## 16.1 Physical Properties of the Sun

TUTORIAL SuperSpaceship—Voyage to the Sun

The Sun is the sole source of light and heat for the maintenance of life on Earth. The Sun is a **star**—a glowing ball of gas held together by its own gravity and powered by nuclear fusion at its center. In its physical and chemical properties, the Sun is similar to most other stars, regardless of when and where they formed. Indeed, our Sun appears to be a rather typical star, lying right in the middle of the observed ranges of stellar mass, radius, brightness, and composition. Far from detracting from our interest in the Sun, this very mediocrity is one of the main reasons that astronomers study it—they can apply knowledge of solar phenomena to many other stars in the universe.

### Overall Properties

The Sun's radius, roughly 700,000 km, is determined most directly by measuring the angular size (0.5°) of the Sun and then employing elementary geometry. ∞ (Sec. 1.6) The Sun's mass, $2.0 \times 10^{30}$ kg, follows from Newton's laws of motion and gravity, applied to the observed orbits of the planets. ∞ *(More Precisely 2-2)* The average solar density derived from its mass and volume, approximately 1400 kg/m$^3$, is quite similar to that of the jovian planets and about one-quarter the average density of Earth.

Solar rotation can be measured by timing sunspots and other surface features as they traverse the solar disk. ∞ (Sec. 2.4) These observations indicate that the Sun rotates in about a month, but it does not do so as a solid body. Instead, it spins *differentially*, like Jupiter and Saturn—faster at the equator and slower at the poles. ∞ (Sec. 11.1) The equatorial rotation period at the equator is about 25 days. Sunspots are never seen above latitude 60° (north or south), but at that latitude they indicate a 31-day period. Other measurement techniques, such as those discussed in Section 16.2, reveal that the Sun's rotation period continues to increase as we approach the poles. The polar rotation period is not known with certainty, but it may be as long as 36 days.

The Sun's surface temperature is measured by applying the radiation laws to the observed solar spectrum. ∞ (Sec. 3.4) The distribution of solar radiation has the approximate shape of a blackbody curve for an object at about 5800 K. The average solar temperature obtained in this way is known as the Sun's *effective temperature*.

Having a radius of more than 100 Earth radii, a mass of more than 300,000 Earth masses, and a surface temperature well above the melting point of any known material, the Sun is clearly a body that is very different from any other we have encountered so far.

### Solar Structure

The Sun has a surface of sorts—not a solid surface (the Sun contains no solid material), but rather that part of the brilliant gas ball we perceive with our eyes or view through a heavily filtered telescope. This "surface"—the part of the Sun that emits the radiation we see—is called the **photosphere**. Its radius is about 700,000 km. However, the thickness of the photosphere is probably no more than 500 km, less than 0.1 percent of the radius, which is why we perceive the Sun as having a well-defined, sharp edge (Figure 16.1).

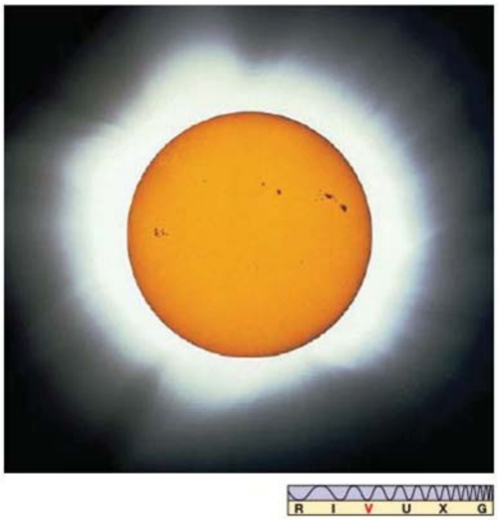
The main regions of the Sun are illustrated in Figure 16.2 and summarized in Table 16.1. We will discuss them all in more detail later in the chapter. Just above the photosphere is the Sun's lower atmosphere, called the **chromosphere**, about 1500 km thick. From 1500 km to 10,000 km above the top of the photosphere lies a region called the **transition zone**, in which the temperature rises dramatically. Above 10,000 km, and stretching far beyond, is a tenuous (thin), hot upper atmosphere: the **solar corona**. At still greater distances, the corona turns into the **solar wind**, which flows away from the Sun and permeates the entire solar system. ∞ (Sec. 6.5) Extending down some 200,000 km below the photosphere is the **convection zone**, a region where the material of the Sun is in constant convective motion. Below the convection zone lies the **radiation zone**, in which solar energy is transported toward the surface by radiation rather than by convection. The term ***solar interior*** is often used to mean both the radiation and convection zones. The central **core**, roughly 200,000 km in radius, is the site of powerful nuclear reactions that generate the Sun's enormous energy output.

### Luminosity

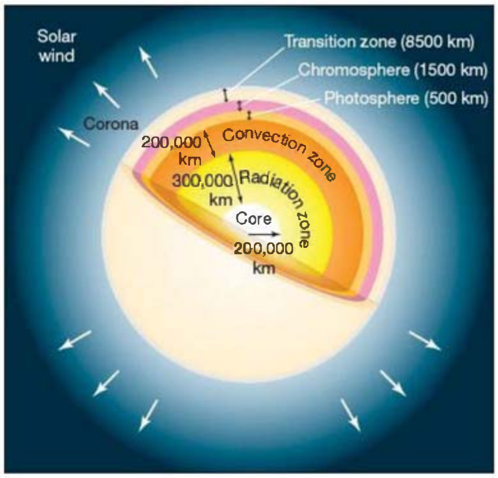
The properties of size, mass, density, rotation rate, and temperature are familiar from our study of the planets. But the Sun has an additional property, perhaps the most important of all from the point of view of life on Earth: The Sun *radiates* a great deal of energy into space, uniformly (we assume) in all directions. By holding a light-sensitive device—a photoelectric cell, perhaps—perpendicular to the Sun's rays, we can measure how much solar energy is received per square meter of surface area every second. Imagine our detector as having a surface area of 1 square meter (1 m$^2$) and as being placed at the top of Earth's atmosphere. The amount of solar energy reaching this surface each second is a quantity known as the **solar constant**, whose value is approximately 1400 watts per square meter (W/m$^2$).

About 50 to 70 percent of the incoming energy from the Sun reaches Earth's surface; the rest is intercepted by the atmosphere (30 percent) or reflected away by clouds (0 to 20 percent). Thus, on a clear day, a sunbather's body having a total surface area of about 0.5 m$^2$ receives solar energy at a rate of roughly $1400 \text{ W/m}^2 \times 0.70$ (70 percent) $\times\ 0.5 \text{ m}^2 \approx 500$ W, equivalent to the output of a small electric room heater or five 100-watt lightbulbs.

Let us now ask about the *total* amount of energy radiated in all directions from the Sun, not just the small fraction



▲ FIGURE 16.1 **The Sun** The inner part of this composite, filtered image of the Sun shows a sharp solar edge, although our star, like all stars, is made of a gradually thinning gas. The edge appears sharp because the solar photosphere is so thin. The outer portion of the image is the solar corona, normally too faint to be seen, but visible during an eclipse, when the light from the solar disk is blotted out. Note the blemishes; they are sunspots. ∞ (Sec. 2.4) *(NOAO)*



▲ FIGURE 16.2 **Solar Structure** The main regions of the Sun, not drawn to scale, with some physical dimensions labeled. The photosphere is the visible "surface" of the Sun. Below it lie the convection zone, the radiation zone, and the core. Above the photosphere, the solar atmosphere consists of the chromosphere, the transition zone, and the corona.

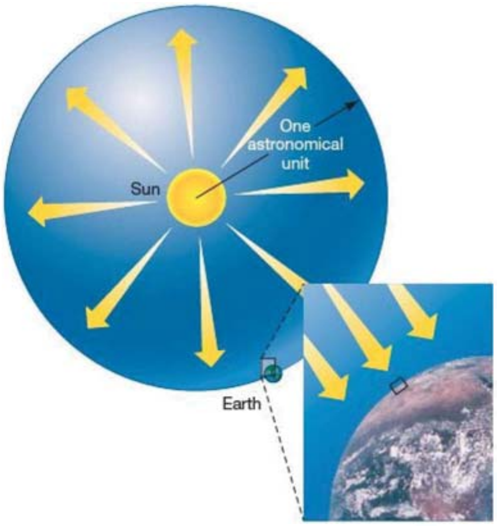
intercepted by our detector or by Earth. Imagine a three-dimensional sphere is centered on the Sun and just large enough that its surface intersects Earth's center (Figure 16.3). The sphere's radius is 1 AU, and its surface area is therefore $4\pi \times (1\ \mathrm{AU})^2$, or approximately $2.8 \times 10^{23}\ \mathrm{m}^2$. Multiplying the rate at which solar energy falls on each square meter of the sphere (i.e., the solar constant) by the total surface area of our imaginary sphere, we can determine the total rate at which energy leaves the Sun's surface. This quantity is known as the **luminosity** of the Sun. It turns out to be just under $4 \times 10^{26}$ W.

The Sun is an enormously powerful source of energy. *Every second*, it produces an amount of energy equivalent to the detonation of about 10 billion 1-megaton nuclear

**TABLE 16.1 The Standard Solar Model**

| Region | Inner Radius (km) | Temperature (K) | Density (kg/m$^3$) | Defining Properties |
|---|---|---|---|---|
| Core | 0 | 15,000,000 | 150,000 | Energy generated by nuclear fusion |
| Radiation zone | 200,000 | 7,000,000 | 15,000 | Energy transported by electromagnetic radiation |
| Convection zone | 496,000* | 2,000,000 | 150 | Energy carried by convection |
| Photosphere | 696,000* | 5800 | $2 \times 10^{-4}$ | Electromagnetic radiation can escape—the part of the Sun we see |
| Chromosphere | 696,500* | 4500 | $5 \times 10^{-6}$ | Cool lower atmosphere |
| Transition zone | 698,000* | 8000 | $2 \times 10^{-10}$ | Rapid increase in temperature |
| Corona | 706,000* | 3,000,000 | $10^{-12}$ | Hot, low-density upper atmosphere |
| Solar wind | 10,000,000 | >1,000,000 | $10^{-23}$ | Solar material escapes into space and flows outward through the solar system |

* *These radii are based on the accurately determined radius of the photosphere. The other radii quoted are approximate, round numbers.*



▲ FIGURE 16.3 **Solar Luminosity** We can draw an imaginary sphere around the Sun so that the sphere's surface passes through Earth's center. The radius of this imaginary sphere equals 1 AU. Overall, Earth receives energy from the Sun at a rate of roughly 200 million gigawatts—ten thousand times the current energy consumption of our entire planet. The "solar constant" is the amount of power striking a 1-$m^2$ detector at Earth's distance, as suggested by the inset. By multiplying the sphere's surface area by the solar constant, we can measure the Sun's luminosity—the amount of energy it emits each second.

bombs. Six seconds worth of solar energy output, suitably focused, would evaporate all of Earth's oceans. Three minutes would melt our planet's crust. The scale on which the Sun operates simply defies earthly comparison. Let's begin our more detailed study with a look at where all this energy comes from.

**PROCESS OF SCIENCE CHECK**

✔ Why must we assume that the Sun radiates equally in all directions when we compute the solar luminosity from the solar constant?

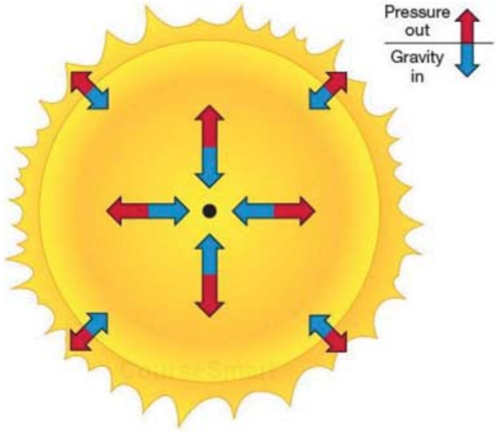
## 16.2 The Solar Interior

How do astronomers know about conditions in the interior of the Sun? As we have just seen, the fact that the Sun shines tells us that its center must be very hot, but our direct knowledge of the solar interior is actually quite limited. (See Section 16.7 for a discussion of one important "window" we do have into the solar core.) Lacking direct measurements, researchers must use other means to probe the inner workings of our parent star. To this end, they construct *mathematical models* of the Sun, combining all available data with theoretical insight into solar physics to find the model that agrees most closely with observations. ∞ (Sec. 1.2) Recall from Chapter 11 how similar techniques are used to infer the structures of the jovian planets. ∞ (Sec. 11.3) The result in the case of the Sun is the **standard solar model,** which has gained widespread acceptance among astronomers.

### Modeling the Structure of the Sun

The Sun's bulk properties—its mass, radius, temperature, and luminosity—do not vary much from day to day or from year to year. Although we will see in Chapter 20 that stars like the Sun do change significantly over periods of *billions* of years, for our purposes here this slow evolution may be ignored. On "human" time scales, the Sun may reasonably be thought of as unchanging.

Based on this simple observation, as illustrated in Figure 16.4, theoretical models generally begin by assuming that the Sun is in a state of **hydrostatic equilibrium,** in which pressure's outward push exactly counteracts gravity's inward pull. This stable balance between opposing forces is the basic reason that the Sun neither collapses under its own weight nor explodes into interstellar space. ∞ *(More Precisely 8-1)* The assumption of hydrostatic equilibrium, coupled with our knowledge of some basic physics, then lets us predict the density and temperature in the solar interior. This information, in turn, allows the model to make predictions about other observable solar properties—luminosity, radius, spectrum, and so on—and the internal details of the model are fine-tuned until the predictions agree with



▲ FIGURE 16.4 **Hydrostatic Equilibrium** In the interior of a star such as the Sun, the outward pressure of hot gas exactly balances the inward pull of gravity. This is true at every point within the star, guaranteeing its stability.