CHAPTER

25

Solar Radiation, Black Bodies, Heat Budget, and Radiation Balance

The sun is the battery that drives processes on earth, including evaporation, transpiration, and the ascent of water in plants. Therefore, it is essential to understand the sun's energy. In this chapter, we study solar radiation and the laws associated with a black body, because the sun can be considered to be a black body. We calculate the heat budget at the surface of the earth and define the radiation balance.

25.1 SOLAR RADIATION

All bodies emit radiant energy in the form of electromagnetic waves when they are at a temperature above absolute zero (−273.16 °C or −459.69 °F = hypothetical point at which a substance would have no molecular motion and no heat). The source of this *thermal radiation* or *temperature radiation* is the incessant molecular motion. During collisions, or more generally as a result of interactions between molecules, part of their energy is transformed into radiation. Conversely, radiation can be absorbed by the molecules and converted into kinetic and potential energy, thereby raising the temperature of the body (Van Wijk and Scholte Ubing, 1966; p. 62). (We ignore radiation from radioactive materials. This is another type of radiation.)

Solar radiation reaches the outer surface of the earth's atmosphere with an almost constant intensity of about 1400 W/m^2 or 2.0 $cal/cm^2/min$ measured perpendicularly to the solar beam (Johnson, 1954). About 98% is contained in the wavelength interval 0.2−4.5 μm, including about 40−45% in the 0.4−0.7 μm range (visible) (Figure 25.1), and about 2% at wavelengths shorter and longer than these limits. The distribution of the

http://dx.doi.org/10.1016/B978-0-12-420022-7.00025-2

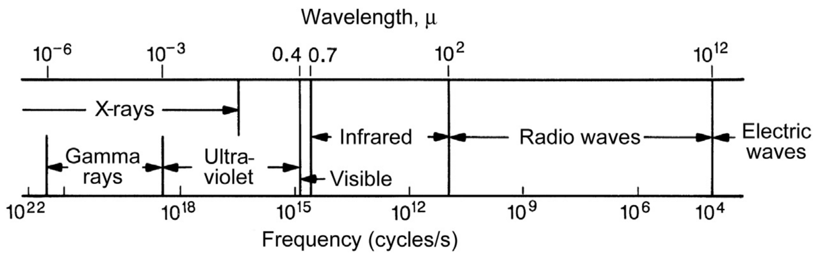

FIGURE 25.1 Electromagnetic spectrum on logarithmic wavelength and frequency scales. *From Rosenberg (1974), p. 6. This material is used by permission of John Wiley & Sons, Inc.*

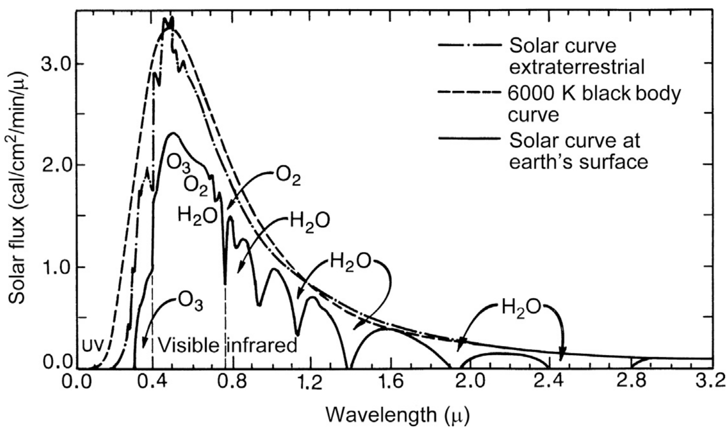

FIGURE 25.2 Theoretical and actual spectra of solar radiation at the top of the atmosphere and the actual spectrum at the earth's surface. *From Rosenberg (1974), p. 9. This material is used by permission of John Wiley & Sons, Inc.*

incident flux with wavelength can be regarded as comparatively smooth, with few major gaps and a peak at the wavelength of green light (about 0.5 μm). Throughout the main region, the distribution of incident flux with wavelength corresponds roughly with that expected from radiation theory for a perfect absorber and emitter at a temperature of 6000 K (Figure 25.2) (Slatyer, 1967; p. 28). (We soon will define a perfect absorber and emitter.)

25.2 TERRESTRIAL RADIATION

In contrast to solar radiation, the earth's temperature is roughly 300 K. The black body radiation (which we will define soon), corresponding to this temperature, has its maximum spectral intensity at approximately

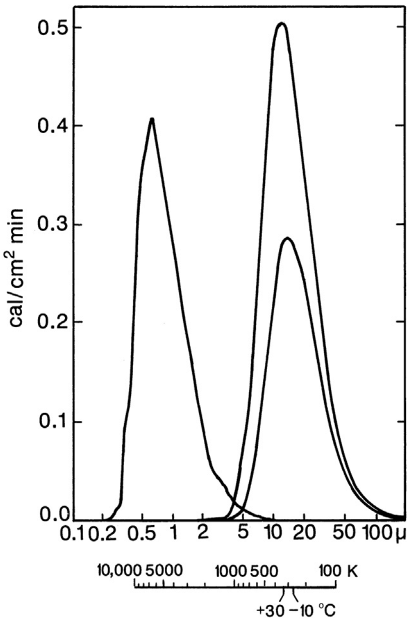

FIGURE 25.3 Distribution of intensity of two bands of atmospheric radiation, according to wavelength. The curve on the left is for shortwave (solar) radiation and the two curves on the right are for long-wave (terrestrial) radiation. The taller curve on the right corresponds to earth temperature of 30 °C and the curve nested inside it is for earth temperature of −10 °C. *From Geiger (1965), p. 8. This material is used by the permission of the legal successor to Rudolph Geiger, Prof. Dr. Walter Geiger, Perlschneider Str. 18, 81241 Munich, Germany.*

10 μm and 98% of its energy is contained in the wavelength interval 0.5–80 μm (Van Wijk and Scholte Ubing, 1966; pp. 74, 92; Slatyer, 1967; p. 29). In consequence, the spectral range of solar radiation and terrestrial thermal radiation, although overlapping slightly, can be considered as completely separate (Figure 25.3). The former (solar radiation), although containing some infrared radiation, is commonly called short-wave radiation, and the latter (terrestrial thermal radiation) is called long-wave radiation (Slatyer, 1967; p. 29).

25.3 DEFINITION OF A BLACK BODY

Before we continue further, let us define black-body radiation, using the description of Shortley and Williams (1971, pp. 323–326). All materials at temperatures above absolute zero are continually emitting radiation. As the temperature of a solid is increased, the energy radiated from the solid increases rapidly. The amount of radiant power emitted by a solid depends significantly on the character of the surface of the solid.

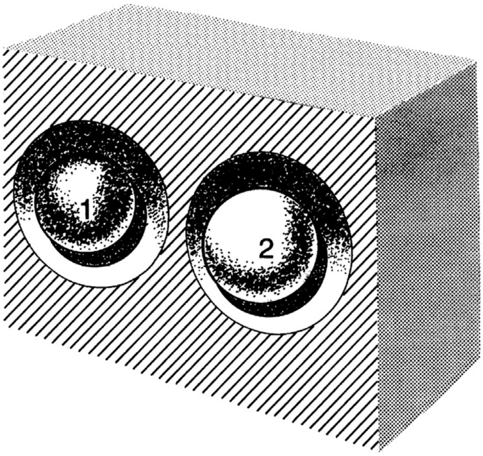

FIGURE 25.4 Two spherical bodies of the same size but of different materials suspended within evacuated spherical cavities. *From Shortley, G. and Williams, D., ©1971. Elements of Physics, 5th ed., p. 323. Reprinted by permission of Pearson Education, Inc: Upper Saddle River, New Jersey.*

In beginning the discussion of radiation, it is helpful to define a "perfect radiator", whose rate of radiation is the maximum possible for its temperature. That such a maximum exists can be shown by considering the inverse process, *absorption*.

Figure 25.4 shows in cross section a solid object maintained at a uniform temperature T throughout. Within this solid there are two identical evacuated spherical cavities containing opaque bodies of the same size but of different materials; for example, body 1 may be made of wood and body 2 may be made of polished metal. It is found by experiment that as a result of radiative interchanges of heat, the temperatures of bodies one and two eventually become equal to the temperature T of the enclosing walls and remain at that temperature, in accordance with the general principle of thermal equilibrium.

We assume that the inner walls of the cavities are perfectly absorbing. Then the only radiation reaching bodies 1 and 2 is that *radiated* by the inner walls of the cavities; these cavity walls do not reflect any radiation and return it to the bodies. Under these circumstances, the radiant energy incident per second on unit area of each body will be the same; call it E, in W/m^2. Of the incident radiation E, a certain fraction will be reflected and the remainder will be absorbed. As indicated in Figure 25.5, let ρ denote the fraction of the incident radiation that is reflected and α denote the fraction that is absorbed; ρ is called the *reflectance* and α the *absorptance*. These quantities are dimensionless and their sum is unity for the surface of any opaque body; $\alpha + \rho = 1$. The product $\rho_1 E$ gives the radiant power reflected from unit area of body 1, while $\rho_2 E$ gives the radiant power reflected from unit area of body 2, in W/m^2. Similarly, $\alpha_1 E$ and $\alpha_2 E$ give the radiant power absorbed per unit area of bodies 1 and 2.

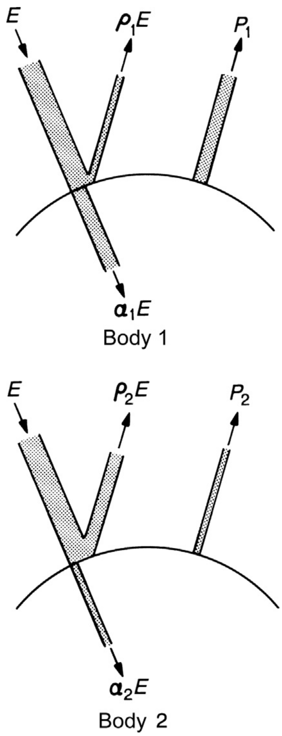

FIGURE 25.5 Radiant energy incident per second on unit area, E (W/m^2), of the two bodies illustrated in Figure 25.4. Of the incident radiation E, a certain fraction will be reflected, ρ, and the remainder will be absorbed, α. The radiated power per unit area (W/m^2) is P_1 for body 1 and P_2 for body 2. The figure shows that the rate of absorption equals the rate of emission. *From Shortley, G. and Williams, D., ©1971. Elements of Physics, 5th ed., p. 324. Reprinted by permission of Pearson Education, Inc: Upper Saddle River, New Jersey.*

Now, let the radiated power per unit area, in W/m^2, be P_1 for body 1 and P_2 for body 2. If the temperatures of the bodies in Figures 25.4 and 25.5 are to remain constant, as much energy must be lost per second by radiant emission as is gained by absorption and we may write

$$\text{rate of absorption} = \text{rate of emission},$$

or

$$\alpha_1 E = P_1 \tag{25.1}$$

and

$$\alpha_2 E = P_2. \tag{25.2}$$

Dividing the first equation by the second, we find that

$$\alpha_1/\alpha_2 = P_1/P_2, \quad \text{or} \quad P_1/\alpha_1 = P_2/\alpha_2. \tag{25.3}$$

Equation 25.3, and the observed temperature equality, give *Kirchhoff's principle of radiation*, which states: *The ratio of the rates of radiation of any two surfaces at the same temperature is equal to the ratio of the absorptances of the two surfaces*. Qualitatively, we can say that good radiators are good absorbers. (For a biography of Kirchhoff, see the Appendix, Section 25.13.)

Now we return to the problem of defining a perfect radiator. There is a maximum value of the absorptance α. Because no surface can absorb *more* than *all* of the incident radiation, the maximum value α can have is unity. In view of Eqn (25.3), we may say that a surface having the maximum rate of radiation is one that has the maximum absorptance and is, therefore, one that absorbs all radiation incident upon it. Such a surface is *black* to all types of radiation. Therefore, we may define a perfect radiator as follows: A *perfect radiator* is a body that absorbs all incident radiation and is, therefore, called a *black body*. A perfect radiator is a perfect absorber.

25.4 EXAMPLE OF A BLACK BODY

No material surface absorbs all of the radiation incident upon it. Even lampblack reflects about 1% of the incident radiation. In practice, a perfectly black surface can be most closely approximated by a very small opening in the wall of a large cavity such as the one shown schematically in Figure 25.6. Radiation may enter or leave the cavity through the opening. Of the radiation entering through the opening, a part is absorbed by the interior walls of the cavity and a part is reflected. Of the part reflected, only a small fraction escapes through the opening and the remainder is again partially absorbed and partially reflected by the walls. After repeated reflections, all of the entering radiation is absorbed except for the small portion that escapes through the opening. The opening, therefore, approximates a *black surface* or *perfect absorber*.

The inside walls of the cavity are radiating as well as absorbing, and a part of this radiation escapes through the opening. It can be shown that if the walls are at a uniform temperature T, the radiation that escapes is almost identical with the radiation that would be emitted by a perfect radiator at temperature T. The hole closely approximates the surface of a black body emitting so-called *black-body radiation*. To indicate the accuracy of this approximation, we note that computation shows that even if the interior surface of a sphere has an absorptance of only 1/2, a 25 cm sphere with a 5 cm hole will absorb 99% of diffuse radiation (coming equally from all directions) incident on the hole, and hence will radiate through the hole 99% of the radiation of a perfect radiator. A smaller hole will do correspondingly better (Shortley and Williams, 1971; p. 325).

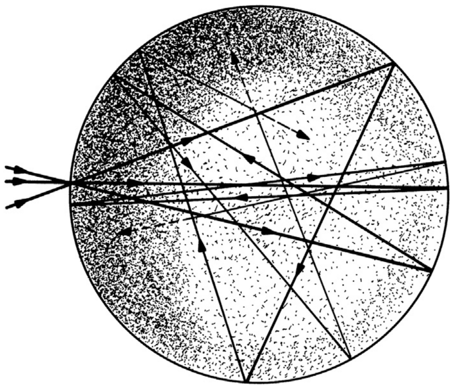

FIGURE 25.6 A small hole in the wall of an enclosure, showing complete absorption of several representative rays. *From Shortley, G., and Williams, D., ©1971. Elements of Physics, 5th ed., p. 325. Reprinted by permission of Pearson Education, Inc: Upper Saddle River, New Jersey.*

25.5 TEMPERATURE OF A BLACK BODY

The total radiation emitted from the surface of a body increases rapidly as the temperature of the surface is increased. The quantitative relation between rate of radiation and surface temperature of an ideal radiator or black body is given by the *Stefan–Boltzmann law* and has the form

$$P_{\text{Black}} = \sigma T^4 (\text{black body}), \tag{25.4}$$

where P is the radiated power per unit area. The rate of radiation increases as the *fourth power* of the absolute temperature T. The proportionality constant σ is called the Stefan–Boltzmann constant and has the value $5.670 \times 10^{-8}\ \text{W/m}^2/\text{K}^4$. (For a biography of Stefan, see the Appendix, Section 25.14, and for that of Boltzmann, see Section 25.15.)

25.6 GRAY BODY

The total radiation from many surfaces that are definitely not black also is very nearly proportional to the fourth power of the absolute temperature. This is true of surfaces composed of platinum, iron, tungsten, carbon, and many other materials. In every case, however, the proportionality constant is less than that for an ideal-radiator surface. Such a radiator is called a *gray body*. Because the absorptance α of a gray body is independent of its temperature, we see, by comparison with a black body in Eqns (25.3) and (25.4), that its rate of radiation is (Shortley and Williams, 1971; p. 326)

$$P = \alpha P_{\text{Black}} = \alpha \sigma T^4. \tag{25.5}$$

Because of this relation, α also is called the *emissivity* of the surface.

25.7 SPECTRUM OF A BLACK BODY

The Stefan–Boltzmann law gives the total rate of radiation of a perfect radiator (black body) at absolute temperature T, but gives no information concerning the *spectrum* of a perfect radiator (Shortley and Williams, 1971; p. 843). The spectrum of a perfect radiator is continuous. To discuss the relative amounts of energy in radiation of different wavelengths in the spectrum, we introduce the quantity P_λ, which gives the radiated power per unit area in a unit wavelength range at wavelength λ. This quantity, called the spectral radiance, can be determined by means of a spectrometer. What is observed in actuality is the amount of radiant power contained in a short wavelength interval between λ and $\lambda + \Delta\lambda$. The radiant power per unit area of source, emitted in this wavelength range, is given by $P_\lambda \Delta\lambda$, represented by the shaded area in Figure 25.7. The unit in which P_λ is measured is W/m^2 per unit wavelength interval; for example, W/m^2 per nanometer.

Plots of the distribution of power in the spectrum of a black body at different temperatures are shown by the solid lines in Figure 25.8. These curves all have two basic similarities in form:

1. They do not cross; the curves for higher temperatures are above the curves for lower temperatures at all wavelengths.
2. The maxima of the curves are displaced toward shorter wavelengths as the temperature of the black body is increased.

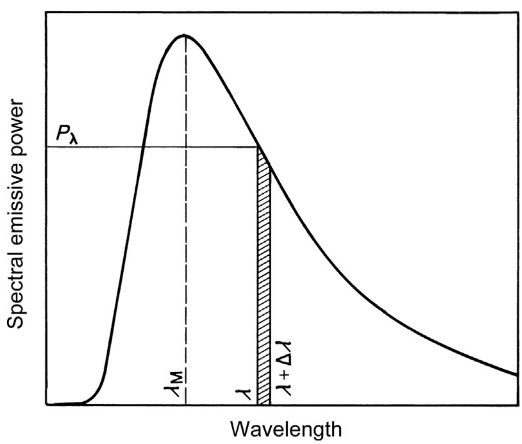

FIGURE 25.7 Power radiated per unit area as a function of wavelength; definition of P_λ. *From Shortley, G., and Williams, D., ©1971. Elements of Physics, 5th ed., p. 844. Reprinted by permission of Pearson Education, Inc: Upper Saddle River, New Jersey.*

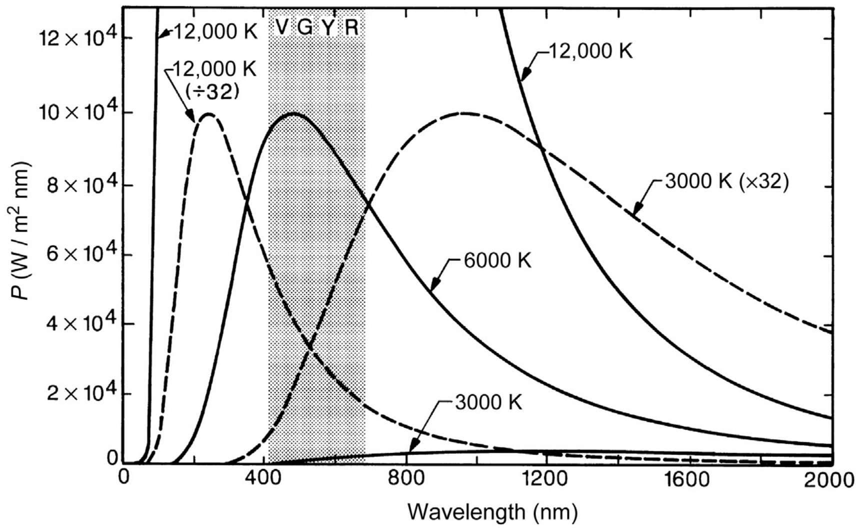

FIGURE 25.8 The solid lines show plots of black-body radiation curves for temperatures of 3000, 6000, and 12,000 K. Broken lines show the 3000 K curve with ordinates multiplied by 32 and the 12,000 K curve with ordinates divided by 32; this adjustment brings the maxima of these curves to the same value as the maximum of the 6000 K curve. *From Shortley, G., and Williams, D., ©1971. Elements of Physics, 5th ed., p. 844. Reprinted by permission of Pearson Education, Inc: Upper Saddle River, New Jersey.*

The progressive shift of maximum toward the violet end of the spectrum accounts for the observed change in color of a radiating metal body from red through white to blue as its temperature is increased. Sunlight has the characteristics of black-body radiation corresponding to a temperature of about 6000 K and serves to define "white". Incandescent-lamp filaments are much cooler (about 3000 K) and give light that is more orange than daylight. Certain stars, such as Vega (12,000 K) are much hotter and appear blue. These points regarding color are illustrated by the broken curves in Figure 25.8, in which the ordinates of the 3000- and 12,000-degree curves have been scaled so that all three curves are plotted with the same maximum.

The wavelength λ_M of the maximum of the curve (see Figure 25.7) is found experimentally to vary inversely as the absolute temperature, according to the law

$$\lambda_M = A/T \tag{25.6}$$

where A is a constant whose value is 2.8978×10^6 nm K. This relation is called *Wien's displacement law*. (For a biography of Wien, see the Appendix, Section 25.16.) Thus with each doubling of temperature (see Figure 25.8), the value of λ_M is divided by 2 (Shortley and Williams, 1971; pp. 843–845).

25.8 SUN'S TEMPERATURE

With our knowledge about black bodies, the Stefan–Boltzmann law, and Wien's displacement law, we now return to solar radiation. The sun's surface temperature T_s can be calculated with the Stefan–Boltzmann law. The Stefan–Boltzmann constant can be expressed as 8.26×10^{-11} cal/cm^2/min/K^4 (Geiger, 1965; p. 6). Geiger (1965, p. 7) says, since radiation decreases with the square of the distance, and the sun's radius is $s = 695{,}560$ km, the earth's radius R is negligible in comparison with the distance M of the sun from the earth,

$$\left(\sigma T_s^4\right)/k = M^2/s^2, \tag{25.7}$$

from which the value of T_s is found to be 5793 K (Geiger, 1965; p. 7) ($M = 150 \times 10^6$ km; $R = 6370$ km).

25.9 EARTH'S TEMPERATURE

The Stefan–Boltzmann law also provides a conclusion about the earth's mean temperature, based on the assumption that the earth radiates like a black body. Because the earth's temperature is subject to variations in time, but remains unchanged on the whole over thousands of years, the amount radiated by the surface of the sphere of area $4\pi R^2$ must be equal to the quantity received by the cross-sectional area πR^2 multiplied by the solar constant k. The mean surface temperature of the earth T_E, calculated from the equation

$$(\sigma T_E)\left(4\pi R^2\right) = k\pi R^2 \tag{25.8}$$

is found to be 278 K = 5 °C. The surface temperature of the earth observed near the ground is higher (14 °C), because of the protective effect of the atmosphere, which is correspondingly cooler at higher levels (−50 to −80 °C) (Geiger, 1965; p. 7).

25.10 COMPARISON OF SOLAR AND TERRESTRIAL RADIATION

Even if the quantity of radiation received from the sun is equal to that radiated by the earth, the two types of radiation are fundamentally different in quality. The total intensity of solar radiation is spread over a wide range of wavelengths. According to Wien's displacement law (Eqn (25.6)), the product of the temperature T of a radiating body and the wavelength corresponding to maximum intensity of radiation, λ_M, is constant. With T in °K and λ_M in microns (Geiger, 1965; p. 7)

$$T\lambda_M = 2880\ (^\circ\mathrm{K}, \mu). \tag{25.9}$$

As noted earlier, the higher the temperature of a body, the farther the radiation maximum is displaced toward shorter wavelengths. For the surface temperature of 5793 K (calculated temperature of sun; see earlier), λ_M is 0.50 μm; the observed maximum is 0.47 μm, which means a higher temperature of the sun. The difference shows that the sun radiates only approximately as a black body. In either case, the most intense solar radiation occurs in the blue-green range of visible light. The wavelength of maximum intensity of radiation for the earth's actual surface temperature of 14 °C or 287 K is about 10.0 μm, which is well into the invisible infrared (Geiger, 1965; p. 7) (Figure 25.1).

Distribution of intensities over the spectrum is so asymmetric that 25% of the total radiation lies below λ_M, in the short-wavelength range, and 75% is above λ_M. It is therefore appropriate to introduce a wavelength λ_s as a center of balance, such that 50% of the total intensity lies on either side of it; then $T\lambda_s = 4100(^\circ\mathrm{K}, \mu)$. In Figure 25.3, below the abscissa, which has a logarithmic wavelength scale, is shown a scale of temperature determined by this equation. For solar radiation, λ_s is 0.7 μm, in the visible red. Forty percent of solar radiation lies within the infrared part of the spectrum (Geiger, 1965; p. 8). On the left in Figure 25.3 is the curve of solar radiation from observations. The area enclosed by the curve represents the total intensity, hence the solar constant, reduced to one quarter (for the reasons mentioned earlier) for comparison with the earth's radiation. The two distribution curves on the right correspond to earth temperatures of +30 °C and −10 °C. The figure makes it clear that in meteorology it is correct to distinguish between two fundamentally different streams of radiation. Solar radiation and diffuse sky radiation are in the range from 0.3 to 2.2 μm. Radiation emitted by the earth and its atmosphere lies between 6.8 and about 100 μm. The intervening range from 2.2 to 6.8 μm is used by both types of radiation to the extent of less than 5%. Hence there is a marked division between the two kinds of radiation, which we shall refer to as short-wavelength and long-wavelength radiations (Geiger, 1965; pp. 8–9).

25.11 HEAT BUDGET

Now let us turn to the heat budget at the surface of the earth. We shall use Geiger's description (1965, pp. 9–10). We assume an ideal case in which the earth's surface is entirely horizontal and extensive. In this case, the boundary between ground and atmosphere is a plane. The plane contains no heat, but under normal circumstances a considerable exchange of heat occurs across it. The quantities that determine this heat exchange will now be discussed.

Radiation S is the first (major) factor of heat exchange. Heat arrives at the earth's surface from the sun, the sky, and the atmosphere (insolation). Heat is sent back into space (outgoing or terrestrial radiation). Factors that add heat to the surface of the ground are considered positive; those that subtract heat from it are negative. The sum of insolation and outgoing radiation, that is, the balance, decides in individual cases whether S is positive or negative. In Geiger's (1965) book, the unit for S, as for all factors in the heat budget, is cal/cm^2/min, also called in English the langley per minute, abbreviated ly/min. These are not SI units. The SI unit is W/m^2 (1 W = 1 J/s = 0.239 cal/s).

The second factor B is determined by the flow of heat from the ground to the surface or in the reverse direction. During a cold winter night heat flows upward through the ground and B is, therefore, positive; on a summer afternoon, B is negative because heat is transported downward from the surface.

Third, the air above the ground plays a part in the exchange of heat L. This factor also may be positive or negative. Transport of heat to or from the ground depends not only on physical heat conduction, as within the ground, but also on mass exchange (eddy diffusion) because of the great mobility of the air.

Fourth, there is the effect of evaporation V. This is measured, like all the other heat-economy factors, in calories per square centimeter per minute (Geiger, 1965) or W/m^2. The quantity of heat in calories required to evaporate 1 g of water is called the latent heat of vaporization and varies with temperature. At 25 °C, it is 583 cal/g. If a round figure of 600 cal/g is used for temperatures above 0 °C, then V in cal/cm^2/min corresponds to the evaporation of a certain depth of water in millimeters per hour. Normally V is negative, but positive values are possible, as when dew or hoarfrost forms on the surface and heat of condensation or sublimation is released.

From the surroundings of the area under consideration, there can flow warmer or colder, moister or drier, air, a process that is called *advection*. This advection process has an effect on the heat economy of the area and upsets the assumption on which the previous discussion was based, namely that horizontal counter-influences are absent. We introduce the additional advection process by defining the factor Q.

Precipitation may entail a gain or a loss of heat for the ground, depending on its temperature, and this is given by the symbol N. Over oceans, lakes, and rivers, the factor W, for the exchange of heat between water and its surface, is used instead of B.

The complete equation for the heat exchange at a flat vegetation-free ground surface is:

$$S + B\,(\text{or } W) + L + V + Q + N = 0. \tag{25.10}$$

Note: Geiger was a German, so the letters stand for German words, as follows: S = die Sonne (the sun); B = der Boden (the soil); W = das Wasser (the water); L = die Luft (the air); V = die Verdunstung or die Verdampfung (the evaporation); Q = die Quer (*in die Quer* in German means "crosswise"); N = der Niederschlag (the rain).

25.12 RADIATION BALANCE

Now let us consider specifically the factor S in Eqn (25.10), because it is the most important factor taking part in the heat exchange at the surface of the earth. We continue with Geiger's (1965, pp. 12–13) analysis.

The symbol S means the radiation balance or net radiation. If insolation is greater than outgoing (terrestrial) radiation, the balance is positive; if it is less, the balance is negative. A negative balance is described as a net loss of radiation. Sometimes the term "outgoing radiation" is used to designate the Stefan–Boltzmann radiation loss and sometimes for the negative radiation balance. Geiger (1965) uses the term "effective outgoing radiation" and avoids the ambiguous term "outgoing radiation."

The radiation balance consists of two radiation streams of different spectral ranges (Figure 25.3). There is a short-wavelength part only as long as the sun shines, that is, during the daytime. Radiation reaching the surface of the earth consists of that part of direct solar radiation I that is not reflected by clouds, absorbed by the atmosphere, or scattered diffusely, and also that part of the nondirectional sky radiation H that represents diffusely scattered radiation that has reached the ground and provides "daylight" within the visible spectrum. The value of $I + H$ reaching a horizontal surface is called *global radiation*. Part of this radiation is reflected by the earth's surface. This short-wavelength reflected radiation R depends on the nature of the ground, in contrast to $I + H$. The reflection factor or *albedo* is the ratio of the reflected to the incident radiation, usually expressed as a percentage (Table 25.1).

Incoming long-wavelength radiation is of no significance in the radiation balance of the earth as a planet. It is, however, of great importance for the radiation balance of the earth's surface. The atmosphere of the earth contains water vapor, ozone, and other gases (Figure 25.2), all of which absorb radiation and emit it according to Kirchhoff's law (Eqn (25.3)). This long-wavelength atmospheric radiation G is termed counterradiation, because it counteracts the terrestrial radiation loss. It

TABLE 25.1 Albedo of Various Surfaces for Total Solar Radiation with Diffuse Reflection (Both Short Wavelength)

Surface	Percent Reflected
Fresh snow cover	75–95
Compressed snow	70
Melting snow	30–65
Dense cloud cover	60–90
Old snow cover	40–70
Clean firn snow	50–65
Dry salt cover	50
Light sand dunes, surf	30–60
Clean glacier ice	30–46
Dirty firn snow	20–50
Lime	45
Granite	15
Quartz sand	35
Sandy soil	15–40
Meadows and fields	12–30
Prairie, wet	22
Prairie, dry	32
Stubble fields	15–17
Grain crops	10–25
Pine, spruce wood	10–14
Deciduous wood	16–37
Yellow leaves (autumn)	33–36
Desert, midday	15
Desert, low solar altitude	35
Bare fields	12–25
Wet plowed fields	5–14
Densely built-up areas	15–25
Woods	5–20
Grass, green	16–27

TABLE 25.1 Albedo of Various Surfaces for Total Solar Radiation with Diffuse Reflection (Both Short Wavelength)—cont'd

Surface	Percent Reflected
Grass, dried	16–19
Dark clay, wet	2–8
Dark clay, dry	16
Sand, wet	9
Sand, dry	18
Dark cultivated soil	7–10
Water surfaces, sea	3–10
Water, 0–30 °C	2
Water, 60 °C	6
Water, 85 °C	58

From Geiger (1965), p. 15, and Van Wijk and Scholte Ubing (1966), p. 87. This material is used by the permission of Dr. Walter Geiger, legal successor to Prof. Dr. Rudolf Geiger, Perlschneider Str. 18, 81241 Munich, Germany.

occurs both by day and by night, and, in fact, is somewhat greater during the day, because it is dependent on temperature.

It might be expected that part of this long-wavelength radiation would also be lost through reflection by the ground. However, the earth's natural surface cover can be considered to resemble a black body. In general, the albedo of natural surfaces is less than 5%. Snow cover, which reflects so strongly within the visible spectrum that newly fallen snow produces a striking improvement in light conditions, is practically an ideal black body for long waves, reflecting at the most 0.5% of the incident radiation.

According to the Stefan–Boltzmann law, the radiation emitted by the soil surface by day and by night would be exactly σT^4 (T is the surface temperature), if the ground were a black body. As just stated, this condition is largely fulfilled by natural surfaces. To the extent that it is not fulfilled, the outgoing radiation will be reduced according to Kirchhoff's law. But at the same time, the amount of outgoing long-wavelength reflected radiation would be increased, and it is not possible to distinguish it instrumentally from the terrestrial radiation.

The radiation balance S is, therefore, given by the equation

$$S = I + H + G - \sigma T^4 - R \left(\text{cal/cm}^2/\text{min} \;\text{ or }\; \text{W/m}^2\right) \tag{25.11}$$

The last two factors in Eqn (25.11) depend on the nature of the ground surface, while the first three on the right-hand side of the equation are

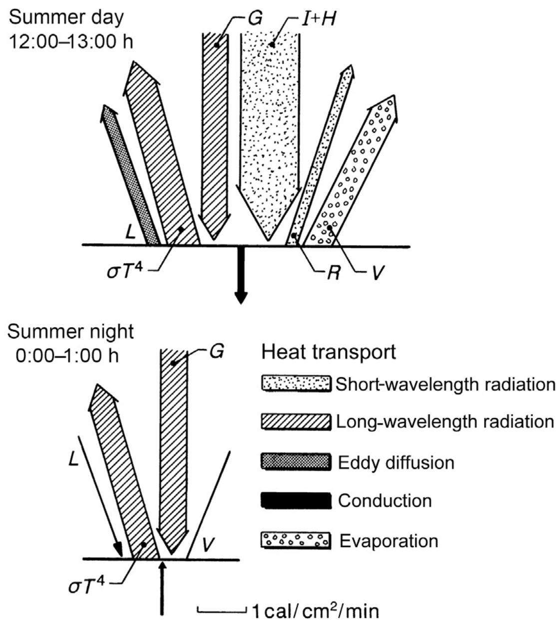

FIGURE 25.9 The importance of radiation as compared with the other factors in the heat budget. I, direct solar radiation; H, diffusely scattered radiation; G, long-wave atmospheric radiation; σT^4, radiation emitted by soil surface; R, short-wave reflected radiation; L, heat; V, evaporation; $I + H$, global radiation. *From Geiger (1965), p. 14. This material is used by the permission of the legal successor to Rudolf Geiger Prof. Dr. Walter Geiger, Perlschneider Str. 18, 81241 Munich, Germany.*

independent of it. Figure 25.9 shows the magnitude of these factors for a summer day and a summer night.

25.13 APPENDIX: BIOGRAPHY OF GUSTAV KIRCHHOFF

Gustav Robert Kirchhoff (1824–1887), the German physicist who established spectroscopy on a sound theoretical basis and studied complex electrical circuits as well as radiation, was born at Königsberg (Kaliningrad) on March 12, 1824. He was educated at the university of his native town. After acting as *Privatdozent* in Berlin (1847–1850), he became extraordinary professor of physics in Breslau in 1850. Four years later he was appointed professor of physics in Heidelberg, and in 1875 he was transferred to Berlin, where he remained for the rest of his life.

Kirchhoff's contributions to experimental and mathematical physics were numerous and important. In his work in electricity, he modified the resistance bridge, brought to public attention by Wheatstone (see Chapter 22), and developed a theorem that gives the distribution of currents in a network. Kirchhoff extended Ohm's theory for a linear conductor (see Chapter 22) to the case of conductors in three dimensions, and so generalized the equations dealing with the flow of electricity in conductors. Another important piece of work was the demonstration that an electric disturbance is propagated along wire with the same velocity as light is propagated in free space (Preece, 1971a).

His name is best known for the researches, in conjunction with the great German chemist Robert Wilhelm Bunsen (1811–1899), on the development of spectrum analysis. The rich period of Kirchhoff's life was the 20 years he taught in Heidelberg and worked with Bunsen. It was during the years 1859–1862 that these great investigators together made the outstanding discoveries of spectrum analysis. At the time the physical laboratory in Heidelberg was unpretentious and was located in a house, the "Riesengebäude," then 150 years old. The memorable researches were carried on in a small room. In 1857 Bunsen and Henry E. Roscoe first described the Bunsen burner. This new burner furnished Bunsen and Kirchhoff with a nonluminous gas flame of fairly high temperature, in which chemical substances could be vaporized and a spectrum could be obtained, due purely to the luminous vapor (Cajori, 1929; p. 168).

To Kirchhoff belongs the merit of having enunciated a complete account of the theory of spectrum analysis. He established the method on a solid basis. He gave the explanation of the Fraunhofer lines and thus opened up to investigation a new field in spectrum analysis applied to the composition of celestial bodies (Preece, 1971a). Although spectrum analysis, as a terrestrial science, was due equally to Kirchhoff and Bunsen, its celestial applications belong to Kirchhoff alone. Kirchhoff's explanation of the Fraunhofer lines was epoch-making. Said Helmholtz (1821–1894; German physicist), "It has in fact most extraordinary consequences of the most palpable kind, and has become of the highest importance for all branches of natural science. It has excited the admiration and stimulated the fancy of men as hardly any other discovery has done, because it has permitted an insight into worlds that seemed forever veiled for us." In this connection, Kirchhoff frequently related the following story. The question of whether or not Fraunhofer's lines reveal the presence of gold in the sun was being investigated at the time. Kirchhoff's banker remarked on this occasion: "What do I care for gold in the sun if I cannot fetch it down here?" Shortly afterward Kirchhoff received from England a medal for his discovery, and its value in gold. While handing it over to his banker, he observed, "Look here, I have succeeded at last in fetching some gold from the sun" (Cajori, 1929; p. 169).

Kirchhoff's researches concerning radiation played a leading role. He defined a perfect black body, and, as to the experimental realization of it, he suggested a closed box with black walls inside, kept at a constant temperature and having a very small opening through which radiation may pass from the inside to the outside. He died in Berlin on October 17, 1887 (Preece, 1971a).

25.14 APPENDIX: BIOGRAPHY OF JOSEF STEFAN

Josef Stefan (1835–1893), the Austrian physicist who made original contributions to the kinetic theory of gases, hydrodynamics, and radiation, was born on March 24, 1835, at St. Peter near Klagenfurt. He was educated at the University of Vienna, where he became doctor of philosophy in 1858; then *Privatdozent* in mathematical physics; in 1863 professor ordinarius of physics; and in 1866 director of the Physical Institute. He was a distinguished member of the Vienna Academy of Sciences, of which he was appointed secretary in 1875. Before Stefan's work, Kirchhoff had already described the perfect radiator as the perfectly black body, namely, one that absorbed all the radiation that fell on it and reflected none, but emitted radiation of all wavelengths. Stefan showed empirically in 1879 that the radiation of such a body was proportional to the fourth power of its absolute temperature, a relationship since known as Stefan's law or as the Stefan–Boltzmann law after it had been deduced by Ludwig Boltzmann in 1884 from thermodynamic considerations. Stefan's law was one of the first important steps leading to the understanding of blackbody radiation from which the quantum idea of radiation sprang. Stefan died on January 7, 1893, in Vienna (McKie, 1971).

25.15 APPENDIX: BIOGRAPHY OF LUDWIG BOLTZMANN

Ludwig Boltzmann (1844–1906), Austrian physicist, made important contributions to many branches of physics. His greatest achievements were the development of statistical mechanics and the statistical explanation of the second law of thermodynamics. He was born in Vienna on February 20, 1844, and studied at the university there, receiving his doctorate in 1866. He held professorships in mathematics (Vienna, 1873–1876), experimental physics (Graz, 1876–1889), and theoretical physics (Graz, 1869–1873; Munich, 1889–1893; Vienna, 1894–1900; Leipzig, 1900–1902; Vienna, 1902–1906). Despite his several professorships, theoretical physics was his real vocation (Klein, 1971).

In 1905, when he was professor of theoretical physics at the University of Vienna, Boltzmann was invited to give a course of lectures in the summer session at the University of California in Berkeley. His recollections of that summer survive in his popular essay, "Reise eines deutschen Professors ins Eldorado." An abridged translation is presented in *Physics Today* (Boltzmann, 1905). Boltzmann's great sense of humor is evident in this writing.

When Boltzmann began his scientific work, he attacked the problem, until then unconsidered, of explaining the second law of thermodynamics on the basis of the atomic theory of matter. In a series of papers published during the 1870s, Boltzmann showed that the second law could be understood by combining the laws of mechanics, applied to the motions of the atoms, with the theory of probability. In this way, he made clear that the second law is an essentially statistical law and that a system will approach a state of thermodynamic equilibrium, because the equilibrium state is overwhelmingly the most probable state. The entropy function of thermodynamics, whose behavior shows the trend to equilibrium and whose maximum value characterizes the equilibrium state, is itself a measure of the probability of the macroscopic state. (The equation relating entropy and probability is engraved on the monument at Boltzmann's grave in Vienna.) He built much of the structure of statistical mechanics, a structure later elaborated by the U.S. mathematical physicist Josiah Willard Gibbs (1839–1903) (Klein, 1971).

Apart from Boltzmann's work on statistical mechanics, he made extensive calculations in the kinetic theory of gases. He was also one of the first Europeans to recognize and to expound on the importance of James Clerk Maxwell's (1831–1879; Scottish physicist) theory of electromagnetism, a subject on which he published a two-volume treatise. Boltzmann also derived, using thermodynamics, Stefan's law for black-body radiation, a derivation that Hendrik Antoon Lorentz (1853–1928, Dutch physicist who got the Nobel Prize in physics in 1902) called "a true pearl of theoretical physics" (Klein, 1971).

Boltzmann's work in statistical mechanics was strongly attacked by Wilhelm Ostwald (1853–1932; German chemist who received the Nobel Prize in chemistry in 1909) and the energeticists who did not believe in atoms and wanted to base all of physical science on energy considerations only. Boltzmann also suffered from misunderstandings, on the part of others, about his ideas on the nature of irreversibility. They did not fully grasp the statistical nature of his reasoning. He was fully justified against both sets of opponents by the discoveries in atomic physics, which began shortly before 1900 and by the fluctuation phenomena, such as Brownian motion, which could be understood only by statistical mechanics (Klein, 1971). In 1905, Einstein explained Brownian motion (Isaacson, 2009; pp. 25, 27) by means of Boltzmann's ideas (Cercignani, 1998; p. 102), but Boltzmann died apparently before he knew about Einstein's confirmation of his work. Cercignani (1998) gives an in-depth discussion of the scientific world in which Boltzmann lived.

Depressed by the criticism of his work, Boltzmann took his own life by hanging on September 5, 1906, at Duino, near Trieste, Italy (Klein, 1971).

25.16 APPENDIX: BIOGRAPHY OF WILHELM WIEN

Wilhelm Wien (1864–1928), German physicist and Nobel Prize winner, was born January 13, 1864, at Gaffken, East Prussia. He studied at the universities of Göttingen, Heidelberg, and Berlin, and in 1890 entered the Physicotechnical Institute near Berlin as assistant to Helmholtz. In 1896, he was appointed professor at the technical high school in Aachen. In 1899 he went to Giessen; in 1900 to Würzburg; and in 1920 to Munich. He wrote on optical problems; on radiation, especially black-body radiation, for which in 1911 he was awarded the Nobel Prize; on water and air currents, on discharge through rarefied gases, cathode rays, and X-rays. Wien's most important contributions to black-body radiation are contained in three laws named after him, the most famous of these being known as Wien's displacement law. His autobiography was published posthumously under the title *Aus dem Leben und Wirken eines Physikers* (1930). Wien died on August 30, 1928, in Munich (Preece, 1971b).

References

Boltzmann, L., 1905. A German professor's trip to El Dorado. Phys. Today 45 (1), 44–51, 1992. (Translated by Bertram Schwarzschild).

Cajori, F., 1929. A History of Physics. Macmillan, New York.

Cercignani, C., 1998. Ludwig Boltzmann: The Man Who Trusted Atoms. Oxford University Press, New York.

Geiger, R., 1965. The Climate Near the Ground, revised ed. Harvard University Press, Cambridge, Massachusetts. Translated by Scripta Technica, Inc.

Isaacson, W., 2009. Einstein. The Life of a Genius. HarperCollins, New York.

Johnson, F.S., 1954. The solar constant. J. Meteorol. 11, 431–439.

Klein, M.J., 1971. Boltzmann, Ludwig. Encyclopaedia Britannica 3, 893.

McKie, D., 1971. Stefan, Josef. Encyclopaedia Britannica 21, 198.

Preece, W.E. (Ed.), 1971a. Kirchhoff, Gustav. Encyclopaedia Britannica, vol. 13, p. 383.

Preece, W.E. (Ed.), 1971b. Wien, Wilhelm. Encyclopaedia Britannica, vol. 23, p. 499.

Rosenberg, N.J., 1974. Microclimate: The Biological Environment. Wiley, New York.

Shortley, G., Williams, D., 1971. Elements of Physics, fifth ed. Prentice-Hall, Englewood Cliffs, New Jersey.

Slatyer, R.O., 1967. Plant–Water Relationships. Academic Press, London.

Van Wijk, W.R., Scholte Ubing, D.W., 1966. Radiation. In: van Wijk, W.R. (Ed.), Physics of Plant Environment, second ed. North-Holland, Amsterdam, pp. 62–101.