"All men have the stars," he answered, "but they are not the same things for different people. For some, who are travelers, the stars are guides. For others they are no more than little lights in the sky. For others, who are scholars, they are problems. For my businessman they were wealth. But all these stars are silent. You—you alone—will have the stars as no one else has them."

—Antoine de Saint-Exupéry, from *The Little Prince*

On a clear, dark night, a few thousand stars are visible to the naked eye. Many more become visible through binoculars, and a powerful telescope reveals so many stars that we could never hope to count them. Like each individual person, each individual star is unique. Like all humans, all stars have much in common.

Today, we know that stars are born from clouds of interstellar gas, shine brilliantly by nuclear fusion for millions to billions of years, and then die, sometimes in dramatic ways. In this chapter, we'll discuss how we study and categorize stars and how we have come to realize that stars, like people, change over their lifetimes.

15.1 PROPERTIES OF STARS

Imagine that an alien spaceship flies by Earth on a simple but short mission: The visitors have just 1 minute to learn everything they can about the human race. In 60 seconds, they will see next to nothing of any individual person's life. Instead, they will obtain a collective "snapshot" of humanity that shows people from all stages of life engaged in their daily activities. From this snapshot alone, they must piece together their entire understanding of human beings and their lives, from birth to death.

We face a similar problem when we look at the stars. Compared with stellar lifetimes of millions or billions of years, the few hundred years humans have spent studying stars with telescopes is rather like the aliens' 1-minute glimpse of humanity. We see only a brief moment in any star's life, and our collective snapshot of the heavens consists of such frozen moments for billions of stars. From this snapshot, we try to reconstruct the life cycles of stars.

Thanks to the efforts of hundreds of astronomers studying this snapshot of the heavens, stars are no longer mysterious points of light in the sky. We now know that all stars have much in common with the Sun. They all form in great clouds of gas and dust, and each one begins its life with roughly the same chemical composition as the Sun: About three-quarters of a star's mass at birth is hydrogen, and about one-quarter is helium, with no more than about 2% consisting of elements heavier than helium. Nevertheless, stars are not all the same; they differ in such properties as size, age, brightness, and temperature. We'll devote most of this and the next two chapters to understanding how and why stars differ. First, however, let's explore how we measure three of the most fundamental properties of stars: luminosity, surface temperature, and mass.

How do we measure stellar luminosities?

If you go outside on any clear night, you'll immediately see that stars differ in brightness. Some stars are so bright that we can use them to identify constellations [Section 2.1]. Others are so dim that our naked eyes cannot see them at all. However, these differences in brightness do not by themselves tell us anything about how much light these stars are generating, because the brightness of a star depends on its distance as well as on how much light it actually emits. For example, the stars Procyon and Betelgeuse, which make up two of the three corners of the Winter Triangle (see Figure 2.2), appear about equally bright in our sky. However, Betelgeuse actually emits about 5000 times as much light as Procyon. It has about the same brightness in our sky because it is much farther away.

SEE IT FOR YOURSELF

Until the 20th century, people classified stars primarily by their brightness and location in our sky. On the next clear night, find a favorite constellation and visually rank the stars by brightness. Then look to see how that constellation is represented on the star charts in Appendix I. Why do the star charts use different size dots for different stars? Do the brightness rankings on the star chart agree with what you see?

Because two similar-looking stars can be generating very different amounts of light, we need to distinguish clearly between a star's brightness in our sky and the actual amount of light that it emits into space (Figure 15.1):

- When we talk about how bright stars look in our sky, we are talking about **apparent brightness**—the brightness of a star as it appears to our eyes. We define the apparent brightness of any star in our sky as the amount of power (energy per second) reaching us *per unit area.* (A more technical term for apparent brightness is *flux.*)

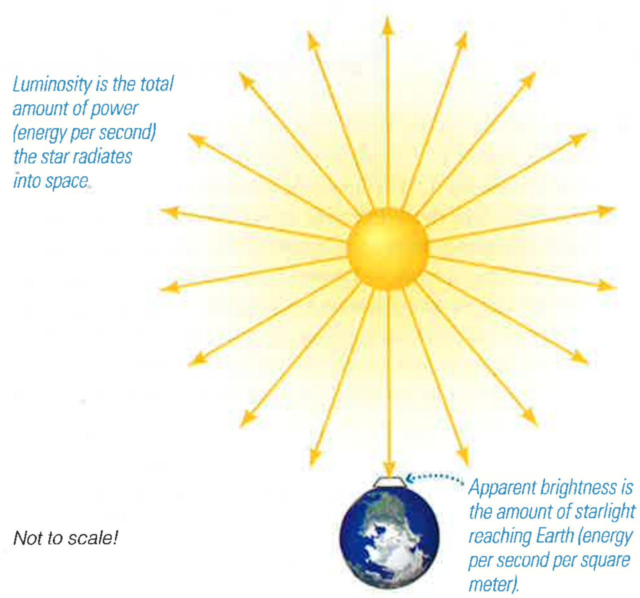

FIGURE 15.1 Luminosity is a measure of power, and apparent brightness is a measure of power per unit area.

- When we talk about how bright stars are in an absolute sense, regardless of their distance, we are talking about **luminosity**—the total amount of power that a star emits into space.

We can understand the difference between apparent brightness and luminosity by thinking about a 100-watt light bulb. The bulb always puts out the same amount of light, so its luminosity doesn't vary. However, its apparent brightness depends on your distance from the bulb: It will look quite bright if you stand very close to it, but quite dim if you are far away.

The Inverse Square Law for Light The apparent brightness of a star or any other light source obeys an *inverse square law* with distance, much like the inverse square law that describes the force of gravity [Section 4.4]. For example, if we viewed the Sun from twice Earth's distance, it would appear dimmer by a factor of $2^2 = 4$. If we viewed it from 10 times Earth's distance, it would appear dimmer by a factor of $10^2 = 100$.

Figure 15.2 shows why apparent brightness follows an inverse square law. The same total amount of light must pass through each imaginary sphere surrounding the star. If we focus on the light passing through the small square on the sphere located at 1 AU, we see that the same amount of light must pass through *four* squares of the same size on the sphere located at 2 AU. Each square on the sphere at 2 AU therefore receives only $\frac{1}{2^2} = \frac{1}{4}$ as much light as the square on the sphere at 1 AU. Similarly, the same amount of light passes through *nine* squares of the same size on the sphere located at 3 AU, so each of these squares receives only $\frac{1}{3^2} = \frac{1}{9}$ as much light as the square on the sphere at 1 AU. Generalizing, the amount of light received per unit area decreases with increasing distance by the square of the distance—an inverse square law.

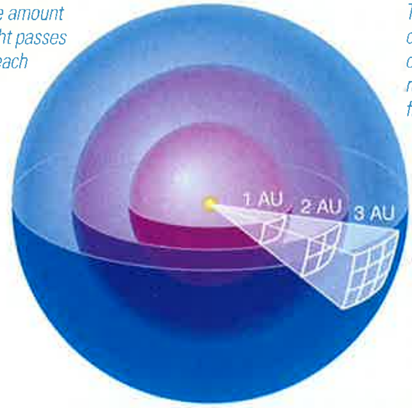

FIGURE 15.2 The inverse square law for light: The apparent brightness of a star declines with the square of its distance.

This inverse square law leads to a very simple and important formula relating the apparent brightness, luminosity, and distance of any light source. We will call it the **inverse square law for light**:

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times \text{distance}^2}$$

Because the standard units of luminosity are watts [Section 14.1], the units of apparent brightness are *watts per square meter.* (The 4π in the formula above comes from the fact that the surface area of a sphere is given by $4\pi \times \text{radius}^2$.)

In principle, we can always determine a star's apparent brightness by carefully measuring the amount of light we receive from the star per square meter. We can then use the inverse square law to calculate a star's luminosity if we can first measure its distance, or to calculate a star's distance if we somehow know its luminosity.

MATHEMATICAL INSIGHT 15.1

The Inverse Square Law for Light

We can derive the inverse square law for light by extending the idea illustrated in Figure 15.2. Suppose we are located a distance d from a star with luminosity L. The apparent brightness of the star is the power per unit area that we receive at our distance, d. We find this apparent brightness by imagining a giant sphere with radius d (similar to any of the three spheres in Figure 15.2) and surface area $4\pi \times d^2$. (The surface area of any sphere is $4\pi \times \text{radius}^2$.) All the star's light passes through the imaginary sphere, so the apparent brightness at any point on this sphere is simply the star's luminosity, L, divided by the sphere's surface area; carrying out the division gives us the inverse square law for light:

$$\text{apparent brightness} = \frac{\text{star's luminosity}}{\text{surface area of imaginary sphere}} = \frac{L}{4\pi \times d^2}$$

EXAMPLE: What is the Sun's apparent brightness in our sky?

SOLUTION:

Step 1 Understand: The Sun's apparent brightness is the power per unit area that we receive in the form of sunlight. We find this power with the inverse square law for light, using the Sun's luminosity and Earth's distance from the Sun; for unit consistency, we put the Earth-Sun distance in meters.

Step 2 Solve: The Sun's luminosity is $L_{Sun} = 3.8 \times 10^{26}$ watts, and Earth's distance from the Sun is $d = 1.5 \times 10^{11}$ meters. The Sun's apparent brightness is therefore

$$\frac{L}{4\pi \times d^2} = \frac{3.8 \times 10^{26}\text{ watts}}{4\pi \times (1.5 \times 10^{11}\text{ m})^2} = 1.3 \times 10^3\text{ watts/m}^2$$

Step 3 Explain: The Sun's apparent brightness is about 1300 watts per square meter at Earth's distance. This is the maximum power per unit area that could be collected by a detector on Earth that directly faces the Sun, such as a solar power (or *photovoltaic*) cell.