronomers trying to understand the structure of our Galaxy or probing its puzzling, but distant, center (see **The Milky Way Galaxy**).

Interstellar Grains

Before we get to the details about interstellar dust, we should perhaps get one concern out of the way. Why couldn't it be the interstellar *gas* that reddens distant stars and not the dust? We already know from everyday experience that atomic or molecular gas is almost transparent. Consider Earth's atmosphere. Despite its very high density compared with that of interstellar gas, it is so transparent as to be practically invisible. (Gas does have a few specific spectral lines, but they absorb only a tiny fraction of the light as it passes through.)The quantity of *gas* required to produce the observed absorption of light in interstellar space would have to be enormous. The gravitational attraction of so great a mass of gas would affect the motions of stars in ways that could easily be detected. Such motions are not observed, and thus, the interstellar absorption cannot be the result of gases.

Although gas does not absorb much light, we know from everyday experience that tiny solid or liquid particles can be very efficient absorbers. Water vapor in the air is quite invisible. When some of that vapor condenses into tiny water droplets, however, the resulting cloud is opaque. Dust storms, smoke, and smog offer familiar examples of the efficiency with which solid particles absorb light. On the basis of arguments like these, astronomers have concluded that widely scattered *solid* particles in interstellar space must be responsible for the observed dimming of starlight. What are these particles made of? And how did they form?

Observations like the pictures in this chapter show that a great deal of this dust exists; hence, it must be primarily composed of elements that are abundant in the universe (and in interstellar matter). After hydrogen and helium, the most abundant elements are oxygen, carbon, and nitrogen. These three elements, along with magnesium, silicon, iron—and perhaps hydrogen itself—turn out to be the most important components of interstellar dust.

Many of the dust particles can be characterized as sootlike (rich in carbon) or sandlike (containing silicon and oxygen). Grains of interstellar dust are found in meteorites and can be identified because the abundances of certain isotopes are different from what we see in other solar system material. Several different interstellar

dust substances have been identified in this way in the laboratory, including graphite and diamonds. (Don't get excited; these diamonds are only a billionth of a meter in size and would hardly make an impressive engagement ring!)

The most widely accepted model pictures the grains with rocky cores that are either like soot (rich in carbon) or like sand (rich in silicates). In the dark clouds where molecules can form, these cores are covered by icy mantles (Figure 20.16). The most common ices in the grains are water (H_2O), methane (CH_4), and ammonia (NH_3)—all built out of atoms that are especially abundant in the realm of the stars. The ice mantles, in turn, are sites for some of the chemical reactions that produce complex organic molecules.

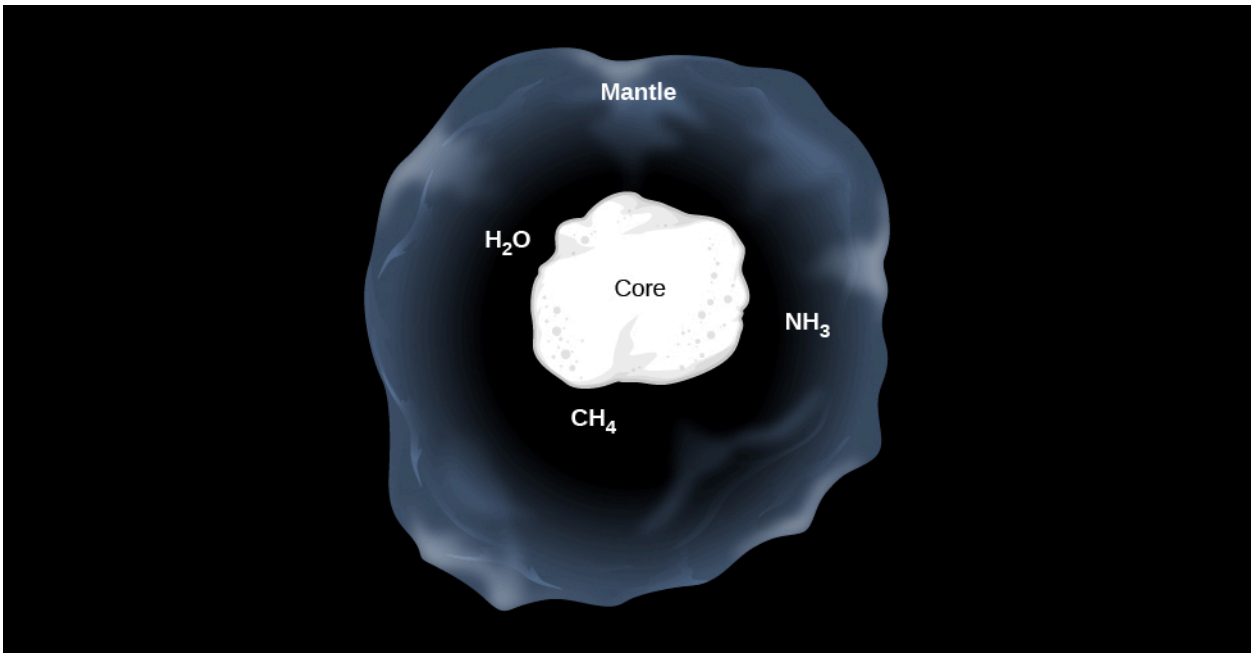


Figure 20.16 Model of an Interstellar Dust Grain. A typical interstellar grain is thought to consist of a core of rocky material (silicates) or graphite, surrounded by a mantle of ices. Typical grain sizes are 10^{-8} to 10^{-7} meters. (This is from 1/100 to 1/10 of a micron; by contrast, human hair is about 10–200 microns wide.)

Typical individual grains must be just slightly smaller than the wavelength of visible light. If the grains were a lot smaller, they would not block the light efficiently, as Figure 20.13 and other images in this chapter show that it does.

On the other hand, if the dust grains were much larger than the wavelength of light, then starlight would not be reddened. Things that are much larger than the wavelength of light would block both blue and red light with equal efficiency. In this way we can deduce that a characteristic interstellar dust grain contains 10^6 to 10^9 atoms and has a diameter of 10^{-8} to 10^{-7} meters (10 to 100 nanometers). This is actually more like the specks of solid matter in cigarette smoke than the larger grains of dust you might find under your desk when you are too busy studying astronomy to clean properly.

20.4 COSMIC RAYS

Learning Objectives

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

- Define cosmic rays and describe their composition
- Explain why it is hard to study the origin of cosmic rays, and the current leading hypotheses about where

they might come from

In addition to gas and dust, a third class of particles, noteworthy for the high speeds with which they travel, is found in interstellar space. **Cosmic rays** were discovered in 1911 by an Austrian physicist, Victor Hess, who flew simple instruments aboard balloons and showed that high-speed particles arrive at Earth from space (**Figure 20.17**). The term "cosmic ray" is misleading, implying it might be like a ray of light, but we are stuck with the name. They are definitely particles and have nearly the same composition as ordinary interstellar gas. Their behavior, however, is radically different from the gas we have discussed so far.

Figure 20.17 Victor Hess (1883–1964). Cosmic-ray pioneer Victor Hess returns from a 1912 balloon flight that reached an altitude of 5.3 kilometers. It was on such balloon flights that Hess discovered cosmic rays.

The Nature of Cosmic Rays

Cosmic rays are mostly high-speed atomic nuclei and electrons. Speeds equal to 90% of the speed of light are typical. Almost 90% of the cosmic rays are hydrogen nuclei (protons) stripped of their accompanying electron. Helium and heavier nuclei constitute about 9% more. About 1% of cosmic rays have masses equal to the mass of the electron, and 10–20% of these carry positive charge rather than the negative charge that characterizes electrons. A positively charged particle with the mass of an electron is called a *positron* and is a form of *antimatter* (we discussed antimatter in **The Sun: A Nuclear Powerhouse**).

The abundances of various atomic nuclei in cosmic rays mirror the abundances in stars and interstellar gas, with one important exception. The light elements lithium, beryllium, and boron are far more abundant in cosmic rays than in the Sun and stars. These light elements are formed when high-speed, cosmic-ray nuclei of carbon, nitrogen, and oxygen collide with protons in interstellar space and break apart. (By the way, if you, like most readers, have not memorized all the elements and want to see how any of those we mention fit into the sequence of elements, you will find them all listed in **Appendix K** in order of the number of protons they contain.)

Cosmic rays reach Earth in substantial numbers, and we can determine their properties either by capturing them directly or by observing the reactions that occur when they collide with atoms in our atmosphere. The total energy deposited by cosmic rays in Earth's atmosphere is only about one-billionth the energy received from the Sun, but it is comparable to the energy received in the form of starlight. Some of the cosmic rays come to Earth from the surface of the Sun, but most come from outside the solar system.

Where Do They Come From?

There is a serious problem in identifying the source of cosmic rays. Since light travels in straight lines, we can tell where it comes from simply by looking. Cosmic rays are charged particles, and their direction of motion can be changed by magnetic fields. The paths of cosmic rays are curved both by magnetic fields in interstellar space and by Earth's own field. Calculations show that low-energy cosmic rays may spiral many times around Earth before entering the atmosphere where we can detect them. If an airplane circles an airport many times before landing, it is difficult for an observer to determine the direction from which it originated. So, too, after a cosmic ray circles Earth several times, it is impossible to know where its journey began.

There are a few clues, however, about where cosmic rays might be generated. We know, for example, that magnetic fields in interstellar space are strong enough to keep all but the most energetic cosmic rays from escaping the Galaxy. It therefore seems likely that they are produced somewhere inside the Galaxy. The only likely exceptions are those with the very highest energy. Such cosmic rays move so rapidly that they are not significantly influenced by interstellar magnetic fields, and thus, they could escape our Galaxy. By analogy, they could escape other galaxies as well, so some of the highest-energy cosmic rays that we detect may have been created in some distant galaxy. Still, most cosmic rays must have their source inside the Milky Way Galaxy.

We can also estimate how far typical cosmic rays travel before striking Earth. The light elements lithium, beryllium, and boron hold the key. Since these elements are formed when carbon, nitrogen, and oxygen strike interstellar protons, we can calculate how long, on average, cosmic rays must travel through space in order to experience enough collisions to account for the amount of lithium and the other light elements that they contain. It turns out that the required distance is about 30 times around the Galaxy. At speeds near the speed of light, it takes perhaps 3–10 million years for the average cosmic ray to travel this distance. This is only a small fraction of the age of the Galaxy or the universe, so cosmic rays must have been created fairly recently on a cosmic timescale.

The best candidates for a source of cosmic rays are the supernova explosions, which mark the violent deaths of some stars (and which we will discuss in **The Death of Stars**). The material ejected by the explosion produces a shock wave, which travels through the interstellar medium. Charged particles can become trapped, bouncing back and forth across the front of the shock wave many times. With each pass through the shock, the magnetic fields inside it accelerate the particles more and more. Eventually, they are traveling at close to the speed of light and can escape from the shock to become cosmic rays. Some collapsed stars (including star remnants left over from supernova explosions) may, under the right circumstances, also serve as accelerators of particles. In any case, we again find that the raw material of the Galaxy is enriched by the life cycle of stars. In the next section, we will look at this enrichment process in more detail.

LINK TO LEARNING

You can watch a **brief video about the Calorimetric Electron Telescope (CALET) (https://openstax.org/l/30CALETvid)** mission, a cosmic ray detector at the International Space Station. The link takes you to NASA Johnson's "Space Station Live: Cosmic Ray Detector for ISS."

20.5 THE LIFE CYCLE OF COSMIC MATERIAL

Learning Objectives

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

- Explain how interstellar matter flows into and out of our Galaxy and transforms from one phase to another, and understand how star formation and evolution affects the properties of the interstellar medium
- Explain how the heavy elements and dust grains found in interstellar space got there and describe how dust grains help produce molecules that eventually find their way into planetary systems

Flows of Interstellar Gas

The most important thing to understand about the interstellar medium is that it is not static. Interstellar gas orbits through the Galaxy, and as it does so, it can become more or less dense, hotter and colder, and change its state of ionization. A particular parcel of gas may be neutral hydrogen at some point, then find itself near a young, hot star and become part of an H II region. The star may then explode as a supernova, heating the nearby gas up to temperatures of millions of degrees. Over millions of years, the gas may cool back down and become neutral again, before it collects into a dense region that gravity gathers into a giant molecular cloud (Figure 20.18)

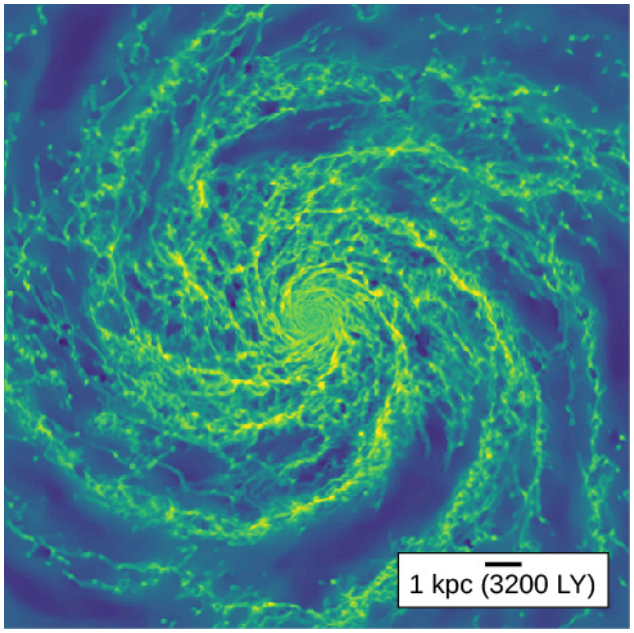


Figure 20.18 Large-Scale Distribution of Interstellar Matter. This image is from a computer simulation of the Milky Way Galaxy's interstellar medium as a whole. The majority of gas, visible in greenish colors, is neutral hydrogen. In the densest regions in the spiral arms, shown in yellow, the gas is collected into giant molecular clouds. Low-density holes in the spiral arms, shown in blue, are the result of supernova explosions. (credit: modification of work by Mark Krumholz)

At any given time in the Milky Way, the majority of the interstellar gas by mass and volume is in the form of atomic hydrogen. The much-denser molecular clouds occupy a tiny fraction of the volume of interstellar space but add roughly 30% to the total mass of gas between the stars. Conversely, the hot gas produced by supernova explosions contributes a negligible mass but occupies a significant fraction of the volume of interstellar space. H II regions, though they are visually spectacular, constitute only a very small fraction of either the mass or

volume of interstellar material.

However, the interstellar medium is not a closed system. Gas from intergalactic space constantly falls onto the Milky Way due to its gravity, adding new gas to the interstellar medium. Conversely, in giant molecular clouds where gas collects together due to gravity, the gas can collapse to form new stars, as discussed in **The Birth of Stars and the Discovery of Planets outside the Solar System**. This process locks interstellar matter into stars. As the stars age, evolve, and eventually die, massive stars lose a large fraction of their mass, and low-mass stars lose very little. On average, roughly one-third of the matter incorporated into stars goes back into interstellar space. Supernova explosions have so much energy that they can drive interstellar mass out of the Galaxy and back into intergalactic space. Thus, the total amount of mass of the interstellar medium is set by a competition between the gain of mass from intergalactic space, the conversion of interstellar mass into stars, and the loss of interstellar mass back into intergalactic space due to supernovae. This entire process is known as the **baryon cycle**—baryon is from the Latin word for "heavy," and the cycle has this name because it is the repeating process that the heavier components of the universe—the atoms—undergo.

The Cycle of Dust and Heavy Elements

While much of the mass of the interstellar medium is material accreted during the last few billion years from intergalactic space, this is not true of the elements heavier than hydrogen and helium, or of the dust. Instead, these components of the interstellar medium were made inside stars in the Milky Way, which returned them to the interstellar medium at the end of their lives. We will talk more about this process in later chapters, but for now just bear in mind what we learned in **The Sun: A Nuclear Powerhouse**. What stars "do for a living" is fuse heavier elements from lighter ones, producing energy in the process. As stars mature, they begin to lose some of the newly made elements to the reservoir of interstellar matter.

The same is true of dust grains. Dust forms when grains can condense in regions where gas is dense and cool. One place where the right conditions are found is the winds from luminous cool stars (the red giants and supergiants we discussed in **The Stars: A Celestial Census**). Grains can also condense in the matter thrown off by a supernova explosion as the ejected gases begin to cool.

The dust grains produced by stars may grow even further when they spend time in the dense parts of the interstellar medium, inside molecular clouds. In these environments, grains can stick together or gather additional atoms from the gas around them, growing larger. They also facilitate the production of other compounds, including some of the more complex molecules we discussed earlier.

The surfaces of the dust grains (see **Cosmic Dust**)—which would seem very large if you were an atom—provide "nooks and crannies" where these atoms can stick long enough to find partners and form molecules. (Think of the dust grains as "interstellar social clubs" where lonely atoms can meet and form meaningful relationships.) Eventually, the dust grains become coated with ices. The presence of the dust shields the molecules inside the clouds from ultraviolet radiation and cosmic rays that would break them up.

When stars finally begin to form within the cloud, they heat the grains and evaporate the ices. The gravitational attraction of the newly forming stars also increases the density of the surrounding cloud material. Many more chemical reactions take place on the surfaces of grains in the gas surrounding the newly forming stars, and these areas are where organic molecules are formed. These molecules can be incorporated into newly formed planetary systems, and the early Earth may have been seeded in just such a way.

Indeed, scientists speculate that some of the water on Earth may have come from interstellar grains. Recent observations from space have shown that water is abundant in dense interstellar clouds. Since stars are formed from this material, water must be present when solar systems, including our own, come into existence. The water in our oceans and lakes may have come initially from water locked into the rocky material that accreted

to form Earth. Alternatively, the water may have been brought to Earth when asteroids and comets (formed from the same cloud that made the planets) later impacted it. Scientists estimate that one comet impact every thousand years during Earth's first billion years would have been enough to account for the water we see today. Of course, both sources may have contributed to the water we now enjoy drinking and swimming in.

Any interstellar grains that are incorporated into newly forming stars (instead of the colder planets and smaller bodies around them) will be destroyed by their high temperatures. But eventually, each new generation of stars will evolve to become red giants, with stellar winds of their own. Some of these stars will also become supernovae and explode. Thus, the process of recycling cosmic material can start all over again.

20.6 INTERSTELLAR MATTER AROUND THE SUN

Learning Objectives

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

- Describe how interstellar matter is arranged around our solar system
- Explain why scientists think that the Sun is located in a hot bubble

We want to conclude our discussion of interstellar matter by asking how this material is organized in our immediate neighborhood. As we discussed above, orbiting X-ray observatories have shown that the Galaxy is full of bubbles of hot, X-ray-emitting gas. They also revealed a diffuse background of X-rays that appears to fill the entire sky from our perspective (**Figure 20.19**). While some of this emission comes from the interaction of the solar wind with the interstellar medium, a majority of it comes from beyond the solar system. The natural explanation for why there is X-ray-emitting gas all around us is that the Sun is itself inside one of the bubbles. We therefore call our "neighborhood" the Local Hot Bubble, or **Local Bubble** for short. The Local Bubble is much less dense—an average of approximately 0.01 atoms per cm^3—than the average interstellar density of about 1 atom per cm^3. This local gas has a temperature of about a million degrees, just like the gas in the other superbubbles that spread throughout our Galaxy, but because there is so little hot material, this high temperature does not affect the stars or planets in the area in any way.

What caused the Local Bubble to form? Scientists are not entirely sure, but the leading candidate is winds from stars and supernova explosions. In a nearby region in the direction of the constellations Scorpius and Centaurus, a lot of star formation took place about 15 million years ago. The most massive of these stars evolved very quickly until they produced strong winds, and some ended their lives by exploding. These processes filled the region around the Sun with hot gas, driving away cooler, denser gas. The rim of this expanding superbubble reached the Sun about 7.6 million years ago and now lies more than 200 light-years past the Sun in the general direction of the constellations of Orion, Perseus, and Auriga.

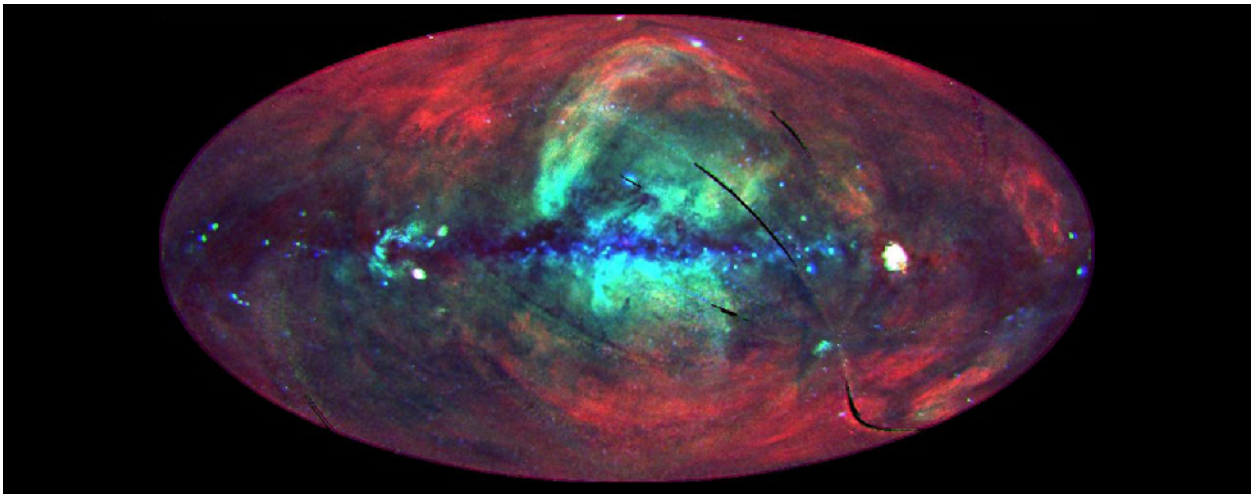


Figure 20.19 Sky in X-Rays. This image, made by the ROSAT satellite, shows the whole sky in X-rays as seen from Earth. Different colors indicate different X-ray energies: red is 0.25 kiloelectron volts, green is 0.75 kiloelectron volts, and blue is 1.5 kiloelectron volts. The image is oriented so the plane of the Galaxy runs across the middle of the image. The ubiquitous red color, which does not disappear completely even in the galactic plane, is evidence for a source of X-rays all around the Sun. (credit: modification of work by NASA)

A few clouds of interstellar matter do exist within the Local Bubble. The Sun itself seems to have entered a cloud about 10,000 years ago. This cloud is warm (with a temperature of about 7000 K) and has a density of 0.3 hydrogen atom per cm^3—higher than most of the Local Bubble but still so tenuous that it is also referred to as **Local Fluff** (Figure 20.20). (Aren't these astronomical names fun sometimes?)

While this is a pretty thin cloud, we estimate that it contributes 50 to 100 times more particles than the solar wind to the diffuse material between the planets in our solar system. These interstellar particles have been detected and their numbers counted by the spacecraft traveling between the planets. Perhaps someday, scientists will devise a way to collect them without destroying them and to return them to Earth, so that we can touch—or at least study in our laboratories—these messengers from distant stars.

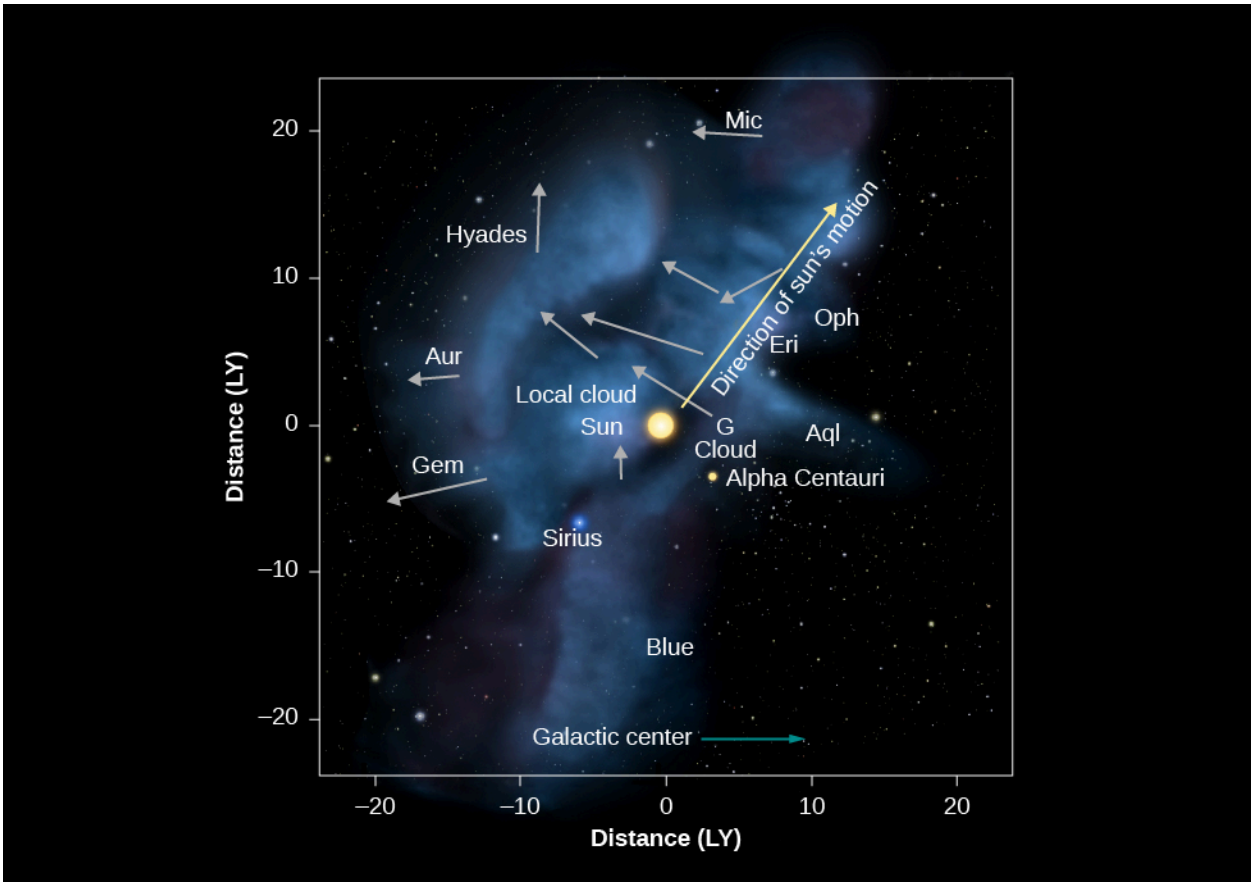


Figure 20.20 Local Fluff. The Sun and planets are currently moving through the Local Interstellar Cloud, which is also called the Local Fluff. Fluff is an appropriate description because the density of this cloud is only about 0.3 atom per cm^3. In comparison, Earth's atmosphere at the edge of space has around 1.2×10^{13} molecules per cm^3. This image shows the patches of interstellar matter (mostly hydrogen gas) within about 20 light-years of the Sun. The temperature of the Local Interstellar Cloud is about 7000 K. The arrows point toward the directions that different parts of the cloud are moving. The names associated with each arrow indicate the constellations located on the sky toward which the parts of the cloud are headed. The solar system is thought to have entered the Local Interstellar Cloud, which is a small cloud located within a much larger superbubble that is expanding outward from the Scorpius-Centaurus region of the sky, at some point between 44,000 and 150,000 years ago and is expected to remain within it for another 10,000 to 20,000 years. (credit: modification of work by NASA/Goddard/Adler/University Chicago/Wesleyan)

CHAPTER 20 REVIEW

KEY TERMS

baryon cycle the cycling of mass in and out of the interstellar medium, including accretion of gas from intergalactic space, loss of gas back into intergalactic space, and conversion of interstellar gas into stars

cosmic rays atomic nuclei (mostly protons) and electrons that are observed to strike Earth's atmosphere with exceedingly high energies.

H II region the region of ionized hydrogen in interstellar space

interstellar dust tiny solid grains in interstellar space thought to consist of a core of rocklike material (silicates) or graphite surrounded by a mantle of ices; water, methane, and ammonia are probably the most abundant ices

interstellar extinction the attenuation or absorption of light by dust in the interstellar medium

interstellar medium (ISM) (or interstellar matter) the gas and dust between the stars in a galaxy

Local Bubble (or Local Hot Bubble) a region of low-density, million degree gas in which the Sun and solar system are currently located

Local Fluff a slightly denser cloud inside the Local Bubble, inside which the Sun also lies

molecular cloud a large, dense, cold interstellar cloud; because of its size and density, this type of cloud can keep ultraviolet radiation from reaching its interior, where molecules are able to form

nebula a cloud of interstellar gas or dust; the term is most often used for clouds that are seen to glow with visible light or infrared

reddening (interstellar) the reddening of starlight passing through interstellar dust because dust scatters blue light more effectively than red

SUMMARY

20.1 The Interstellar Medium

About 15% of the visible matter in the Galaxy is in the form of gas and dust, serving as the raw material for new stars. About 99% of this interstellar matter is in the form of gas—individual atoms or molecules. The most abundant elements in the interstellar gas are hydrogen and helium. About 1% of the interstellar matter is in the form of solid interstellar dust grains.

20.2 Interstellar Gas

Interstellar gas may be hot or cold. Gas found near hot stars emits light by fluorescence, that is, light is emitted when an electron is captured by an ion and cascades down to lower-energy levels. Glowing clouds (nebulae) of ionized hydrogen are called H II regions and have temperatures of about 10,000 K. Most hydrogen in interstellar space is not ionized and can best be studied by radio measurements of the 21-centimeter line. Some of the gas in interstellar space is at a temperature of a million degrees, even though it is far away in hot stars; this ultra-hot gas is probably heated when rapidly moving gas ejected in supernova explosions sweeps through space. In some places, gravity gathers interstellar gas into giant clouds, within which the gas is protected from

starlight and can form molecules; more than 200 different molecules have been found in space, including the basic building blocks of proteins, which are fundamental to life as we know it here on Earth.

20.3 Cosmic Dust

Interstellar dust can be detected: (1) when it blocks the light of stars behind it, (2) when it scatters the light from nearby stars, and (3) because it makes distant stars look both redder and fainter. These effects are called reddening and interstellar extinction, respectively. Dust can also be detected in the infrared because it emits heat radiation. Dust is found throughout the plane of the Milky Way. The dust particles are about the same size as the wavelength of light and consist of rocky cores that are either sootlike (carbon-rich) or sandlike (silicates) with mantles made of ices such as water, ammonia, and methane.

20.4 Cosmic Rays

Cosmic rays are particles that travel through interstellar space at a typical speed of 90% of the speed of light. The most abundant elements in cosmic rays are the nuclei of hydrogen and helium, but electrons and positrons are also found. It is likely that many cosmic rays are produced in supernova shocks.

20.5 The Life Cycle of Cosmic Material

Interstellar matter is constantly flowing through the Galaxy and changing from one phase to another. At the same time, gas is constantly being added to the Galaxy by accretion from extragalactic space, while mass is removed from the interstellar medium by being locked in stars. Some of the mass in stars is, in turn, returned to the interstellar medium when those stars evolve and die. In particular, the heavy elements in interstellar space were all produced inside stars, while the dust grains are made in the outer regions of stars that have swelled to be giants. These elements and grains, in turn, can then be incorporated into new stars and planetary systems that form out of the interstellar medium.

20.6 Interstellar Matter around the Sun

The Sun is located at the edge of a low-density cloud called the Local Fluff. The Sun and this cloud are located within the Local Bubble, a region extending to at least 300 light-years from the Sun, within which the density of interstellar material is extremely low. Astronomers think this bubble was blown by some nearby stars that experienced a strong wind and some supernova explosions.

FOR FURTHER EXPLORATION

Articles

Goodman, A. “Recycling the Universe.” *Sky & Telescope* November (2000): 44. Review of how stellar evolution, the interstellar medium, and supernovae all work together to recycle cosmic material.

Greenberg, J. “The Secrets of Stardust.” *Scientific American* December (2000): 70. The makeup and evolutionary role of solid particles between the stars.

Knapp, G. “The Stuff between the Stars.” *Sky & Telescope* May (1995): 20. An introduction to the interstellar medium.

Nadis, S. “Searching for the Molecules of Life in Space.” *Sky & Telescope* January (2002): 32. Recent observations of water in the interstellar medium by satellite telescopes.

Olinto, A. “Solving the Mystery of Cosmic Rays.” *Astronomy* April (2014): 30. What accelerates them to such high energies.

Reynolds, R. “The Gas between the Stars.” *Scientific American* January (2002): 34. On the interstellar medium.

Websites And Apps

Barnard, E. E., Biographical Memoir: http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/barnard-edward.pdf (http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/barnard-edward.pdf) .

Cosmicopia: http://helios.gsfc.nasa.gov/cosmic.html (http://helios.gsfc.nasa.gov/cosmic.html) . NASA's learning site explains about the history and modern understanding of cosmic rays.

DECO: https://wipac.wisc.edu/deco (https://wipac.wisc.edu/deco) . A smart-phone app for turning your phone into a cosmic-ray detector.

Hubble Space Telescope Images of Nebulae: http://hubblesite.org/gallery/album/nebula/ (http://hubblesite.org/gallery/album/nebula/) . Click on any of the beautiful images in this collection, and you are taken to a page with more information; while looking at these images, you may also want to browse through the slide sequence on the meaning of colors in the Hubble pictures (http://hubblesite.org/gallery/behind_the_pictures/meaning_of_color/ (http://hubblesite.org/gallery/behind_the_pictures/meaning_of_color/)).

Interstellar Medium Online Tutorial: http://www-ssg.sr.unh.edu/ism/ (http://www-ssg.sr.unh.edu/ism/) . Nontechnical introduction to the interstellar medium (ISM) and how we study it; by the University of New Hampshire astronomy department.

Messier Catalog of Nebulae, Clusters, and Galaxies: http://astropixels.com/messier/messiercat.html (http://astropixels.com/messier/messiercat.html) . Astronomer Fred Espenak provides the full catalog, with information and images. (The Wikipedia list does something similar: https://en.wikipedia.org/wiki/List_of_Messier_objects (https://en.wikipedia.org/wiki/List_of_Messier_objects) .

Nebulae: What Are They?: http://www.universetoday.com/61103/what-is-a-nebula/ (http://www.universetoday.com/61103/what-is-a-nebula/) . Concise introduction by Matt Williams.

Videos

Barnard 68: The Hole in the Sky: https://www.youtube.com/watch?v=Faz5rgdQSo4 (https://www.youtube.com/watch?v=Faz5rgdQSo4) . About this dark cloud and dark clouds in interstellar space in general (02:08).

Horsehead Nebula in New Light: http://www.esa.int/spaceinvideos/Videos/2013/04/The_Horsehead_Nebula_in_new_light (http://www.esa.int/spaceinvideos/Videos/2013/04/The_Horsehead_Nebula_in_new_light) . Tour of the dark nebula in different wavelengths; no audio narration, just music, but explanatory material appears on the screen (03:03).

Hubblecast 65: A Whole New View of the Horsehead Nebula: http://www.spacetelescope.org/videos/heic1307a/ (http://www.spacetelescope.org/videos/heic1307a/) . Report on nebulae in general and about the Horsehead specifically, with ESO astronomer Joe Liske (06:03).

Interstellar Reddening: https://www.youtube.com/watch?v=H2M80RAQB6k (https://www.youtube.com/watch?v=H2M80RAQB6k) . Video demonstrating how reddening works, with Scott Miller of Penn State; a bit nerdy but useful (03:45).

COLLABORATIVE GROUP ACTIVITIES

A. The Sun is located in a region where the density of interstellar matter is low. Suppose that instead it were located in a dense cloud 20 light-years in diameter that dimmed the visible light from stars lying outside it by a factor of 100. Have your group discuss how this would have affected the development of civilization on Earth. For example, would it have presented a problem for early navigators?

B. Your group members should look through the pictures in this chapter. How big are the nebulae you see in the images? Are there any clues either in the images or in the captions? Are the clouds they are part of significantly bigger than the nebulae we can see? Why? Suggest some ways that we can determine the sizes of nebulae.

C. How do the members of your group think astronomers are able to estimate the distances of such nebulae in our own Galaxy? (Hint: Look at the images. Can you see anything between us and the nebula in some cases. Review **Celestial Distances**, if you need to remind yourself about methods of measuring distances.)

D. The text suggests that a tube of air extending from the surface of Earth to the top of the atmosphere contains more atoms than a tube of the same diameter extending from the top of the atmosphere to the edge of the observable universe. Scientists often do what they call "back of the envelope calculations," in which they make very rough approximations just to see whether statements or ideas are true. Try doing such a "quick and dirty" estimate for this statement with your group. What are the steps in comparing the numbers of atoms contained in the two different tubes? What information do you need to make the approximations? Can you find it in this text? And is the statement true?

E. If your astronomy course has involved learning about the solar system before you got to this chapter, have your group discuss where else besides interstellar clouds astronomers have been discovering organic molecules (the chemical building blocks of life). How might the discoveries of such molecules in our own solar system be related to the molecules in the clouds discussed in this chapter?

F. Two stars both have a reddish appearance in telescopes. One star is actually red; the other's light has been reddened by interstellar dust on its way to us. Have your group make a list of the observations you could perform to determine which star is which.

G. You have been asked to give a talk to your little brother's middle school class on astronomy, and you decide to talk about how nature recycles gas and dust. Have your group discuss what images from this book you would use in your talk. In what order? What is the one big idea you would like the students to remember when the class is over?

H. This chapter and the next (on **The Birth of Stars**) include some of the most beautiful images of nebulae that glow with the light produced when starlight interacts with gas and dust. Have your group select one to four of your favorite such nebulae and prepare a report on them to share with the rest of the class. (Include such things as their location, distance, size, way they are glowing, and what is happening within them.)

EXERCISES

Review Questions

1. Identify several dark nebulae in photographs in this chapter. Give the figure numbers of the photographs, and specify where the dark nebulae are to be found on them.
2. Why do nebulae near hot stars look red? Why do dust clouds near stars usually look blue?
3. Describe the characteristics of the various kinds of interstellar gas (HII regions, neutral hydrogen clouds, ultra-hot gas clouds, and molecular clouds).
4. Prepare a table listing the different ways in which dust and gas can be detected in interstellar space.
5. Describe how the 21-cm line of hydrogen is formed. Why is this line such an important tool for understanding the interstellar medium?
6. Describe the properties of the dust grains found in the space between stars.
7. Why is it difficult to determine where cosmic rays come from?
8. What causes reddening of starlight? Explain how the reddish color of the Sun's disk at sunset is caused by the same process.
9. Why do molecules, including H_2 and more complex organic molecules, only form inside dark clouds? Why don't they fill all interstellar space?
10. Why can't we use visible light telescopes to study molecular clouds where stars and planets form? Why do infrared or radio telescopes work better?
11. The mass of the interstellar medium is determined by a balance between sources (which add mass) and sinks (which remove it). Make a table listing the major sources and sinks, and briefly explain each one.
12. Where does interstellar dust come from? How does it form?

Thought Questions

13. **Figure 20.2** shows a reddish glow around the star Antares, and yet the caption says that is a dust cloud. What observations would you make to determine whether the red glow is actually produced by dust or whether it is produced by an H II region?
14. If the red glow around Antares is indeed produced by reflection of the light from Antares by dust, what does its red appearance tell you about the likely temperature of Antares? Look up the spectral type of Antares in **Appendix J**. Was your estimate of the temperature about right? In most of the images in this chapter, a red glow is associated with ionized hydrogen. Would you expect to find an H II region around Antares? Explain your answer.
15. Even though neutral hydrogen is the most abundant element in interstellar matter, it was detected first with a radio telescope, not a visible light telescope. Explain why. (The explanation given in **Analyzing Starlight** for the fact that hydrogen lines are not strong in stars of all temperatures may be helpful.)
16. The terms H II and H_2 are both pronounced "H two." What is the difference in meaning of those two terms? Can there be such a thing as H III?
17. Suppose someone told you that she had discovered H II around the star Aldebaran. Would you believe her? Why or why not?

18. Describe the spectrum of each of the following:

A. starlight reflected by dust,

B. a star behind invisible interstellar gas, and

C. an emission nebula.

19. According to the text, a star must be hotter than about 25,000 K to produce an H II region. Both the hottest white dwarfs and main-sequence O stars have temperatures hotter than 25,000 K. Which type of star can ionize more hydrogen? Why?

20. From the comments in the text about which kinds of stars produce emission nebulae and which kinds are associated with reflection nebulae, what can you say about the temperatures of the stars that produce NGC 1999 (**Figure 20.13**)?

21. One way to calculate the size and shape of the Galaxy is to estimate the distances to faint stars just from their observed apparent brightnesses and to note the distance at which stars are no longer observable. The first astronomers to try this experiment did not know that starlight is dimmed by interstellar dust. Their estimates of the size of the Galaxy were much too small. Explain why.

22. New stars form in regions where the density of gas and dust is relatively high. Suppose you wanted to search for some recently formed stars. Would you more likely be successful if you observed at visible wavelengths or at infrared wavelengths? Why?

23. Thinking about the topics in this chapter, here is an Earth analogy. In big cities, you can see much farther on days without smog. Why?

24. Stars form in the Milky Way at a rate of about 1 solar mass per year. At this rate, how long would it take for all the interstellar gas in the Milky Way to be turned into stars if there were no fresh gas coming in from outside? How does this compare to the estimated age of the universe, 14 billion years? What do you conclude from this?

25. The 21-cm line can be used not just to find out where hydrogen is located in the sky, but also to determine how fast it is moving toward or away from us. Describe how this might work.

26. Astronomers recently detected light emitted by a supernova that was originally observed in 1572, just reaching Earth now. This light was reflected off a dust cloud; astronomers call such a reflected light a “light echo” (just like reflected sound is called an echo). How would you expect the spectrum of the light echo to compare to that of the original supernova?

27. We can detect 21-cm emission from other galaxies as well as from our own Galaxy. However, 21-cm emission from our own Galaxy fills most of the sky, so we usually see both at once. How can we distinguish the extragalactic 21-cm emission from that arising in our own Galaxy? (Hint: Other galaxies are generally moving relative to the Milky Way.)

28. We have said repeatedly that blue light undergoes more extinction than red light, which is true for visible and shorter wavelengths. Is the same true for X-rays? Look at **Figure 20.19**. The most dust is in the galactic plane in the middle of the image, and the red color in the image corresponds to the reddest (lowest-energy) light. Based on what you see in the galactic plane, are X-rays experiencing more extinction at redder or bluer colors? You might consider comparing **Figure 20.19** to **Figure 20.14**.

29. Suppose that, instead of being inside the Local Bubble, the Sun were deep inside a giant molecular cloud. What would the night sky look like as seen from Earth at various wavelengths?

30. Suppose that, instead of being inside the Local Bubble, the Sun were inside an H II region. What would the night sky look like at various wavelengths?

Figuring For Yourself

31. A molecular cloud is about 1000 times denser than the average of the interstellar medium. Let's compare this difference in densities to something more familiar. Air has a density of about 1 kg/m^3, so something 1000 times denser than air would have a density of about 1000 kg/m^3. How does this compare to the typical density of water? Of granite? (You can find figures for these densities on the internet.) Is the density difference between a molecular cloud and the interstellar medium larger or smaller than the density difference between air and water or granite?

32. Would you expect to be able to detect an H II region in X-ray emission? Why or why not? (Hint: You might apply Wien's law)

33. Suppose that you gathered a ball of interstellar gas that was equal to the size of Earth (a radius of about 6000 km). If this gas has a density of 1 hydrogen atom per cm^3, typical of the interstellar medium, how would its mass compare to the mass of a bowling ball (5 or 6 kg)? How about if it had the typical density of the Local Bubble, about 0.01 atoms per cm^3? The volume of a sphere is $V = (4/3)\pi R^3$.

34. At the average density of the interstellar medium, 1 atom per cm^3, how big a volume of material must be used to make a star with the mass of the Sun? What is the radius of a sphere this size? Express your answer in light-years.

35. Consider a grain of sand that contains 1 mg of oxygen (a typical amount for a medium-sized sand grain, since sand is mostly SiO_2). How many oxygen atoms does the grain contain? What is the radius of the sphere you would have to spread them out over if you wanted them to have the same density as the interstellar medium, about 1 atom per cm^3? You can look up the mass of an oxygen atom.

36. H II regions can exist only if there is a nearby star hot enough to ionize hydrogen. Hydrogen is ionized only by radiation with wavelengths shorter than 91.2 nm. What is the temperature of a star that emits its maximum energy at 91.2 nm? (Use Wien's law from **Radiation and Spectra**.) Based on this result, what are the spectral types of those stars likely to provide enough energy to produce H II regions?

37. In the text, we said that the five-times ionized oxygen (OVI) seen in hot gas must have been produced by supernova shocks that heated the gas to millions of degrees, and not by starlight, the way H II is produced. Producing OVI by light requires wavelengths shorter than 10.9 nm. The hottest observed stars have surface temperatures of about 50,000 K. Could they produce OVI?

38. Dust was originally discovered because the stars in certain clusters seemed to be fainter than expected. Suppose a star is behind a cloud of dust that dims its brightness by a factor of 100. Suppose you do not realize the dust is there. How much in error will your distance estimate be? Can you think of any measurement you might make to detect the dust?

39. How would the density inside a cold cloud (T = 10 K) compare with the density of the ultra-hot interstellar gas ($T = 10^6$ K) if they were in pressure equilibrium? (It takes a large cloud to be able to shield its interior from heating so that it can be at such a low temperature.) (Hint: In pressure equilibrium, the two regions must have nT equal, where n is the number of particles per unit volume and T is the temperature.) Which region do you think is more suitable for the creation of new stars? Why?

40. The text says that the Local Fluff, which surrounds the Sun, has a temperature of 7500 K and a density 0.1 atom per cm^3. The Local Fluff is embedded in hot gas with a temperature of 10^6 K and a density of about 0.01 atom per cm^3. Are they in equilibrium? (Hint: In pressure equilibrium, the two regions must have nT equal, where n is the number of particles per unit volume and T is the temperature.) What is likely to happen to the Local Fluff?