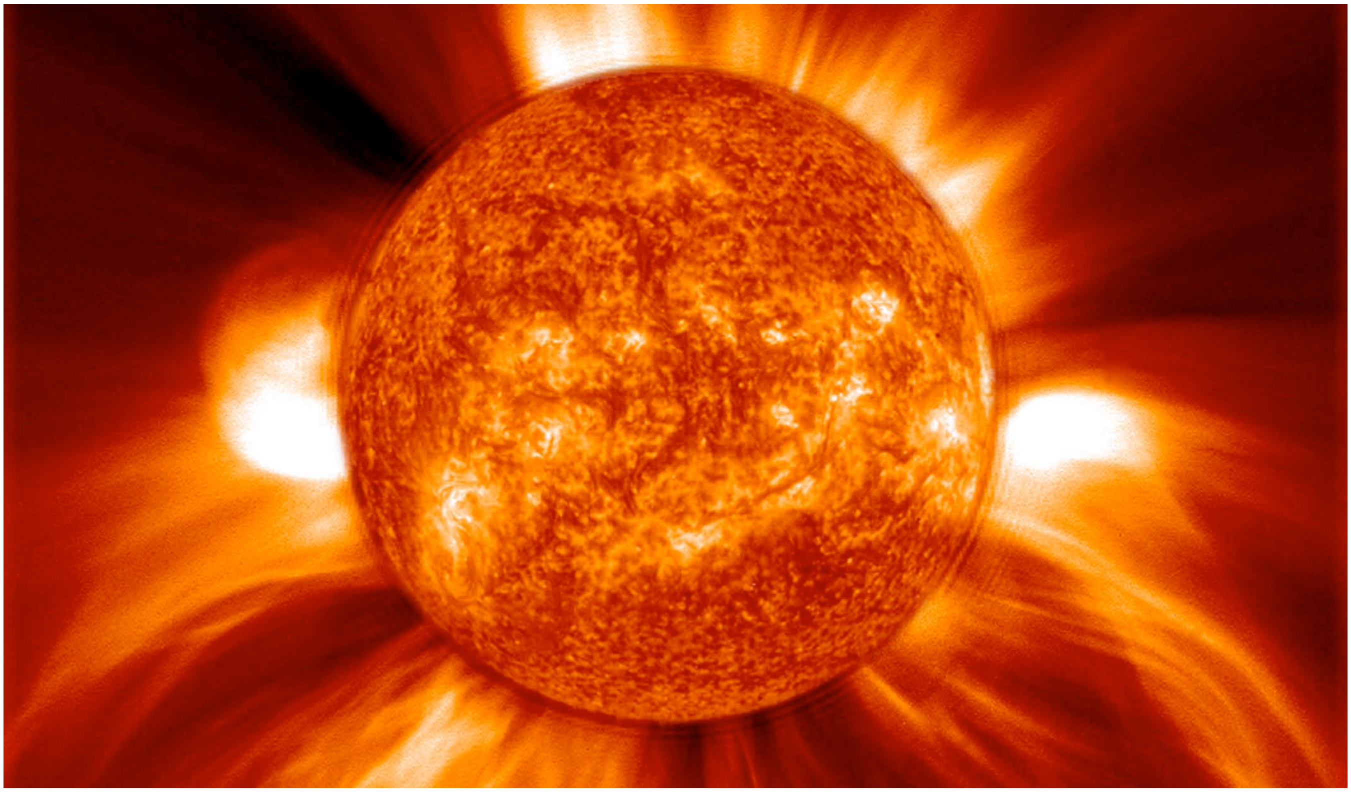
CHAPTER 4: SOLAR RADIATION AND EARTH

MICHAEL PIDWIRNY



The Sun - source of solar radiation. The Sun supplies the Earth with a constant stream of solar radiation. This solar radiation is the ultimate source of energy for virtually all of the process taking place in the Earth's atmosphere, biosphere, hydrosphere, and lithosphere. *(Source: NASA - Solar and Heliospheric Observatory)*

STUDENT LEARNING OUTCOMES

After reading this chapter you should be able to:

- Describe the properties and nature of electromagnetic radiation.
- Define the processes of radiation emission and absorption.
- Explain the relationship between the quantity and quality of radiation emitted by an object and temperature.
- Outline how solar radiation is produced and transported to our planet.
- Explain how our planet's motions and orbital geometry with the Sun influences the amount of insolation received on the Earth's surface.
- Describe how changes in day length and the Sun's angle of incidence cause temporal and spatial variations in potential insolation on our planet.

NATURE OF RADIATION

In the previous chapter, we learned that the Sun supplies the Earth with most of the energy required to run the various systems found on our planet. The Sun's energy is in the form of **electromagnetic radiation** or radiant energy. This type of energy has the ability to travel through the voids of space. When received by the Earth, sunlight is converted into heat energy or used by plants for photosynthesis. At this point in the textbook, we need to learn more about electromagnetic radiation. This additional knowledge will play an important role in helping us understand how the various abiotic and biotic systems on our planet are powered.

WAVES AND PHOTONS

All objects above the temperature of absolute zero (-273.15°C or -459.67°F) give off energy in the form of electromagnetic waves to their surrounding environment. This radiation is emitted from these bodies and travels at the speed of light in all directions away from the object. We see this phenomenon every time a light bulb is switched on. Many different types of radiation have been identified (**Figure 4.1**). Each of them can be defined by a physical characteristic known as wavelength.

English physicist Thomas Young first demonstrated the idea that radiation has wave-like characteristics in 1801. This idea was the result of an experiment where light was passed through an opaque screen with two parallel slits. On a white surface some distance away from the slits, Young noticed two bright bars of light that corresponded to the openings on the opaque screen. He also noticed a pattern of alternating bright and dark bands on either side of the bright bars. These additional patterns suggested that the two beams of light created by the slits were refracting with each other. Young concluded that this interference must be due to the fact that light travels as a wave (**Figure 4.2**).

A **wavelength** can be defined as the distance from a specified position on one wave to the same location on the next successive wave (**Figure 4.3**). The wavelength of electromagnetic radiation can vary from being infinitely short to infinitely long (**Figure 4.1**). The wavelength of the Sun's radiation spans a range or **spectrum** from approximately 0.1 to 4.0 μ m (micrometers). The

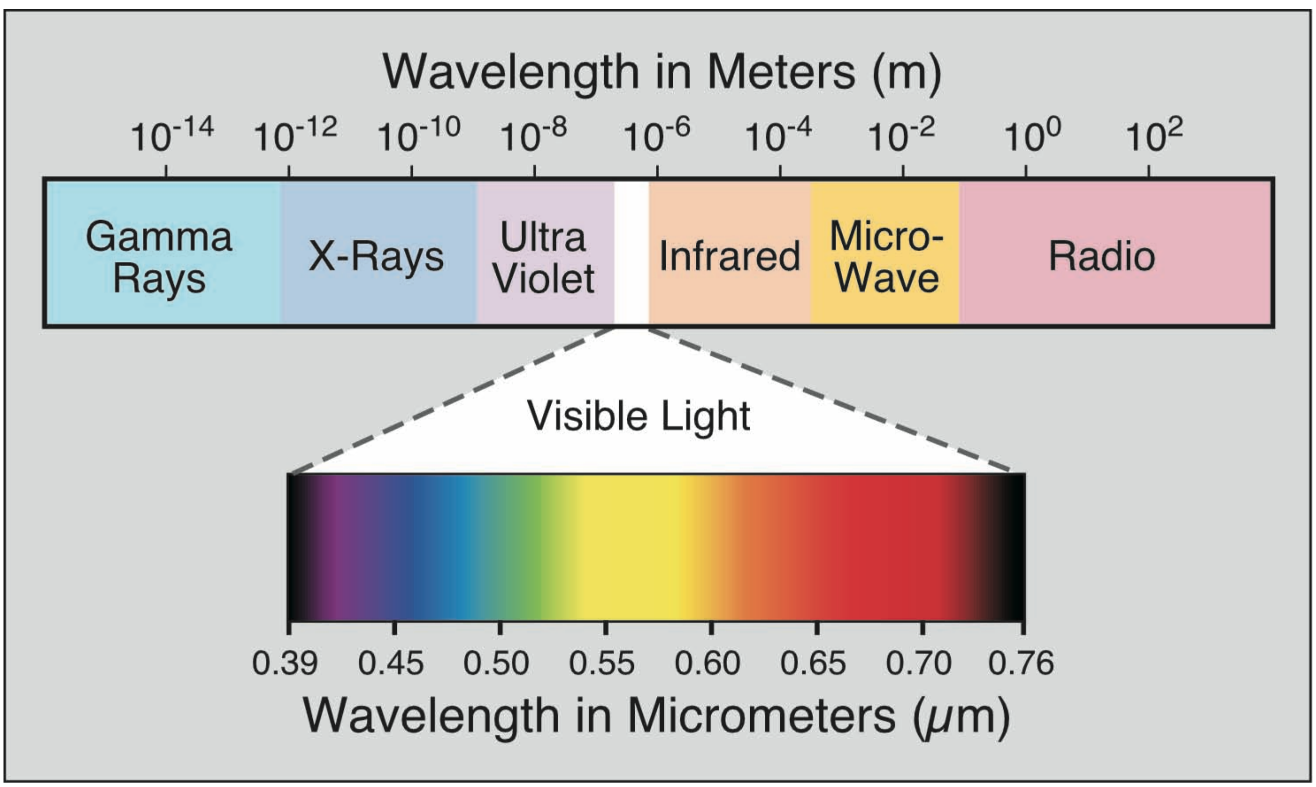


FIGURE 4.1 Some of the various types of electromagnetic radiation as defined by wavelength. This representation of the electromagnetic spectrum extends from very long radio waves to extremely short gamma rays. Visible light has a spectrum that ranges from 0.40 to 0.71 micrometers (μm). *(Image Copyright: Michael Pidwirny)*

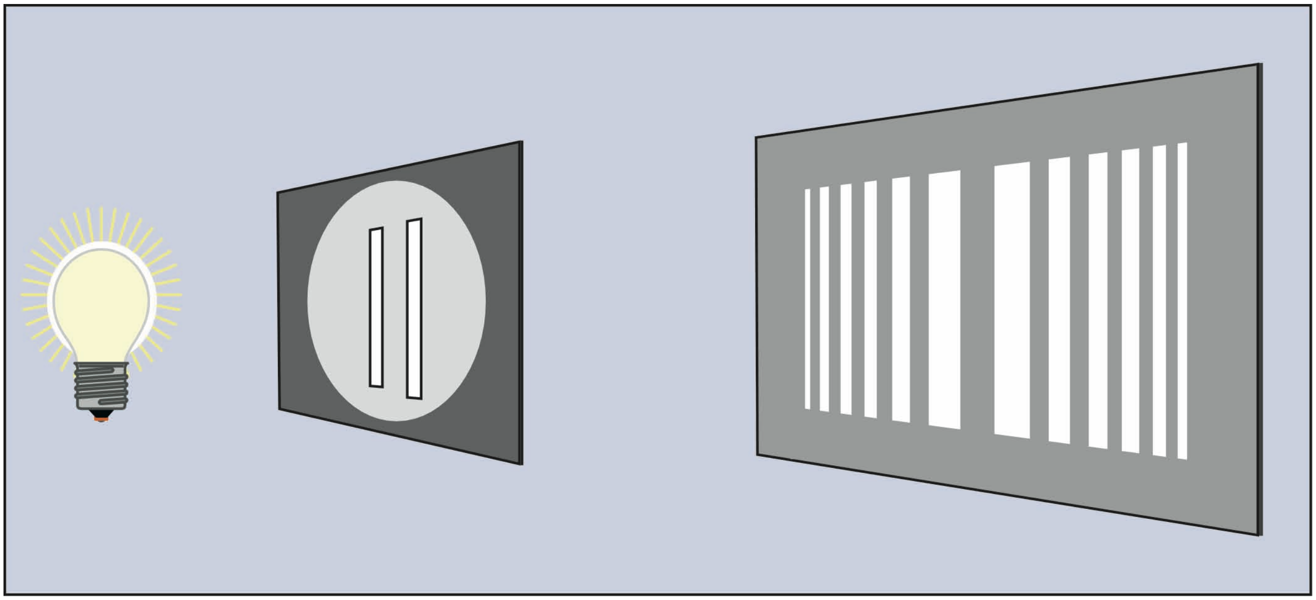


FIGURE 4.2 Thomas Young's 1801 light wave experiment projected light through two open slits on an opaque screen. The projection behind the screen consisted of more than two beams of light. The extra bars of light indicated that the two beams of light that where interfering with each other beyond the opaque screen. This interference occurred because the traveling light rays were moving side-to-side in a wave-like fashion. The side-to-side travel caused the beams of light to contact each occasionally leading to the refraction of some of the light in a slightly altered direction. The additional light bars found on either side of the original beams were created by the altered rays of light. *(Image Copyright: Michael Pidwirny)*

wavelength of **visible light** is between 0.40 to 0.71 µm, and the Sun emits only a portion (44%) of its radiation in this smaller zone. **Figure 4.4** describes the various spectral color bands that make up visible light. The band from 0.1 to 0.4 µm is called **ultraviolet radiation**. About 7% of the Sun's emission is in this wavelength spectrum. About 48% of the Sun's radiation falls in the region between 0.71 to 4.0 µm. This band is called **infrared radiation**. Scientists have divided the infrared spectrum into two sub-bands called the **near infrared** (0.71 to 1.5 µm) and **far infrared** (1.5 to 4.0 µm).

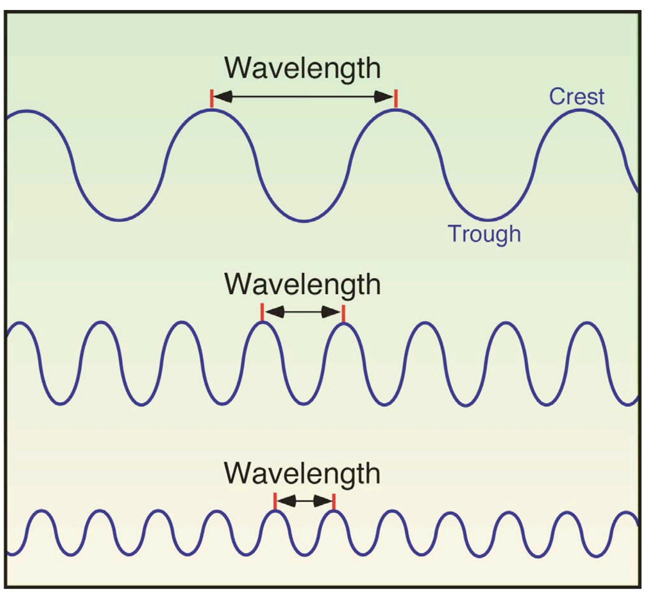


FIGURE 4.3 Wavelength measurement. The distance from the top of a wave crest to the next is equal to one wavelength. *(Image Copyright: Michael Pidwirny)*

Other experiments on electromagnetic radiation suggested that this form of energy may also behave like a stream of subatomic particles. These tiny packets of energy are called **photons**. Photons are quite different from particles of matter. They have no mass, they take up no space, and they are always traveling at the speed of light. Photons are similar to matter in one important characteristic; they can be charged with energy. The amount of energy stored in a photon varies inversely with wavelength or in other words shorter wavelengths have more energy than longer wavelengths.

Emission and Absorption

Radiation is created from the conversion of other forms of energy. This conversion takes place in the atomic structure of matter where excited electrons generate and release radiation (photons). Matter normally creates radiation from the internal heat energy of atomic motion. Once created, the majority of the radiation then travels out

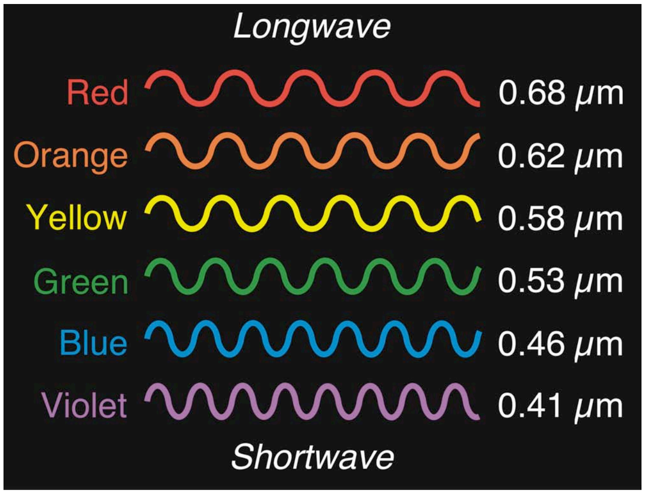


FIGURE 4.5 Components of visible light. Visible light is actually composed of six identifiable color bands. The average wavelength of each of these bands is shown on the right. This illustration also indicates that terms shortwave and longwave can be applied to the bands to describe their wavelength in a relative sense. *(Image Copyright: Michael Pidwirny)*

of the mass into the surrounding environment (some of the radiation is trapped when it strikes the object's other atoms). This process is called **emission** and it occurs as long as an object has a temperature above absolute zero. Radiation emission also causes a net loss of heat energy from an object over time. Thus, objects will experience a drop in temperature if there is a net loss of radiation from their surface.

We can gain a better understanding of how radiation emission works by looking at a familiar process. This process is the generation of light by a light bulb. Light is produced in light bulbs by passing electrical energy through a tungsten filament at the center of a glass bulb. This electrical flow creates heat energy in the atoms of the filament. At this higher energy state, the electrically produced heat energy causes electrons in the filament's atoms to become excited with additional energy (**Figure 4.5**). Electrons in any type of substance can have different energy levels. An increase in atomic energy usually causes an electron to temporarily move into an orbit that is farther away from the nucleus. The electron maintains this new orbit for only a fraction of a second. The electron then converts the extra atomic energy into a photon, causing it to drop back to its normal orbit. This photon then leaves the filament and travels out of the bulb at the speed of light. The process of photon formation in the light bulb repeats itself over and over again as long as electricity is supplied to the filament. Turn the electricity off and the creation of light stops.

The quantity of radiation released from an object depends on its temperature. Objects of a higher temperature release more radiation than bodies that are cooler. To emit radiation in the visible light band, the filaments in light bulbs have to achieve a temperature of about 2200°C (4000°F). The association between temperature and the quantity of emission is essentially constant for all bodies in the Universe. Because of this consistency, this correlation can be described with an equation. The **Stefan-Boltzmann Law** describes this relationship mathematically for a special type of radiating object known as a blackbody. Simply put, a **blackbody** is an object that emits the maximum amount of radiation possible for a given temperature. In reality, no substance found in the Universe is a perfect emitter of radiation. Many solids, liquids, and dense gases do tend to radiate closely to the blackbody rate. The equation for the Stefan-Boltzmann Law is as follows:

$$\text{Radiation Output in Wm}^{-2} = \sigma T^4$$

where σ (Greek letter sigma) is a constant value equal to 5.67 x 10^{-8} Wm^{-2} K^4 and T is temperature measured in Kelvin units.

According to the Stefan-Boltzmann Law, a proportional increase in temperature leads to an exponential increase in radiation output. This fact can be observed in **Table 4.1**. According to the data in the table, the amount of radiation produced with each 100°C increase in temperature from -200 to 500°C is not the same. It becomes exponentially larger with each 100°C step. We can also use this law to calculate the radiative output for the Earth and the Sun. With an average surface temperature of 288 K (15°C or 59°F) the Earth is predicted to emit about 390 Wm^{-2} (watts per square meter). The Sun's temperature is about 5800 K (5527°C or 9981°F). At this temperature, the emission of radiation will be around 64,000,000 Wm^{-2}. The Sun's release of radiation is 160,000 times greater than the Earth's emission. If a body has a temperature of 0 K (-273.15°C or -459.67°F), **absolute zero**, the law predicts that radiation emission will be zero. In Chapter 3, the third law of thermodynamics suggested that atomic motion would stop at this same temperature. The connection between these two phenomena is quite simple. Radiation can only be created if **kinetic energy** exists in an atom.

The temperature of an object also influences the quality of radiation it emits. **Figure 4.6** describes the radiation curves (spectrums) for the Earth and the Sun which have average surface temperatures of 15°C (288 K

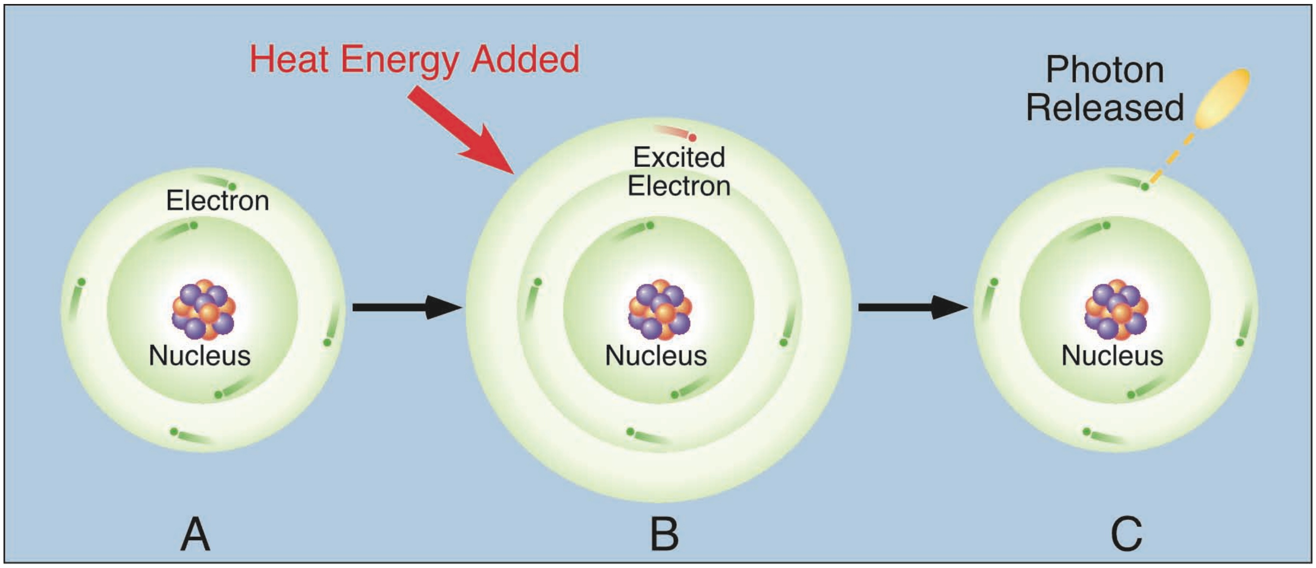


FIGURE 4.5 Photon emission process. Photons can be produced by the addition of heat energy to an atom. Before the heat is added the atom's electrons travel normally in their orbits (A). The addition of heat can cause an electron to gain enough energy that it momentarily jumps into a higher orbit (B). The excited electron then quickly converts the additional energy it gained into a photon (C). The creation and release of the photon causes the electron to return to its normal orbit about the nucleus. Note that heat is not the only type of energy that can create photons. Photons can also be produced by electricity, chemical energy, frictional heating, or nuclear decay. *(Image Copyright: Michael Pidwirny)*

or 59°F) and 5527°C (5800 K or 9981°F), respectively. From the curves, we can observe that these two bodies emit their radiation at different wavelength bands. Most of the Earth's radiation is centered at a wavelength of about 10 µm (micrometers). The much hotter Sun emits most of its radiation at a lower wavelength of about 0.5 µm. Once again, the relationship shown here can be defined mathematically. This mathematical relationship is known as Wien's Law. **Wien's Law** calculates the wavelength of maximum emission for a radiating body. The formula for this law is

$$\text{Wavelength of Maximum Emission } (\mu m) = \frac{2898}{\text{Temperature (K)}}$$

Table 4.2 describes the wavelength of maximum emission for objects with a variety of temperatures. The data in this table suggests that increasing the temperature of radiating body causes the wavelength of maximum emission to decrease.

Matter also has the ability to absorb radiation. The process of **absorption** is in many ways the opposite of emission (**Figure 4.7**). The absorption of a photon by an atom causes one of its electrons to become excited because of energy transfer. For a short period of time, the electron jumps to an orbital further away from the atom's nucleus.

TABLE 4.1 Output of radiation in watts per square meter (Wm^{-2}) for selected object temperatures. The values show that each successive 100°C change in temperature corresponds to an exponential increase in radiation emission.

Temperature (°C)	Radiation Output (Wm^{-2})	Difference from Previous Value (Wm^{-2})
-200	2	
-100	51	49
0	315	264
100	1098	783
200	2838	1740
300	6112	3274
400	11,631	5519
500	20,244	8613

After this brief period, it returns to its normal orbit and the energy transferred in the electron is converted into heat energy. This heat energy then causes an increase in kinetic motion of the entire atom.

A mutual relationship tends to exist between a substance's ability to absorb and emit radiation. As a result, near blackbody emitters of radiation tend to be good absorbers of the same wavelengths. There are some substances that show an interesting characteristic where they only emit and absorb specific disconnected wavelength bands. Such substances are called **selective emitters** and **selective absorbers** of radiation. Some of the gases found in planet's atmosphere exhibit this property (**Figure 4.8**). For example, methane (CH_4) is a selective absorber and emitter of radiation in two narrow bands centered at 3 and 7 µm.

TABLE 4.2 Wavelength of maximum radiation emission for selected object temperatures.

Temperature (°C)	Temperature in Kelvin (K)	Wavelength of Maximum Emission in Micrometers (µm)
-100	173	17.0
0	273	10.6
15 (Earth's Average Global Temperature)	288	10.1
100	373	7.1
200	473	6.1
300	573	5.1
400	673	4.3
500	773	3.7
5527 (Sun's Average Surface Temperature)	5800	0.5

SOLAR OUTPUT AND THE EARTH

Almost all of the energy that drives the various systems (climate systems, ecosystems, hydrologic systems, etc.) found on the Earth originates from the Sun. The Sun has been creating electromagnetic energy or radiation for well over 4.5 billion years. Most of the Sun's radiation is produced at the core of this body through nuclear fusion (**Figure 4.9**). The core occupies an area from the Sun's center to about a quarter of the star's radius. At the core, gravity pulls all of the mass of the Sun inward and creates intense pressure. This pressure is high enough to cause the atomic fusion of atomic masses.

For each second of the solar **nuclear fusion** process, 700 million tons of hydrogen is converted into the heavier atom helium. Since its formation 4.5 billion years ago, the Sun has used up about half of the hydrogen found in its core. The solar nuclear process also creates immense heat that causes atoms to discharge photons. Temperatures at the core are about 15 million Kelvins (15 million °C or 27 million °F). Each photon that is created travels about one micrometer before being absorbed by an adjacent gas molecule. This absorption then causes the heating of the neighboring atom and it re-emits another photon that again travels a short distance before being absorbed by another atom. This process then repeats itself many times over before the photon can finally be emitted to outer space at the Sun's surface. During the last 20% of the journey to the surface the energy is transported more by convection than by radiation. It takes a photon approximately 100,000 to 200,000 years or about 10^{25} absorptions and re-emissions

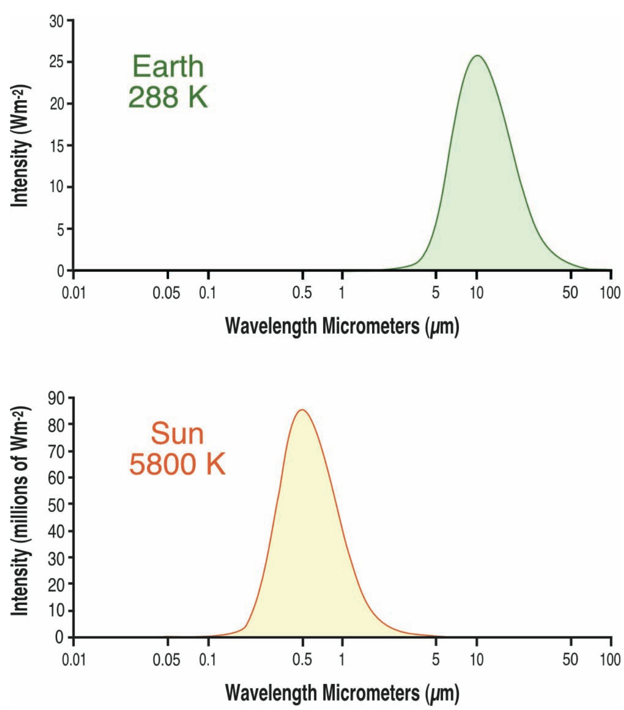


FIGURE 4.6 Radiation spectrums for the Earth and Sun. Output measurements are in watts per square meter (Earth) and millions of watts per square meter (Sun). *(Image Copyright: Michael Pidwirny)*

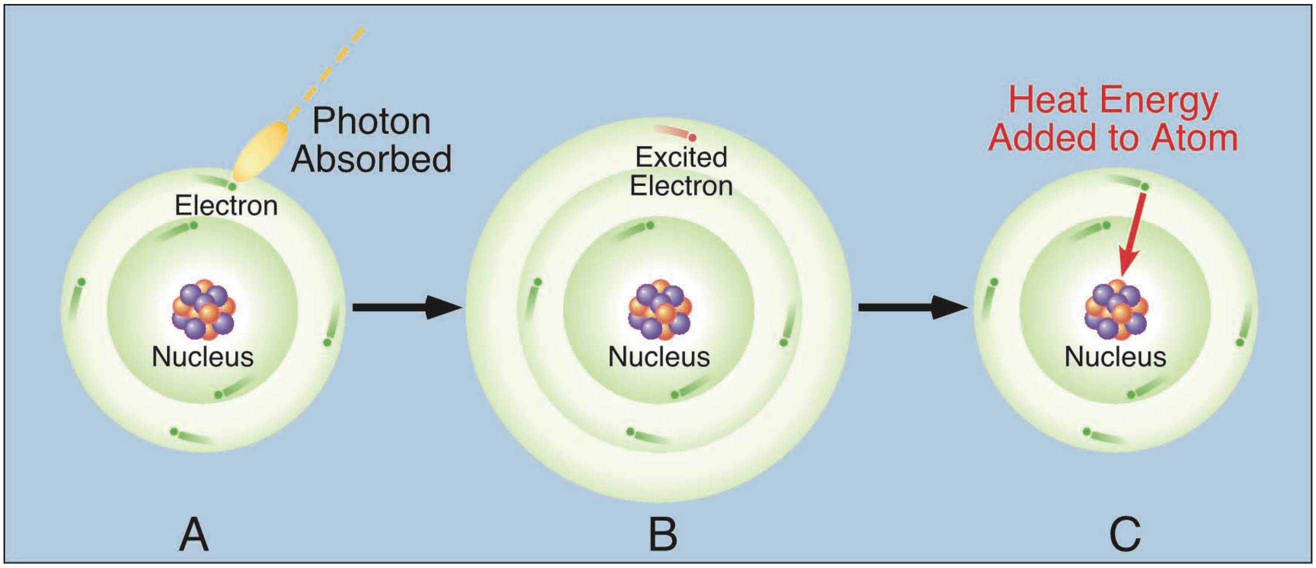


FIGURE 4.7 Photon absorption process. Photons can be absorbed by the electrons found orbiting the nucleus of an atom. (A). The absorption of a photon causes an electron to gain enough energy for it to briefly jump into a higher orbit (B). The excited electron then quickly converts the additional energy it gained into heat energy and returns to its usual orbit (C). This heat energy is then passed on to the rest of the atom. *(Image Copyright: Michael Pidwirny)*

to make the journey from the core to the Sun's surface. The trip from the Sun's surface to the Earth takes about 8 minutes.

The radiating surface of the Sun is called the **photosphere**. The photosphere has an average temperature of about 5800° K (5527°C or 9981°F). Some of the Sun's emitted electromagnetic radiation occurs in the visible band centered at 0.5 µm. The total quantity of energy emitted from the Sun's surface is approximately 64,000,000 Wm^{-2} (watts per square meter). The radiation emitted by the Sun passes through space until it is intercepted by planets and other celestial objects. The distance the solar radiation has traveled determines how intense the light will be striking these objects. We can model this process with a physical law known as the **Inverse Square Law** (**Figure 4.10**). This law simply states that the intensity (I) of solar radiation varies inversely with the square of the distance (d) from the Sun. As a result of this law, if the intensity of radiation at a given distance is one unit, at twice the distance the intensity will become only one-quarter. At three times the distance, the intensity will become only one-ninth of its original intensity at a distance of one unit, and so on.

Given the amount of energy radiated by the Sun and the average Earth-Sun distance of 149.5 million km, the amount of radiation intercepted by the outer limits of the atmosphere can be calculated to be around 1370 Wm^{-2}. For general purposes, the energy output of the Sun can be considered unvarying and is consequently known as the **solar constant**. This concept is not entirely correct. Satellite measurements have shown that the output of the Sun is quite variable at timescales of less than a few years (**Figure 4.11**). Researchers have also speculated that the

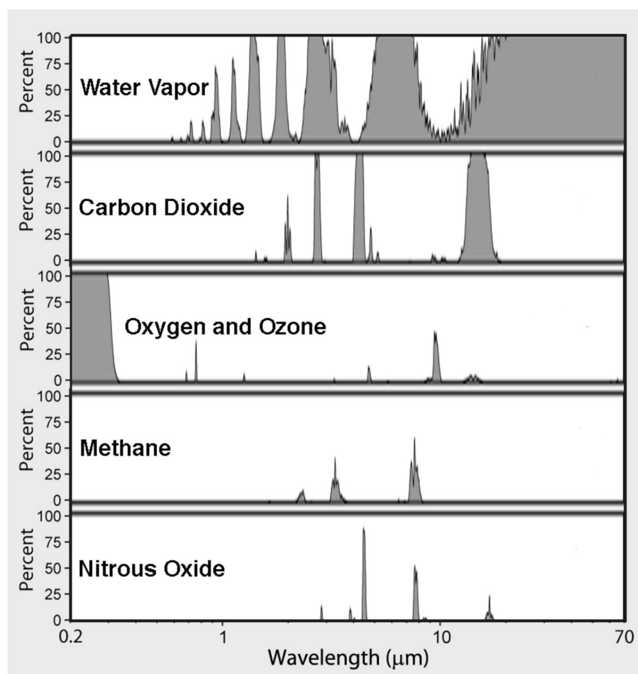


FIGURE 4.8 Percent radiation absorption and emission effectiveness of some common gases in Earth's atmosphere. CH_4 – methane, N_2O – nitrous oxide, O_2 – oxygen, O_3 – ozone, CO_2 – carbon dioxide, and H_2O – water vapor. *(Image Copyright: Michael Pidwirny)*

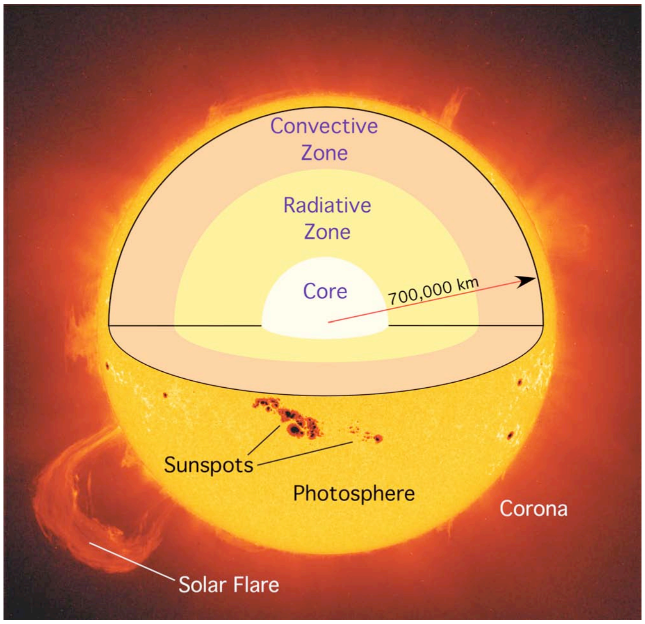


FIGURE 4.9 Major parts of the Sun. Solar energy is produced at the core of the Sun by nuclear fusion. This energy is then radiated to the convection zone, where mixing transfers the energy to the photosphere. The photosphere is the surface that emits solar radiation to space. On the photosphere, localized cool areas called sunspots occur. Erupting from the photosphere, are solar flares composed of gas, electrons, and radiation. The corona is the upper portion of the Sun's atmosphere. *(Modified Image: Michael Pidwirny)*

colder global temperatures experienced during the period known as the **Little Ice Age** (1550-1850 A.D.) may have been cause by a decrease in solar radiation. This hypothesis, however, is difficult to prove conclusively because accurate data on solar output of radiation only goes back to about 1978.

Sunspots, Prominences, and Solar Flares

The Sun's photosphere also contains dark **sunspots** that have a temperature several hundred degrees cooler than the rest of the photosphere (**Figure 4.12**). Sunspots always occur in pairs with the two spots being connected together by intense magnetic fields that originate from the Sun's interior. Researchers have found that the number of sunspots on the Sun tends to vary in a cyclical fashion over time (**Figure 4.13**). This cycle has been measured to have an average period of about 11 years. Scientists also believe that the cycling of sunspots may be associated with changes in the Earth's climate. We will examine this relationship in greater depth later on in the textbook.

Sunspots can also produce prominences and solar flares. **Prominences** are clouds of gas that can extend into space by 50,000 km or more (**Figure 4.9**). These features can exist for two to three months. A **solar flare** is a violent explosion on the Sun that releases gas, electrons, visible light, ultra-violet light, and X-rays to space. Some of the radiation and particles ejected by solar flares can reach our planet's magnetic field. This meeting produces the Earth's **Aurora Borealis** (Northern Lights) and **Aurora Australis** (Southern Lights) in the upper atmosphere (**Figure 4.14**). Solar flares can also disrupt Earth-based radio communications, satellite transmissions, and can cause power surges and even blackouts in power-line grids.

EARTH GEOMETRY AND MOTIONS

Earth Rotation and Revolution

The term **Earth rotation** refers to the spinning of our planet on its axis. Because of rotation, the Earth's surface moves at the equator at a speed of about 467 m (1532 ft)

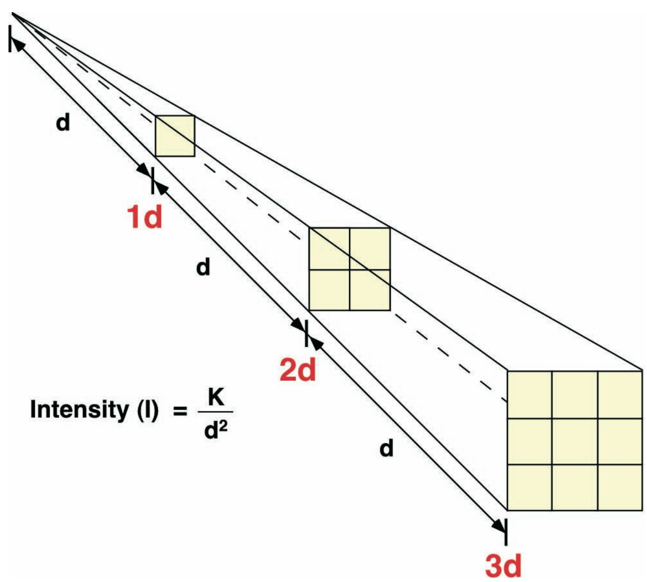


FIGURE 4.10 According to the Inverse Square Law the diffusion of radiation is geometrically related to distance traveled. In the equation given, **K** is the intensity of the radiation at one unit distance (1d). At two unit distances (2d), the intensity of the radiation is determined by dividing **K** by the square of the new distance from the source. The same procedure is used to determine the intensity at three unit distances from the source. *(Image Copyright: Michael Pidwirny)*

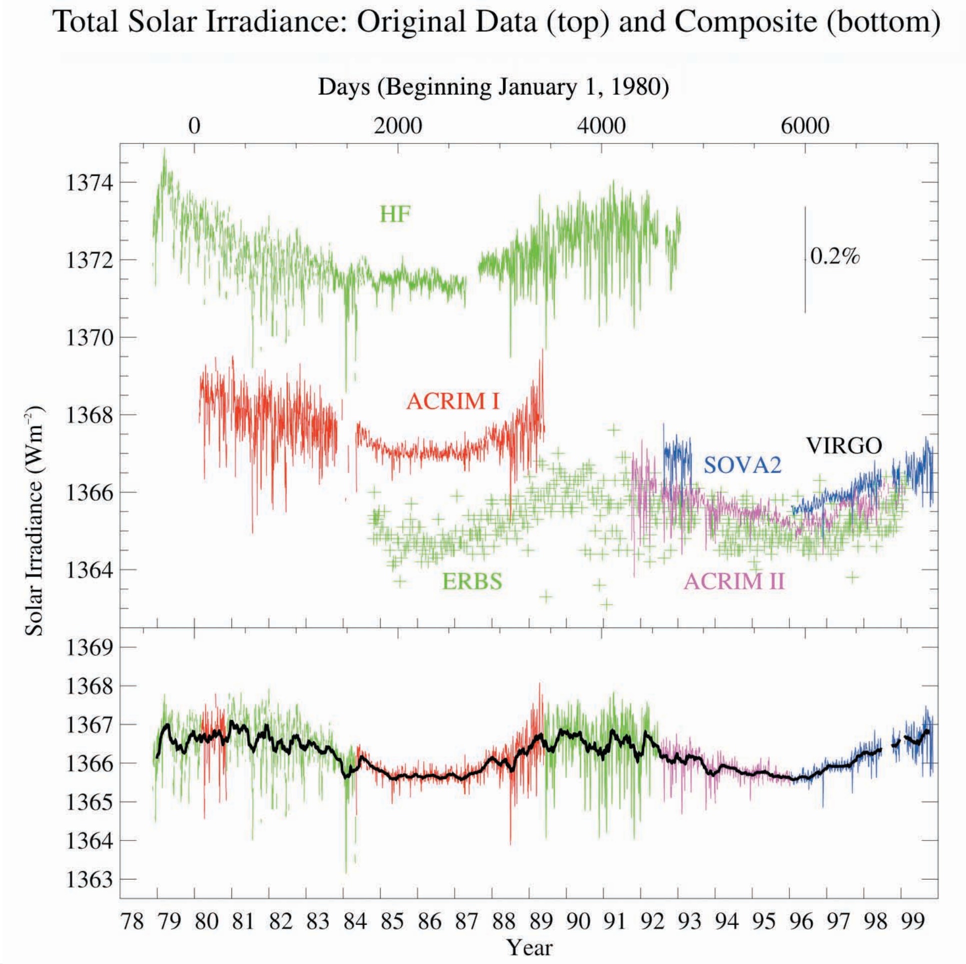


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FIGURE 4.11 Measurements of solar irradiance outside the Earth's atmosphere from six independent space-based radiometers since 1978 (top). This data has been re-calibrated and combined to produce the composite total solar irradiance graph (bottom). These graphs indicate that the sun's output varies with the 11-year sunspot cycle by about 0.1 percent. Temporary drops (few days) in output of up to 0.3 percent are the result of large sunspots passing over the visible region of the sun. The 11-year peak in sunspot numbers is accompanied by an increase in magnetic activity that causes a general rise in the radiation output. This increase in output exceeds the isolated cooling effects of the sunspots. *(Source: Foukal, P., C. Frohlich, H. Spruit and T. M. L. Wigley. 2006. Variations in solar luminosity and their effect on the Earth's climate. Nature 443: 161-166.)*

per second or slightly over 1675 km (1040 mi) per hour. If you could look down at the Earth's North Pole from space you would notice that the direction of rotation is counter-clockwise (**Figure 4.15**). The opposite is true if you viewed the Earth from the South Pole. One rotation takes exactly twenty-four hours and is called a **mean solar day**. The Earth's rotation is responsible for the daily cycles of day and night. At any one moment in time, one half of the Earth is in sunlight, while the other half is in darkness. The edge dividing the daylight from night is called the **circle of illumination** (see **Figure 4.18**). The Earth's rotation also creates the apparent movement of the Sun across the horizon (**Figure 4.16**).

The orbit of the Earth around the Sun is called **Earth revolution**. This celestial motion takes 365.26 days to complete one cycle. Further, the Earth's orbit around the Sun is not circular, but oval or elliptical (**Figure 4.17**). An elliptical orbit causes the Earth's distance from the Sun to vary annually. Yet, this phenomenon is not responsible for the Earth's seasons! This variation in the distance from the Sun causes the amount of solar radiation received by the Earth to annually vary by about 6%. **Figure 4.17** illustrates the positions in the Earth's revolution where it is closest and farthest from the Sun. On January 3, **perihelion**, the Earth is closest to the Sun (147.3 million km or 91.5 million mi). The Earth is farthest from the Sun on July 4, or **aphelion** (152.1 million km or 94.5 million mi). The

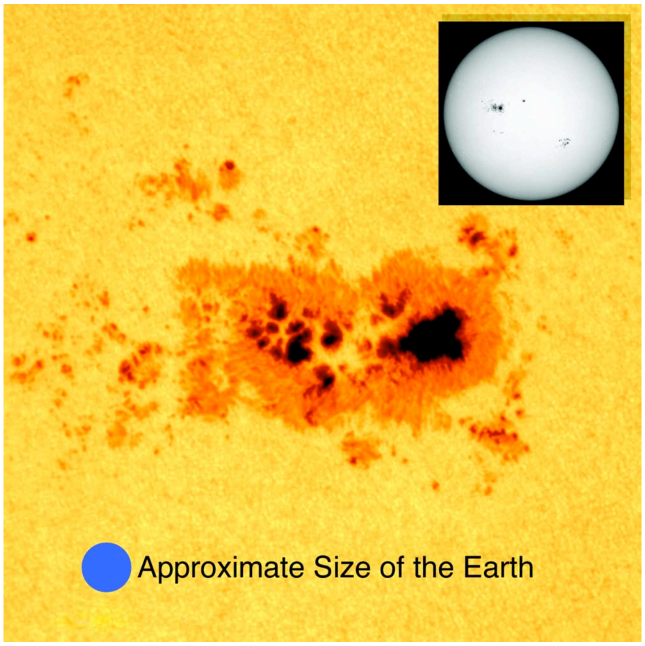

FIGURE 4.12 Large sunspot group observed on September 23, 2000. This group of sunspots covered an a dozen times larger than the entire surface of the Earth! Sunspots are caused by intense magnetic fields emerging from the Sun's interior. *(Source: NASA - Solar and Heliospheric Observatory)*

average distance of the Earth from the Sun over a one-year period is about 149.6 million km (93.0 million mi).

Tilt of the Earth's Axis

The **ecliptic plane** can be defined as a two-dimensional flat surface that geometrically intersects the Earth's orbital path around the Sun. On this plane, the Earth's axis is not at right angles to this surface, but inclined at an angle of about 23.5°From the perpendicular. **Figure 4.18** shows a side view of the Earth in its orbit about the Sun on four important dates: **June solstice**, **September equinox**, **December solstice**, and **March equinox**. Note that the angle of the Earth's axis in relation to the ecliptic plane and the **North Star** on these four dates remains unchanged. Yet, the relative position of the Earth's axis to the Sun does change during this cycle. This circumstance is responsible for the annual changes in the height of the Sun above the horizon. It also causes the seasons, by controlling the intensity and duration of sunlight received by locations on the Earth. **Figure 4.19** shows an overhead view of this same phenomenon. In this view, we can see how the circle of illumination changes its position on the Earth's surface. During the two equinoxes, the circle of illumination cuts through the North Pole and

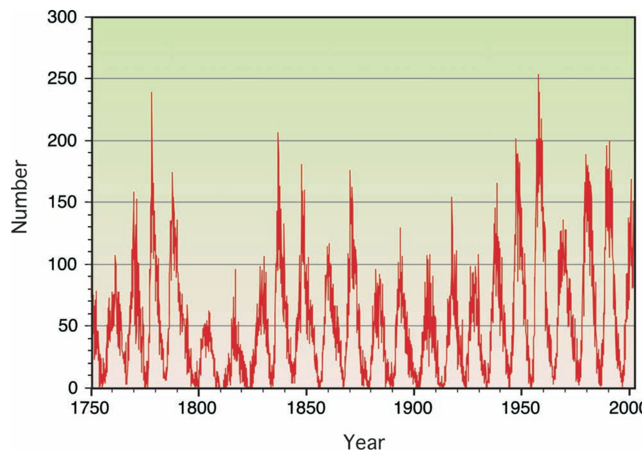

FIGURE 4.13 Monthly sunspot numbers from 1750 to 2001. Sunspots form with a somewhat regular pattern over time. Peak sunspot numbers occur on average about every 11 years. *(Source: Solar Influences Data Analysis Center - Royal Observatory of Belgium)*

the South Pole. On the June solstice, the circle of illumination is tangent to the Arctic Circle (66.5°N) and the region above this latitude receives 24 hours of daylight. The Arctic Circle is in 24 hours of darkness during the December solstice.

On June 21 or 22, also called the **summer solstice** in the Northern Hemisphere, the Earth is positioned in its orbit so that the North Pole is leaning 23.5° toward the Sun (**Figures 4.18**, **4.19** and **4.20**). During the June solstice, all locations North of the equator have day lengths greater than twelve hours, while all locations South of the equator have day lengths less than twelve hours (**Table 4.3**). On

FIGURE 4.14 The Aurora Borealis, or Northern Lights, above Bear Lake, Alaska. Auroral activity is caused by the interaction of atomic oxygen in the upper atmosphere with the van Allen Radiation Belts. Auroras are most commonly seen at locations poleward of 65°N and 65°S during spring and fall. *(Source: Wikipedia)*

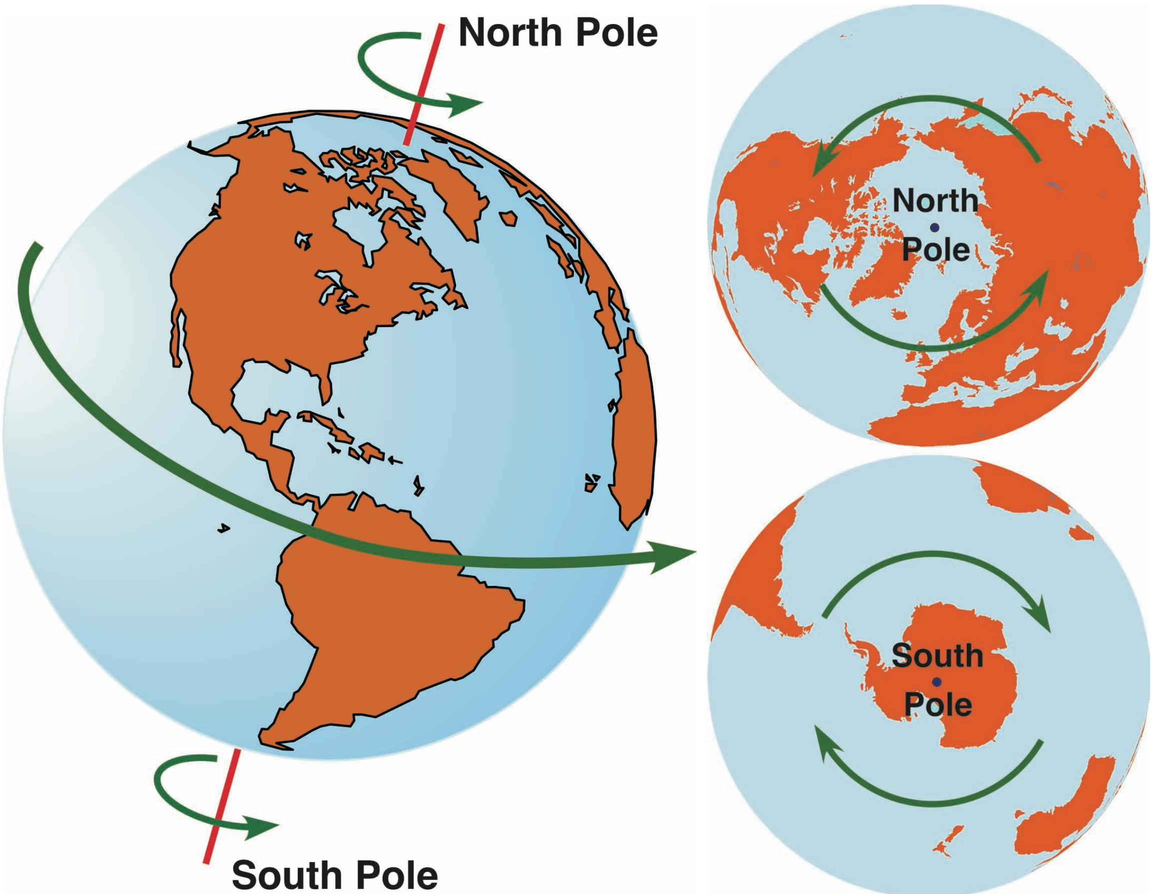

FIGURE 4.15 The movement of the Earth about its axis is known as Earth rotation. The direction of this movement varies with the viewer's position. From the North Pole the rotation appears to move in a counter-clockwise fashion. Looking down at the South Pole the Earth's rotation appears clockwise. *(Image Copyright: Michael Pidwirny)*

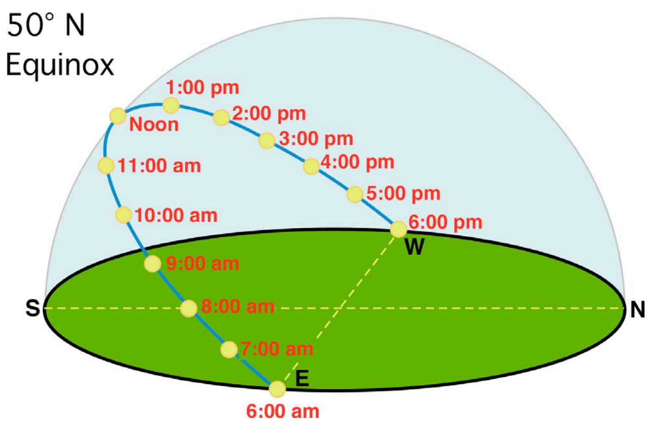

FIGURE 4.16 The apparent daily movement of the Sun across the sky is caused by the rotation of the Earth on its axis during the equinox. *(Image Copyright: Michael Pidwirny)*

December 21 or 22, also called the **winter solstice** in the Northern Hemisphere, the Earth is positioned so that the South Pole is leaning 23.5 degrees toward the Sun (**Figures 4.18**, **4.19** and **4.20**). During the December solstice, all locations North of the equator have day lengths less than twelve hours, while all locations South of the equator have day lengths exceeding twelve hours (**Table 4.3**).

On September 22 or 23, also called the **autumnal equinox** in the Northern Hemisphere, neither pole is tilted toward or away from the Sun (**Figures 4.18**, **4.19** and **4.21**). In the Northern Hemisphere, March 20 or 21 marks the arrival of the **vernal equinox** or spring when once again the poles are not tilted toward or away from the Sun. Day lengths on both of these days, regardless of latitude, are exactly 12 hours.

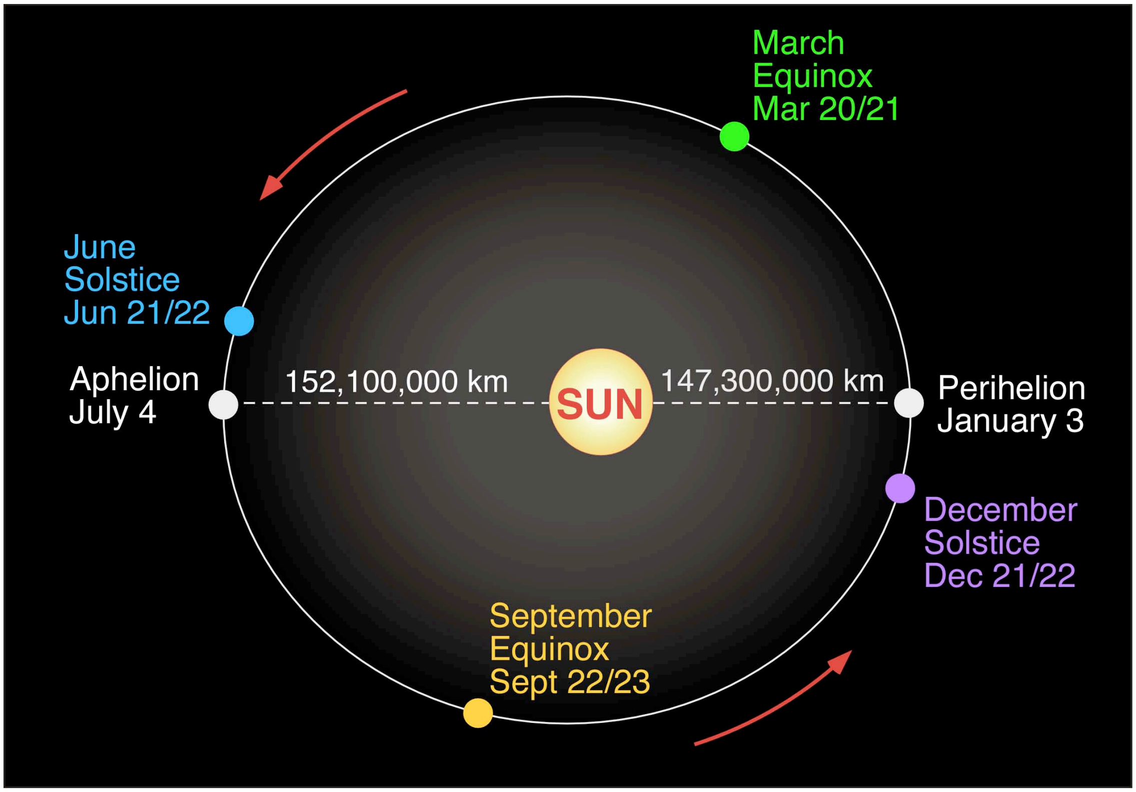

FIGURE 4.17 Earth orbit around Sun. Position of the equinoxes, solstices, aphelion, and perihelion relative to the Earth's orbit around the Sun. *(Image Copyright: Michael Pidwirny)*

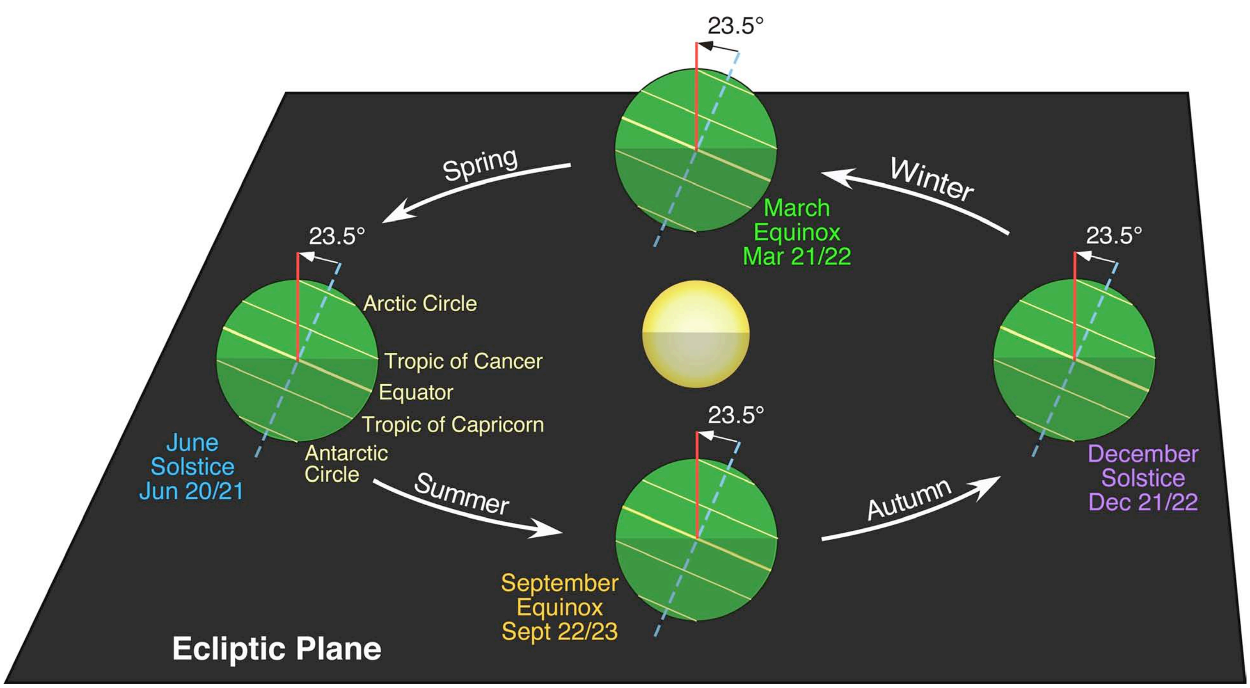

FIGURE 4.18 Earth's rotational axis and the ecliptic plane. The Earth's rotational axis is tilted 23.5° from the red line drawn perpendicular to the ecliptic plane. This tilt remains the same anywhere along the Earth's orbit around the Sun. *(Image Copyright: Michael Pidwirny)*

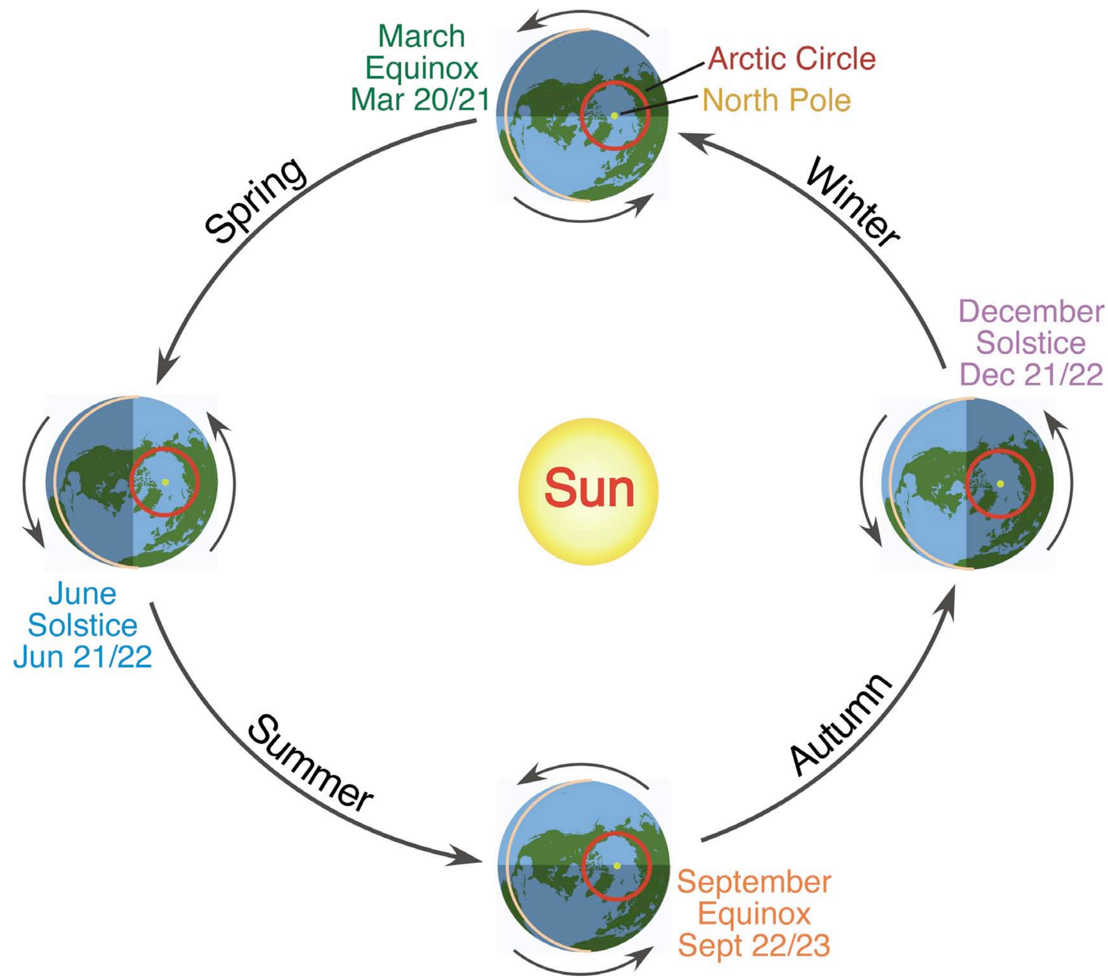

FIGURE 4.19 Annual change in the position of the Earth in its revolution around the Sun. In this graphic, we are viewing the Earth from a position in space that is above the North Pole (yellow dot) during the June solstice, the December solstice, and the two equinoxes. Note how the position of the North Pole on the Earth's surface does not change. However, its position relative to the Sun does change and this shift is responsible for the seasons. The red circle on each of the Earths represents the Arctic Circle (66.5°N). During the June solstice, the area above the Arctic Circle is experiencing 24 hours of daylight because the North Pole is tilted 23.5° toward the Sun. The Arctic Circle experiences 24 hours of night when the North Pole is tilted 23.5° away from the Sun in the December solstice. During the two equinoxes, the circle of illumination cuts through the polar axis and all locations on the Earth experience 12 hours of day and night. *(Image Copyright: Michael Pidwirny)*

Axis Tilt and Solar Altitude

The annual change in the relative position of the Earth's axis in relationship to the Sun causes the height of the Sun or **solar altitude** to vary in our skies. Solar altitude is normally measured from either the southern or northern point along the horizon and begins at zero degrees. Maximum solar altitude occurs when the Sun is directly overhead and has a value of 90°. The total variation in maximum solar altitude for any location on the Earth over a one-year period is 47° (Earth's tilt 23.5° x 2 = 47°). This variation is due to the annual changes in the relative position of the Earth to the Sun.

Figure 4.22 shows the changes in solar altitude for locations at the North Pole, 50°N, and the equator for the equinoxes and two solstices. In all of these diagrams, the Sun reaches its maximum altitude at a time described as **solar noon**. At 50°N latitude maximum solar altitude varies from 63.5° on the June solstice to 16.5° on the December solstice. During the equinoxes, the height of the Sun for this mid-latitude location reaches a maximum of 40°. Maximum solar height for the equator goes from 66.5°

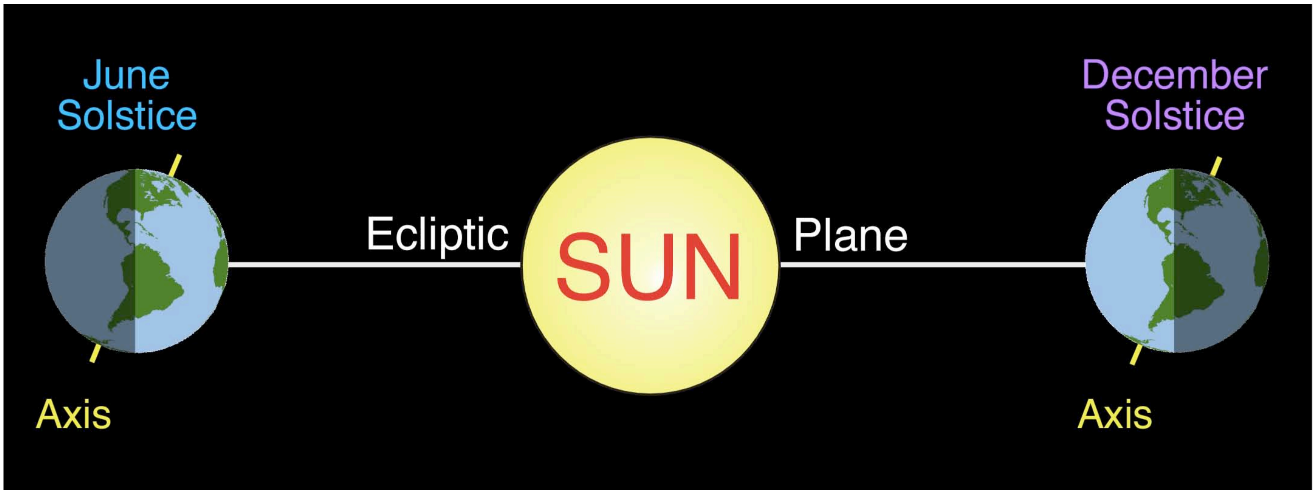

FIGURE 4.20 During the June solstice the Earth's North Pole is tilted 23.5° towards from the Sun relative to the circle of illumination. This phenomenon keeps all places above a latitude of 66.5°N in 24 hours of sunlight (summer), while locations below a latitude of 66.5°S are in total darkness (winter). The North Pole is tilted 23.5° away from the Sun relative to the circle of illumination during the December solstice. On this date, all places above a latitude of 66.5°N are now in darkness (winter), while locations below a latitude of 66.5°S receive 24 hours of daylight (summer). *(Image Copyright: Michael Pidwirny)*

TABLE 4.3 Day lengths for selected latitudes on the two equinoxes and two solstices (hours and minutes).

Latitude	December Solstice December 21-22	March Equinox March 20-21	June Solstice June 20-21
90°N	0:00	Sun at Horizon	24:00
80°N	0:00	12:00	24:00
70°N	0:00	12:00	24:00
66.5°N	Sun at Horizon	12:00	24:00
60°N	5:33	12:00	18:27
50°N	7:42	12:00	16:18
40°N	9:08	12:00	14:52
30°N	10:04	12:00	13:56
20°N	10:48	12:00	13:12
10°N	11:25	12:00	12:35
Equator	12:00	12:00	12:00
10°S	12:35	12:00	11:25
20°S	13:12	12:00	10:48
30°S	13:56	12:00	10:04
40°S	14:52	12:00	9:08
50°S	16:18	12:00	7:42
60°S	18:27	12:00	5:33
66.5°S	24:00	12:00	Sun at Horizon
70°S	24:00	12:00	0:00
80°S	24:00	12:00	0:00
90°S	24:00	Sun at Horizon	0:00

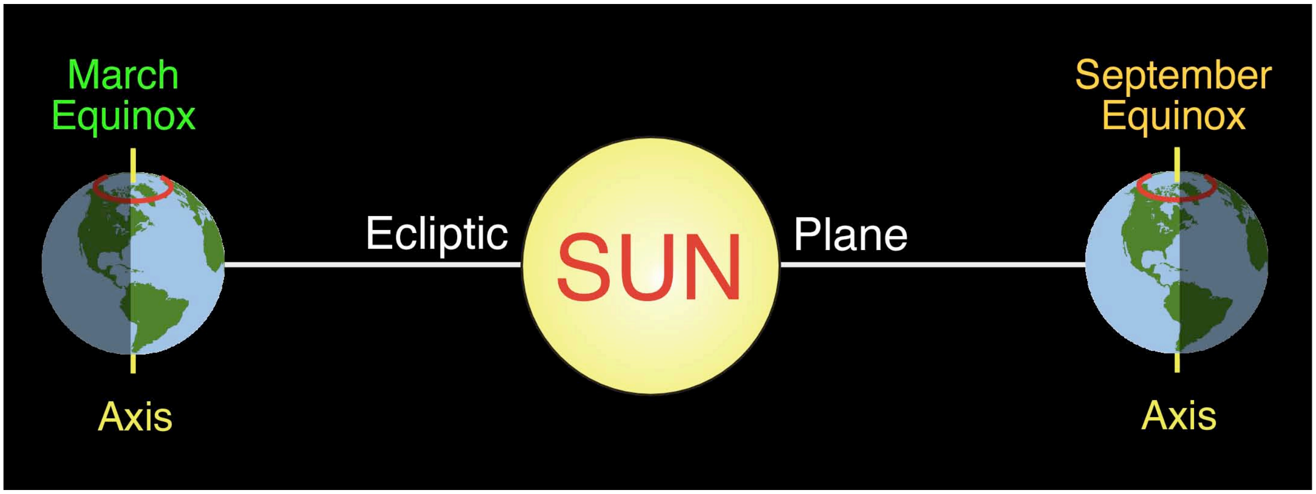

FIGURE 4.21 During the equinoxes, the axis of the Earth is not tilted toward or away from the Sun and the circle of illumination cuts through the poles. This situation does not mean that the 23.5° tilt of the Earth no longer exists. The vantage point of this graphic shows that the Earth's axis is inclined 23.5° toward the viewer for both dates (see Figure s 4.19 and 4.20). The red circles shown in the graphic are the Arctic Circle. *(Image Copyright: Michael Pidwirny)*

above the northern end of the horizon during the June solstice, to directly overhead (90°) on the fall and spring equinoxes, and then down to 66.5° above the southern end of the horizon during the Winter solstice. At the North Pole, the Sun reaches its highest altitude (23.5° above the horizon) during the June solstice. Also, note that on this day the Sun does not rise or set. The Sun just makes a complete revolution around the sky at a fixed height and solar noon technically occurs all day long. On the equinoxes, the sphere of the Sun appears halfway above the horizon. Once again, it does not rise or set, just moves completely around the horizon in a period of 24 hours. During the December solstice, the North Pole is halfway through a six-month period of total darkness. If we could see the Sun through the Earth's surface, it would be located 23.5° below the horizon.

The location on the Earth where the Sun is directly overhead at solar noon is known as the **subsolar point**. The subsolar point occurs on the equator during the equinoxes (**Figure 4.23**). On these dates, the axis of the Earth is perpendicular to the ecliptic plane and the poles are not tilted away or towards the Sun (**Figure 4.21**). During the June solstice, the subsolar point moves to the Tropic of Cancer (23.5°N) because at this time the North Pole is tilted 23.5° toward the Sun (**Figure 4.20**). **Figure 4.24** shows how the subsolar point gradually changes from one day to the next over a period of one-year. Note that on this graph, the subsolar point is located at the Tropic of Capricorn (23.5°S) during the December solstice when the South Pole is angled 23.5° toward the Sun (**Figure 4.20**).

DAILY AND ANNUAL CYCLES OF INSOLATION

In the previous section, we learned that the Earth's seasons are controlled by changes in the duration and intensity of Sun's electromagnetic radiation or **insolation** (**in**coming **sol**ar radi**ation**). Both of these factors are in turn governed by the annual change in the position of the Earth's axis relative to the Sun.

We have learned that yearly changes in the position of the Earth's axis cause the location of the Sun to wander 47° across our skies. Changes in the location of the Sun have a direct effect on the intensity of insolation. The intensity of incoming solar radiation is largely a function of the **angle of incidence**, the angle at which the Sun's rays strike the Earth's surface. If the Sun is positioned directly overhead or 90°From the horizon, the insolation strikes the surface of the Earth at right angles and is most intense. If the Sun is 45° above the horizon, the sunlight strikes the Earth's surface at an angle. This causes the rays to be spread out over a larger surface area, thereby reducing the intensity of the radiation. **Figure 4.25** shows the effect of changing the angle of incidence from 90 to 45°. As illustrated, the lower Sun angle (45°) causes the radiation to spread over a much larger surface area. This surface area is approximately 40% greater than the area covered by an angle of 90°. Accordingly, the increase in surface area receiving the solar rays reduces the intensity of the light by 30%.

We can also model the effect the angle of incidence has on insolation intensity with the following simple

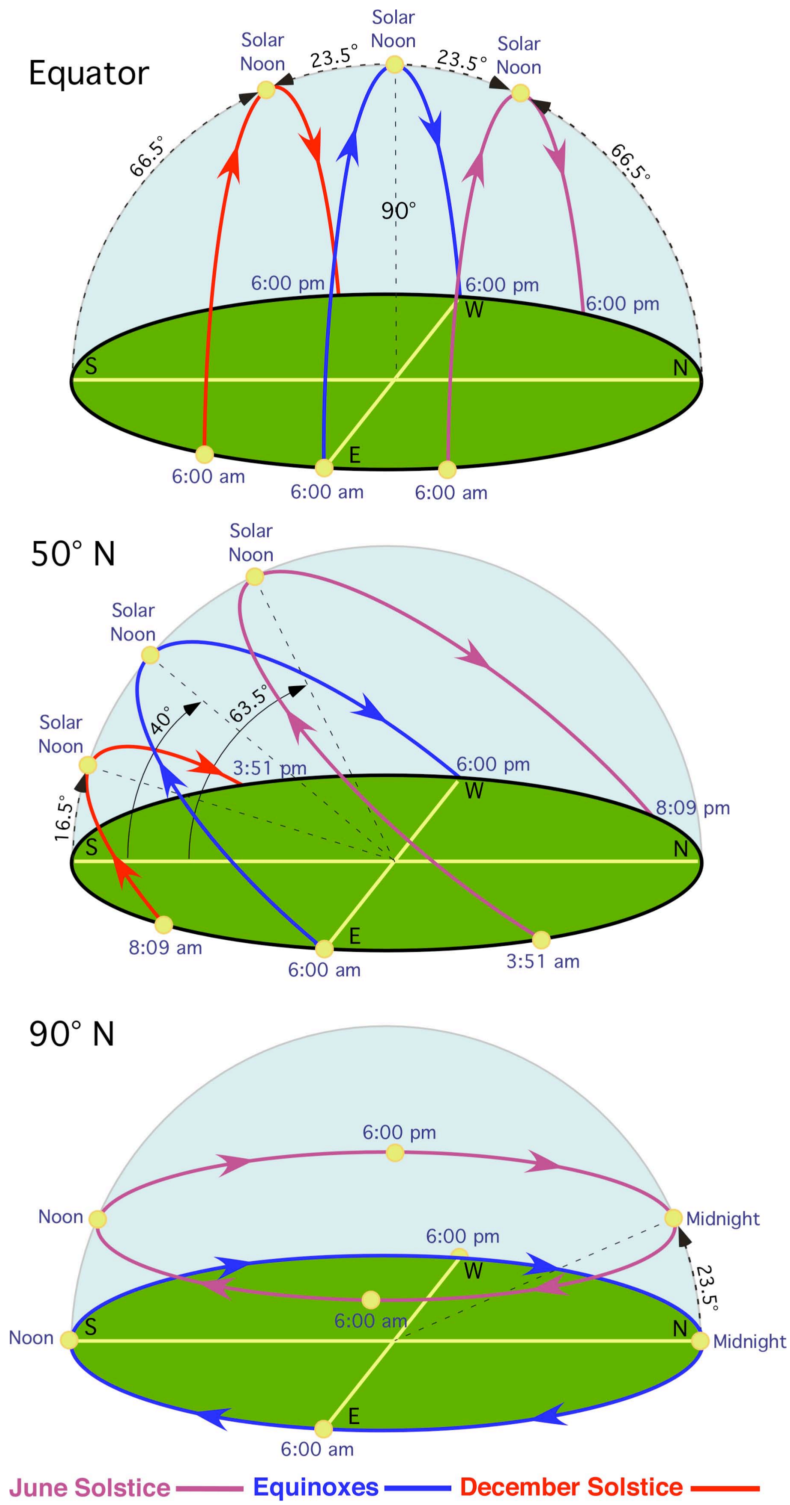

FIGURE 4.22 Daily solar paths for different times of the year at the equator, 50°N, and 90°N. Notice that the equator experiences 12 hours daylight for the four dates shown. At 50°N day length is longest during the June solstice and shortest during the December solstice. The North Pole (90°N) experiences 24 hours of daylight during the summer solstice and 24 hours of night on the winter solstice. During the equinoxes, the Sun is located halfway above the horizon all day long. *(Image Copyright: Michael Pidwirny)*

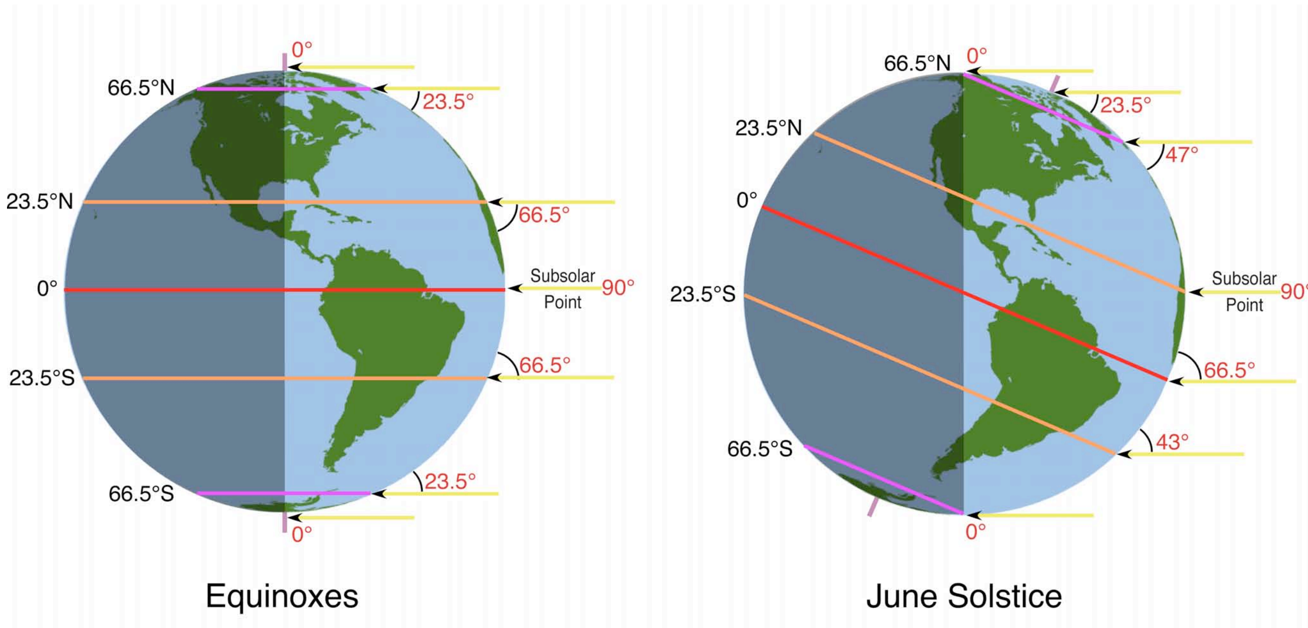

FIGURE 4.23 Relationship of maximum Sun height to selected latitudes for the equinoxes (left) and June solstice (right). The red values on the right of the globes are maximum solar altitudes at solar noon. Black numbers on the left indicate the location of the Equator, Tropic of Cancer (23.5°N), Tropic of Capricorn (23.5°S), Arctic Circle (66.5°N), and the Antarctic Circle (66.5°S). The location of the North and South Poles are also identified. During the equinox, the equator is the location on the Earth with a Sun angle of 90 degrees for solar noon. Note how maximum Sun height declines with latitude as you move away from the Equator. For each degree of latitude traveled maximum Sun height decreases by the same amount. At equinox, you can also calculate the noon angle by subtracting the location's latitude from 90°. During the June solstice, the Sun is now directly overhead at the Tropic of Cancer. All locations above this location have maximum Sun heights that are 23.5° higher from the equinox situation. Places above the Arctic Circle are in 24 hours of daylight. Below the Tropic of Cancer the noon angle of the Sun drops one degree in height for each degree of latitude traveled. At the Antarctic Circle, maximum Sun height becomes 0° and locations south of this point on the Earth are in 24 hours of darkness. *(Image Copyright: Michael Pidwirny)*

equation:

$$\text{Intensity} = \text{SIN}\ (A)$$

where, A is the angle of incidence and SIN is the sine function found on most calculators. Using this equation we can determine that an angle of 90° gives us a maximum intensity of 1.00 or 100%. We can compare this maximum value with values determined for other angles of incidence given in **Table 4.4**. Note the values in this table are expressed as a percentage of the maximum value that occurs when the Sun is directly overhead.

The yearly changes in the position of the Earth's axis relative to the Sun also cause seasonal variations in day length to all locations outside of the equator. Longest days occur during the summer solstice for locations north of the equator and on the winter solstice for locations in the Southern Hemisphere. For every day of the year, the equator experiences identical periods of day and night. Day and night is also of equal length for all Earth locations on the September and March equinoxes. **Figure 4.26** describes the change in the length of day for locations at the equator, 30, 50, 60, and 70° North and South over a one-year period. The figure suggests that days are longer than nights in the Northern Hemisphere from the March equinox to the September equinox. Between the September equinox to March equinox, days are shorter than nights in the Northern Hemisphere. The opposite is true in the Southern Hemisphere. The figure also shows that the winter to summer variation in day length increases with increasing latitude. This phenomenon enhances the seasonal variation in insolation received for locations in the middle and high latitudes.

Figure 4.27 (diagram A) describes the potential insolation (as measured outside the Earth's atmosphere) available for all locations on the Earth over a one-year period. The values plotted on this graph take into account

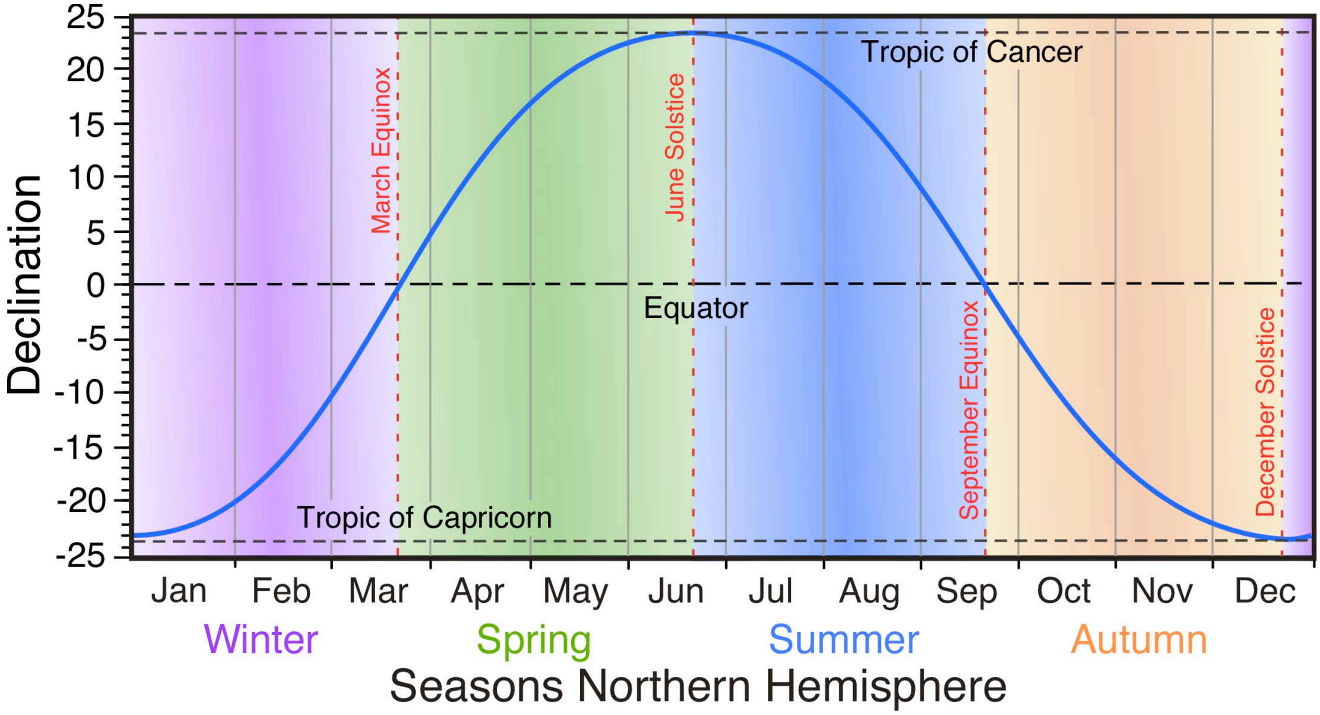

FIGURE 4.24 Angle of the Sun's declination and latitude of the subsolar point throughout the year. Seasons are for the Northern Hemisphere. *(Image Copyright: Michael Pidwirny)*

TABLE 4.4 Effect of Sun angle on the intensity of incoming solar radiation.

Sun Angle	Percent Intensity Relative to a Sun Angle of 90°
80°	98%
70°	94%
60°	87%
50°	77%
40°	64%
30°	50%
20°	34%
10°	17%
0°	0%

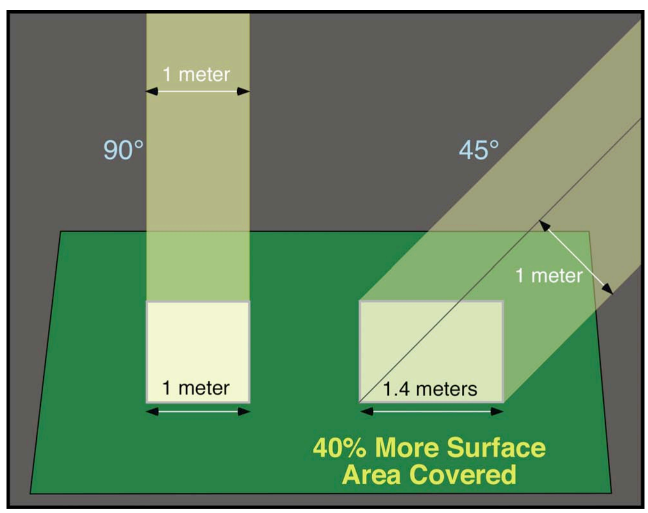

FIGURE 4.25 The Sun's angle of incidence determines the intensity of the insolation received at the Earth's surface. Solar radiation is most intense when the Sun is directly overhead (90°). Reducing the Sun's altitude to 45° decreases the intensity of the insolation by 30% because the ray's are now spread over a larger area. *(Image Copyright: Michael Pidwirny)*

the combined effects of angle of incidence and day length duration. Locations at the equator show the least amount of variation in insolation over a one-year period (**Figure 4.27** - diagram B). These slight changes in insolation result only from the annual changes in the altitude of the Sun above the horizon, as the duration of daylight at the equator is always 12 hours (**Table 4.3**). The peaks in insolation intensity correspond to the two equinoxes when the Sun is directly overhead. The two annual minimums of insolation occur on the solstices when the maximum height of the Sun above the horizon reaches an angle of 66.5°.

The most extreme variations in insolation received in the Northern Hemisphere occur at 90°N (**Figure 4.27** - diagram C). During the June solstice this location receives more potential incoming solar radiation than any other location graphed. At this time the Sun never sets. In fact, it remains at an altitude of 23.5° above the horizon for the whole day. From September 22 (September equinox) to March 21, (March equinox) no insolation is received at 90° North. At this stage in the Sun's seasonal migration it moves below the horizon because the northern axis of the Earth is now tilted away from the Sun.

The annual insolation curve for locations at 50°N best approximates the seasonal changes in solar radiation intensity received in the mid-latitudes (**Figure 4.27** – diagram D). Maximum values of insolation are received at the June solstice when day length and angle of incidence are at their maximum. During the June solstice, day length is 18 hours and 27 minutes (**Table 4.3**) and the angle of the Sun reaches a maximum height above the horizon of 63.5°. Minimum values of insolation are received at the December solstice when day length and angle of incidence are at their minimum. During the December solstice, day length is only 5 hours and 33 minutes and the angle of the midday Sun only reaches a value of 16.5° above the horizon.

In Chapter 5, we will explore how these spatial and temporal variations in potential insolation are modified by atmospheric and surface factors.

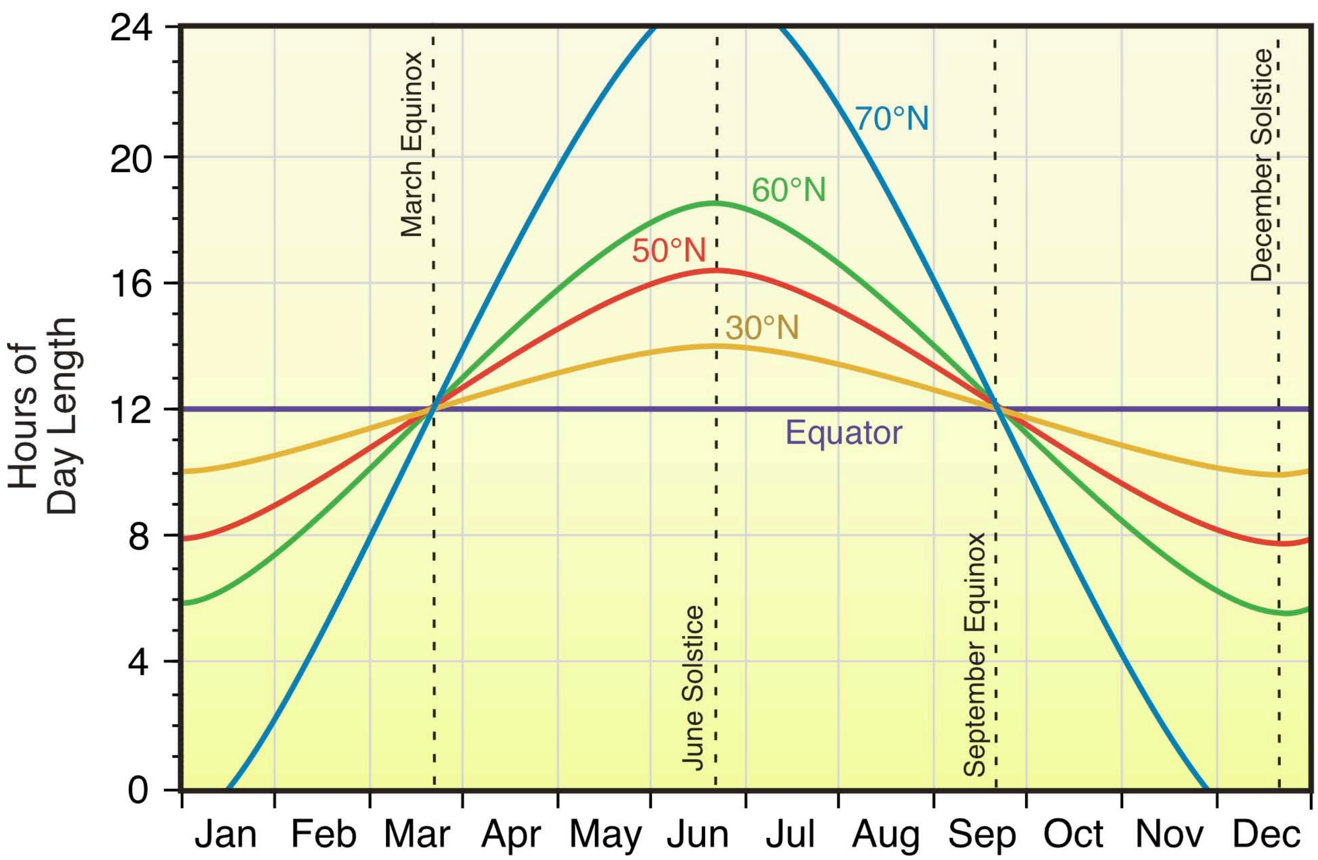

FIGURE 4.26 Annual variations in day length for locations at the equator, 30°, 50°, 60°, and 70° North latitude. *(Image Copyright: Michael Pidwirny)*

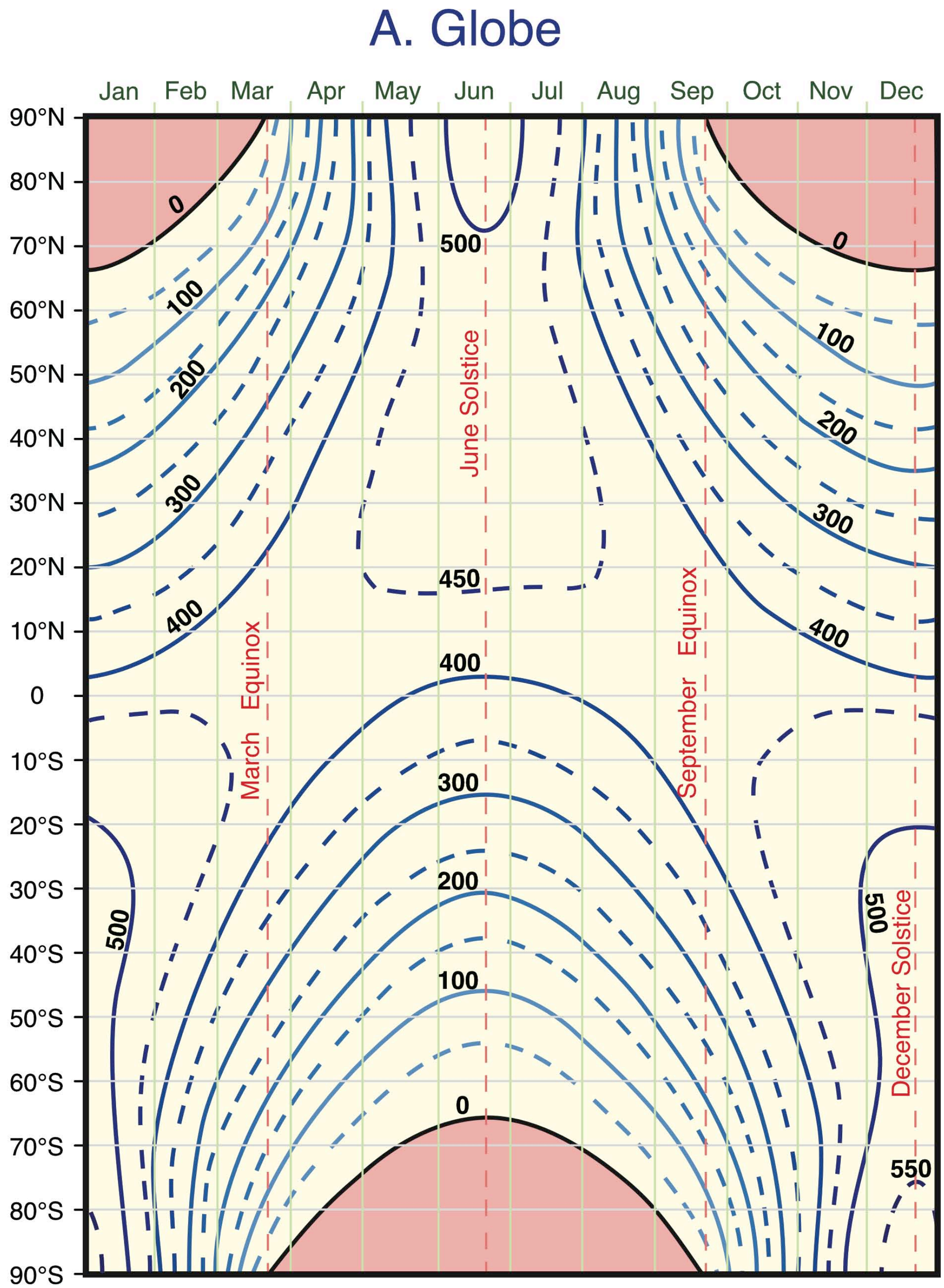

FIGURE 4.27 Daily insolation at the top of the atmosphere in Wm^{-2}. (A) Describes the availability of insolation by latitude and month. The dates for the equinoxes, June solstice, and December solstice are also shown. Pink zones indicate times and location where there is no daily sunshine. (B) Shows the annual variation in daily insolation for the equator. At the equator little annual variation in insolation occurs because of consistent 12-hour days and relatively high Sun angles all year long. (C) Describes the annual variations in daily insolation for 90°N. Note that this location experiences six months of darkness from the September equinox to the March equinox. (D) Portrays the annual variation in daily insolation for 50°N. Mid-latitude locations show large seasonal variations in insolation that peak in the June solstice. Lowest quantities of insolation are received during the December solstice. *(Image Copyright: Michael Pidwirny)*

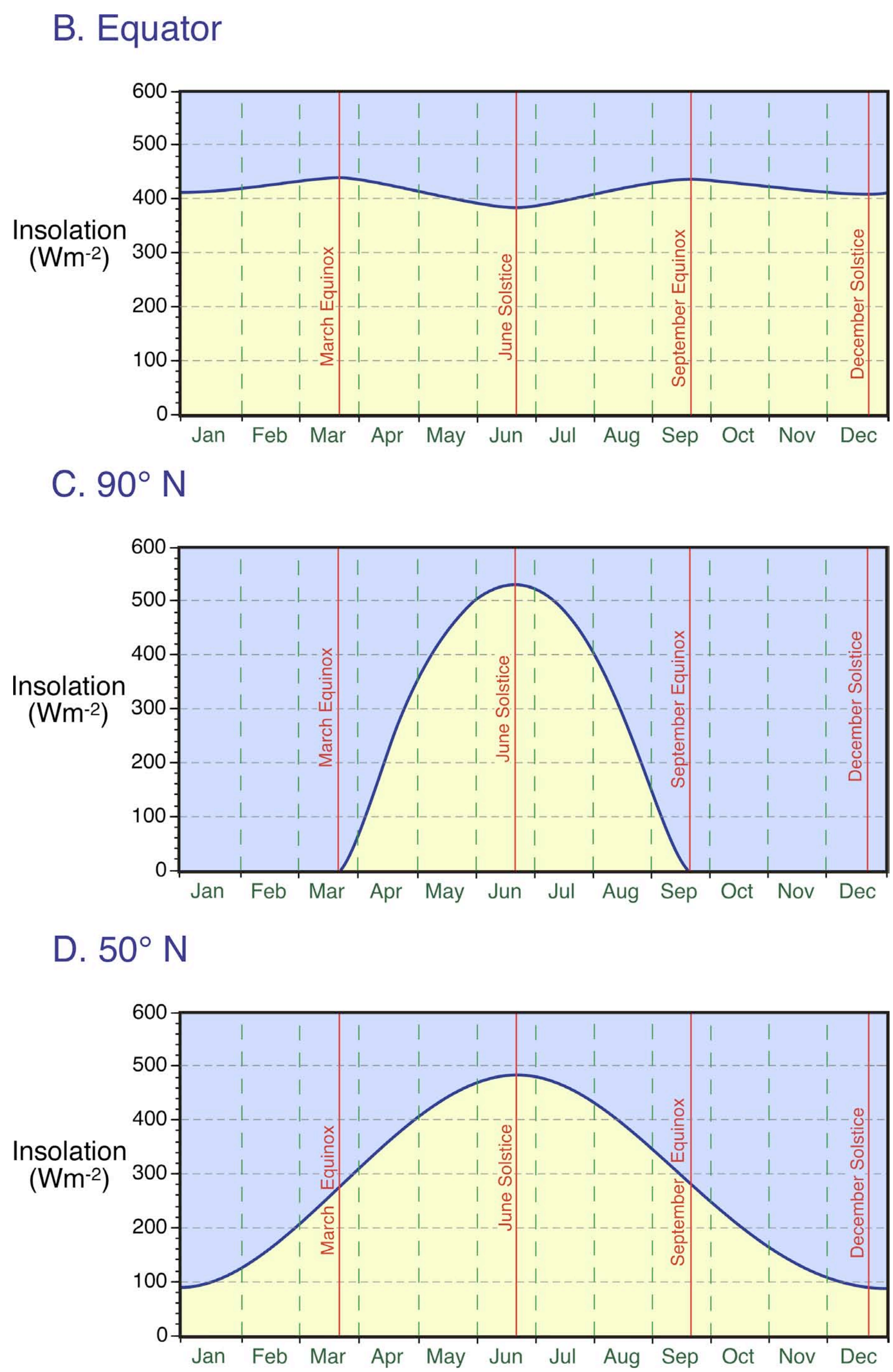

FIGURE 4.27 - CONTINUED Daily insolation at the top of the atmosphere in Wm^{-2}. (A) Describes the availability of insolation by latitude and month. The dates for the equinoxes, June solstice, and December solstice are also shown. Pink zones indicate times and location where there is no daily sunshine. (B) Shows the annual variation in daily insolation for the equator. At the equator little annual variation in insolation occurs because of consistent 12-hour days and relatively high Sun angles all year long. (C) Describes the annual variations in daily insolation for 90°N. Note that this location experiences six months of darkness from the September equinox to the March equinox. (D) Portrays the annual variation in daily insolation for 50°N. Mid-latitude locations show large seasonal variations in insolation that peak in the June solstice. Lowest quantities of insolation are received during the December solstice. *(Image Copyright: Michael Pidwirny)*

CHAPTER SUMMARY

- Radiation is a form of energy that is emitted by all material objects found in the Universe. The emission of radiation results in a net loss of energy within any body. This energy can be returned to the object by the process of absorption.
- Radiation behaves in very predictable ways. The temperature of the radiating object determines the wavelength of radiation emitted by a body. Wavelength of emission becomes shorter with an increase temperature. Temperature also has an influence on an object's total output of radiation. Higher temperatures lead to greater quantities of radiation emission.
- The Sun is the major source of energy for most biotic and abiotic systems on the Earth. The Sun creates large amounts of electromagnetic radiation through atomic fusion of hydrogen into helium. This process creates vast amounts of heat energy.
- The surface output of radiation for Sun is about 64,000,000 Wm^{-2}. The wavelength of this solar output ranges from the ultraviolet to far infrared spectrum.
- About 44% of the Sun's output is in the visible band, which we are able to see.
- As solar energy travels through space its intensity decreases with distance traveled. Only a small percentage of the energy emitted by the Sun is actually received by the Earth. This quantity is often called the solar constant and it amounts to about 1370 Wm^{-2}.
- The Earth's rotation and its geometric relationships with the Sun influence the amount of solar energy received by our planet. These factors cause predictable changes in the Sun's angle of incidence and day length. Together, these changes are responsible for the Earth's seasons.
- On the Earth, solar radiation is most intense when the Sun is directly overhead in the sky. Lowering the Sun's height reduces the intensity of sunlight by spreading it over more of the Earth's surface.
- Day length varies annually for most locations on the Earth. The exception to this rule is locations along the equator where equal day and night occur all year long.
- Outside of the equator, the annual variation in length of day and night gets more extreme as we approach the poles.
- In the Northern Hemisphere, the longest days occur during the June solstice. Long days plus relatively high Sun angles are responsible for the annual peak in potential insolation that occurs on this date.
- Potential insolation reaches its lowest levels in the Northern Hemisphere during the December solstice. This coincides with the shortest days and the lowest Sun angles.

IMPORTANT TERMS

Absolute zero
Absorption
Angle of incidence
Aphelion
Aurora Australis
Aurora Borealis
Autumnal equinox
Blackbody
Circle of illumination
December solstice
Earth revolution
Earth rotation
Ecliptic plane
Electromagnetic Radiation
Emission
Far infrared
Infrared radiation
Insolation
Inverse Square Law
June solstice
Kinetic energy
Little Ice Age
March equinox
Mean solar day
Near infrared
North Star
Nuclear fusion
Perihelion
Photon
Photosphere
Prominence
Selective absorber
Selective emitter
September equinox
Solar altitude
Solar constant
Solar flare
Solar noon
Spectrum

Stefan-Boltzmann Law
Subsolar point
Summer solstice
Sunspot
Ultraviolet radiation
Vernal equinox
Visible light
Wavelength
Wien's Law
Winter solstice

CHAPTER REVIEW QUESTIONS

1. Describe radiation's wave-like and particle-like properties.
2. Discuss emission and absorption as they relate to radiation.
3. How does a radiating body's temperature influence the quantity and quality of radiation emitted?
4. Explain how the Sun makes radiation? Why is the intensity of this radiation about 64,000,000 Wm^{-2} at the Sun's surface?
5. Discuss the relationship that exists between intensity of radiation and distance from the radiating object.
6. Define the following properties of our planet: Earth rotation and Earth revolution.
7. What influence does Earth rotation have on solar insolation received at the equator over a 24-hour period?
8. How does the tilt of the Earth's axis effect the position of the circle of illumination for the two equinoxes and solstices?
9. Explain how the annual change in the Earth's tilt relative to the Sun effects the height of the Sun for locations at the equator, 50°S, and the South Pole?
10. What is insolation? How does angle of incidence influence its intensity?
11. Why are changes in the Sun's angle of incidence and day length responsible for the Earth's seasons in the mid-latitudes?

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