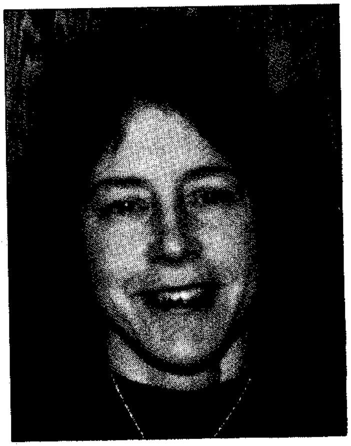
ARE MANUFACTURED EMISSIONS OF CO_2 WARMING OUR CLIMATE?

Barbara Levi
Physics Today



Barbara Goss Levi is a senior associate editor of Physics Today. She received her B.A. from Carleton College (1965) and her Ph.D. from Stanford University (1971) in particle physics. In addition to teaching (at Georgia Tech and Rutgers) and writing about physics, she has worked at Princeton University on such problems as energy conservation and arms control. Dr. Levi is a fellow of the American Physical Society and of the American Association for the Advancement of Science. She was co-editor of Global Warming: Physics and Facts, published in 1992 by the American Institute of Physics.

In the past few years stories about "global warming" have filled the news. Scientists have warned that the world's climate may grow warmer if the activities of our civilization continue to spew carbon dioxide and certain other gases into the atmosphere. The possible consequences might include the flooding of many coastal cities, the disruption of current weather patterns, and the failure of many agricultural products and ecological species. But there is no firm evidence that global warming has yet begun. So the question is whether our nation and others should undertake measures now to cut our production of carbon dioxide—just in case. It sounds prudent, but many of the measures may affect you personally. The carbon dioxide that civilization has added to the atmosphere comes from the burning of fossil fuels—coal, oil, and gas. These fuels stoke our electrical power plants and power our automobiles. Will you one day have to choose between your car or your climate?

Before humans came along, Earth's atmosphere already contained some carbon dioxide, and this carbon dioxide, along with water vapor and a few other gases in the atmosphere, has made our planet more comfortably warm than it would be without them. But our civilization is adding roughly 22 billion tons of carbon dioxide into the air every year, and much of that carbon dioxide will stay there for 50–200 years. As a result, most scientists concur that the Earth will grow warmer. However, they don't know for sure how high the mercury will rise nor how fast it will climb. The global temperature seems to have risen between 0.3 and 0.6 C° over the last 100 years, but no one can prove beyond doubt that carbon dioxide was the cause.

The climate is such a complex system that making firm predictions requires very sophisticated computer models. Nevertheless, it is rather easy to understand the basic mechanism by which carbon dioxide now warms our planet. In this essay we try to understand by a simple model exactly what factors and equations determine the temperature of the Earth as we know it. That will help us in turn to understand how an increase in carbon dioxide is likely to affect this temperature.

The Earth's temperature is largely determined by the radiation it receives from the sun. The sun, like all warm bodies, such as smoldering logs or glowing light bulbs, radiates heat in the form of electromagnetic radiation. For our purposes here, you need to know only that electromagnetic radiation is a form of wave motion and that the waves carry energy. The intensity of radiation I emitted by any body is very strongly dependent on the temperature of that body, according to a relation known as the Stefan–Boltzmann law:

$$I = \epsilon\sigma T^4, \quad (1)$$

where I is the power (in watts) radiated from a 1-m^2 area of any object that is at a temperature T (K). Two constants appear in this equation: σ is known as the Stefan–Boltzmann constant (5.67×10^{-8} W/m$^2\cdot$K^4) and ϵ is the emissivity of the radiating body, that is, its tendency to give off radiation. For a perfect radiator, $\epsilon = 1$, and for other bodies $\epsilon < 1$. Note the strong dependence of the radiated power on temperature: a body with twice the temperature will radiate 16 times more energy over the same time interval.

Problem 1
Use the Stefan–Boltzmann law to estimate the intensity of the solar radiation emitted by the sun, assuming that it is a perfect radiator and that its surface temperature is 6000 K. Then find the solar intensity at the Earth's surface, remembering that the solar energy will be spread over a spherical surface whose radius is equal to the mean distance from the sun to the Earth (1.495×10^{11} m). The sun's radius is about 6.96×10^{8} m.

The rate of solar energy reaching the Earth per unit area is known as the solar constant S and its measured value is approximately 1360 W/m^2. (Why do you think that the answer you calculated was somewhat larger than the measured value?) If that energy continually streamed into the Earth, and the Earth radiated no energy back, our planet would continue to get warmer and warmer. For the Earth (or any object) to remain at an equilibrium temperature, the rate of energy absorbed by the Earth must be exactly balanced by the rate of energy radiated outward by the Earth. This principle of energy balance determines the temperature of the Earth.

The solar constant tells us the power of radiation falling on each unit of area. To find the radiation intercepted by the Earth we must multiply the solar constant by the area of the two-dimensional projection of Earth's surface. This projection is a circle whose area equals πR_E^2. Not all this solar power is absorbed by the Earth: measurements indicate that about 30% of the incident sunlight is reflected back to space. This reflectivity is called the albedo α and it is expressed in terms of the fraction of sunlight (0.3) that is reflected. A fraction $(1 - \alpha)$ is absorbed by the Earth.

The power radiated by the Earth is the intensity given by the Stefan–Boltzmann law multiplied by the surface area of the Earth, $4\pi R_E^2$. For this calculation we assume that the emissivity of the Earth is 1. Equating the incoming solar power to the power radiated by the Earth, we get

$$\pi R_E^2 (1 - \alpha) S = 4\pi R_E^2 \sigma T_E^4 \quad (2)$$

or

$$(1 - \alpha) S / 4\sigma = T_E^4. \quad (3)$$

Solving for T_E, we get

$$T_E = [(1 - \alpha) S / 4\sigma]^{1/4} = 255 \text{ K } (-18°\text{C}). \quad (4)$$

This temperature is in fact just about the temperature that satellites have measured at the outer edge of the atmosphere. It sounds pretty chilly! But remember that in this calculation we have ignored the atmospheric gases that surround the Earth. The actual average global temperature at the surface of the Earth is a much more comfortable $T_s = 288$ K (15°C), or 33 C° warmer. The Earth's surface is kept at this more habitable temperature by its blanket of atmospheric gases and particles (Fig. 1).

Actually, there are only certain gases within the atmosphere that help keep the surface warm. Those gases, which we call "greenhouse gases," have two key properties: they largely transmit radiation at very short wavelengths, such as the solar radiation, and they strongly absorb radiation at longer wavelengths, such as those emitted by the Earth. (The radiation emitted by the Earth—or by any other body at about room temperature—is called "thermal energy.") The curves in Fig. 2*a* show how the intensity of radiation emitted from a perfect radiator varies with wavelength. The purple curve corresponds to a body (like the sun) at a temperature of 6000 K, and the red curve represents a body at 255 K (like the Earth). The curves in Figs. 2*b* and 2*c* show the wavelengths at which the main greenhouse gases—carbon dioxide and water—absorb this radiation. Although both these gases absorb radiation at several wavelengths emitted by the Earth, only water vapor appreciably absorbs some of the radiation from the sun. Thus most solar radiation passes straight through to the Earth but a lot of the

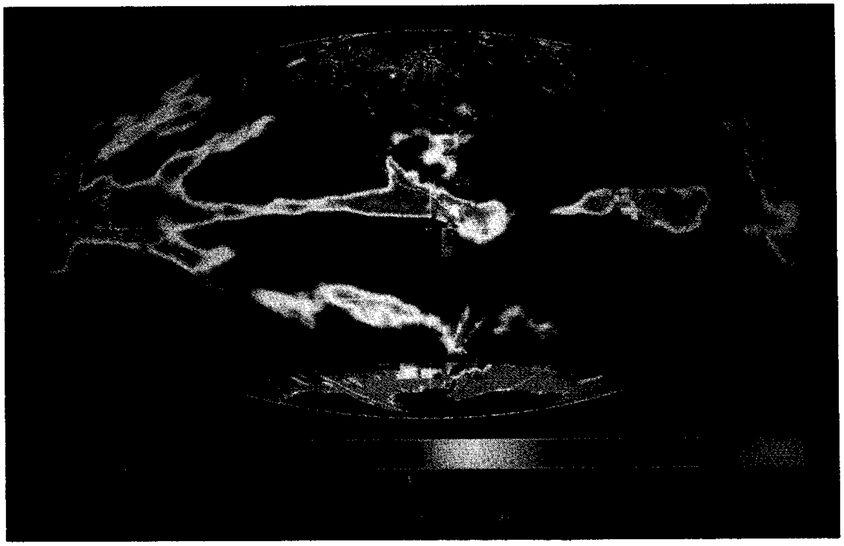


FIGURE 1 Data taken by satellites to study Earth's climate. The colors here show how much long-wavelength radiation is trapped by clouds—an effect that tends to warm the Earth. Note the high intensities over the Indian Ocean, where there are deep cirrus clouds. Clouds also reflect radiation, tending to cool the Earth. In the normal atmosphere the net effect of clouds is to cool the climate.

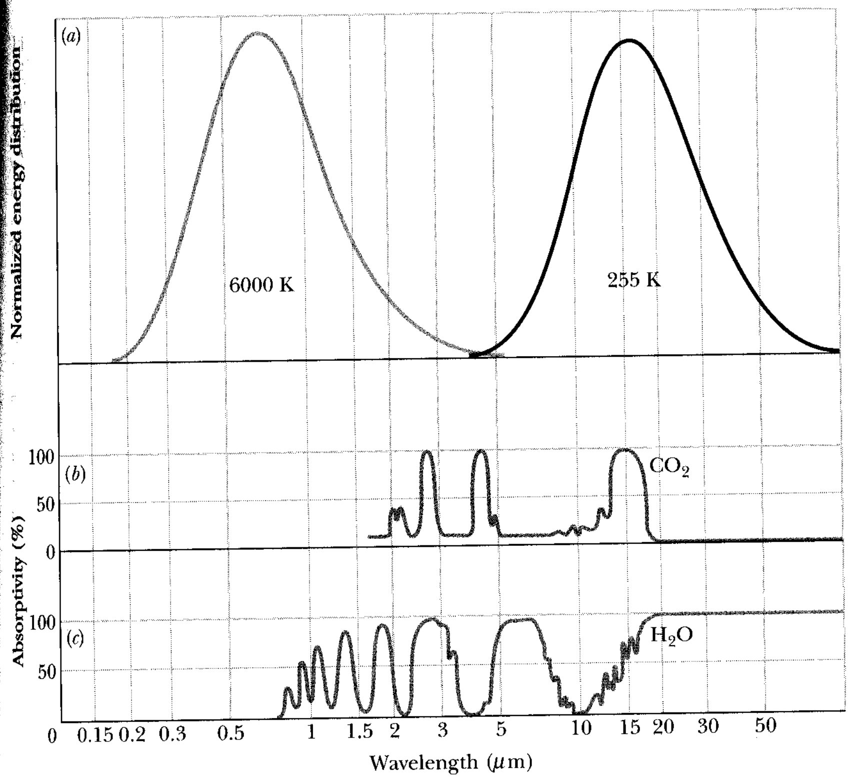


FIGURE 2 (*a*) Purple and red curves show the intensity of radiation emitted at each wavelength for perfect radiators at 6000 K (purple curve) and 255 K (red curve). The purple curve approximately represents the incoming solar radiation, and the red curve approximates the Earth's outgoing radiation. (*b, c*) Peaks in these curves show the wavelengths at which molecules of water and carbon dioxide in the atmosphere strongly absorb radiation. Note that these gases absorb more of the Earth's radiation than the solar radiation. Adapted from J. P. Pleixoto and H. O. Oort, *Physics of Climate*, American Institute of Physics, 1992, Fig. 6.2.

Earth's radiation gets trapped by the atmosphere.

To get an intuitive idea of how these gases affect the temperature, imagine that Earth initially did not have this blanket of greenhouse gases so that its surface was at the temperature of 255 K we calculated earlier. Suppose some greenhouse gases are now suddenly added to the Earth's atmosphere. At first Earth's surface will continue to radiate the amount of energy dictated by its temperature according to the Stefan–Boltzmann law: that intensity just balances the inward flux from the sun. But now the greenhouse gases will absorb some of this energy. These gases will reradiate the energy, some of it back to Earth's surface. The surface now will receive more energy than it is giving off and must warm. As it warms it will give off more radiant energy. The surface will continue to warm until it reaches the temperature at which the energy fluxes balance.

We can calculate the temperature at which the Earth will reach this balance by constructing a simple model. See Fig. 3. The model has two layers: the atmosphere and Earth's surface. We make the simplifying assumption that the sun's radiation S' passes unattenuated through the greenhouse gases to the surface, but that Earth's thermal radiation, denoted E, is completely trapped by the greenhouse gases in the atmosphere. These atmospheric gases absorb Earth's radiation and they reradiate the energy uniformly in all directions, as shown by the arrows labeled A. You can see from the diagram that the net effect is that Earth's surface receives not only the radiation from the sun but also the power reradiated by the atmosphere.

In Fig. 3 the incoming solar radiation is denoted by S', and its value is just the unreflected solar energy $(1 - \alpha)S$ divided by 4. (The factor of 4 comes from the fact that the radiation emitted by the Earth is proportional to its total surface area while the radiation that Earth receives is proportional to its projected area: the ratio of those two areas is 4.)

Energy conservation requires that the energy flows in and out be balanced at each of the two layers.

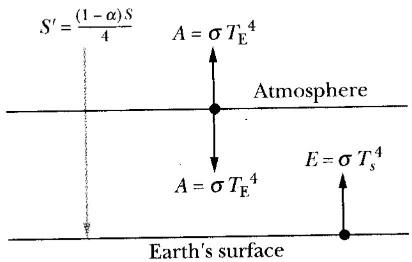


FIGURE 3 Simple model of Earth's radiation balance relates the incoming radiation from the sun S' to the radiation emitted by Earth's surface E and the radiation emitted by the atmosphere A. At the top of the atmosphere the outgoing radiation A must equal the incoming radiation S'. Similarly, at the Earth's surface E must equal $S' + A$.

Thus we get the following two equations:

top of the atmosphere: $S' = A$; (5)

surface of the Earth: $S' + A = E$. (6)

If we substitute the value of A given by Eq. 5 into Eq. 6 and recall that the power radiated by Earth can be written in terms of the Stefan–Boltzmann law, we get

$$E = 2S'$$

or

$$T_s^4 = 2(1 - \alpha)S/4\sigma, \quad (7)$$

$$T_s = 303 \text{ K } (30°\text{C}). \quad (8)$$

Our answer is larger than the observed surface temperature of 15°C, but we have ignored some very important effects in our simple model. Can you think of some of them? One is that the greenhouse gases actually absorb some of the solar radiation and transmit some of the Earth's thermal radiation.

Problem 2
In the two-layer model, consider the case in which the atmosphere absorbs a fraction $a < 1$ of the Earth's radiation. In this case, the radiation leaving the top of the atmosphere will include a faction of the radiation from the Earth's surface that has not been absorbed by the atmosphere. What value of absorptivity a would the atmosphere have to have for the surface temperature to have the observed value of 288 K?

Another effect ignored in the simple model is the energy carried away from the surface by evaporation as well as radiation. A third is that the atmosphere is not a single layer at one temperature but is stratified, with its temperature gradually decreasing with altitude, up to about 10 km. Yet a fourth excluded factor is convection: as air near the surface of the Earth is warmed, it rises, carrying some of the heat with it to higher altitudes. Furthermore a realistic model would have to consider the variations of solar intensity with latitude, the subsequent convection currents driven by the temperature differences between equator and poles, surface topology, the effects of clouds, and the interactions between the oceans, atmosphere, land, and ice masses. (Figure 4 shows a more realistic diagram of energy flows within the Earth–atmosphere system.) Those scientists who have tackled this problem have spent decades to develop very detailed computer models that require the most advanced computers we have.

Problem 3
In the early 1980s a team of five scientists warned that a nuclear war might set off a "nuclear winter," or period of dramatically cold weather. This deep cold would result if the fires ignited by nuclear weapons sent enough soot into the atmosphere essentially to block out the sun. Add a third layer—soot—above the atmosphere in the simple model. Assume that the soot absorbs all the incoming sunlight and lets out all the thermal radiation from the Earth and atmosphere. Calculate the effective surface temperature of the Earth. (The question of how severe a "nuclear winter" might be is still debated and requires far more sophisticated treatment than our simple model!)

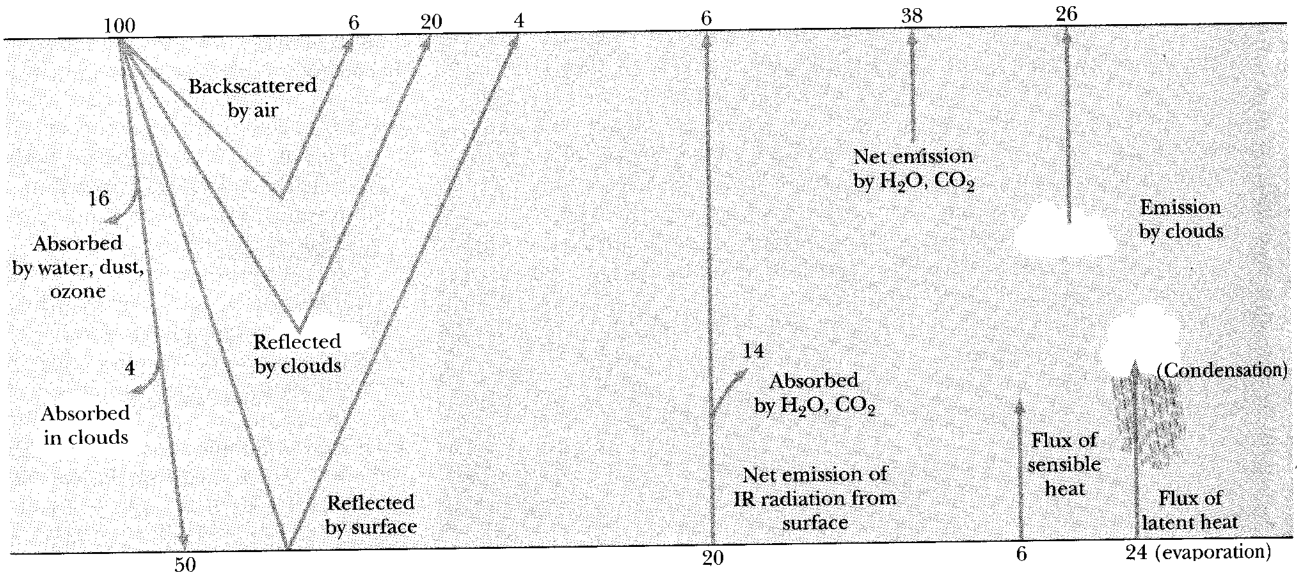


FIGURE 4 Fluxes of energy in the atmosphere are more complex than those in the simple model. The numbers are the energy fluxes expressed as a percentage of the incoming radiation, which is 100. Adapted from J. P. Pleixoto and H. O. Oort, *Physics of Climate,* American Institute of Physics, 1992, Fig. 6.3.

The carbon dioxide emitted by human activities has already increased the atmospheric concentrations by 25%, to 350 parts per million, by volume. If we continue to produce carbon dioxide and other greenhouse gases at current rates, the concentrations may reach a level in the next 50 years or so that is twice that of the pre-industrial era. The computerized climate models now developed calculate that this doubling of CO_2 will increase Earth's temperature by somewhere between 1.5 and 4.5 C°. The rise might be greater in some portions of the globe than in others and might everywhere be accompanied by other climate effects, such as altered patterns of rainfall or increased incidences of hurricanes, as well as a rise in the sea levels. No one knows whether the pace of climate change might outstrip the ability of natural ecosystems or human institutions to adapt. And yet, major efforts to cut down on CO_2 emissions are expected to be quite costly. Nevertheless, several panels of scientists have begun to call for prudent measures to curb emissions of carbon dioxide or other gases such as chlorofluorocarbons (which already pose a threat to the ozone layer), methane, and nitrous oxides. If their recommendations are followed, you may not have to give up driving your car, but you certainly might have to buy one that gets many more miles to the gallon—or runs on something other than fossil fuel!

Answers

1. 7.35×10^7 W/m^2; 1590 W/m^2 (20% greater than the measured value).
2. $2 - 2S'/\sigma T_s^4 = 0.78$.
3. $[(1 - \alpha)S/8\sigma]^{1/4} = 214$ K.

Box 5-2 Tools of the Astronomer's Trade

Using the Laws of Blackbody Radiation

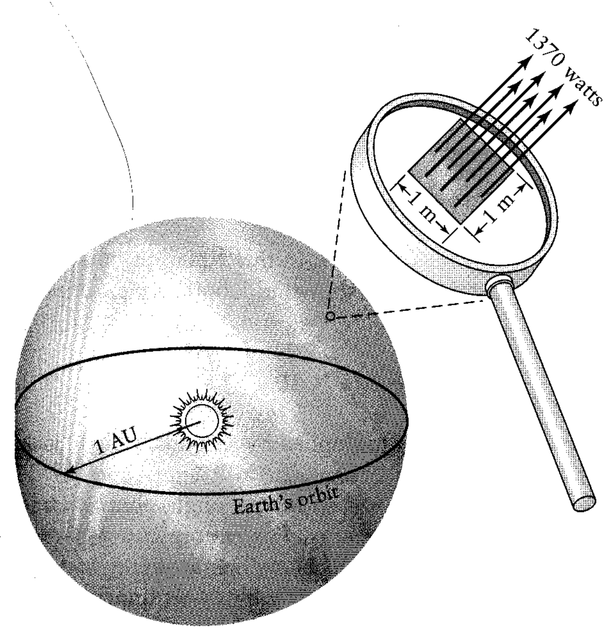
The Sun and stars behave like nearly perfect blackbodies. Wien's law and the Stefan-Boltzmann law can therefore be used to relate the surface temperature of the Sun or a distant star to the energy flux and wavelength of maximum emission of its radiation. The following examples show how to do this.

EXAMPLE: The surface temperature of the Sun can be determined using Wien's law. The Sun emits energy over a wide range of wavelengths, but the maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0×10^{-7} m. From Wien's law, we find the Sun's surface temperature $T_\odot$ to be

$$T_\odot = \frac{0.0029}{\lambda_{max}} = \frac{0.0029}{5.0 \times 10^{-7}} = 5800 \text{ K}$$

This is about the same temperature as an iron welding arc. (The symbol $\odot$ is the standard astronomical symbol for the Sun.)

EXAMPLE: We can also find the Sun's surface temperature using the Stefan-Boltzmann law. Using detectors above the Earth's atmosphere, astronomers have measured the average flux of solar energy arriving at Earth; this value, called the **solar constant,** is equal to 1370 W m^{-2}. However, the quantity *F* in the Stefan-Boltzmann law refers to the flux measured at the Sun's surface, not at the Earth.



To determine the value of *F*, we first imagine a huge sphere of radius 1 AU with the Sun at its center, as shown in the figure. Each square meter of that sphere receives 1370 watts of power from the Sun, so the total energy radiated by the Sun per second is equal to the solar constant multiplied by the sphere's surface area. The result, called the **luminosity** of the Sun and denoted by the symbol $L_\odot$, is $L_\odot = 3.90 \times 10^{26}$ W. That is, in 1 second the Sun radiates 3.90×10^{26} joules of energy into space. Because we know the size of the Sun, we can compute the energy flux (energy emitted per square meter per second) at its surface. The radius of the Sun is $R_\odot = 6.96 \times 10^8$ m, and the Sun's surface area is $4\pi R_\odot^2$. Therefore, its energy flux is the luminosity (total energy emitted by the Sun per second) divided by the surface area (the number of square meters of surface):

$$F_\odot = \frac{L_\odot}{4\pi R_\odot^2} = \frac{3.90 \times 10^{26} \text{ W}}{4\pi(6.96 \times 10^8 \text{ m})^2} = 6.41 \times 10^7 \text{ W m}^{-2}$$

Notice that the solar constant of 1370 W m^{-2} is very much less than this. By the time the Sun's radiation reaches Earth, it is spread over a greatly increased area.

Once we have the Sun's energy flux $F_\odot$, we can use the Stefan-Boltzmann law to find the Sun's surface temperature $T_\odot$:

$$T_\odot^4 = \frac{F_\odot}{\sigma} = 1.13 \times 10^{15} \text{ K}^4$$

Taking the fourth root (the square root of the square root) of this value, we find the surface temperature of the Sun to be $T_\odot$ = 5800 K. This result agrees with the value we computed in the previous example using Wien's law.

EXAMPLE: Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. We can use Wien's law to calculate the wavelength (λ_{max}) at which Sirius emits most intensely:

$$\lambda_{max} = \frac{0.0029}{T} = \frac{0.0029}{10{,}000} = 2.9 \times 10^{-7} \text{ m} = 290 \text{ nm}$$

Sirius therefore emits light most intensely in the ultraviolet. In the visible part of the spectrum, it emits more blue light than red light (see the curve for 12,000 K in Figure 5-10), so Sirius has a distinct blue color.

(continued on following page)