1

Light of the Sun

1.1 Ultimate Power

The Sun is the source of all of our power. Its radiation energizes our planet, warms the ground and sea, lights our days, strengthens our bodies, and sustains life on the Earth. Green leaves of growing plants absorb sunlight, giving them the energy to decompose atmospheric carbon dioxide into carbon and gaseous oxygen. The oxygen is liberated back into the atmosphere, where we breathe it, and the carbon is deposited in plants. When we burn the wood of a tree, the carbon reunites with atmospheric oxygen. Long-dead, compressed plants provide the petroleum, coal, and natural gas that energize the lights of our house and power the vehicles we drive while also increasing the amount of carbon dioxide in the atmosphere.

The Sun's warmth is the source of our weather and the arbiter of our climate, producing the winds and cycling the water from sea to clouds and rain. Hydroelectric power plants are energized by water running back to the sea. Wind power also is driven by the Sun. Uneven solar heating of different parts of the Earth produces the winds, which blow from hot to cold regions.

The Earth glides through space at exactly the right distance from the Sun for life to thrive on our planet's surface, whereas other planets in the solar system freeze or fry: We sit in the "comfort zone." Any closer and the oceans would boil away, as on Venus; farther out, the ground would be a frozen wasteland, resembling Mars, which is now in a global ice age. We receive exactly the right amount of energy from the Sun to keep most of our water in liquid form, which is a requirement for life as we know it. Turn off the Sun's powerhouse and in only a few months, we would all be under ice.

The rising Sun has been celebrated since ancient times, in many religions, and by artists and poets. Its radiance dispels the darkness, brings us joy, and warms our souls. A smile comes to our face when the Sun returns, in a moment captured in the lyrics of a popular Beatles song:

2   The Life and Death of Stars

> Here comes the Sun
> Here comes the Sun and I say
> It's all right[1]

1.2 The Closest Star

How far away is the Sun? The mean distance separating the Earth and the Sun is known as the *astronomical unit* (AU) and it provides the crucial unit of planetary distance. Yet, for a very long time, no one knew exactly how big it was. We now know that this distance is 150 million kilometers, but it took a long time to find that out.

By the end of the seventeenth century, astronomers and other scientists had a good understanding of how the planets move around the Sun, but they could produce a scale model of the solar system that only provided relative distances of the planets from the Sun. The true distances and speeds of motion of the planets remained unknown.

It is no wonder then that obtaining a precise value for the Sun–Earth distance played an important role in the astronomy of the eighteenth and nineteenth centuries. The quest for accuracy in its measurement involved hundreds of trips to remote countries, tens of thousands of observations and photographs, and the lifetime work of several astronomers. They first determined the separations of the Earth and a nearby planet, such as Venus or Mars, and then used this planetary distance to infer the separation of the Earth and the Sun.

The distance of a nearby planet can be estimated by measuring the angular separation in the apparent direction of the planet when observed simultaneously from two widely separated locations on the Earth. This angle is known as the *parallax*, from the Greek *parallaxis* meaning the "value of an angle." If both the parallax and the separation between the two observers are known, then the distance of a planet can be determined by triangulation. This is based on the geometric fact that if we know the length of one side of a triangle and the angles of the two corners, then all of the other dimensions can be calculated.

The parallax technique to estimate a planet's distance is similar to the way our eyes infer how far away objects are. To see the effect, hold up a finger in front of your nose. First look at your finger with one eye open and the other eye closed; then alternate the open and closed eyes. Any nearby background object at one side of your finger seems to move to the other side, making a parallax shift. When this is repeated for a more distant object, the shift is less. In other words, the more distant an object, the smaller the parallax shift, and vice versa.

Because angular measurements were involved, the AU was naturally specified by an angle called the *solar parallax*, which is defined as half of the angular separation of the Sun as viewed from opposite sides of the Earth. More than a century of estimates for the solar parallax are shown in Figure 1.1 and discussed in Focus 1.1.
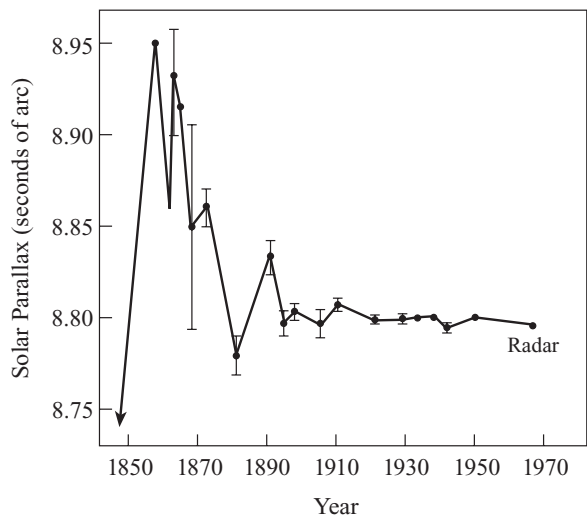
Figure 1.1. **Distance to the Sun**. Values of the solar parallax obtained from measurements of the parallaxes of Venus, Mars, and the asteroid Eros between 1850 and 1970. The solar parallax, designated by $\pi_\odot$, is half the angular displacement of the Sun viewed from opposite sides of the Earth. The error bars denote the probable errors in the determination; the points for 1941, 1950, and 1965 all have errors smaller than the plotted points. In the 1960s, the newly developed radar (i.e., radio detection and ranging) technology enabled determination of the Sun's distance with an accuracy of about 1,000 meters. The radar value of the solar parallax is 8.79405 seconds of arc.

Focus 1.1 Distance of the Sun

The distance separating the Earth and the Sun, known as the astronomical unit (AU), is determined by first estimating the distance between the Earth and a nearby planet. This planetary distance then can be used to specify the AU. The distance of Venus from the Sun, for example, is equal to one half of the difference between the Earth and Venus when it is closest and farthest away, on the other side of the Sun. When the Venus–Sun distance is known, we can infer the distance of any other planet from the Sun using Kepler's third law (see Section 2.1), which relates the orbital periods and orbital distances of the planets.

For more than a century, the distances of Venus and Mars were determined by triangulation from different points on the Earth. It involved measurements of the parallax, or angular difference in the apparent direction of the planet, as observed from widely separated locations.

In 1672, Giovanni Domenico Cassini, an Italian astronomer and the first director of the Paris Observatory, obtained an early triangulation of Mars, combining his observations from Paris with those taken from Cayenne, French Guiana. The planet was then in opposition, at its closest approach to the Earth. From the two sets of observations, obtained 7,200 kilometers apart, it was possible to estimate the distance to Mars and to infer a value of 139 million kilometers for the AU.

(*continued*)

Focus 1.1 (*continued*)

Astronomers in the eighteenth and nineteenth centuries attempted to improve the measurement accuracy of the Sun's distance during the rare occasions when Venus crossed the face of the Sun in 1761, 1769, 1874, and 1882. The method also involved comparison of observations from widely separated locations to determine the distance by triangulation. Subsequent measurements of the distance to the nearby asteroid, named 433 Eros, during its closest approaches to the Earth, resulted in an estimated 150 million kilometers for the AU.

Significant improvements in the precision of planetary distances came in the late 1960s by bouncing pulsed radio waves off of Venus and timing the echo. The roundtrip travel time – about 276 seconds when Venus is closest to the Earth – was measured using accurate atomic clocks. A precise distance to Venus then was obtained by multiplying half of the roundtrip time by the speed of light. The distance of Venus from the Sun is equal to one half of the difference between the Earth and Venus when it is closest and farthest away, on the other side of the Sun. The value of the AU, inferred from the radar determination of the distance of Venus, is 149,597,870 kilometers, with an accuracy of about 1 kilometer; for the accuracy required in most astronomical calculations, 1 AU is equal to 149.6 million kilometers.

Nowadays, the Earth–Sun light travel time – or the time for light to travel across 1 AU – is given as a primary astronomical constant and has the exact value of 499.004782 seconds. The AU is equal to the product of this travel time and the speed of light, which moves at precisely 299,792.458 kilometers per second.

The time for light to travel across the 1-AU distance is used now as a primary astronomical constant, and it is approximately 499 seconds(s), which corresponds to an AU of about 149.6 million kilometers – approximately 10,000 times the diameter of the Earth. Once an accurate value for the Sun's distance is obtained, the Earth's mean orbital velocity can be determined by assuming – to a first approximation – a circular orbit and dividing the Earth's orbital circumference by its orbital period of one year. The Earth's orbital velocity is 29,800 meters per second, abbreviated as 29,800 m s^{-1}. This is equivalent to approximately 107,000 kilometers per hour, much faster than a vehicle moves on a highway.

By way of comparison, it takes 4.24 years, or approximately 134 million seconds, for light to travel from the next nearest star other than the Sun. This star is called Proxima Centauri and it is located at a distance of 268,000 AU.

Therefore, the Sun is about a quarter-million times nearer to the Earth than the next nearest star. Because of this closeness, the Sun is approximately 100 billion times brighter than any other star. This brilliance and proximity permit detailed investigations that are not possible for any other star. As a result, studies of the Sun provide the foundation and benchmark for an understanding of other stars.

Because of its proximity, we are linked more closely to the life-sustaining Sun than to any other star. Although our unaided eyes can see about 6,000 stars in the night sky – and telescopes reveal hundreds of billions of them – our own daytime star, the Sun, is special;
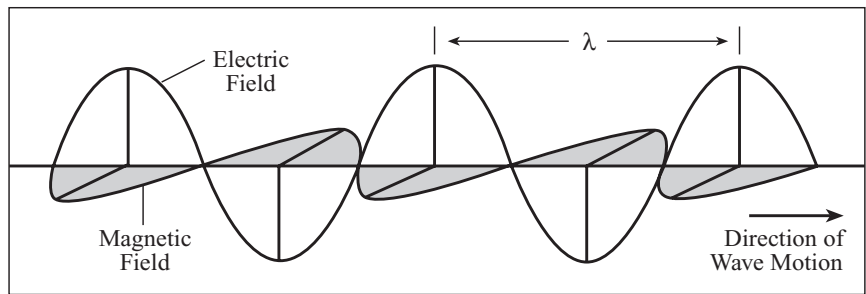
Figure 1.2. Electromagnetic waves. All forms of radiation consist of electrical and magnetic fields that oscillate at right angles to each other and to the direction of travel. They move through empty space at the speed of light. The separation between adjacent wave crests is called the *wavelength of the radiation* and usually is designated by the lowercase Greek letter lambda, λ.

nothing else in the universe is so critically important to us. As the English poet Francis William Bourdillon wrote:

> The night has a thousand eyes,
> And the day but one;
> Yet the light of the bright world dies,
> With the dying Sun.
>
> The mind has a thousand eyes,
> And the heart but one;
> Yet the light of a whole life dies
> When love is done.[2]

The Sun draws us to the other stars, and to understand how the Sun or any other star operates, we must examine its radiation, which spreads out and carries energy in all directions.

1.3 Waves of Light

Our perception of the universe is governed almost solely by the electromagnetic radiation received from cosmic objects. This radiation, which is the primary way that energy is transported in the universe, is known as *electromagnetic radiation* because it propagates by the interplay of oscillating electrical and magnetic waves.

In common with any wave, electromagnetic radiation has a wavelength, denoted by the lowercase Greek letter λ; different types of electromagnetic radiation differ in their wavelength, although they propagate at the same speed. Like waves on water, radiation waves have crests and troughs; but, unlike water waves, electromagnetic waves can propagate in empty space. A wavelength is the distance between successive crests or successive troughs (Fig. 1.2) and usually is measured in units of a meter, abbreviated m.

We are all familiar with the colorful display of a rainbow, which is sunlight bent into separate wavelengths by droplets of water. A crystal chandelier or compact disk similarly display the spectrum of visible light, arranging the colors by their different wavelengths. From short to long waves, the colors in the spectrum of visible light correspond to violet,

Table 1.1. *Approximate wavelengths of the colors*[a]

Color	Wavelength (nm)
Violet	420
Blue	470
Green	530
Yellow	580
Orange	610
Red	660

[a] The wavelengths are specified in nanometers, in which 1 nanometer, abbreviated nm, is equal to 1/billionth of a meter, or 1 nm = 10^{-9} meters. Another wavelength unit used in optically visible light astronomy is the *Ångström*, abbreviated Å, where 1 Å = 0.1 nm = 10^{-10} meters.

blue, green, yellow, orange, and red (Table 1.1). Light from the Sun or a light bulb often is called *white light* because it contains all of the colors, whereas black denotes the absence of color, when we see no light.

Sometimes radiation is described by its frequency, which indicates how fast the radiation *oscillates*, or moves up and down. The frequency of a wave is the number of wave crests passing a stationary observer every second.

In 1865, the Scottish scientist James Clerk Maxwell derived the equations that describe electromagnetic waves. He demonstrated that all waves move with the speed of light, which is designated by the symbol c. Two years later, the German physicist Heinrich Hertz extended Maxwell's results by building equipment to produce and detect certain invisible electromagnetic waves, which are now known as *radio waves*. In his honor, the unit of frequency is named the *Hertz*, abbreviated Hz; 1 Hz is equivalent to 1 cycle per second. Radio stations, for example, are denoted by their call letters and the frequency of their broadcasts in MHz, in which 1 MHz equals 1 million Hz.

The product of wavelength and frequency is equal to the speed of light; therefore, radiation at a shorter wavelength has a higher frequency and a longer wavelength has a lower frequency. All electromagnetic waves, regardless of wavelength or frequency, travel through empty space at the same constant speed – that is, the speed of light, at precisely 299,792,458 m s^{-1}. This speed is independent of reference in space and time, and it is the maximum speed allowable anywhere (Focus 1.2).

Focus 1.2 Light, the Fastest Thing Around

It was once thought that light moves instantaneously through space, but we now know that it travels at a very fast but finite speed, which was first inferred from observations of Jupiter's moon Io in the seventeenth century. The king of France had directed Giovanni Domenico Cassini, director of the Paris Observatory, to use such observations to improve knowledge of terrestrial longitude and maps of France. The Danish astronomer Ole Rømer, who also worked at the observatory, and Cassini noticed a varying time between eclipses of Io by Jupiter. Although Io's orbital period

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was approximately 42 hours, the duration of the orbit seemed to decrease when Jupiter was closer to the Earth and increase when it moved away, with a total time difference of approximately 22 minutes. Both Cassini and Roemer concluded that it was not Io's orbit around Jupiter that varied but rather the time it took Jupiter's light to reach the Earth when our planet was in different parts of its orbit around the Sun and closer to or farther from Jupiter.

Neither astronomer gave a value for the speed of light, which would have been equal to the diameter of the Earth's orbit divided by the time difference – or approximately 227,000,000 m s^{-1}.

More refined laboratory measurements during subsequent centuries indicated that light is always moving at a constant speed with the precise velocity of $c = 299,792,458$ m s^{-1}. Light emitted by any star moves through empty space for all time, never stopping or slowing down and never coming to rest. Moreover, nothing outruns light; it is the fastest thing around.

1.4 Invisible Rays

There is much more to the observable universe than meets the eye. In addition to visible light, there is invisible radiation. The invisible domains include infrared and radio waves – with wavelengths longer than that of red light – and ultraviolet rays, x-rays, and gamma rays, whose wavelengths are shorter than violet light. They all are electromagnetic waves and part of the same family, moving in empty space at the speed of light, but we cannot see them.

A display of the intensity of radiation as a function of wavelength is known as a *spectrum* – Latin for "appearance" or "apparition" – and the electromagnetic spectrum describes the types and wavelengths of electromagnetic radiation (Fig. 1.3). From short to long wavelengths, the electromagnetic spectrum includes gamma rays, x-rays, ultraviolet radiation, visible light, infrared radiation, and radio waves. Our eyes can detect a narrow range of wavelengths, which include the visible colors, and these wavelengths comprise only one small segment of the much broader electromagnetic spectrum. This band of light also is termed *visible radiation* to distinguish it from *invisible radiation*, which cannot be seen by the human eye. The most intense radiation of the Sun – and many other stars – is emitted at these wavelengths, and our atmosphere permits it to reach the ground.

In 1800, the German-born English astronomer William Herschel discovered infrared radiation when he put a beam of sunlight through a prism to spread it into its spectral components. He noticed that an unseen portion of sunlight warmed a thermometer placed beyond the red edge of the visible spectrum. The thermometer recorded higher temperatures in the invisible infrared sunlight than in normal visible sunlight. Herschel called them "calorific rays" because of the heat they generated; the term *infrared* did not appear until the late nineteenth century.

Humans "glow in the dark," emitting infrared radiation, but cannot see the heat; it is outside our range of vision. The military uses special infrared detectors to sense and locate heat generated by the enemy in total darkness. Soldiers can locate the enemy at night by
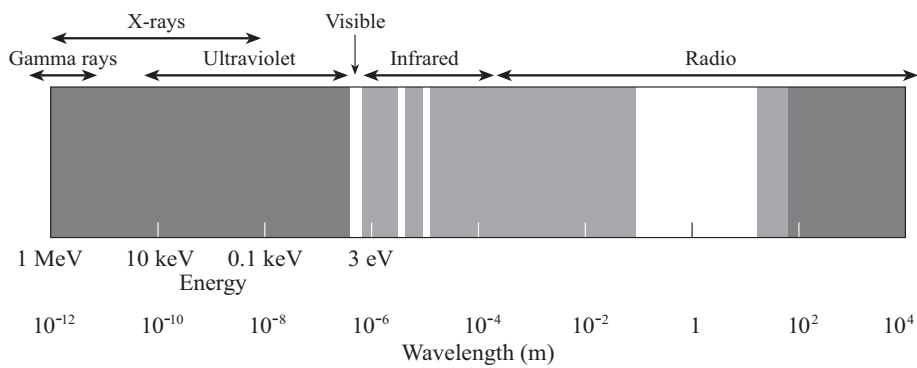
Figure 1.3. **Electromagnetic spectrum**. Radiation from cosmic objects can be emitted at wavelengths from less than 10^{-12} m to greater than 10^4 m, where m denotes meters. The visible spectrum that we see with our eyes is a very small portion of the entire range of wavelengths. Lighter shading indicates a greater transparency of the Earth's atmosphere to cosmic radiation. It only penetrates the Earth's atmosphere at visible and radio wavelengths, respectively represented by the narrow and broad white areas. Electromagnetic radiation at short gamma-ray, x-ray, and ultraviolet wavelengths, represented by the dark areas, is absorbed in our atmosphere; therefore, the universe is now observed in these spectral regions from above the atmosphere in Earth-orbiting satellites.

using night-vision goggles with infrared sensors that detect a person's heat, and spy satellites use infrared telescopes to detect heat radiated by rocket exhaust and large concentrations of troops and vehicles.

Most ultraviolet and infrared radiation coming from cosmic objects does not pass through our atmosphere, and all cosmic x-rays and gamma rays are absorbed there, so these rays never reach the ground. To look at the universe with these invisible wavelengths, we must loft telescopes above the obscuring atmosphere. This was done first by using balloons and sounding rockets, followed by Earth-orbiting satellites with telescopes that view the cosmos at invisible ultraviolet, infrared, x-ray, and gamma-ray wavelengths.

Radio waves are the only type of invisible radiation that is not absorbed in the Earth's atmosphere, but they are too long to enter the eye and not sufficiently energetic to affect vision. Radiation at radio wavelengths even can pass through rain clouds; therefore, the radio universe can be observed on cloudy days and in stormy weather just as a car radio or cell phone works even when it is raining or snowing.

1.5 The Radiation Energy of the Sun

The Unit of Energy

The *joule* is the unit of energy in the International System of units, abbreviated as SI from the French *Système International d'unités*. The SI unit of energy is named for the English physicist James Prescott Joule. When an SI unit is used in written English, it begins with a lowercase letter (e.g., joule) but it is abbreviated with an uppercase first letter (e.g., J).

One joule is the work required to produce 1 watt of power for 1 second; therefore, a power of 1 J s^{-1} is equivalent to 1 watt.

One joule is twice the kinetic energy of a mass of 1 kilogram, abbreviated 1 kg, moving at a speed of 1 meter per second, or 1 m s^{-1}. This amount of energy is a small number relative to the mass and speed of cosmic objects. The Sun, for example, has a mass of about 2,000 billion billion billion kilograms, or 2×10^{30} kg, and moves through space at a speed of approximately 220,000 m s^{-1}.

Even an ordinary table lamp with a 100-watt light bulb uses only 100 J s^{-1}, whereas the Sun liberates significantly more power: some 382.8 million billion billion J s^{-1}, written as 3.828×10^{26} J s^{-1}.

The Solar Constant

As solar radiation spreads out into space, it is dispersed into an ever-increasing volume; the distant Earth therefore collects only a small fraction of the total energy radiated by the Sun. The *solar constant* specifies the amount of the Sun's radiation that arrives at our planet. It is denoted by the symbol $f_\odot$ and is defined precisely as the total amount of radiant solar energy per unit time per unit area reaching the top of the Earth's atmosphere at the Earth's mean distance from the Sun. (Any physical parameter of the Sun is denoted by a subscript $\odot$, a circle with a dot at the center.) Artificial satellites have been used to accurately measure the solar constant, obtaining a value of $f_\odot = 1,361$ J s^{-1} m^{-2}.

The Sun's Luminosity

The intensity of radiation per unit area falls off as the inverse square of the distance from the source of radiation. This effect is observed when watching the increased brightness of a vehicle's headlights as it approaches and its distance decreases, or when watching the dimming taillights as the vehicle moves away to greater distance.

We can use the solar constant and the Earth−Sun distance to determine the total amount of energy radiated by the Sun every second. At the Earth's mean distance of 1 AU from the Sun, the solar radiation per unit area is diminished by 4π (AU)^2, which is the surface area of a sphere at this distance. We therefore infer the Sun's luminosity, denoted $L_\odot$, by multiplying the solar constant with this area to obtain $L_\odot = 4\ \pi\ f_\odot$ (AU)$^2 = 3.828 \times 10^{26}$ J s^{-1}, where 1 AU $= 1.496 \times 10^{11}$ m.

1.6 The Size and Temperature of the Sun's Visible Disk

Any incandescent body shines because it is hot. The wire filament in an incandescent light bulb, for example, is heated to a white-hot temperature of about 3,000 K to produce its luminous glow. As it turns out, the visible solar disk is just about twice that hot, and its much greater luminosity is due to its vastly larger size.

The solar radius, denoted $R_\odot$, can be determined from observations of the Sun's angular size and distance (Fig. 1.4), and these measurements indicate that the solar radius $R_\odot = 6.955 \times 10^8$ m, which is 109 times the radius of the Earth. With a radius of nearly 0.7 billion meters, or 700 million kilometers, the Sun could contain a million planets like ours.

Once we know the radius and luminosity of the Sun, we can determine the effective temperature of the Sun's visible disk. The luminosity of any hot, incandescent gas increases with the square of the radius and the fourth power of the temperature, according to a famous
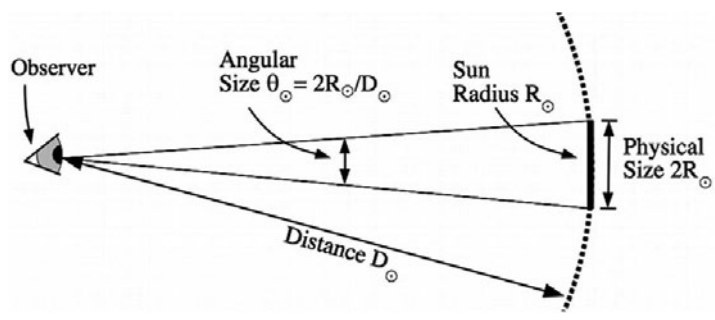
Figure 1.4. The Sun's angular size and radius. The solar radius can be determined from the Sun's angular size and distance. As long as this angle is small, the physical size is only a small arc of a large circle, denoted by the dashed line, and the angular size is the ratio of the physical size to the distance. Astronomers specify this angle as a partial arc of a full circle of 360 degrees; for the Sun, it is about 32 minutes of arc, in which there are 60 minutes of arc in 1 degree. This angle has been enlarged to display it in this illustration. In mathematics, the *radian* is the standard unit of angular measure. It describes the angle subtended by a circular arc as the length of the arc divided by the radius of the arc. When the arc length is equal to the arc radius, the angle is 1 radian. We can convert between the two methods of describing angles by noting that the circumference of a circle is 2π times its radius; therefore, 1 radian is equal to 360 degrees/(2π), or 57.2958 degrees. For the Sun, the angular size $\theta_\odot = 2R_\odot/D_\odot$ radians, where $R_\odot$ denotes the Sun's radius and the mean distance of the Sun, $D_\odot$, is 1 AU. The observed angular size of the Sun corresponds to a radius of 695.5 million meters.

expression known as the *Stefan–Boltzmann law*. It means that a bigger and/or hotter star shines with greater energy per unit time, which is analogous to saying a bigger or hotter fire burns brighter. The relevant numbers for the Sun's absolute luminosity and radius indicate that the visible solar disk has a temperature very close to 6,000 K and precisely 5,780 K.

No solid material can exist at this temperature, not even the wire filament of a light bulb; the material will melt and completely evaporate when made this hot. This is what happened at the visible solar disk, where all elements are present in gaseous form.

Incidentally, astronomers use the kelvin temperature scale that starts from absolute zero, which is the temperature at which atoms and molecules cease to move. The unit for this scale is written kelvin, without an uppercase K, or is simply denoted by an uppercase K. Water freezes at 273 K and boils at 373 K.

Any hot gas with the radius and disk temperature of the Sun will emit the Sun's luminosity. This emission, like that of any hot gas, is known as *thermal radiation*.

1.7 Thermal Radiation

An ideal thermal radiator is known as a *blackbody*. By definition, a blackbody absorbs all of the radiation that falls on it and reflects none – hence, the term *black*. A black shirt similarly will absorb most of the visible sunlight falling on it and reflect no colors.

Thermal radiation is emitted by a gas in thermal equilibrium and arises by virtue of an object's heat, or temperature. A single temperature characterizes thermal radiation.

Any hot gas that is in *thermal equilibrium*, with a temperature above absolute zero, will attempt to radiate away its energy. The emission from such a thermal radiator is found at all