14.8 THERMAL RADIATION

An object emits thermal radiation while simultaneously absorbing some of the thermal radiation emitted by other objects. The rate of absorption may be less than, equal to, or greater than the rate of emission.

All bodies emit energy through electromagnetic radiation—due to the oscillation of electric charges in the atoms. Thermal radiation consists of electromagnetic waves that travel at the speed of light. Unlike conduction and convection, radiation does not require a material medium; the Sun radiates heat to Earth through the near vacuum of space.

When solar radiation reaches Earth, it is partially absorbed and partially reflected. The absorbed portion increases the Earth's internal energy. If absorption and reflection were the whole story, Earth's internal energy would continuously increase; but the Earth also emits radiation, which carries energy away. Since the temperature of the Earth remains relatively constant, it must emit energy at the same rate, on average, that it absorbs energy from the Sun. Thus, there is an equilibrium between absorption and emission.

Conceptual Example 14.13

An Alligator Lying in the Sun

An alligator crawls out into the Sun to get warm. Solar radiation is incident on the alligator at the rate of 300 W; 70 W of it is reflected. (a) What happens to the other 230 W? (b) If the alligator emits 100 W, does its body temperature rise, fall, or stay the same? Ignore heat flow by conduction and convection.

Solution and Discussion (a) When radiation falls on an object, some can be absorbed, some can be reflected, and—for a transparent or translucent object—some can be transmitted through the object without being absorbed or reflected. Since the alligator is opaque, no radiation is transmitted through it. All the radiation is either absorbed or reflected, so the other 230 W is absorbed. (b) Since 230 W is absorbed while 100 W is emitted, the alligator absorbs more radiation than it emits. Absorption increases internal energy while emission decreases it, so the alligator's internal energy is increasing at a rate of 130 W. Thus, we expect the alligator's body temperature to rise. (The actual rate of increase of internal energy would be smaller since conduction and convection carry heat away as well.)

Conceptual Practice Problem 14.13 Maintaining Constant Temperature

After some time elapses, the alligator's body temperature reaches a constant level. The rate of absorption is still 230 W. If the alligator loses heat by conduction and convection at a rate of 90 W, at what rate does it emit radiation?

Stefan's Radiation Law

An idealized body that absorbs all the radiation incident upon it is called a **blackbody**. A blackbody absorbs not only all visible light, but infrared, ultraviolet, and all other wavelengths of electromagnetic radiation. It turns out (see Conceptual Question 23) that a good *absorber* is also a good *emitter* of radiation. A blackbody emits more radiant power per unit surface area than any real object at the same temperature. The rate at which a blackbody emits radiation per unit surface area is proportional to the fourth power of the *absolute* temperature:

Stefan's law of radiation (blackbody):

$$\mathcal{P} = \sigma A T^4 \qquad (14\text{-}15)$$

In Eq. (14-15), A is the surface area and T is the surface temperature of the blackbody *in kelvins*. Since Stefan's law involves the absolute temperature and not a temperature difference, °C *cannot* be substituted. The universal constant σ (Greek letter sigma) is called *Stefan's constant*:

$$\sigma = 5.670 \times 10^{-8}\ \text{W/(m}^2\cdot\text{K}^4) \qquad (14\text{-}16)$$

The fourth-power temperature dependence implies that the power emitted is extremely sensitive to temperature changes. If the absolute temperature of a body doubles, the energy emitted increases by a factor of $2^4 = 16$.

Since real bodies are not perfect absorbers and therefore emit less than a blackbody, we define the **emissivity** (e) as the ratio of the emitted power of the body to that of a blackbody at the same temperature. Then Stefan's law becomes

Stefan's law of radiation:

$$\mathcal{P} = e\sigma AT^4 \quad \textbf{(14-17)}$$

The emissivity ranges from 0 to 1; $e = 1$ for a perfect radiator and absorber (a blackbody) and $e = 0$ for a perfect reflector. The emissivity for polished aluminum, an excellent reflector, is about 0.05; for soot (carbon black) it is about 0.95. Human skin, no matter what the pigmentation, has an emissivity of about 0.97 in the infrared part of the spectrum. Many objects have high emissivities in the infrared even though they may reflect a fair amount of the visible light incident on them.

Radiation Spectrum

The electromagnetic radiation we are concerned with falls into three wavelength ranges. Infrared radiation includes wavelengths from about 100 μm down to 0.7 μm. The wavelengths of visible light range from about 0.7 μm to about 0.4 μm. Ultraviolet wavelengths are less than 0.4 μm.

The total power radiated is not the only thing that varies with temperature. Figure 14.17 shows the radiation spectrum—a graph of how much radiation occurs as a function of wavelength—for blackbodies at two different temperatures. The wavelength at which the maximum power is emitted decreases as temperature increases. Objects at ordinary temperatures emit primarily in the infrared—around 10 μm in wavelength for 300 K. The Sun, since it is much hotter, radiates primarily at shorter wavelengths. Its radiation peaks in the visible (no surprise there) but includes plenty of infrared and ultraviolet as well. The wavelength of maximum radiation is inversely proportional to the absolute temperature:

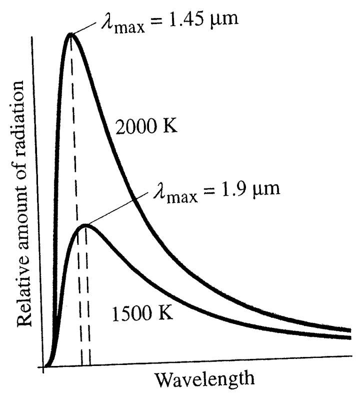

Figure 14.17 Graphs of blackbody radiation as a function of wavelength at two different temperatures. At the higher temperature, the wavelength of maximum radiation is shorter (Wien's law) and the total power radiated, represented by the area under the graph, increases (Stefan's law).

Wien's Law

$$\lambda_{max} T = 2.898 \times 10^{-3}\ \text{m·K} \quad \textbf{(14-18)}$$

where the temperature T is the temperature in kelvins and λ_{max} is the wavelength of maximum radiation in meters.

As the temperature of the blackbody rises to 1000 K and above, the peak intensity shifts toward shorter wavelengths until some of the emitted radiation falls in the visible. Since the longest visible wavelengths are for red light, the heated body glows dull red. As the temperature of the blackbody continues to increase, the red glow becomes brighter red, then orange, then yellow-white, and eventually blue-white as the blackbody emits more and more visible light. When the body is emitting all the colors of the visible spectrum, the glow appears white to the eye. When something is red-hot, it is not as hot as something that is white-hot.

Example 14.14
Temperature of the Sun

The maximum rate of energy emission from the Sun occurs in the middle of the visible range—at about $\lambda = 0.5$ μm. Estimate the temperature of the Sun's surface.

Strategy We assume the Sun to be a blackbody. Then the wavelength of maximum emission and the surface temperature are related by Wien's law.

Solution Given: $\lambda_{max} = 0.5$ μm $= 5 \times 10^{-7}$ m. Then from Wien's law, we know that the product of the wavelength for maximum power emission and the corresponding temperature for the power emission is

$$\lambda_{max} T = 2.898 \times 10^{-3}\ \text{m·K}$$

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Example 14.14 Continued

We can solve for the temperature since we know λ_{max}:

$$T = \frac{2.898 \times 10^{-3}\ \text{m·K}}{5 \times 10^{-7}\ \text{m}} = 6000\ \text{K}$$

Discussion Quick check: an object at 300 K has $\lambda_{max} \approx 10\ \mu\text{m}$, which is 20 times the λ_{max} in the radiation from the Sun (0.5 μm). Since λ_{max} and T are inversely proportional, the Sun's surface temperature is 20 times 300 K = 6000 K.

Practice Problem 14.14 Wavelengths of Maximum Power Emission for Skin

The temperature of skin varies from 30°C to 35°C depending on the blood flow near the skin surface. What is the range of wavelengths of maximum power emission from skin?

Simultaneous Emission and Absorption of Thermal Radiation

Net rate of energy transfer due to emission and absorption of thermal radiation

An object simultaneously emitting and absorbing thermal radiation has a *net* rate of heat flow due to thermal radiation given by $\mathcal{P}_{net} = \mathcal{P}_{emitted} - \mathcal{P}_{absorbed}$. Suppose an object with surface area A and temperature T is bathed in thermal radiation coming from its surroundings in all directions that are at a *uniform* temperature T_s. Then the *net* rate of heat flow due to thermal radiation is

$$\mathcal{P}_{net} = e\sigma AT^4 - e\sigma AT_s^4 = e\sigma A(T^4 - T_s^4) \qquad \textbf{(14-19)}$$

A body emits energy even if it is at the same temperature as its surroundings; it just emits at the same rate that it absorbs, so $\mathcal{P}_{net} = 0$. If $T > T_s$, the object emits more thermal radiation than it absorbs. If $T < T_s$, the object absorbs more thermal radiation than it emits.

Why is the rate of *absorption* proportional to the *emissivity*? Because a good emitter is also a good absorber. The emissivity e measures not only how much the object emits compared to a blackbody; it also measures how much the object *absorbs* compared to a blackbody. A blackbody at the same temperature as its surroundings would have to absorb radiation at the rate $\mathcal{P}_{absorbed} = \sigma AT_s^4$ to exactly balance the rate of emission. However, emissivity does depend on temperature. Equation (14-19) assumes the emissivity at temperature T is the same as the emissivity at temperature T_s. If T and T_s are very different, we would have to modify Eq. (14-19) to use two different emissivities.

Do not substitute temperature in Celsius degrees into Eq. (14-19). The quantity inside the parentheses might look like a temperature difference, but it is not. The two kelvin temperatures are raised to the fourth power, *then* subtracted—which is not the same as the corresponding two Celsius temperatures subjected to the same mathematical operations. By the same token, do not subtract the temperatures in kelvins and then raise to the fourth power. The difference of the fourth powers is not equal to the difference raised to the fourth power, as can be readily demonstrated:

$$(2^4 - 1^4) = 15 \quad \text{but} \quad (2 - 1)^4 = 1$$

Making the Connection: thermography

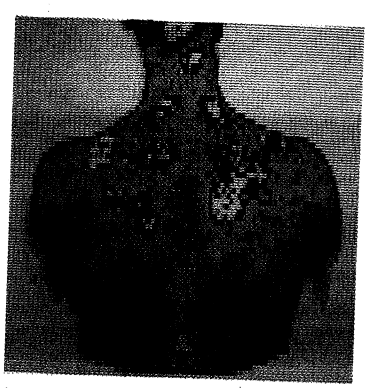

Figure 14.18 Thermography of a backache. The magenta areas are warmer than the surrounding tissue, revealing the location of the source of pain.

Medical Applications of Thermal Radiation

Thermal radiation from the body is used as a diagnostic tool in medicine. "Instant-read" thermometers work by measuring the intensity of thermal radiation in the patient's ear. A thermogram shows whether one area is radiating more heat than it should, indicating a higher temperature due to abnormal cellular activity. For example, when a broken bone is healing, heat can be detected at the location of the break just by placing a hand lightly on the area of skin over the break. Infrared detectors, originally developed for military uses (nightscopes, for example), can be used to detect radiation from the skin. The radiation is absorbed and an electrical signal is produced that is then used to produce a visual display (Fig. 14.18). Thermography has been used to screen travelers at airports in Asia for the high fever that accompanies infection with severe acute respiratory syndrome (SARS).

Example 14.15

Thermal Radiation from Human Body

A person of body surface area 2.0 m^2 is sitting in a doctor's examining room with no clothing on. The temperature of the room is 22°C and the person's average skin temperature is 34°C. Skin emits about 97% as much as a blackbody at the same temperature for wavelengths in the infrared region, where most of the emission occurs. At what *net* rate is energy radiated away from the body?

Strategy Both radiation and absorption occur in the infrared—the absolute temperatures of the skin and the room are not very different. Therefore, we can assume that 97% of the incident radiation from the room is absorbed. Equation (14-19) therefore applies. We must convert the Celsius temperatures to kelvins.

Given: surface area, $A = 2.0\ m^2$; $T_{room} = 22°C$; skin temperature, $T = 34°C$; fraction of energy emitted, $e = 0.97$

To find: net rate of energy transfer, $\mathcal{P}_{net}$

Solution The temperature of the skin surface is

$$T = 273 + 34 = 307\ K$$

and of the room is

$$T_s = 273 + 22 = 295\ K$$

The net rate of energy transfer between the room and the body is

$$\mathcal{P}_{net} = e\sigma A(T^4 - T_s^4)$$

Substituting,

$$\mathcal{P}_{net} = 0.97 \times 5.67 \times 10^{-8}\ W/(m^2 \cdot K^4) \times 2.0\ m^2 \times (307^4 - 295^4)\ K^4 = 140\ W$$

Discussion 140 W is a significant heat loss because the body also loses about 10 W by convection and conduction. To stay at a constant body temperature, an inactive person must give off heat at a rate of 90 W to account for basal metabolic activity; if the rate of heat loss exceeds that, the body temperature starts to drop. The patient had better wrap a blanket around his body or start running in place.

We need only the fraction of energy emitted and absorbed by the body; the emissivity of the walls of the room is irrelevant. If the walls are poor emitters, then they also absorb poorly, so they reflect radiation. The amount of radiation incident on the body is the same.

Practice Problem 14.15 The Roller Blader Radiates

Find how much energy per unit time the roller blader in Example 14.12 loses by radiation from her body. Her skin temperature is 35°C and the air temperature is 30°C. Her surface area is 1.2 m^2 of which 75% is exposed to the air. Assume skin has $e = 0.97$.

Example 14.16

Radiative Equilibrium of Earth

Radiant energy from the Sun reaches Earth at a rate of 1.7×10^{17} W. An average of about 30% is reflected and the rest is absorbed. Energy is also radiated by the atmosphere. Assuming that the atmosphere emits as a blackbody in the infrared ($e = 1$), calculate the temperature of the atmosphere. (The Sun's radiation peaks in the visible part of the spectrum, but the Earth's radiation peaks in the infrared due to its much lower surface temperature.)

Strategy Earth must radiate the same power as it absorbs. We use Stefan's law to find the rate at which energy is radiated as a function of temperature and then equate that to the rate of energy absorption.

Solution Earth absorbs 70% of the incident solar radiation. To have a relatively constant temperature, it must emit radiation at the same rate:

$$\mathcal{P} = 0.70 \times 1.7 \times 10^{17}\ W = 1.2 \times 10^{17}\ W$$

From Stefan's law,

$$\mathcal{P} = e\sigma AT^4$$

where we take $e = 1$ since the atmosphere is assumed to emit as a blackbody. The surface area of the Earth is

$$A = 4\pi R_E^2$$

Solving Stefan's law for T yields

$$T = \left(\frac{\mathcal{P}}{e\sigma A}\right)^{1/4}$$

Now we substitute numerical values:

$$T = \left(\frac{\mathcal{P}}{e\sigma 4\pi R_E^2}\right)^{1/4} = \left[\frac{1.2 \times 10^{17}\ W}{1 \times 5.67 \times 10^{-8}\ W/(m^2 \cdot K^4) \times 4\pi\,(6.4 \times 10^6\ m)^2}\right]^{1/4} = 253\ K = -20°C$$

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Example 14.16 Continued

Discussion Remember that –20°C is supposed to be the average temperature of the *atmosphere*, not of the Earth's surface. This relatively simple calculation gives impressively accurate results. To find the temperature of the Earth's surface, we must take the greenhouse effect into account.

Practice Problem 14.16 Reflecting Less Incident Radiation

If the Earth were to reflect 25% of the incident radiation instead of 30%, what would be the average temperature of the atmosphere?

Making the Connection: global warming and the greenhouse effect

The Greenhouse Effect

The Earth receives heat by radiation from the Sun. The atmosphere helps trap some of the radiation, acting rather like the glass in a greenhouse. When sunlight falls upon the glass of a greenhouse, most of the visible radiation and short-wavelength infrared (*near-infrared*) travel right on through; the glass is transparent to those wavelengths. The glass absorbs much of the incoming ultraviolet radiation. The radiation that gets through the glass is mostly absorbed inside the greenhouse. Since the inside of the greenhouse is much cooler than the Sun, it emits primarily infrared radiation (IR). The glass is not transparent to this longer-wavelength IR; much of it is absorbed by the glass. The glass itself also emits IR, but in both directions: half of it is emitted back inside the greenhouse. The absorption of IR by the glass keeps the greenhouse warmer than it would otherwise be. (The glass in a greenhouse has a second function not mirrored in the Earth's atmosphere—it prevents heat from being carried away by convection.)

The Earth is something like a greenhouse, where the atmosphere fulfills the role of the glass. Like glass, the atmosphere is largely transparent to visible and near-IR; the ozone layer in the upper atmosphere absorbs some of the ultraviolet. The atmosphere absorbs a great deal of the longer-wavelength IR emitted by Earth's surface. The atmosphere *radiates* IR in two directions: back toward the surface and out toward space (Fig. 14.19). "Greenhouse gases" such as CO_2 and water vapor are particularly good absorbers of IR. The higher the concentration of greenhouse gases in the atmosphere, the more IR is absorbed and the warmer the Earth's surface becomes. Even small changes in the average surface temperature can have dramatic effects on climate.

In applying Stefan's radiation law to the Earth, there are some complications. One is the effect of the cloud cover. Clouds are quite reflective, but they are sometimes there and sometimes not. The heating of the lakes and oceans causes water to evaporate and form clouds. The clouds then serve as a screen and reflect sunlight away from the Earth, reducing the temperature again.

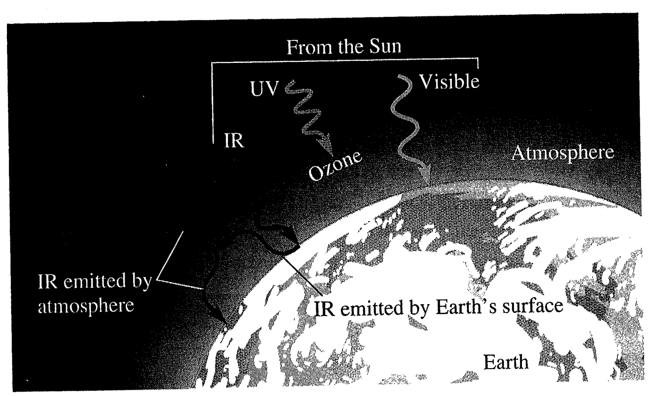

Figure 14.19 The global greenhouse effect. In this *simplified* diagram, all the UV from the Sun is absorbed by the atmosphere, while all the visible and IR from the Sun is transmitted. The Earth absorbs the visible and IR and radiates longer-wavelength IR. The longer-wavelength IR is absorbed by the atmosphere, which itself radiates IR both back toward the surface and out toward space.