L6: Blackbody Radiation

We have so far discussed in *geometrical optics* how light behaves as a *ray*, and we have discussed how, under certain conditions, light behaves as a *wave*. We now discuss the fact that, under yet different circumstances, light definitely behaves as a particle. When these particle characteristics of light were first discovered around the year 1900 they started to shake the foundations of classical physics, since the physics accepted at that time treated light solely as an electromagnetic wave. We therefore use the year 1900 as the beginning of a new era of physics, called *Modern Physics*. We begin our study of modern physics with a discussion of the topic that started it all – *blackbody radiation*.

Blackbody Radiation I

As described by Maxwell, radiation, whether in the form of visible light or invisible regions of the *electromagnetic* (EM) spectrum, can be described as an EM wave. These EM waves carry energy with them as they propagate, so that (EM) *radiation* is one form of energy transfer. (You may remember from your first-semester physics course that the other forms are *conduction*, in which a warm object in contact with a cooler object transfers energy to the cooler object, and *convection*, in which a bulk volume of higher-energy content material is transported through lower-energy content material, such as when warm air rises through surrounding cooler air.)

All objects emit radiation as a result of their temperature—the hotter they are, the more radiation energy they emit per unit time. This emitted radiation consists of all of the wavelengths in the EM spectrum (*not* just the visible region!). The various wavelengths emitted by an object comprise what is called the ***emission spectrum*** of that object.

If we were to place a brick on a table (in a room with no windows) and turn off the lights, we would not be able to see the brick. How can this be if the brick really emits radiation at *all* wavelengths, *including* the visible region of the spectrum? The answer is that the *amount* of energy emitted by the brick in the visible region of the spectrum is so small that our eyes cannot detect it. If the brick were in *thermodynamic equilibrium* with the room – that is, if it were at the same temperature as the room – then the majority of the radiation that it would emit would be in the *infrared* region of the EM spectrum, a region to which our eyes are not sensitive.

It is important to note that, if the brick were at the same temperature as the room (which we assume remains at a constant temperature, and has no heating or cooling equipment to stabilize its temperature), then we would not expect it to cool down or to heat up as it sits on the table top (assuming that we didn't have it in an oven or a refrigerator!). But if it is constantly emitting radiation, which carries energy with it, then it should be constantly *losing* energy and therefore *cooling* off! What is wrong here?!

If it is true that the brick emits radiation and therefore energy as a result of its temperature, then the only way that the brick can remain in thermal equilibrium with the room so that its temperature does not change is if it is also constantly *absorbing* energy from its surroundings. (If you think about this from the point of view of the room, this only makes sense. If the brick is constantly giving energy to the room in the form of EM radiation, then the room should be heating up. But if it is staying at the same temperature, it must somehow be getting rid of the extra energy – it is giving it back to the brick!)

If an object is in thermal equilibrium with its surroundings, then it must be constantly absorbing the same amount of energy that it is emitting.

Blackbody Radiation II

Let's say that we were now to heat up the brick – maybe to a temperature of about *500 K* (remember that room temperature is about *300 K*). In the dark room we would still not be able to *see* the brick, but we would be able to *feel* it – we would feel its warmth even if we were not touching it. This is of course a result of the greater intensity of infrared radiation emitted by the brick as a result of its increased temperature. As the brick is heated more and more, we would feel the increased heat that it would emit until eventually, when the brick reaches a temperature of about *1000 K*, we would start being able to *see* the brick glow with a dull red color. If the brick's temperature were increased even further, we would see it glow with a brighter red and then an orange-red color, until eventually, when its temperature reaches about *1700 K*, the brick would glow with a "white-hot" color. This color would be a result of the fact that, at this point, the brick is emitting a good bit of radiation in all regions of the visible region of the spectrum, so the colors combine to appear white to our eyes.

Again, if the temperature of the brick were to remain constant, then it must be absorbing the same amount of energy as it is radiating. If we've been heating the brick on some sort of heating coils, then the brick has been heated by *conduction*. Let's say that we wish to examine an object at a constant temperature which is heated solely by radiation, just as it is constant trying to cool itself by *radiating* energy. In particular, let's consider two closed boxes, one colored a dull black and the other a shiny white. If we were to place both of these boxes out in the direct sunlight and measure the temperatures inside the two boxes, we would find that the black box reaches a higher equilibrium temperature than the white box (*no surprise here!*). This tells us *two* things. First, that the black box is *absorbing* more radiation energy from the sun than the white box, and second (*can you guess it?*), since the "equilibrium temperature" means that the boxes' temperatures have reached a *constant* (equilibrium) value, that the black box must be *emitting* more energy than the white box! (More precisely, it's really the *rate* of absorption and emission that must be the same.) This means that the black box is a very efficient absorber *and* emitter of radiation.

Following this same reasoning, it follows that a *perfect absorber* of radiation would thus be *perfectly black* (since a perfect absorber of radiation would not reflect *any* radiation incident on it!). Such a perfect absorber is called a ***blackbody***. From our discussion above, it follows that this perfect *absorber* of radiation must also be a *perfect emitter* of radiation!

Now wait a minute! An object which is a perfect absorber of radiation and sucks up any radiation incident on it is called a *blackbody* because it would appear *black*. But if it is also a perfect *emitter* of radiation, why would it still appear black? Shouldn't it be glowing with a brilliant irradiance?! Well, yes and no. Consider a good example of something pretty close to a blackbody: your clothes closet with the door *slightly* ajar. You stand about a meter away from the door to your closet with a flashlight. You shine the flashlight onto the crack in the door; what do you see? What you will most likely see is the outside of the door and the adjacent wall illuminated with the flashlight beam, but inside the closet, through the very narrow crack in the door, you will still just see *darkness*. The closet is absorbing just about all of the light from your flashlight that is incident on it, and it is re-radiating it.

So why don't you see the flashlight beam shining back out through the crack in the door? Because while the light incident on the door crack is primarily in the *visible* region of the EM spectrum (which is, of course, why the flashlight is useful for us!), the perfect emitter of radiation takes that energy and radiates it at *all* wavelengths, *not* just in the visible. This is what we mean by a "perfect emitter" of radiation—the radiation is perfectly emitted throughout the entire EM spectrum! Thus, for objects at or near room temperature, a blackbody will appear black, since most of the radiation is given off at wavelengths which are *not* in the visible region of the spectrum. (We'll have more on this shortly.)

However, if the blackbody were at a higher temperature, then it might *not* appear black to our eyes—indeed, it *might* glow "with a brilliant irradiance" if its temperature is high enough! (The sun is a good example of this.) Therefore, when we say that the "perfect absorber" appears perfectly black, what we mean is that, in *reflected light*, a blackbody appears perfectly black. This does *not* mean that the blackbody does not give off any radiation—quite the contrary, since it *reflects* absolutely *none* of the light incident on it, and since it is a *perfect emitter* of radiation!

The emission spectrum of a blackbody was of particular interest to physicists in the late *1800's*. Indeed, the interest grew as it became more and more apparent that the accepted physics at the time was completely unable to satisfactorily explain the observed blackbody spectrum. That all changed in the year *1900* when Max Planck solved this perplexing problem and began the era known as *modern physics*.

The Blackbody Spectrum

We discussed in the previous section that a perfect absorber and emitter of radiation is called a *blackbody*. The various wavelengths of EM radiation emitted by a blackbody comprise the ***blackbody emission spectrum***. Two examples of such a spectrum are shown in Fig. 6.1.

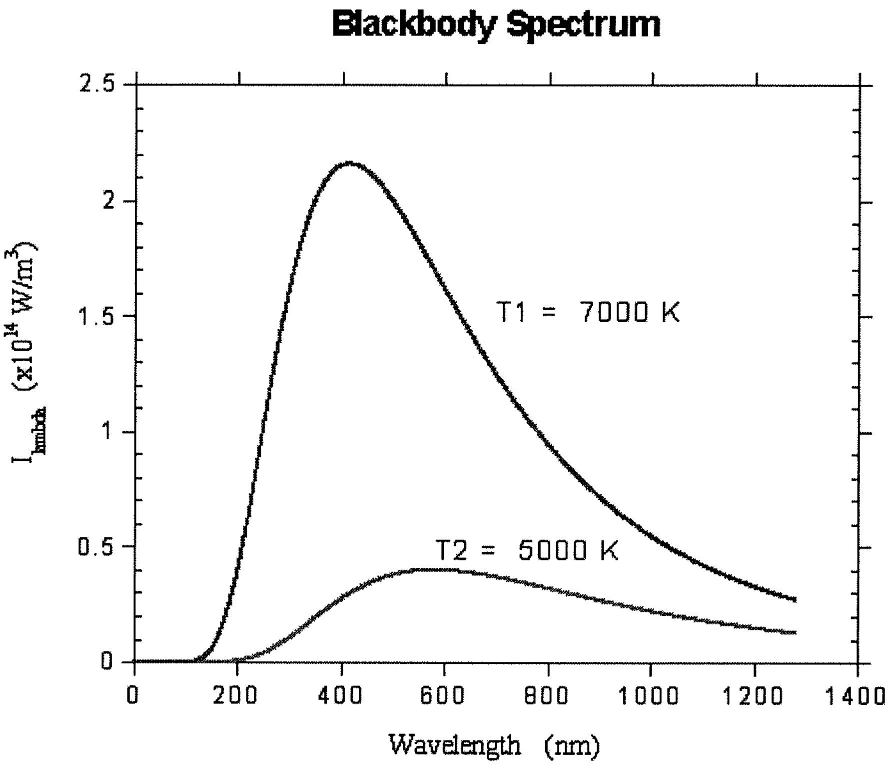


Figure 6.1

The two spectra (plural of *spectrum*) in the figure correspond to two blackbodies having temperatures of $T_1 = 7000\ K$ and $T_2 = 5000\ K$, as labeled in the figure. The independent variable (horizontal axis) is the wavelength λ of the emitted radiation, and the dependent variable is the *intensity* of radiation *per unit wavelength* interval, I_λ. (Remember that *intensity* is the energy per unit time per unit area: J/(s m^2) = W/m^2. Thus, I_λ must have MKS units of (W/m^2)/m = W/m^3.)

Note that the T_1 curve in Fig. 6.1 emits more radiation (per unit time per unit area) throughout the entire spectrum than the T_2 curve. This is of course a result of the fact that $T_1 > T_2$.

Note that each curve in Fig. 6.1 rises from zero, reaches a maximum, and then gradually decreases (the two curves eventually reach zero again as λ approaches *infinity*). Note also that the *higher-temperature* (T_1 = *7000 K*) curve reaches a maximum at a *lower wavelength* than the *lower-temperature* curve. The wavelength at which the blackbody spectrum reaches a maximum is denoted λ_{max}.

The classical physics of EM waves was completely unable to explain the emission spectrum shown above. (This spectrum had been experimentally observed in *1899* by the two scientists *Lummer* and *Pringsheim*.) This was a great puzzle to physicists at the time, as they considered themselves experts on waves and the energy associated with them. (Indeed, they *were* experts in *wave physics*!) Since the EM radiation being absorbed and re-emitted by a blackbody was just waves, there should be no difficulty explaining the emission spectrum. So what was the problem?

The answer to the puzzle came toward the end of the year *1900* when the physicist *Max Planck* found the equation which correctly describes the blackbody emission spectrum:

$$I_\lambda(\lambda) = \frac{2\pi hc^2}{\lambda^5\left(\exp\left(\frac{hc}{\lambda kT}\right)-1\right)}. \qquad (6.1)$$

In Eq. 6.1, T is the temperature of the blackbody *in degrees Kelvin*, c is the speed of light in a vacuum, $c = 3.0 \times 10^8$ *m/s*, k is a constant which had been determined previously from thermodynamic studies called *Boltzmann's constant* (this is just the ideal gas constant per mole), $k = 1.38 \times 10^{-23}$ *J/K*, and h is a constant which Planck made up in his determination of this equation, and is thus called *Planck's constant* in his honor. (The *exponential function* in Eq. (6.1), *exp(x)*, is the same as the function e^x.) By comparing the theoretical curves with the experimental blackbody emission spectra, it is found that

$$h = 6.626 \times 10^{-34}\ J \cdot s. \qquad (6.2)$$

(Actually, Planck found the value 6.55×10^{-34} *J s*. The value given in Eq. 6.2 is the currently accepted value of this constant.)

The Einstein Relation

The amazing thing in Planck's development of the blackbody emission spectrum equation (6.1) was that he had to assume that the radiant energy (such as energy from light waves or other EM radiation) could *not* come in any arbitrary amount as was required by the wave description of EM radiation. Instead, Planck found that the radiant energy only came in little, discrete packets of energy, called ***photons***. The energy in each packet depends on the wavelength of the radiation being considered, and is equal to

$$E = \frac{hc}{\lambda} . \qquad (6.3)$$

Since $\mathbf{c} = \lambda \mathbf{f}$ for an EM wave, it follows that $\mathbf{c}/\lambda = \mathbf{f}$, so that the energy of a photon of light in Eq. (6.3) can also be written in the form

$$E = hf . \qquad (6.4)$$

Actually, Planck hypothesized that the radiant energy inside a blackbody comes in packets of energy $\mathbf{E} = \mathbf{hf}$ only when they interact with the walls of the blackbody. It was *Albert Einstein* who extended this idea and proposed that *all* EM radiation comes in energy packets, which he called *"quanta of light"* (later to be called *photons*) of energy $\mathbf{E} = \mathbf{hf}$. For this reason, the photon-energy equation (6.4) is called the ***Einstein relation***.

Wien's Displacement Law

From Planck's equation for the blackbody spectrum it is possible to obtain two important relations that had been found earlier from thermodynamic arguments and are therefore named for the scientists who first found them. (At the time when these laws were first derived the blackbody spectrum could not yet be explained. It was therefore quite an accomplishment for these scientists to obtain these laws. Once Planck's equation for the blackbody spectrum was known, however, it was a rather straightforward problem in calculus to derive these laws.)

The first of these laws is called the ***Wien Displacement Law***, and tells us how the value of λ_{max} changes (or is *"displaced"*) as the temperature T (*in Kelvin!*) of the blackbody changes:

$$\lambda_{max} T = \beta \qquad (6.5)$$

where $\boldsymbol{\beta = 0.0029}$ ***K m*** is the Wien constant. Note that this law tells us that the wavelength at which the blackbody spectrum has a maximum (that is, the wavelength at which the intensity per unit wavelength interval has the greatest value) is *inversely proportional* to the absolute temperature of the blackbody. (Therefore, if the temperature is *doubled,* the value of λ_{max} will be *halved.*)

It should be noted that *Wilhelm Wien* received the Nobel prize in physics in *1911* for work associated with the displacement law, and Max Planck received the same prize in *1918* for his discovery of energy quanta (*photons*) associated with his derivation of the blackbody spectrum equation.

The Stefan-Boltzmann Law

The second important law associated with the blackbody emission spectrum and which can be derived from Planck's equation (6.1) using calculus is the ***Stefan-Boltzmann Law***, which tells us the *total intensity of radiation* emitted by the surface of the blackbody at *all* wavelengths, I_{total}:

Ideal Blackbody Emmision : $$I_{total} = \frac{E_{total}}{t \cdot A} = \sigma T^4 \qquad (6.6)$$

where $\sigma = 5.67 \times 10^{-8}\ W/(m^2\ K^4)$ ("watts per meter-squared per Kelvin to the fourth") is called the *Stefan-Boltzmann constant.*

Since real objects emit radiation *less* efficiently than a blackbody at the same temperature (since, by definition, a blackbody is an *ideal emitter and absorber* of radiation!), we introduce a (unitless) term called the ***emissivity***, cleverly denoted *e*. The value of the emissivity *e* ranges from near *0* for an object which is a very poor emitter of radiation (and thus a very poor absorber of radiation, such as a mirror), to a value near *1* for a very good emitter of radiation (very close to a *perfect blackbody*, for which of course $e = 1$).

For a *blackbody* (an ideal absorber and emitter of radiation), e = 1.

We thus write the Stefan-Boltzmann Law in the following form for a *real* object:

Real Object Emission : $$I_{total} = \frac{E_{total}}{t \cdot A} = e\sigma T^4 . \qquad (6.7)$$

In this equation we have explicitly shown that the total intensity is equal to the total energy radiated at all wavelengths, E_{total}, divided by the exposed surface area of the blackbody, *A*, and the total time over which the emitted radiation is measured, *t*.

See the tables of physical constants for values of the emissivities of various materials.

Example 6.1

The sun radiates like a blackbody of radius **7.0 x 10^8 m** at a temperature of about **5000 K**. The earth has a radius of about **6.4 x 10^6 m** and is at a distance of about **1.5 x 10^{11} m** from the sun. (a) At what wavelength is the sun's emission the strongest? To what color does this correspond? (b) How much energy is radiated by the sun at all wavelengths each second? (c) The radiant energy leaving the sun moves out equally in all directions. What is the intensity of the sun's radiation when it reaches the earth's distance from the sun? (d) How much of the sun's radiant energy at all wavelengths is incident per second on the earth's surface? (*Be careful!*) (e) If all of the energy in part (d) were assumed to be in the form of EM radiation of wavelength equal to that in part (a) (*it's not*, but let's just pretend for a minute...!), how many photons of light would be incident on the earth's surface each second due to the sun's radiation?

Answers: (a) 580 nm (b) 2.18 x 10^{26} J (c) 770 W/m^2 (d) 9.9 x 10^{16} J (e) 2.9 x 10^{35}

Solution

Solution to Example 6.1

The sun radiates like a blackbody of radius **7.0 x 10^8 m** at a temperature of about **5000 K**. The earth has a radius of about **6.4 x 10^6 m** and is at a distance of about **1.5 x 10^{11} m** from the sun.

(a) At what wavelength is the sun's emission the strongest? To what color does this correspond?

We are given the following data:

Radius of the sun: $\mathbf{R_s = 7.0 \times 10^8}$ **m** Temperature of the sun: **T = 5000 K**

Radius of the Earth: $\mathbf{R_E = 6.4 \times 10^6}$ **m** Earth-Sun distance: $\mathbf{D_{ES} = 1.5 \times 10^{11}}$ **m**

The wavelength at which emission of a blackbody is the strongest is given by the Wien Displacement Law:

$$\lambda_{max} T = \beta$$

where the Wien constant is given by $\beta = 2.9 \times 10^{-3}$ K m. Solving for the wavelength above gives us that

$$\lambda_{max} = 5.8 \times 10^{-7} \text{ m.}$$

This corresponds to approximately yellow light in the visible region of the spectrum.

(b) How much energy is radiated by the sun at all wavelengths each second?

The total amount of energy radiated by the blackbody in all directions each second is related to the total intensity of emission of the entire surface area of a blackbody, I_{total}. This is given by the Stephan-Boltzmann law, which states that

$$I_{total} = \frac{E_{total}}{A \cdot t} = e\sigma T^4$$

where *A* is the total surface area of the blackbody, *t* is the time interval for the emission, *t = 1 s*, *e* is the emissivity of the object (this equals *1* for a blackbody), and σ is the Stephan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4).

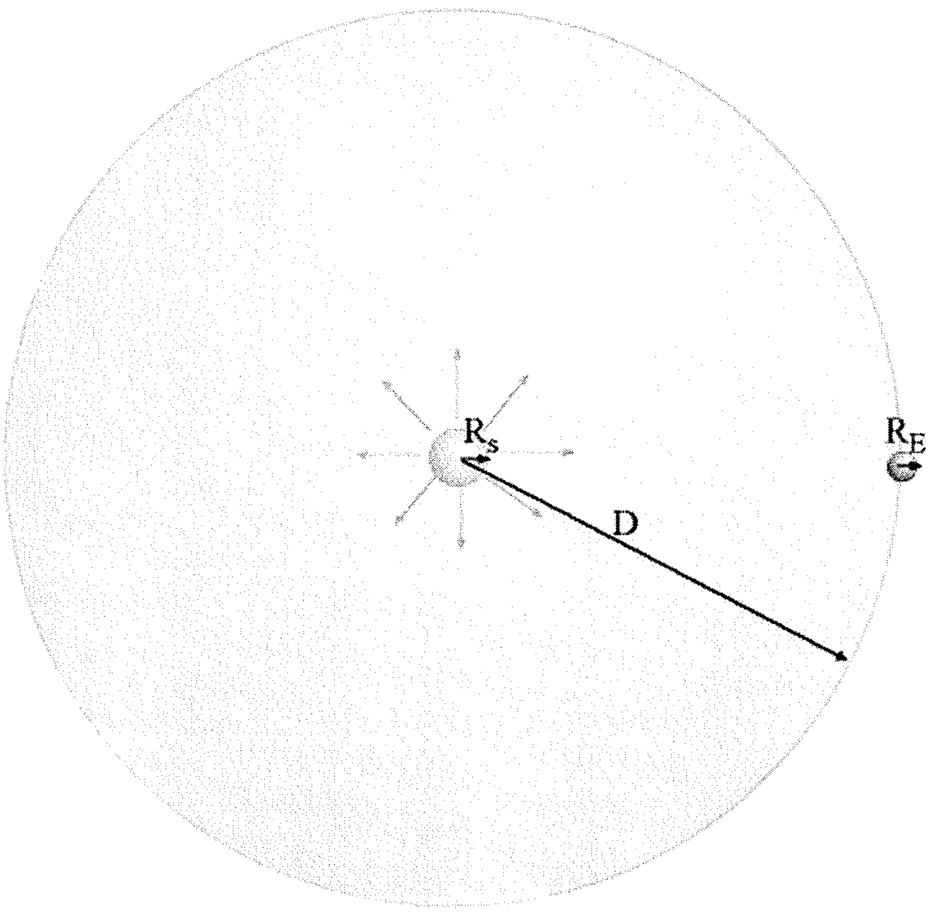
The area of the blackbody is just the surface area of the sun (assumed spherical), which is $A = 4\pi R_s^2 = 6.16 \times 10^{18}$ m^2. We thus get, solving for the total emitted energy E_{total} above,

$$E_{total} = 2.18 \times 10^{26} \text{ J}.$$

(c) The radiant energy leaving the sun moves out equally in all directions. What is the intensity of the sun's radiation when it reaches the earth's distance from the sun?

We must be a bit careful of this part. You must make sure that you match the *area* through which the energy is traveling with the proper energy. that is, whatever energy you use in the equation for intensity, you must make sure that you get the correct area that *that* amount of energy passes through. Let's see how this works....

In part (b) we computed the total energy leaving the surface of the sun, E_{total}. As this energy moves out further and further away from the sun, it moves successively through a series of spheres centered on the sun with larger and larger radii. (The sun's energy moves out equally in all directions, so it moves through successive spheres.) When the sun's radiation reaches the earth's position, it is in the process of passing through the surface of a sphere of radius equal to the distance from the sun to the earth, D_{ES}.

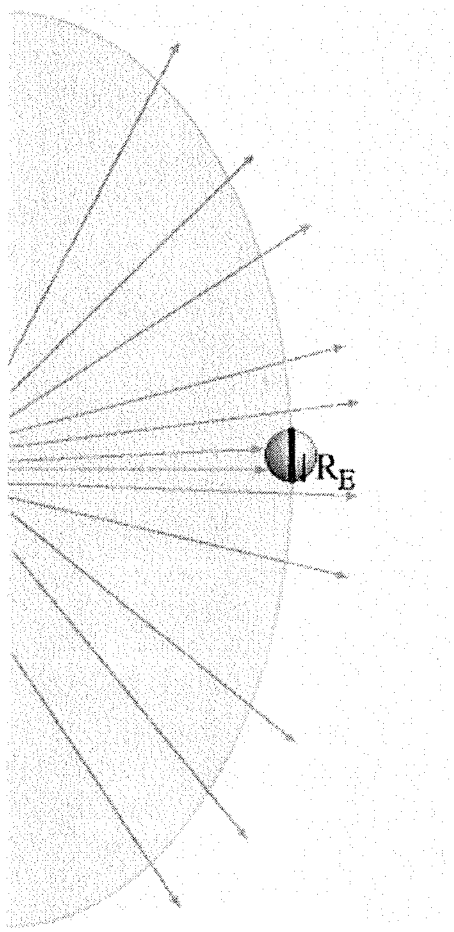


Thus, for an energy equal to the *total* energy emitted by the sun in one second, E_{total}, the area that that energy passes through is equal to the area of a sphere of radius D_{ES}: $A_{ES} = 4\pi D_{ES}^2 = 2.83 \times 10^{23}\ m^2$. The intensity of the sun's radiation at the earth's position is therefore

$$I_E = \frac{E_{total}}{A_{ES} \cdot t} = 770\ \frac{W}{m^2}.$$

(d) How much of the sun's radiant energy at all wavelengths is incident per second on the earth's surface? (*Be careful!*)

OK—this one will get you! This is where we must be *really* careful of areas and energies! We know the intensity of the sun's radiation at the earth's position. This intensity is equal to $I_E = E/(A\ t)$ for *any* energy E and corresponding area A and time t. We are only interested in the energy incident on the earth's surface per second ($t = 1\ s$). Another way of stating this is that we are interested in the total energy *removed* from the sun's radiation due to the earth intercepting some of that radiation. This is the key to many people's confusion.... Consider the diagram below.



The main point here is that the energy removed from the sun's radiation is the *same* as if the earth were flat (like a coin) directly facing the sun. *Think* about it. Say you have a bare light bulb in the middle of a small and otherwise dark room. You have a half-dollar and a ping-pong ball. (We are going to assume here that the radius of the half-dollar and the radius of the ping-pong ball are about the same.) If you get close to the wall and hold up the ping-pong ball (like the earth), you will see a circular shadow on the wall. The shadow represents the energy that was *removed* from the bulb's radiation by the ball. Now let's say that you remove the ball and hold up the coin (facing the bulb) in its place. If the ball and the coin have the same radius, then the shadow on the wall will look *exactly* the same as when the ball was present. This means that the *area* that we should use in the intensity equation is *not* the area of half of a sphere (which after some thought you would probably think you should use), but rather is simply the area of a *circle* (that is, like the area of the coin blocking the bulb's radiation). That is, we should use the area $A_E = \pi R_E^2 = 1.3 \times 10^{14}\ m^2$. We then get that the intensity at the earth's position can be written as

$$I_E = \frac{E_{total,E}}{A_E \cdot t},$$

where $E_{total,E}$ is the total energy removed from the sun's radiation due to the presence of the earth. We then get that

$$E_{total,E} = I_E A_E t = 9.9 \times 10^{16}\ J.$$

(e) If all of the energy in part (d) were assumed to be in the form of EM radiation of wavelength equal to that in part (a) (*it's not*, but let's just pretend for a minute...!), how many photons of light would be incident on the earth's surface each second due to the sun's radiation?

We now assume that all of the radiation energy absorbed by the earth, $E_{total,E}$, is in the form of EM radiation of wavelength $\lambda = 5.8 \times 10^{-7}$ m. The energy of a single photon of this wavelength is given by the Einstein-Planck relation:

$$E_{photon} = \frac{hc}{\lambda} = 3.43 \times 10^{-19}\ J.$$

(Here *h* is Planck's constant, $h = 6.626 \times 10^{-34}$ J s.) The total energy incident on the earth, $E_{total,\ E}$, is just equal to some number *N* of these photons times the energy in *each* of these photons:

$$E_{total,E} = N\, E_{photon}.$$

Therefore,

$$N = \frac{E_{total,E}}{E_{photon}} = 2.9 \times 10^{35}.$$

Solution to Example 6.2

The tungsten filament in a **100 W** light bulb has an area of about **0.26 cm^2** and reaches a temperature of about **3430 ^{o}C** . Assuming that all *100 W* goes into radiant energy, find the emissivity of the tungsten filament.

Compared to the last example, this one is *easy*!

We know that the power of the light bulb is P = 100 W, and the area of the filament is A = 0.26 cm^2 = 0.26 x 10^{-4} m^2. Also, the temperature of the filament reaches T = 3430 ^{o}C = 3700 K (don't forget—temperatures in *Kelvin*!). We wish to find the emissivity of the filament.

The equation for the total intensity emitted by a radiating object is given by

$$I_{total} = e\sigma T^4 = \frac{E}{A \cdot t} = \frac{P}{A},$$

since the power is defined to be the *energy per unit time* (1 watt = 1 joule per second; *! W = 1 J/s*). We thus get that

$$e = \frac{P}{\sigma T^4 A} = 0.36.$$

That's it!

Sample Quiz 6

1. A good example of a *blackbody* is

a. a shiny black car b. a mirror. c. a deep red Christmas ball.

d. a closet with the door slightly ajar. e. the deep blue sky.

2. An object in thermal equilibrium with its surroundings must

a. have a black color. b. emit as much radiation as it absorbs. c. be at 300 K.

d. reflect the same color as its surroundings. e. refract light from its surroundings.

3. The higher the temperature of a blackbody, the

a. more radiation it emits. b. smaller it must be. c. more black it appears.

d. larger the radius of curvature. e. more it conducts energy.

4. The wavelength λ_{max} stands for

a. the largest possible wavelength of radiation emitted by a blackbody.

b. the largest possible frequency of radiation emitted by a blackbody.

c. the wavelength at which the temperature of the blackbody is the largest.

d. the wavelength at which the intensity of radiation emitted by a blackbody is the largest.

e. the wavelength of maximum wave speed in the emitted radiation.

5. Tomorrow we will have

a. another of our extremely simple-minded quizzes which do nothing but insult our intelligence.

b. a HUGE activity. c. birthday cake. d. the same as (a).

e. our first test, for which we've been studying religiously.

Answers

Answers to Sample Quiz 6

1. d

2. b

3. a

4. d

5. e

Homework 6

1. A metal nugget is heated up in a furnace. As it gets hotter and hotter, it eventually starts glowing with a red, and orange, and eventually with a yellow color. Estimate the temperature of the nugget at each of these colors.

2. A blackbody has a temperature of **3,500 K** and an exposed area of **7.9 cm^2**. (a) At what wavelength does the blackbody radiate the most intensely? (b) How much energy is emitted by the blackbody at all wavelengths in one hour?

3. At what wavelength does the human body radiate most intensely? To what part of the electromagnetic spectrum does this correspond?

4. A star has a radius of **8.5×10^9 m** and acts like a blackbody of temperature **4,300 K**. A planet of radius **2.7×10^7 m** orbits the star at a distance of **7.5×10^{11} m**. (a) At what wavelength is the star's emission the strongest? What color would it appear? (b) What is the intensity of radiation at all wavelengths leaving the star's surface? (c) How much energy leaves the star's surface at all wavelengths each second? (d) How much energy leaves the star's surface in a time of one (Earth) year? (e) What is the intensity of radiation emitted by the star at all wavelengths at the position of the star's planet? (f) If it takes this planet **3.7** earth-years to orbit its star once, then how much energy is incident on the planet at all wavelengths during one orbital period, assuming that the planet's orbit is circular?

5. A small sphere of radius **15 cm** is at a temperature of **1500 K**. In a time of **2.0 h** (*hours*) it emits a total energy of **1.73×10^8 J** at all wavelengths. What is the emissivity of the sphere?

Answers

Answers to Homework 6

1. 4,140 K (700 nm); 4,600 K (630 nm); 5,000 K (580 nm)

2. (a) 829 nm (b) 2.4×10^7 J

3. 9,350 nm = 9.35 μm This is the infrared region of the electromagnetic spectrum.

4. (a) 670 nm; orange/red (b) 1.9×10^7 W/m^2 (c) 1.7×10^{28} J (d) 5.4×10^{35} J (e) 2,400 W/m^2 (f) 6.4×10^{26} J

5. 0.296