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Solar Energy

Chapter One

Types of Energy Sources

The sources of energy can be classified into tow broad categories:−

- Fossil Sources
- Renewable Sources

Fossil sources comprise the traditional types of fuels, mainly, crude oil, natural gas and coal. These types will be depleted in the near future and the humanity should seek alternative sources. The traditional fuels also produce harmful byproducts that pollute the environment.

Renewable sources are always compensated by the nature and are clean sources with no harmful pollutants. There are many types of renewable energies, the most important are: −

- Solar energy
- Wind energy
- Geothermal energy
- Sea waves energy
- Biomass energy

The most important type of the above five types is **solar energy**. Extensive research efforts are devoted to study, invent and test devices and systems that are operated on solar energy.

Advantages of solar energy

- Available everywhere.
- Simple to harness.
- Systems require the least maintenance.
- Suitable for variety of applications.

Disadvantages of solar energy

- Low heat flux (which requires large collection areas).
- Not available at night and cloudy weathers (which requires effective storage means).
- Inherently changing with time and location.
- Systems are more expensive than in fossil fuels.

Applications of solar energy

Solar energy can be utilized in two major branches: −

- **Solar photovoltaic cells** at which the solar radiation is directly converted to DC current or can be stored in batteries. Solar cells are appropriate for low−power applications such as lighting and small electronic devices; however, large areas of cell fields can produce considerable amounts of power. The cell efficiency in general is less than 20%.
- **Solar thermal systems** at which the solar radiation is converted to thermal energy that can be carried by working fluids or stored in suitable materials. Solar thermal systems are more efficient than solar cells and can be utilized in various fields, such as: −

❖ Domestic and industrial water heating
❖ Air-conditioning and refrigeration
❖ Distillation and desalination
❖ Drying of food crops
❖ Electric power generation

The Sun Model

The sun is the ultimate origin of most of the energy presently available on earth.

This includes the energy for direct heating, as well as wind energy, hydroelectric power,and energy derived from fossil fuels. Fossil fuels exist today as a consequence of photosyn-
thesis, the process through which plants convert solar energy to chemical energy. A complete understanding of solar energy technology is only possible with a thorough analysis of solar radiation.

The sun, our closest star, provides the energy to maintain life on earth and produces the necessary gravitational attraction to keep our planet in a nearly circular orbit. It has :

The mass of sun **<u>MΘ= {1.99x 10^{30} kg (=3.3x 10^{5} earth masses</u>)**

and **<u>a radius of RΘ = 6.96 x 10^{8}m (=109 earth radius)</u>**

The earth-sun distance varies from

1.0167 AU (aphelion, ~ July 4) الاوج الشمسي

to **0.983 AU (perihelion, ~ {January 4)** الحضيض الشمسي

1 AU (LAU =1 astronomical unit = 1.5 x 10" m).

The distance = 1.5 x10^{11}m

is believed that the interior temperature is about 15 million kelvins.

The chemical composition of the sun mainly hydrogen with a lesser amount of helium

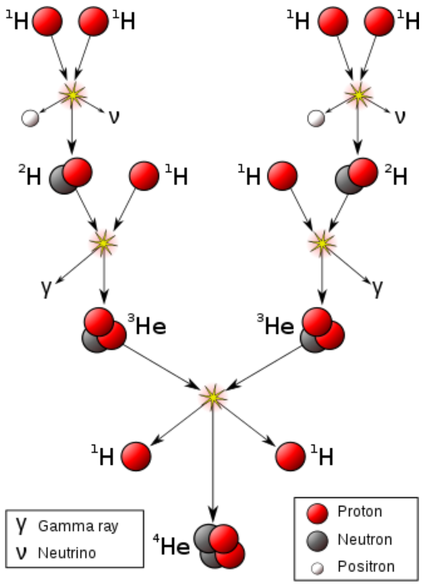
These two elements, which account for 96 to 99 percent of the sun's mass, are under enormous pressure and only the large gravitational pull of the sun keeps this mass together.

Energy is generated in the interior through the nuclear fusion of hydrogen into helium. The proton-proton chain reaction is one of the most important reactions taking place in the center of the sun, whereby hydrogen turns into helium, and it also takes place in the stars,. Another chain of interaction that takes place in the sun and stars and derives its energy from. The proton-proton interaction is predominant in the sun and in stars with or smaller masses of the sun.

This reaction is characterized by the release of <u>large energy</u> that is created by the nuclear fusion of hydrogen and produces helium. In this reaction, the mass of the resulting helium is <u>less</u> than the mass of hydrogen involved in the reaction by 1% (this decrease is called mass deficiency). This lack of mass turns into energy according to Einstein's equation for mass-energy equivalence, which is $\mathbf{E = mc^2}$

ويبدأ تفاعل البروتون-بروتون عند أقل درجة حرارة لازمة لحدوث الاندماج النووي. وهو تفاعل من الممكن أن يبدأ عند 3 مليون درجة كلفن. وتكون جميع الذرات المشتركة في التفاعل متأينة، أي تكون إلكتروناتها قد انفصلت عنها بسبب الحرارة العالية (وتسمى تلك الحالة للمادة بلازما). وبسبب توافر الحرارة العالية في مركز الشمس وفي النجوم تكون حالة المادة فيها في حالة البلازما.

ويتناسب معدل إنتاج الطاقة عن طريق تفاعل بروتون-بروتون مع القوة (الأس) 6 لدرجة الحرارة. أي أنه عنما تزيد درجة الحرارة بنسبة 5 % يزيد معدل التفاعل بنسبة 34% وبالتالي تزيد الطاقة بتلك النسبة.
بالنسبة إلى التفاعل الجاري في الشمس فهو يجري عند درجة حرارة تصل إلى 12 مليون كلفن وتحت ضغط عالي جداً في مركز الشمس



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This energy finds its way to the surface and is eventually emitted into space primarily in the form of electromagnetic radiation.
The surface of the sun, the photosphere, is actually a transition region in which the density falls off rapidly.
As we move from the interior of the sun to the outer part of the photosphere, we pass from an optically opaque medium to a relatively transparent one.
Furthermore, the temperature falls to approximately 6000 K.
Above the photosphere is the sun’s atmosphere, which is called the chromosphere because it selectively absorbs certain colors of the radiation emitted from the photosphere.
Most of the radiation reaching us emanates from the **photosphere** so that the solar spectrum is determined by the optical and thermal properties of the solar surface.
The simple model being used here assumes that the sun behaves as a black body whose surface is maintained at T ~ 6000 K. This surface temperature is kept constant by a source of energy located in the interior.
As a result of this elevated temperature, the surface glows and electromagnetic radiation is emitted in all directions of space (Figure 1).

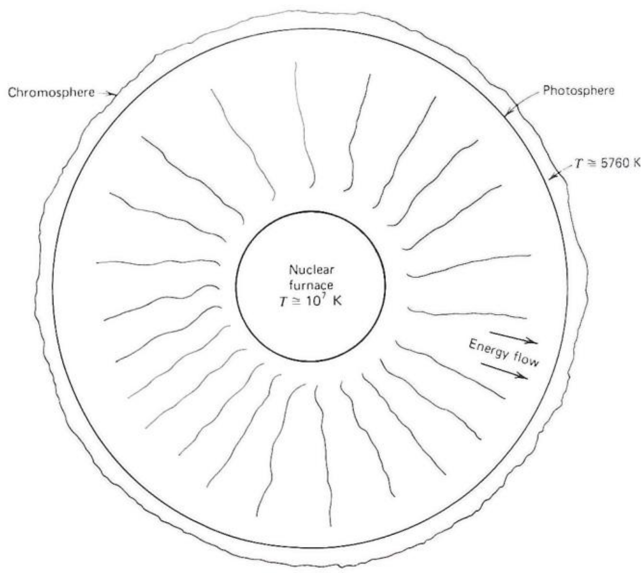

Fig 1/ A simplified model of the sun

Black Body Emission

Electromagnetic radiation: is composed of waves of oscillating electric and magnetic fields.

Each wave is characterized by a wavelength λ and frequency v. In free space all the waves travel at the same speed,C= 2.9979 x 10° m/sec.

The frequency, wavelength, and speed of each wave are related by vλ = C

The higher the frequency is, the shorter the wavelength and vice versa.

The entire electromagnetic spectrum is shown in Figure.2

- ⇨ Only a very narrow band of wavelengths, those in the range 400 nm < λ <700nm, are visible to the human eye.”
- ⇨ Those wavelengths bor- dering the visible on the violet end (λ < 400 nm) are called ultraviolet and are invisible.
- ⇨ Those wavelengths bordering on the red (λ > 700nm) are the infrared and are also invisible,
- ⇨ approximately half of the solar radiation is in the infrared: the visible components make up less than 40 percent of the solar energy.

Note

λ nanometer (I nm)=10^{-9} m =10^{-7+}cem. It is often convenient to measure wavelengths in microns (µm), where lµm = 10^{-6}cm so that 1000 nm =1µm. The spectral range of radiation detected by the eye varies among individuals. We will define the visible range to include those wavelengths between 0.4 um and 0.7µm

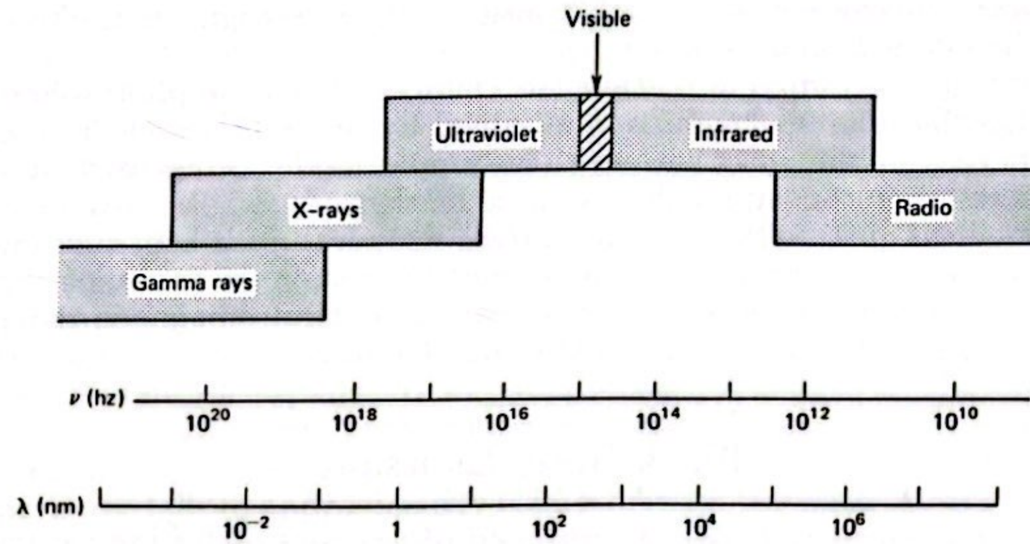

FIGURE 1.2 *The electromagnetic spectrum.*

wavelength. The total flux in the distribution is

$$F = \int_0^\infty F_\lambda \, d\lambda$$

We will define the spectral absorptivity a_λ and the spectral reflectivity r_λ of a body's surface by

$$a_\lambda = \frac{F_\lambda^{(a)}}{F_\lambda^{(i)}} \quad \text{and} \quad r_\lambda = \frac{F_\lambda^{(r)}}{F_\lambda^{(i)}} \tag{1.1}$$

When the body is opaque, what is not reflected from the surface must be absorbed and we may write

$$a_\lambda + r_\lambda = 1 \tag{1.2}$$

Actually, a_λ and r_λ, for a real surface, depend on the wavelength of the incident flux and on the direction of incidence of the radiation. For example, many surfaces absorb radiation well at normal incidence, yet do not absorb efficiently when the radiation is incident at glancing angles. We will neglect this dependence on direction of incidence and assume, for simplicity, that the surface is an *isotropic absorber*. However, the spectral reflectivity and absorptivity do vary appreciably with the wavelength of the incident radiant flux. Many pigments that appear white to the eye because they reflect well in the visible spectrum may in fact be excellent absorbers of infrared radiation.

It is useful to define the following idealizations of real surfaces.

Black Body Any body whose surface absorbs *all* components of incident electromagnetic radiation regardless of the wavelength or the direction of incidence is called a *black body*. For such bodies we have

$$a_\lambda = 1 \qquad (r_\lambda = 0) \text{ for all } \lambda$$

White Body Any body whose surface reflects *all* components of incident electromagnetic radiation regardless of the wavelength and the direction of incidence is called a *white body* (or perfect reflector). For such bodies we have

$$a_\lambda = 0 \qquad (r_\lambda = 1) \text{ for all } \lambda$$

Gray Body Any body whose surface absorptivity is between that of a black body and that of a white body but is *independent* of the wavelength and direction of incidence of the incident radiation is called an (isotropic) *gray body*. For such bodies we have

$$a_\lambda = a \qquad (\text{for all } \lambda) \qquad \text{where } 0 < a < 1$$

No real surfaces are perfectly black or white. For solar radiation, black matte lacquer has a mean absorptivity of $a = 0.97$. Polished silver, which is highly reflective, has $a = 0.07$.

It is an experimental fact of nature that when any opaque body is maintained at a constant temperature its surface emits characteristic electromagnetic radiation called *thermal radiation*. This radiation is generally emitted in all directions and contains all of the wavelengths of the electromagnetic spectrum. The thermal flux leaving the body depends both on the surface characteristics of the body as well as on its Kelvin temperature T. For isotropically absorbing surfaces the emitted thermal flux is isotropic and its spectral distribution is given by

$$\boxed{F_\lambda = \epsilon_\lambda B_\lambda(T)} \qquad (1.3a)$$

where ϵ_λ is a characteristic of the surface called the *spectral emissivity* and where $B_\lambda(T)$ is called *Planck's function*. This universal function of

λ and T is given by

$$\boxed{B_\lambda(T) = \frac{a}{\lambda^5(e^{b/\lambda T} - 1)}} \tag{1.3b}$$

The constants in the function are

$$a = 2\pi hc^2 = 3.7405 \times 10^{-16}\ \mathrm{W-m^2}$$

and

$$b = \frac{hc}{k} = 1.4388 \times 10^{-2}\ \mathrm{m-K}$$

where

h (Planck's constant) $= 6.6252 \times 10^{-34}$ J-s (joule-sec)
c (speed of light) $= 2.9979 \times 10^{8}$ m/sec
k (Boltzmann's constant) $= 1.3806 \times 10^{-23}$ J/K (joule/K)

The total radiant flux emitted by the surface is

$$F = \int_0^\infty \epsilon_\lambda B_\lambda(T)\, d\lambda \tag{1.4}$$

It can be shown from the laws of thermodynamic equilibrium that the thermal emissivity and the optical absorptivity are in fact related. This relationship is established by Kirchhoff's law.[3]

The spectral emissivity of an isotropic surface is equal to its spectral absorptivity or

$$\boxed{\epsilon_\lambda = a_\lambda} \tag{1.5}$$

It follows from Equation 1.5 that the black body for which $a_\lambda = 1$ is the most efficient radiator with $\epsilon_\lambda = 1$ for all wavelengths. Thus for a black body Equation 1.3a gives

$$F_{\lambda\ \mathrm{black}} = B_\lambda(T)$$

[3]This version of Kirchhoff's law is applicable only to idealized isotropic surfaces such as black, white, and gray bodies. The more general form implies that when the thermal radiation leaving a surface is not isotropic, the thermal emissivity in a given direction is equal to the absorptivity of radiation incident from that direction.

so that the function describing the spectral flux emitted by a black surface at a Kelvin temperature T is simply the Planck function. It also follows from Equation 1.5 that a white body ($a = \epsilon = 0$) emits *no* thermal radiation and that a gray body emits radiation according to

$$F_{\lambda\,\mathrm{gray}} = \epsilon B_\lambda(T) \qquad (0 < \epsilon < 1) \tag{1.6}$$

The emission spectrum of a black, gray, and real body at 6000 K is plotted in Figure 1.3.

Note that the spectral function for a black body is equal to the Planck function, whereas the spectral function for a gray body has the same shape but is reduced by a factor ϵ. It is therefore important that we consider the mathematical properties of $B_\lambda(T)$.

Figure 1.4 shows the Planck function as a function of wavelength for various Kelvin temperatures. Each curve has a finite area under it and each has a wavelength, λ_{max}, at which $B_\lambda(T)$ is a maximum. Therefore, at any finite temperature, the energy carried by those components whose wavelengths are either very short or very long is negligibly small. Furthermore, the most energy is carried by those wavelengths in the region where $B_\lambda(T)$ is largest.

It can be shown that the following mathematical properties of $B_\lambda(T)$ are valid.

$$\boxed{\lambda_{max} = \frac{\alpha}{T} \qquad \text{(displacement law)}} \tag{1.7a}$$

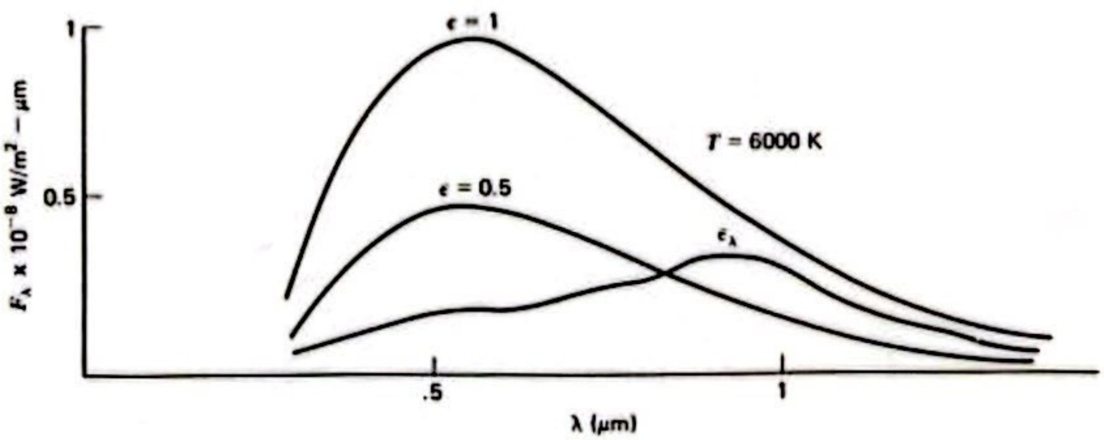

FIGURE 1.3 *The thermal emission spectrum of a black (ϵ = 1), gray (ϵ = 0.5), and real (ϵ_λ) body, each at 6000 K. The real body represented here is a more efficient emitter of infrared radiation than it is of visible radiation.*

and

$$\boxed{\int_0^\infty B_\lambda(T)\, d\lambda = \sigma T^4 \qquad \text{(Stefan–Boltzmann law)}} \tag{1.7b}$$

where α and σ are universal constants.

From Equation 1.7a we observe that the wavelength at which $B_\lambda(T)$ is a maximum varies inversely with the Kelvin temperature. From Equation 1.7b we see that the total area under $B_\lambda(T)$ and consequently the total thermal flux emitted by a black body is proportional to the fourth power of the Kelvin temperature.

In the following presentation we will continue to express all quantities in the MKS (meter-kilogram-second) system. Energy is expressed in joules (J), power (energy/time) in watts (W), and area in m^2. In these units the total flux is in watts/m^2 and the wavelength is conveniently expressed either in meters, microns ($1\ \mu m = 10^{-6}$ m), or nanometers ($1\ nm = 10^{-9}$ m). The constants in Equation 1.7 are

$$\alpha = 2898\ \mu m - K$$

$$\sigma = \frac{5.6696 \times 10^{-8}\ W}{m^2 - K^4} \qquad \text{(Stefan–Boltzmann constant)}$$

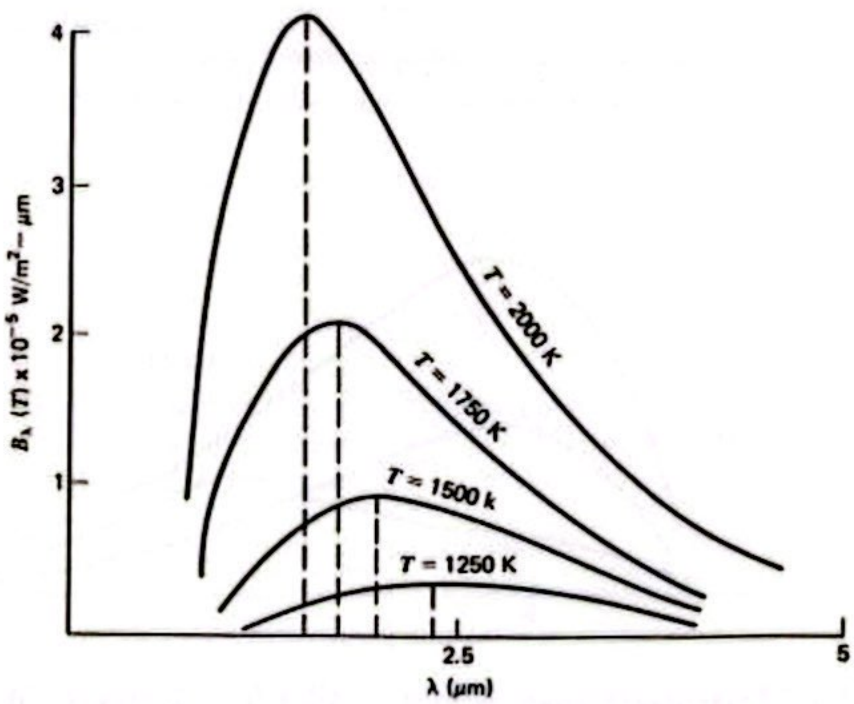

FIGURE 1.4 *The thermal emission spectra of black bodies at different temperatures. The dashed lines mark the values of* λ_{max}.

The λ_{max} of a given Planck distribution is often said to represent the characteristic "color," although it is not necessarily the color detected by the human eye. Nonetheless, the fact that λ_{max} decreases with increasing T explains why a black body appears red hot at some temperature and becomes white hot as the temperature is raised. The whiteness indicates the presence of bluish components. Using Equation 1.7a, we find that a black body at a temperature of 7000 K has a characteristic wavelength $\lambda_{max} = 0.414\ \mu m$ (blue), whereas one with $T = 5800$ K has $\lambda_{max} = 0.500\ \mu m$ (green). If a black body is only at room temperature ($T = 300$ K), then $\lambda_{max} = 966\ \mu m$ (infrared) and the body appears black to the eye.

The total flux emitted by a black body is derived from the Stefan–Boltzmann law Equation 1.7b as

$$F_{black} = \sigma T^4 = (5.67 \times 10^{-8}) T^4 \tag{1.8}$$

Thus black objects whose surfaces are maintained at 7000, 5800, and 300 K, respectively, emit fluxes of 1.36×10^8, 6.4×10^7, and $4.59 \times 10^2\ W/m^2$, respectively. Note the dramatic increase in black-body emission as we raise the Kelvin temperature. Since the emission varies as T^4, a twofold increase in T produces a sixteen fold increase in F_{black}. The gray body generalization of Equation 1.8 is

$$F_{gray} = \epsilon \sigma T^4 \qquad (0 < \epsilon < 1) \tag{1.9}$$

Radiative Emission from the Sun

If we now take the model of the sun to be a black body at a steady-state temperature T, then the radiant flux emitted at the solar surface can be represented by a Planck distribution. The observed spectral distribution of the sun differs slightly from $B_\lambda(T)$ because the sun is neither in radiative equilibrium nor even in steady state. Nevertheless, a good approximation to the solar spectrum is a black-body curve corresponding to a temperature of $T_\odot \simeq 5800$ K, as can be seen from Figure 1.5. We will use this black-body approximation subsequently.

Using Equation 1.7a, we see that the characteristic wavelength of the solar spectrum is

$$\lambda_{max} = \frac{2.9 \times 10^3\ \mu m - K}{5800\ K} = 0.500\ \mu m = 500\ nm$$

which corresponds to green light. From Equation 1.7b we find the

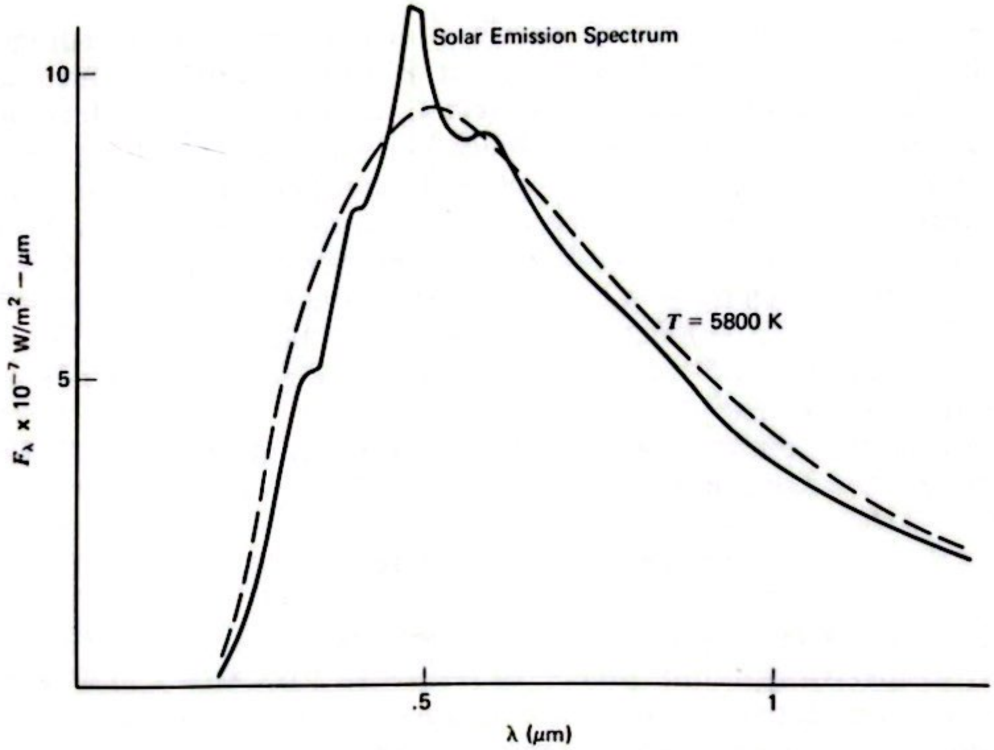

FIGURE 1.5 *The spectral distribution of the flux emitted from the sun's surface. The dashed line is the emission spectrum of a black body at* 5800 K.

total flux leaving the surface of the sun to be

$$F_\odot = \sigma T_\odot^4 = \left(\frac{5.670 \times 10^{-8}\ \text{W}}{\text{m}^2 - \text{K}^4}\right)(5800\ \text{K})^4 = 6.416 \times 10^7\ \text{W/m}^2$$

This radiation is *diffuse* (traveling in all directions) when it leaves the solar surface. The total radiant power emitted from the sun is obtained by multiplying the flux above by the surface area of the sun. We find

$$\begin{aligned} P_\odot &= F_\odot 4\pi R_\odot^2 \\ &\simeq (6.42 \times 10^7\ \text{W/m}^2) 4\pi (6.96 \times 10^8\ \text{m})^2 \\ &\simeq 3.91 \times 10^{26}\ \text{W} \end{aligned}$$

If the sun emits radiation isotropically, this enormous power, called *luminosity* by astronomers, is emitted equally in all directions of space. As the distance from the sun increases, this power is spread over spherical surfaces of increasing area. Consequently, the intensity varies inversely as the square of the distance from the center of the sun. At a distance r the surface area is $4\pi r^2$ so that the radiant flux crossing such a surface is

$$F = \frac{P_\odot}{4\pi r^2} = \frac{4\pi R_\odot{}^2 F_\odot}{4\pi r^2}$$

or

$$\begin{aligned} F &= R_\odot{}^2 F_\odot / r^2 \\ &\simeq \frac{3.11 \times 10^{25}}{r^2}\,\mathrm{W/m^2} \end{aligned} \tag{1.10}$$

Because the earth's distance from the sun varies throughout the year, the total flux reaching the earth also changes. At the mean earth–sun distance of $r = 1.5 \times 10^{11}$ m, the flux is

$$S = F \simeq \frac{3.11 \times 10^{25}}{(1.50 \times 10^{11})^2} = 1382\ \mathrm{W/m^2} \tag{1.11}$$

The value of the flux is called the *solar constant*, which, as already mentioned, is not actually a constant but varies with season and somewhat with solar activity. Note also that the numerical value in Equation 1.11 has been obtained by assuming the solar spectrum to be that of a black body at ~5800 K. If we were to change this temperature to 5762 K, an accurate computation would show that the solar constant would drop to ~1352 W/m^2. The value of the solar constant has been measured by various investigators to range from 1350 to 1382 W/m^2. The discrepancy amounts to approximately 2 percent. We will arbitrarily take 1352 W/m^2 as the value of the solar constant, taking the spectrum temperature to be ~5760 K.

Equation 1.10 is also valid for the spectral distribution and we may write

$$\begin{aligned} S_\lambda &= \frac{R_\odot{}^2}{r^2} F_{\odot\lambda} = \frac{R_\odot{}^2}{r^2} B_\lambda(5760\ \mathrm{K}) \\ &\simeq 2.165 \times 10^{-5}\, B_\lambda(5760\ \mathrm{K})(\text{in } \mathrm{W/m^2\text{-}m}) \end{aligned} \tag{1.12}$$

with

$$S = \int_0^\infty S_\lambda\, d\lambda = 1352\ \mathrm{W/m^2}$$