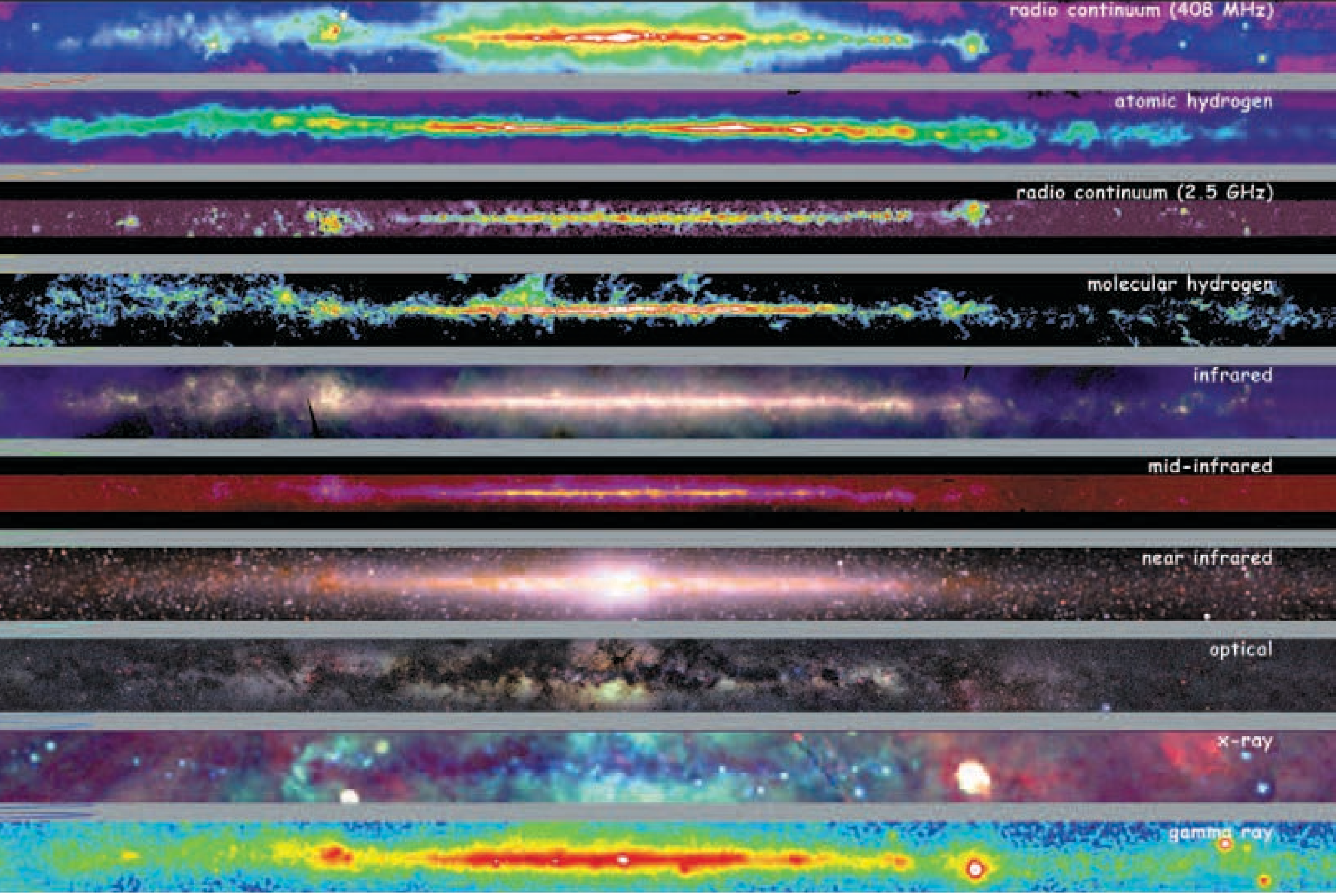


Light and the Electromagnetic Spectrum

4

The Milky Way seen at 10 wavelengths of the electromagnetic spectrum. Courtesy of Astrophysics Data Facility at the NASA Goddard Space Flight Center.

James Clerk Maxwell was born in Edinburgh, Scotland in 1831. His genius was apparent early in his life, for at the age of 14 years, he published a paper in the *Proceedings of the Royal Society of Edinburgh*. One of his first major achievements was the explanation for the rings of Saturn, in which he showed that they consist of small particles in orbit around the planet. In the 1860s, Maxwell began a study of electricity and magnetism and discovered that it should be possible to produce a wave that combines electrical and magnetic effects, a so-called electromagnetic wave. His analysis of this hypothetical wave showed that its speed would be 300,000 kilometers/second. Because this is the speed of light, Maxwell concluded that he had discovered the nature of light: Light is an electromagnetic wave.

In 1888, 9 years after Maxwell's death, radio waves were discovered by Heinrich Hertz and were shown to have properties similar to those of light. This verified Maxwell's prediction. The importance of Maxwell's work is indicated in the following quotation from the Nobel Prize winner Richard Feynman:

> *From a long view of human history—seen from, say ten thousand years from now—there can be little doubt that the most significant event of the 19th century*

◆ *The Feynman Lectures on Physics*. Vol. 2 (Reading, MA: Addison-Wesley Publishing Co., 1964).

will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.

An important part of your study of astronomy is to learn about the objects in our universe, but perhaps more important is to see how astronomy functions by learning *how* we know what we know about these objects. The only thing we obtain from them is the radiation they emit. This radiation, including not only visible light but many other types of radiation, carries to us a tremendous amount of information. To understand how astronomers analyze radiation to answer questions about celestial objects, it is necessary to learn something about radiation itself.

In this chapter, we examine the nature of light and show how we measure three major properties of stars: their temperatures, their compositions (that is, the chemical elements of which they are made), and their speeds relative to the Earth. Recall that we have a tool, in the form of Kepler's third law, which allows us to find the total mass of a binary system. In addition, there are other tools, described elsewhere in this text which allow us to learn more about the stars (for example, how far away and how big they are).

4-1 The Kelvin Temperature Scale

Light transmits energy. We know this because we can clearly feel the warmth of sunshine. When we think of the Sun as an energy source (even though very different from other energy sources, such as a fireplace or a very hot iron bar), an obvious question to ask is how "hot" it is. What is its temperature? Even more important, what do we mean by the term "temperature," and how do we measure it? It should not be surprising that we started measuring temperatures long before we understood what temperature is. Check the accompanying Tools of Astronomy box where we describe the temperature scales currently in use.

Kelvin temperature scale A temperature scale with its zero point at the lowest possible temperature ("absolute zero") and a degree that is the same size (same temperature difference) as the Celsius degree. $T_K = T_C + 273$.

The commonly used temperature scale in science is the ***Kelvin scale***; its zero point corresponds to the lowest temperature possible (absolute zero), about −273°C. The intervals on the Kelvin scale are the same size as on the Celsius scale and, thus, in Kelvin temperature, the freezing point of water is 273 K and the boiling point is 373 K. (No degree symbol is included; the latter temperature is stated as "373 kelvin.") **FIGURE B4-1** includes the Kelvin temperature scale on the right.

We now recognize that temperature is a fundamental quantity, as are mass and time. As such, it cannot be expressed in terms of other quantities; however, it is a good approximation for us to say that given the temperature of an object, such as a pot of water on a stove, we can calculate the average speed of each of its constituent particles; that is, temperature is a measure of their average ***kinetic energy***. As the temperature of an object increases, each of its constituent particles moves faster, whereas as the temperature decreases, the particle speed also decreases (although not in a linear fashion). At absolute zero, we have a state of minimum atomic motion.

kinetic energy An object's energy due to motion. For an object of mass m and speed v, its kinetic energy is equal to $(1/2)mv^2$.

EXAMPLE

A star's surface temperature is 6000 K. What is its temperature in degrees Celsius and Fahrenheit?

SOLUTION

In degrees Celsius, the star's temperature is 6000 − 273 = 5727°C. In degrees Fahrenheit, it is

$$\frac{9}{5} \cdot 5727 + 32 = 10{,}341\text{°F}.$$

For a large enough Kelvin temperature, we can approximate its Celsius equivalent by the same number, while its Fahrenheit equivalent is approximately twice as large in value.

Tools of Astronomy

Temperature Scales

Around 1592, Galileo invented the first device indicating the "degree of hotness" of an object. The invention of the thermometer, in 1631, is credited to J. Rey, a French physician. The scale in common use in the United States is the Fahrenheit scale, but most of us are at least somewhat familiar with the Celsius temperature scale. The freezing point of water is defined as 0°C or 32°F, whereas the boiling point of water is defined as 100°C or 212°F. Because 180 divisions on the Fahrenheit scale correspond to 100 divisions on the Celsius scale, a Fahrenheit degree is smaller than a Celsius degree by a factor of 180/100 = 9/5. Thus, the two scales are related by

$$T_F = 32 + \frac{9}{5} T_C \quad \text{or} \quad T_C = \frac{5}{9} \cdot (T_F - 32).$$

The first two thermometers of **FIGURE B4-1** compare the Fahrenheit and Celsius scales, from extremely low temperatures up to the boiling point of water, but let's think for a minute about what these temperature scales can and cannot tell us. What does it mean to say that object *A* is two (or a thousand) times hotter than object *B*, which is at 0°F? What is then the temperature of object *A*? The obvious answer is 0°F, but we know there is something wrong with this. (We could ask a similar question using 0°C.) Neither scale—nor, for that matter, any other scale that defines its zero mark arbitrarily—has anything to do with what temperature "is." Clearly, we would like to have an "absolute" temperature scale, one on which the zero mark is associated with the lowest temperature possible (absolute zero). Such a scale exists (Figure B4-1). It is called the **Kelvin** scale and is the one commonly used in science; it was first proposed by William Thompson (1824–1907), a British physicist and engineer who was made a baron in 1892, taking the title Lord Kelvin. He contributed important ideas across the entire range of physics.

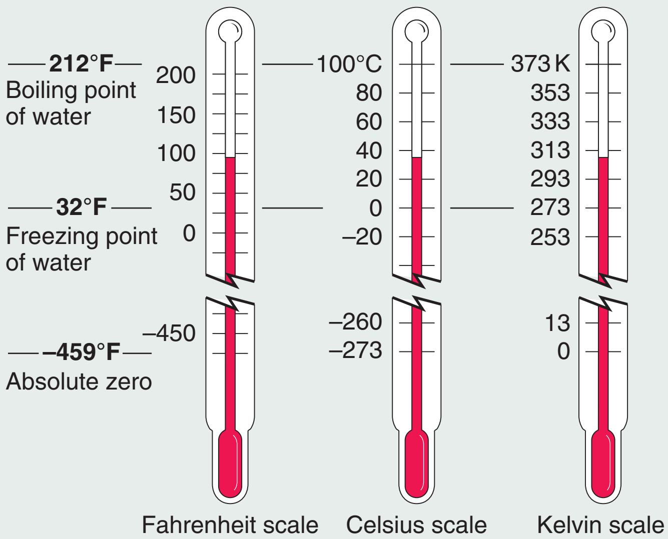


FIGURE B4-1 A comparison of temperature scales.

TRY ONE YOURSELF

Two objects *A* and *B* are identical except that *B* is at 0°C and *A* is twice "as hot" (meaning its temperature is twice as large). What is the temperature of object *A*? (*Hint:* You must work with the Kelvin scale for both objects.)

4-2 The Wave Nature of Light

Our understanding of the nature of light has changed several times over the years. Two lines of thought about light came to us from the ancient Greeks. The first suggested that light is a stream of extremely small, fast-moving particles and that our vision is the result

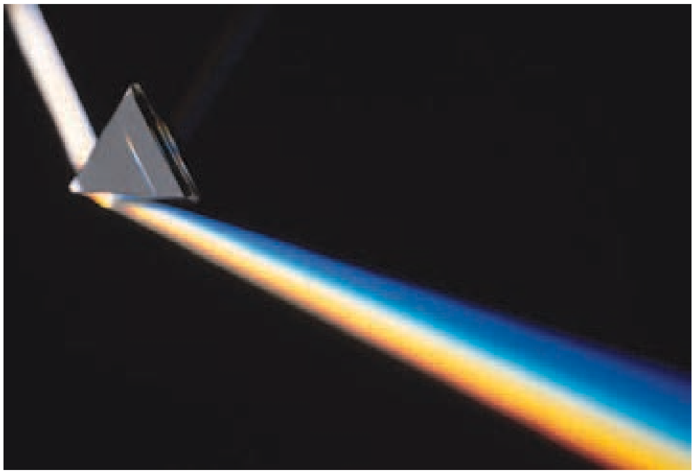


FIGURE 4-1 A prism separates white light into its component colors. This is shown by the beam emerging from the base of the prism and moving toward the bottom right in the image. In the case shown, however, there is an additional beam that emerges from the right of the prism and moves toward the upper right of the image. Why do we not see colors in this beam? ©Comstock Images/Jupiterimages

of the interaction between our eyes and this stream. The second idea, suggested by Aristotle, pictured light as an "aethereal motion." Aristotle added *aether* as the fifth element to his four elements of nature (fire, air, earth, and water) and imagined that it fills all space. According to this idea, our vision is the result of movement of the aether produced by the object we perceive.

The first step away from Aristotle's idea was taken by Newton, who theorized that light consists of tiny, fast-moving particles. **FIGURE 4-1** shows a beam of white light passing through a glass prism. The emerging light is separated into colors—into a ***spectrum***. Newton showed that the prism does not add color to the light, as was previously thought, but rather that color is already contained in white light and that the prism merely separates the light into its colors. He showed this by using a second prism to recombine the colors produced by the first. In a separate experiment, Newton allowed one color of the spectrum created by a prism to pass through a second prism. Because each color of the spectrum remained unchanged by the second prism, he was able to show that color is a fundamental property of light. We see elsewhere in text that analysis of the spectrum of light from stars is extremely important in astronomy.

spectrum The order of colors or wavelengths produced when light is dispersed.

Characteristics of Wave Motion

Light acts like a wave. **FIGURE 4-2** is a simplified drawing of a wave indicating that the distance between successive peaks (crests) of the wave is called the ***wavelength*** (λ). Waves you make by dipping your hand in a swimming pool might have a wavelength of about 2.25 inches.

wavelength The distance from a point on a wave, such as the crest, to the next corresponding point, such as the next crest.

A wave does not sit still, however. Imagine yourself fishing while sitting on a pier, watching waves pass underneath. As the waves move by, they cause the cork on the fishing line to move up and down. This indicates that the water itself moves up and down, rather than along the direction of the wave's motion. As the wave travels along the surface, the water's motion is *primarily* in the vertical direction and not along the direction of the wave. If you count the number of times the cork moves up and down, you might find that it moves through a complete cycle 30 times each minute. We say that the ***frequency*** of the cork's motion is 30 cycles per minute and therefore that the frequency of the wave is 30 cycles/minute. (Frequency is often reported in units of ***hertz***, abbreviated Hz, where 1 hertz = 1 cycle/second.)

frequency The number of repetitions per unit time.

hertz (abbreviated **Hz**) The unit of frequency equal to one cycle per second.

Now suppose you measure the wavelength of the waves and find it is 20 feet. Because each wave, from crest to crest, is 20 feet long and 30 of these waves pass by you each minute, the waves must move at a speed of 600 feet/minute. We multiply wavelength by frequency to obtain the speed of the wave. In equation form,

$$\text{wave speed} = \text{wavelength} \times \text{frequency},$$

or, using symbols,

$$\upsilon = \lambda \times f,$$

where υ = wave speed, λ = wavelength, and f = frequency.

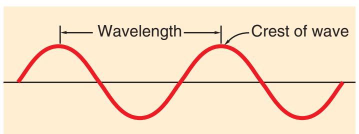


FIGURE 4-2 Wavelength is the distance between successive crests of a wave.

This equation applies to all types of waves, including light and sound waves. An application of its use for sound waves is shown in the next example. If you do the suggested exercise in this example, you will see that a sound of higher frequency has a shorter wavelength, as the speeds are the same. In the example, we use sound rather than light because sound waves have frequencies, velocities, and wavelengths within our everyday experience, whereas light waves do not. Now let's return to light and the spectrum produced when white light shines through a prism.

EXAMPLE

Sound travels at a speed of about 344 meters/second in air at room temperature. What is the wavelength of a sound that has a frequency of 262 Hz? (This is the frequency of the note C in music.)

SOLUTION

We start with the equation,

$$\text{wave speed} = \text{wavelength} \times \text{frequency, or}$$

$$344 \text{ m/s} = \lambda \times 262 \text{ cycles/s.}$$

We now solve the equation for the wavelength of the sound wave and do the calculation:

$$\lambda = \frac{344 \text{ m/s}}{262 \text{ cycles/s}} = 1.31 \text{ m.}$$

TRY ONE YOURSELF

What is the wavelength of a sound that has a frequency of 4000 Hz? (*Hint*: The speed of sound is the same for all frequencies, about 344 meters/second in air at room temperature.)

Light as a Wave

White light is made up of light of many different wavelengths, all traveling at the same speed in a vacuum (and interstellar space is essentially a vacuum). The speed of light (c) is about 300,000 kilometers/second (186,000 miles/second). If a light beam could be made to travel around the Earth's surface, it would circle the globe seven times in one second. Recall that according to Einstein's special theory of relativity, the speed of light in vacuum is always measured as the same speed and is the fastest speed possible in the universe. Check the accompanying Advancing the Model box to find out how we measure this incredibly high speed.

◆ It only takes light 8.3 minutes to reach us from the Sun, but for faraway objects, we see them the way they were millions or even billions of years ago.

We perceive light of different wavelengths as different colors. The wavelength of the reddest of red light is about 7×10^{-7} meters, or 0.0000007 meters. The wavelength decreases across the spectrum from red to violet, and the wavelength at the violet end of the spectrum is about 4×10^{-7} meters. In describing the wavelengths of visible light, a meter is much too long to be convenient, and thus, scientists use another unit—the ***nanometer***. One nanometer (abbreviated nm) is 10^{-9} meters. So the shortest violet wavelength and the longest red wavelength are about 400 nm and 700 nm, respectively.

Can anything travel faster than the speed of light in a vacuum?

nanometer (abbreviated **nm**) A unit of length equal to 10^{-9} meters.

Using the equation $c = \lambda \times f$ to calculate frequencies of light waves, we obtain extremely high frequencies: 400 nm corresponds to 7.5×10^{14} Hz, and 700 nm corresponds to 4.3×10^{14} Hz.

electromagnetic spectrum The entire array of electromagnetic waves.

The particular frequency or wavelength of light in vacuum determines its color; however, the color we see is not a property of the light itself but a manifestation of the system that senses it, that is our eyes, nerves, and brain. Because color is so subjective and people are unable to distinguish between two very similar colors, scientists describe light by referring to wavelength in vacuum (or frequency, as the two quantities are related) rather than color (**TABLE 4-1**). They might mention the color in some cases, but this is to help us better picture the situation: Light can be described more accurately than by simply calling it "red" or "green."

TABLE 4-1
Approximate Vacuum Wavelength* Ranges for the Various Colors

Color	λ (nm)
Violet	380–455
Blue	455–492
Green	492–577
Yellow	577–597
Orange	597–622
Red	622–720

*From now on, whenever we refer to the wavelength of light, we mean its wavelength in vacuum. As light travels from one medium to another, its speed and wavelength change but its frequency remains the same.

4-3 The Electromagnetic Spectrum

The waves we see—visible light—are just a small part of a great range of waves that make up the ***electromagnetic spectrum***. Waves somewhat longer than 700 nm (the approximate limit of red) are called *infrared* waves. **FIGURE 4-3** shows the entire electromagnetic spectrum. The infrared region of the spectrum goes from 700 nm at the border of visible light up to about 10^{-4} meters, which is a tenth of a millimeter or 100,000 nm. Electromagnetic waves longer than that are called *radio* waves. Going the other way, from visible light toward shorter wavelengths, we first encounter *ultraviolet* waves and then *X-rays* and *gamma rays*.

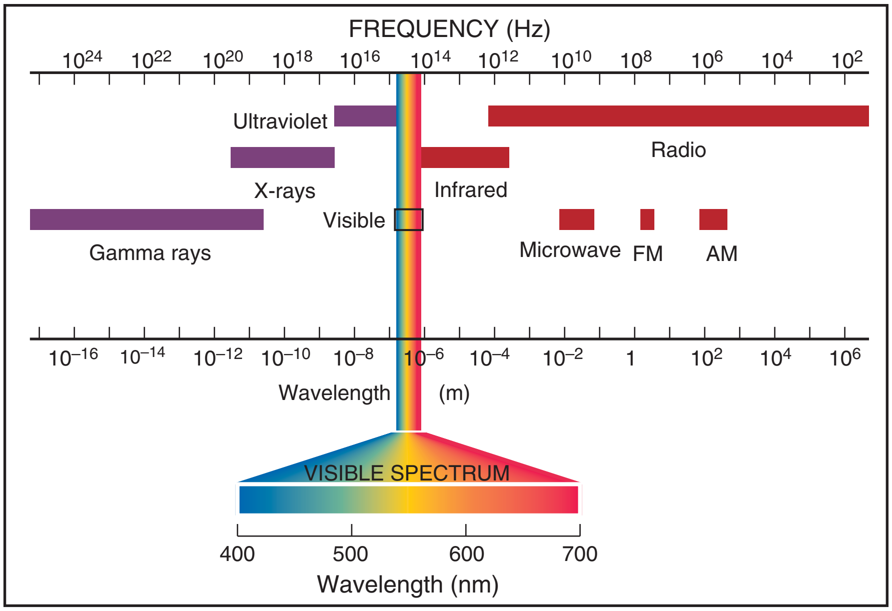


FIGURE 4-3 The electromagnetic spectrum is divided into several regions, depending upon the properties of the radiation. Region boundaries are not well defined. Notice the small portion of the spectrum occupied by visible light.

◆ It is probably not worth memorizing these wavelengths of light waves, but it is handy to remember that the wavelength of visible light ranges from 400 (violet) to 700 (red) nanometers.

◆ The waves are called "electromagnetic" because they consist of combined, perpendicular, oscillating electric and magnetic fields that result when a charged particle accelerates (see Figure B4-9b).

It is important to emphasize that all of these types of waves (or rays, as certain portions of the spectrum are known) are essentially the same phenomenon. They differ in wavelength, and this causes some of their other properties to differ. For example, visible light is just that—visible. Ultraviolet is invisible to us, but it kills living cells and causes our skin to tan or burn. On the other hand, we perceive infrared as "heat" radiation, and yes, the radio waves in the spectrum are the same radio waves we use to transmit messages on Earth. They are handy for carrying messages containing sound and pictures (in the case of television) for several reasons, including the fact that they pass through clouds and bend around obstacles. All of these various waves are electromagnetic waves, just as visible light is. We give the various regions different names because of their properties and the uses we have for them.

Is most of the electromagnetic spectrum made up of visible light?

The electromagnetic spectrum is important to astronomers because celestial objects emit waves in all the different regions of the spectrum. Visible light is a very small fraction of the entire spectrum. We humans tend to regard it as the important part, but this only reveals our limited outlook. Astronomers learn a great deal from the *invisible* radiation emitted by objects in the heavens.

One of our problems with this invisible radiation is that most of it does not pass well through air and, thus, it does not reach the surface of the Earth. Our air is transparent to visible light and to part of the radio spectrum, but most of the rest of the electromagnetic spectrum is blocked to some degree. The chart in **FIGURE 4-4** shows the relative absorbency

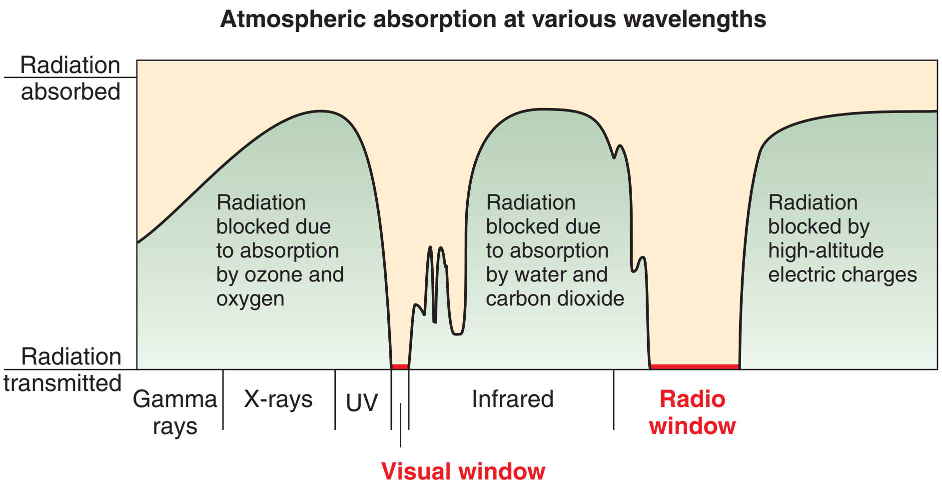


FIGURE 4-4 The height of the curve indicates the relative amount of radiation of a given wavelength blocked by the atmosphere from reaching Earth's surface. The atmosphere is transparent to two regions of the spectrum: visible light and part of the radio region.

Advancing the Model

Measuring the Speed of Light

Today we know that the speed of light c is 2.9979×10^8 m/s. How do we know that? You can't exactly time a light beam with a stop watch. Our understanding of light and its speed parallels the development of the technology that was used to measure this speed.

In the early 1600s, Galileo attempted to measure the speed of light by using his pulse-beat and comparing the time between opening his lantern while on a hilltop and seeing the light from his assistant's lantern from a distant hilltop. His attempts were not successful, but he correctly concluded that light is simply too fast to be measured by the slow human reaction.

Around 1675, the Danish astronomer Ole Roemer made the first accurate measurement of the value of c (**FIGURE B4-2**). Roemer had made many careful observations of Jupiter's moon Io and knew that Io's orbital period is about 1.76 days. As a result, he expected that he could predict Io's eclipses accurately. He was astonished to find that Io seemed to be behind its predicted position when the Earth was farther away from Jupiter (point A) and ahead when the Earth was closer (point B). Roemer correctly attributed this effect to the time required for light to travel from Jupiter to Earth. Light takes about 16.5 minutes to travel across the diameter of the Earth's orbit (2 AU); Roemer's actual measurement was 22 minutes.

Using today's value for the AU (as it was not accurately known during Roemer's time) we find:

$$c = \frac{\text{distance}}{\text{time}} = \frac{2 \times 1.5 \times 10^{11}\ \text{m}}{16.5 \times 60\ \text{s}} \approx 3 \times 10^8\ \text{m/s}.$$

(Roemer's actual calculation gave $c = 2.14 \times 10^8$ m/s.)

In 1849, French physicist Armand Fizeau measured the speed of light using the arrangement shown in **FIGURE B4-3**. His idea was to bounce a light beam between two mirrors, passing through a rotating toothed wheel in each direction. By choosing an appropriate rotation speed, the light beam can be made to pass through one gap on its way to the far mirror and the very next gap on its return to the observer. From the rotation rate, Fizeau calculated the time for the wheel to move from one gap between teeth to the next; this was the time during which light traveled from the wheel to the mirror and back. Dividing the distance by the time, Fizeau calculated $c = 3.15 \times 10^8$ m/s.

We can now routinely make accurate measurements of c in the laboratory. The speed of light in vacuum is now defined to be $c = 299{,}792.458$ km/s. Light has a smaller speed when going through other transparent media, but unless otherwise specified, we use $c = 300{,}000$ km/s.

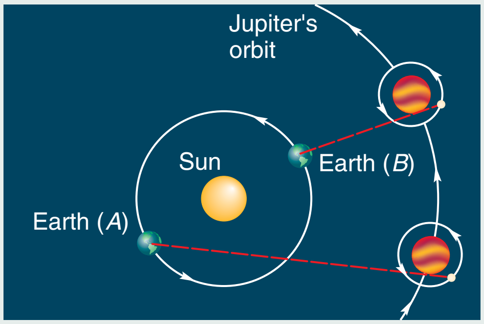


FIGURE B4-2 Roemer's method of measuring the speed of light. The scale of the orbits of Earth and Jupiter has been changed to exaggerate the effect.

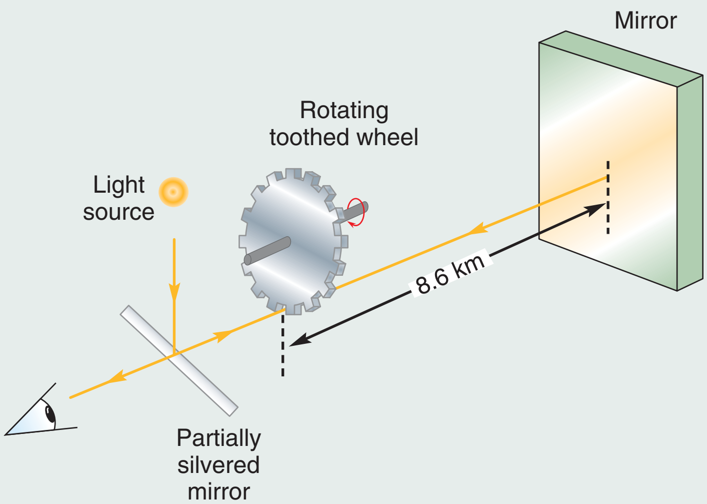


FIGURE B4-3 Fizeau's method of measuring the speed of light.

of the atmosphere to various regions of the spectrum. Where the graph line is highest, the least amount of radiation gets through. Not much ultraviolet radiation, which damages living cells, penetrates to the surface.

Astronomers, however, wish to detect and examine these nonpenetrating radiations from space. They accomplish this by using balloons to carry detectors high into the atmosphere or by using artificial satellites to take detectors completely above the atmosphere. This will be covered elsewhere in this text.

◆ Astronomers refer to *windows* in the atmosphere, saying that there is a visual window and a radio window. This means that our atmosphere allows radiation in these two regions of the spectrum to penetrate to the surface.

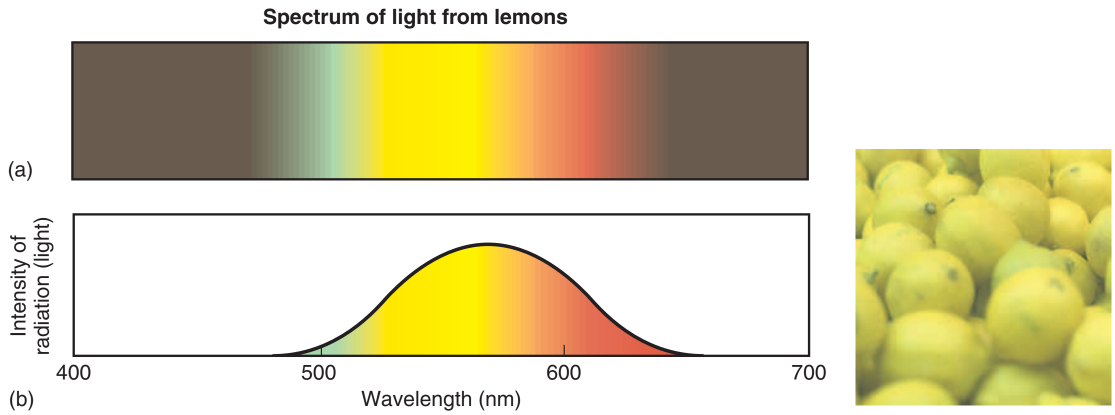


FIGURE 4-5 An example of reflected color. (a) If light reflected from the lemons were sent through a prism to reveal its spectrum, we would see that the lemons reflect mostly yellow light. (b) This graph indicates the relative intensity of the various wavelengths of light from the lemons. Courtesy of Karl Kuhn.

4-4 The Colors of Planets and Stars

How do we analyze the light spectrum from a celestial object to determine some of the object's properties? This analysis can be divided into two parts. First, we look at the overall spectrum, from which we typically determine the color of the object; however, when we look at the spectrum, we are really examining the actual wavelengths of light rather than just the color. The second analysis, discussed later in this chapter, involves examining individual regions of the spectrum.

Color from Reflection: The Colors of Planets

When you see a visible spectrum spread out on a screen, you see a particular color at a given location on the spectrum. This is because a wave whose wavelength is associated with that color is coming to your eye from that spot; however, the color we see in most objects does not correspond to a single wavelength. **FIGURE 4-5a** might be the spectrum of light from some lemons. It contains many different wavelengths of light; however, there is no violet or blue light, and the center of the spectrum is indeed in the yellow. **FIGURE 4-5b** shows a graph that indicates the intensity of light of each wavelength. Where the graph is higher, the light of the corresponding color is brighter. Lemons have this spectrum because when white light strikes them, they absorb some of the wavelengths of the white light, especially blue and violet. They reflect only those we see in their spectrum (the wavelengths centered on the color yellow). This is what determines their color.

Planets have their colors because of a process like that described for the lemons. The rusty red color of Mars, for example, occurs because the material on its surface absorbs some of the wavelengths of sunlight and reflects a combination of wavelengths that looks rusty red to us.

FIGURE 4-6 shows the color spectrum and graph of intensity versus wavelength for the light from the red taillight of a car. The spectrum includes not only many wavelengths in the

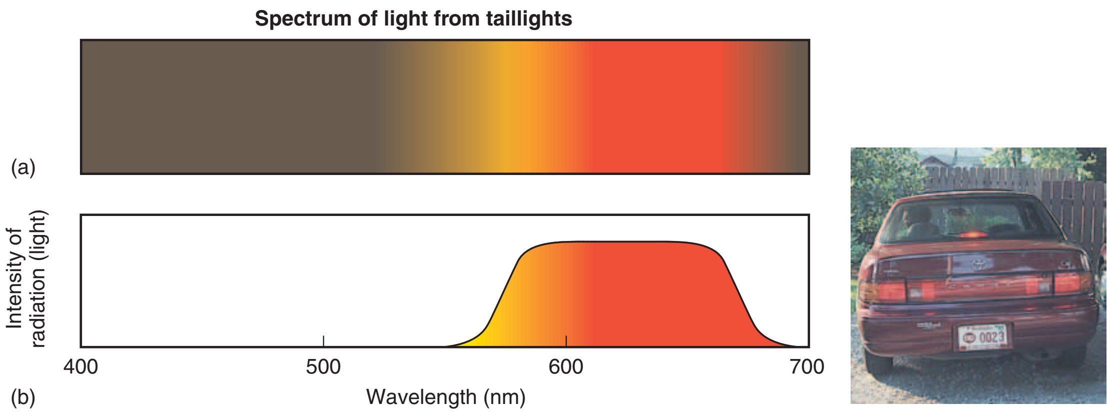


FIGURE 4-6 An example of transmitted light. (a) The spectrum of light from the taillight of this particular car (right). The lightbulb emits white light, but the plastic cover over the bulb absorbs much of the light, letting pass some wavelengths in the red, orange, and yellow regions of the spectrum. (b) This graph indicates the relative intensity of the various wavelengths of light in this case. Courtesy of Karl Kuhn.

red part of the spectrum but also some orange. In this case, the bulb inside the taillight emits white light, but part of that light is absorbed by the plastic cover. The light that gets through the cover has the spectrum in the figure.

In the case of the Sun and other stars, light from the star is produced by emission within the star and some light is absorbed as it passes through the star's outer layer. The effect of this absorption on the color of the star is minimal, but nevertheless, the process is somewhat similar to that described for the taillight of the car. We will look at this in more detail later.

Color as a Measure of Temperature

The light emitted by the Sun and other stars can be compared with light coming from a lightbulb or from the element of an electric stove in an otherwise dark room. Consider what happens when you turn the burner of an electric stove to a low setting. It glows a dull red. The bottom curve in **FIGURE 4-7** is a graph of intensity versus wavelength for this case. This graph includes not only the visible portion of the spectrum, but quite a lot of the infrared. Recall that we experience infrared radiation as heat. In fact, the graph indicates that more infrared radiation is being emitted than visible radiation, and the graph reaches its peak in the infrared portion of the spectrum. Some red light is emitted, but very little light from the center and violet end of the visible spectrum.

◆ We want you to imagine a dark room because in a well-lit room, the lamp and stove element reflect light and you can see them even if they are turned off.

Now turn up the heat on the stove. The burner begins to take on an orange glow. The second curve from the bottom in Figure 4-7 is a graph of intensity versus wavelength for this burner. Compare it with the bottom curve (the red-hot burner). First, the orange burner is emitting more radiation of all wavelengths. This should correspond to your experience, for you can feel that more infrared is being emitted and see that more light is coming from the burner. Second, the peak of the graph has moved over toward the visible portion of the spectrum, toward the shorter wavelengths.

◆ Astronomers usually call the graph of intensity versus wavelength for a star its *thermal spectrum.*

This is about as far as you can go with an electric stove burner. If you have an object with a temperature you can control, you can increase its temperature so that the object emits most of its light in the yellow part of the spectrum. The third curve from the bottom is a graph of such an object. It actually corresponds to the Sun. The fourth curve from the bottom of Figure 4-7 corresponds to an object of even higher temperature. You see that it emits most of its light in the violet part of the spectrum.

The temperatures indicated in Figure 4-7 are typical of surface temperatures of stars. As their sequence indicates, the higher the temperature of a star, the shorter the wavelength at which the star emits most of its energy. The relationship between an object's temperature (T)

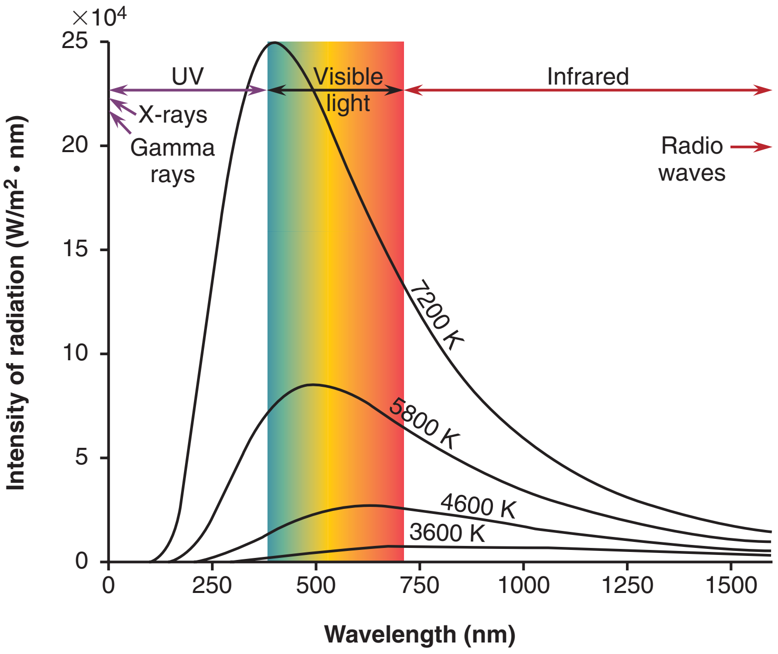


FIGURE 4-7 The bottom curve represents an object (at 3600 K with λ_{max} = 805 nm) that emits mostly infrared radiation. The next curve corresponds to an object (at 4600 K with λ_{max} = 630 nm) that emits most of its light in the orange part of the spectrum. The third curve from the bottom corresponds to the Sun (at 5800 K with λ_{max} = 500 nm). The 7200 K object would most likely seem "blue" because it emits most of its light in the violet part of the spectrum (λ_{max} = 403 nm). Recall that color is subjective.

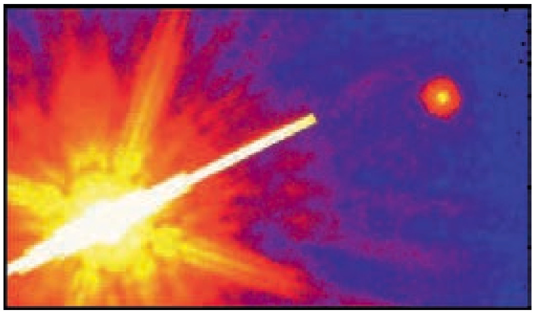


FIGURE 4-8 The *HST* imaged one of the lowest-temperature stars ever seen (upper right). It is a companion to the dwarf star at lower left (GL 105A in the constellation Cetus, 27 ly away). The surface temperature of the cool star may be as low as 2300 degrees Celsius. (The white bar is an effect produced by the camera.) Courtesy of D. Golimowski, Johns Hopkins University/STScI/NASA.

and the wavelength at which maximum emission occurs (λ_{max}) was discovered in 1893 by the German physicist Wilhelm Wien. **Wien's law** is expressed as

$$\lambda_{\max(\text{in nm})} = \frac{2.9 \times 10^6}{T_{(\text{in K})}},$$

where λ_{max} is in nanometers and the temperature is in kelvin. You can check that this equation applies to the curves of Figure 4-7.

FIGURE 4-8 is an image of one of the coolest stars ever found. We often refer to stars by color as a quick way to indicate their temperature: A "white" star is hotter than a "red" star. In practice, of course, a "red" star does not appear red like a Christmas tree bulb, but it definitely has a red tint. To the unpracticed naked eye, color differences between stars are not at all obvious; however, if you have the opportunity to use a telescope to observe pairs of closely spaced stars, you can see this color difference easily.

◆ Beta Cygni (named Alberio) is the second brightest star in the constellation Cygnus. It is the brighter of a closely spaced pair of stars with obvious color differences.

The important point is that by examining the intensity versus wavelength curve for a star and using Wien's law, we can determine the star's surface temperature without ever visiting it!

Blackbody Radiation. Wien's law was derived from theoretical calculations about the radiation that would be emitted from an object that absorbs (or emits) all wavelengths completely. Such an ideal object is called a ***blackbody***, and the radiation it emits is called ***blackbody radiation***. A blackbody emits a ***continuous spectrum***, which has a peak at a certain wavelength λ_{max}, but some energy is emitted at all wavelengths, as shown by the blackbody curves in Figure 4-7. It was found that although the stars are not perfect blackbodies, the theory applies very closely to them, as shown by **FIGURE 4-9**. This figure shows the intensity of the measured solar radiation outside the Earth's atmosphere from 300 to 830 nm; the Sun's spectrum peaks in the visible part of the electromagnetic spectrum, where our eyes have become most sensitive. Superimposed to the data is a curve obtained by assuming that the Sun is a blackbody at 5800 K and that its intensity is measured outside Earth's atmosphere. Compare this curve with the 5800 K curve in Figure 4-7; as we discuss in Section 4-8, radiation from a source decreases in intensity as the inverse square of the distance from the source.

blackbody A theoretical object that absorbs and emits all wavelengths of radiation, so that it is a perfect absorber and emitter of radiation. The radiation it emits is called **blackbody radiation**.

continuous spectrum A spectrum containing an entire range of wavelengths, rather than separate, discrete wavelengths.

The Stefan-Boltzmann Law. Figure 4-7 indicates that the hotter an object is, the more radiation it emits. In 1879 an Austrian physicist, Josef Stefan, discovered the mathematical relationship between temperature and energy emitted, based on data published 14 years earlier. In 1884, another Austrian physicist, Ludwig Boltzmann, used a theoretical argument to show why the relationship occurs. This rule, now called the *Stefan-Boltzmann law*, is

$$F = \sigma T^4,$$

where T is the object's temperature on the Kelvin scale, F, called the energy flux, is the energy it emits per unit time per unit area, and σ (the Greek letter sigma) is a constant, called the *Stefan-Boltzmann constant*, that relates the two quantities. This law tells us that the energy flux of an object is directly proportional to its temperature to the fourth power. If the temperature of an object were to double, its energy flux thus would be 2^4, or 16, times greater than it was before.

In our study of stellar properties, we will discuss how the Stefan-Boltzmann law allows us to find the radius of a star. (From observations, we can find a star's temperature and the total energy it emits each second. Recall the meaning of energy flux and the fact that the surface area of a sphere is proportional to the square of its radius.)

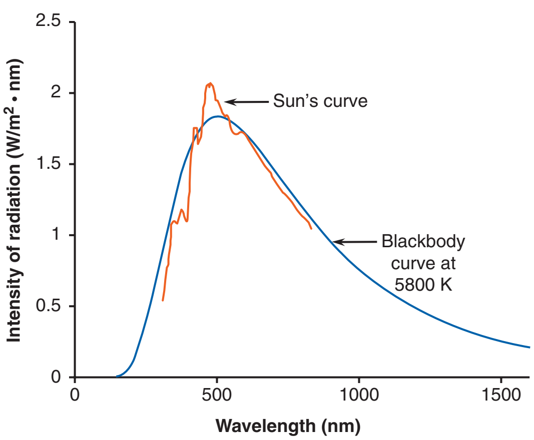


FIGURE 4-9 The Sun is almost an ideal blackbody at 5800 K. The measurements of the Sun's intensity were made above the Earth's atmosphere.

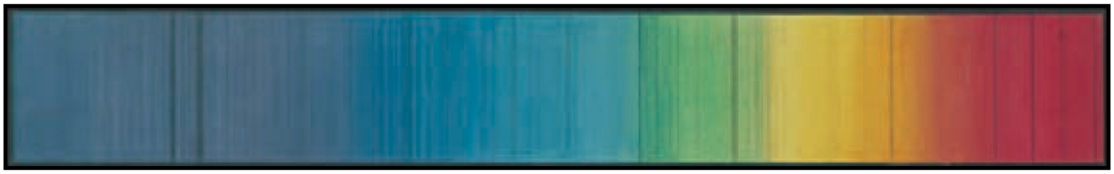


FIGURE 4-10 The Sun's spectrum may appear at first to be a continuous spectrum, but when it is magnified, we see dark lines across it where specific wavelengths do not reach us. Thus, the solar spectrum is an absorption spectrum. © Deutsches Museum, Munich.

4-5 Types of Spectra

The spectrum of visible light shown in Figure 4-1 is a *continuous spectrum*. Such a spectrum is produced when a solid object (in this case the filament of a lamp) is heated to a temperature great enough that the object emits visible light. Not all spectra are of this type, as was discovered nearly 200 years ago.

Kirchhoff's Laws

In 1814, Joseph von Fraunhofer, a German optician, used a prism to produce a solar spectrum. He noticed that the spectrum was not continuous but had a number of dark lines across it (**FIGURE 4-10**). Fraunhofer had no explanation for these dark lines, but it was later discovered that they were the result of the sunlight passing through cooler gases (in the Sun's and the Earth's atmospheres). Then, in the mid-1800s, several German chemists discovered that if gases are heated until they emit light, neither a continuous spectrum nor a spectrum with dark lines is produced; instead, a spectrum made up of *bright* lines appears. Further, they discovered that each chemical element has its own distinctive pattern of lines (**FIGURE 4-11**). This proved to be a very valuable way of identifying the makeup of an unknown substance and was soon developed into a standard technique that allows us to identify the chemical composition of matter.

In the 1860s, Gustav Kirchhoff formulated a set of rules, now called *Kirchhoff's laws*, which summarize how the three types of spectra are produced:

◆ Gustav Kirchhoff (1824–1887) was a German physicist and astronomer whose primary work was in the field of spectroscopy, the study of spectra.

1. A hot, dense glowing object (a solid or a dense gas) emits a continuous spectrum (Figure 4-1).
2. A hot, low-density gas emits light of only certain wavelengths—a bright line spectrum (Figure 4-11).
3. When light having a continuous spectrum passes through a cool gas, dark lines appear in the continuous spectrum—a dark-line spectrum (Figure 4-10).

The dark lines that result when light passes through a cool gas (process 3) have the same wavelengths as the bright lines that are emitted if this same gas is heated (process 2).

Kirchhoff's laws tell us how to produce the various types of spectra, but the science behind the laws—the connection between the laws and the nature of matter—remained a mystery in the 19th century. The connection was finally made in 1913, when a young Danish physicist, Niels Bohr, proposed a new model of the atom.

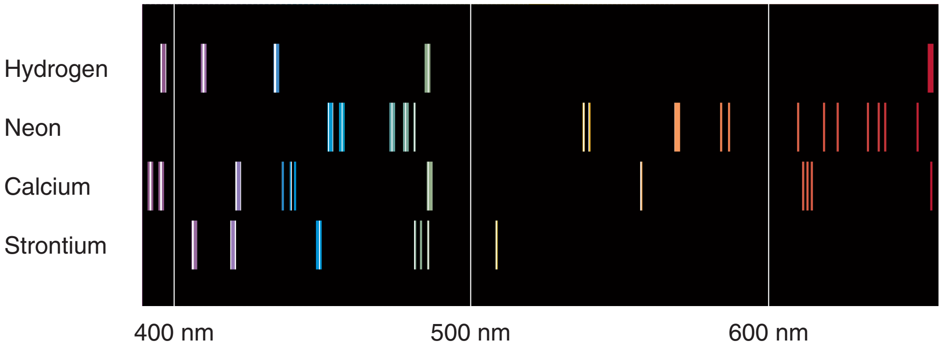


FIGURE 4-11 The visible bright line spectrum of four different chemical elements. Each element emits specific wavelengths of light when it is heated. This applies not only to visible light (shown here) but also to infrared and ultraviolet. Such a spectrum is called an emission spectrum.

Historical Note

Niels Bohr

Niels Bohr (1885–1962) was born into a very cultured Danish home. His father's interest in science led Niels to that subject, and he became known as a student who gave his utmost to every project—a reputation that continued throughout his life.

In 1922 Niels Bohr was awarded the Nobel Prize in physics "for his services in the investigation of the structure of atoms and of the radiation emanating from them." In his acceptance speech, he emphasized the limitations of his theory, and indeed, he seems to have been more aware of its limitations than other scientists who worked with the theory.

Niels' son Aage followed his father in the study of physics and won the Nobel Prize in 1975. One major project on which Niels and Aage Bohr worked together was the development of the atomic bomb. Niels' mother was Jewish, and after Hitler's army overran Denmark, Niels' family (**FIGURE B4-4**) fled their native land to avoid arrest. Niels and Aage came to the United States and helped with the Manhattan Project (the code name for the bomb development effort).

FIGURE B4-4 Niels Bohr and his sons. © AIP Emilio Segré Visual Archive, Margrethe Bohr Collection.

Bohr's contribution to science goes far deeper than the development of the Bohr model of the atom, as important as that is. His philosophical ideas on the nature of physical theory are perhaps his greatest contribution. Many important ideas of modern physics were clarified through the friendly arguments between Bohr and Einstein. Einstein would try to imagine situations in which the new ideas of quantum mechanics (the modern description of matter and energy) did not work, and Bohr would always figure out how quantum mechanics did explain these situations. It is a classic example of how science can progress through the informal discussions between scientists.

4-6 The Bohr Model of the Atom

nucleus (of atom) The central, massive part of an atom.

electron A negatively charged particle that orbits the nucleus of an atom.

The atomic model accepted at that time was due primarily to the New Zealand physicist Ernest Rutherford. His model described the atom as having a ***nucleus*** with a positive electrical charge, circled by ***electrons*** with a negative electrical charge. Positive and negative electrical charges attract one another, and this electrical force holds the electrons in orbit around the nucleus. As an electron orbits the nucleus, it continuously changes direction and thus accelerates; however, according to classical theory, any charged particle moving in a curved path or accelerating in a straight-line path will emit electromagnetic radiation, thus losing energy. Therefore, what keeps the electrons from simply spiraling into the nucleus, leading to collapse of the atom? Bohr's model attempted to answer this question.

Before describing his model, we must emphasize that today we have a much more powerful model of matter and energy (called **Quantum Mechanics**); however, just like we still use Newtonian ideas to describe gravity even though we have the theory of relativity, we still use Bohr's model because many of its conclusions are essentially valid and it provides the basic conceptual tools in understanding atomic structure. Wherever appropriate, we mention important differences between the two models.

Bohr atom The model of the atom proposed by Niels Bohr; it describes electrons in orbit around a central nucleus and explains the absorption and emission of light.

The ***Bohr atom***, as Niels Bohr's model is called, is based on three postulates:

1. Electrons in orbit around a nucleus can have only certain specific energies. To imagine different energies for the electrons, imagine electrons orbiting at different distances from the nucleus. The negatively charged electrons are being attracted to the positively charged nucleus; thus, to pull an electron farther away from the nucleus requires energy. Because only certain energies are possible, we speak of "allowed" orbits for the electrons. The element hydrogen has only one electron, but many possible energy levels and

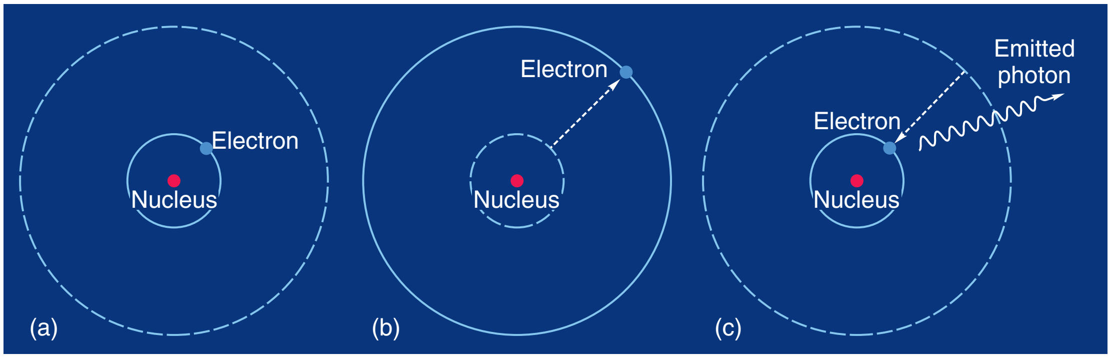


FIGURE 4-12 (a) The electron is in the lowest possible energy state—the ground state. (b) When the atom gains energy (perhaps by collision with another atom), the electron jumps up to a higher orbit. (c) The electron then quickly falls down to its original orbit and, as it does, emits energy in the form of a photon of electromagnetic radiation. The orbits are not drawn to scale.

therefore many allowed orbits. The drawing in **FIGURE 4-12a** depicts the hydrogen atom with its electron in the lowest orbit (the ground state) and also shows, as an example, the next orbit this electron might have. The point of Bohr's first postulate is that the electron can have only specific energies and therefore specific orbits. This is far different from the solar system, where there are no limitations on possible positions of orbits.

Bohr simply assumed that an atomic electron in one of the allowed circular and stable orbits did not radiate any energy. (In the modern view of Quantum Mechanics, the wave-particle duality of light is extended to all entities, including matter. That is, there is a wave aspect associated with an electron, and therefore, there is a wavelength associated to a moving electron. This provides an interesting interpretation of Bohr's model of an atom; an allowed circular orbit has a circumference that is an integer multiple of the electron's wavelength. Also, according to Quantum Mechanics, we can calculate the probability that an electron of a given energy will be at some distance from the nucleus; Bohr's orbit for the same electron simply corresponds to the most probable distance.)

◆ The wave particle duality of light is discussed in a nearby Advancing the Model box.

2. An electron can transit from one energy level to another, changing the energy of the atom. In terms of electron orbits, when energy is added to an atom, the electron moves farther from the nucleus. On the other hand, the atom loses energy when an electron moves from an outer orbit to an inner orbit. This lost energy leaves the atom in the form of electromagnetic radiation.

Our previous discussion of waves and light assumed that light acts as a simple long wave, similar to the waves you can make in a swimming pool. However, as we discuss in a nearby Advancing the Model box, light has a wave-particle duality. In the Bohr model, light is emitted not as continuous waves, but in tiny bursts of energy; each burst is emitted when an electron moves to an orbit closer to the nucleus. These tiny bursts of electromagnetic energy are called ***photons***. The energy of the photon depends on the spacing between electron orbits.

photon The smallest possible amount of electromagnetic energy of a particular wavelength.

3. The energy of a photon determines the frequency of light that is associated with the photon. The greater the energy of the photon, the greater the frequency of light, and vice versa. A photon of violet light thus has more energy than a photon of red light. The relevant equation is

$$E = hf,$$

where E = the energy of the photon, h = a constant (called *Planck's constant*), and f = the frequency of the light.

Every physicist thinks he knows what a photon is. I spent my life to find out what a photon is and I still don't know it.
—Albert Einstein

Emission Spectra

The Bohr model of the atom can be used to explain why only certain wavelengths are seen in the spectrum of light emitted by a hot gas. In its normal, lowest energy state, the electron of a hydrogen atom is in its lowest possible orbit, as indicated in Figure 4-12a. If this atom is given enough energy (perhaps by collisions with other atoms), the electron will jump to the

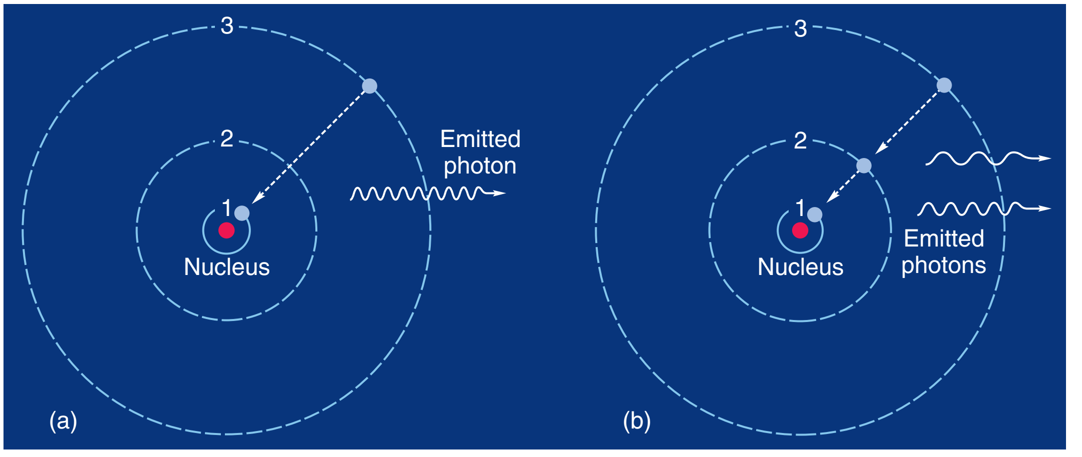


FIGURE 4-13 (a) The electron may fall directly from orbit 3 to orbit 1, emitting a single photon. (b) The electron may fall from orbit 3 to orbit 1 in two steps, emitting two photons whose total energy is equal to the photon emitted in part (a). The orbits are not drawn to scale.

◆ The lowest energy state of an atom is usually called the *ground state*, and the energized states are called *excited states*.

next allowed orbit. **FIGURE 4-12b** illustrates this jump. An atom will not stay in its energized state long. Quickly, the electron falls down to a lower orbit, emitting a photon as it does, as shown in **FIGURE 4-12c**. The energy of this photon is exactly equal to the energy difference between the two orbits. Finally, because the energy of the photon determines the frequency of the radiation, the radiation coming from this atom must be of the corresponding frequency (and color).

We have described one atom emitting one photon. In an actual lamp that contains hot hydrogen gas, there are countless atoms gaining energy and countless atoms emitting photons as they lose energy. Different atoms will have different amounts of energy, depending on the energy they have absorbed (from a collision with another atom, for example). If a particular atom's energy corresponds to the electron being in the third orbit, the atom might release its energy in a single step, as shown in **FIGURE 4-13a**, or in two steps as shown in **FIGURE 4-13b**. That is, there are two different ways for an electron to move from the third to the first orbit.

Let us now assume that enough energy is available to cause electrons to move to even higher orbits. Using similar drawings, you should be able to show that there are four different ways for an electron to move from the fourth to the first orbit, eight different ways to move from the fifth to the first orbit, and so forth. Each jump of an electron for each of the steps involved in each different path corresponds to a certain specific energy and therefore to a certain specific frequency of emitted radiation. The electrons of some atoms will fall by some paths, and the electrons of other atoms will fall by other paths. As a result, radiation of several different frequencies will be emitted from the entire group of atoms. Not all frequencies will be emitted, however—just those that correspond to the electron jumps.

emission spectrum A spectrum made up of discrete frequencies (or wavelengths) rather than a continuous band.

Hence, the spectrum from a heated, low-density gas is not a continuous spectrum. It contains only certain definite frequencies. We call such a spectrum an ***emission spectrum***—the bright line spectrum mentioned earlier.

Refer back to Figure 4-11, which shows the emission spectra of four elements. Each spectrum is different because the allowed energy levels of the atoms are different for each chemical element. No two chemical elements have the same set of energy levels, and thus, no two chemical elements have the same emission spectrum. This provides us with a valuable method of identifying elements, as each has a unique spectral "fingerprint." This process has some important applications here on Earth, but because in this book we are more interested in the stars, we look at a stellar application.

Continuous and Absorption Spectra of the Stars

Kirchhoff's laws tell us that dark line spectra result from light with a continuous spectrum passing through a cool gas. Let us examine this in the case of the Sun.

Tools of Astronomy

The Balmer Series

In Figure 4-11, notice the pattern to the spacing of bright lines in the hydrogen spectrum—they become progressively closer as they approach the blue end of the spectrum. The mathematical relationship that expresses this pattern was found in 1885 by Johann Jacob Balmer, a Swiss teacher. The lines visible in the figure are therefore called the **Balmer series** of spectral lines. This series served as the foundation for Bohr's work, and it is easily explained by Bohr's model of the atom. In **FIGURE B4-5**, the spacing of the lines depicting the orbits of the hydrogen atom represents the relative energy of each of the levels. According to Bohr's model, there is less difference between the energy levels as orbits get farther from the nucleus. The levels thus are spaced closer together toward the top of the figure.

Suppose that an electron is in the lowest energy level, the ground state. This electron will jump to a higher state when a photon of the appropriate energy strikes it. Look at the left side of **FIGURE B4-6**. Five arrows point upward from the ground state, representing electron jumps to higher orbits. On each arrow is printed the wavelength of the photon corresponding to the jump indicated. Each of these wavelengths is less than 400 nm, the shortest wavelength of visible light. They are in the ultraviolet region of the spectrum.

As a gas becomes hotter, more of its atoms have electrons in energy levels above the ground state. Suppose that hydrogen is at a temperature at which a significant number of its electrons are in energy level 2. The middle of Figure B4-6 shows the wavelengths of photons that would cause electrons at this level to jump to a higher level. The wavelengths of the photons that cause jumps from the second level are within the visible range—from 400 to 700 nm—and because energy levels are more closely spaced toward the top of the figure, the wavelengths toward the blue end of the spectrum are closer together. These wavelengths correspond to the wavelengths of the Balmer series.

The first set of wavelengths described previously, those in the ultraviolet region of the spectrum, form the ***Lyman series***. As Figure B4-6 indicates, there is another series that falls in the infrared portion of the spectrum, called the ***Paschen series***.

Thus far, we have discussed the absorption of photons to produce an absorption spectrum. As we noted in the text, the emission spectrum of hydrogen is produced when electrons fall from higher energies to lower. The spectrum shown in Figure 4-11 thus is an emission spectrum that resulted from electrons falling from higher energies to lower levels of the atom.

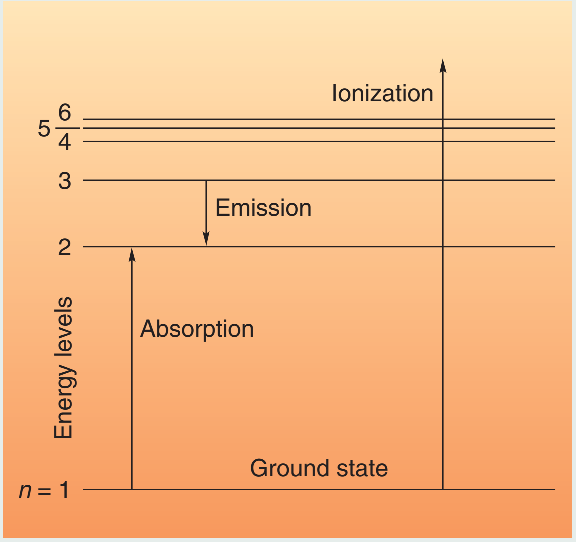


FIGURE B4-5 The energy levels of the hydrogen atom (not drawn to scale). The levels are progressively closer in energy as they are farther from the nucleus. The length of each arrow corresponds to the energy involved in the process. An atom is *ionized* when an electron absorbs enough energy and escapes.

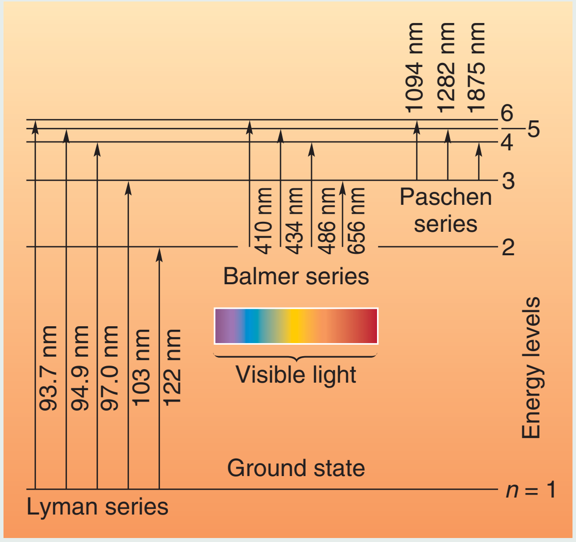


FIGURE B4-6 Electrons that move from the ground state to higher energy levels do so by absorbing photons of the wavelengths shown. Electron jumps for the first three series of the hydrogen atom's spectrum are represented here.

Advancing the Model

Evidence for the Wave-Particle Duality of Light

In the 1660s, English scientist Robert Hooke challenged Newton's particle model of light for the first time. He proposed a simple wave theory in which light was the manifestation of fast oscillations in the aether. He reasoned that this model better explained the color patterns observed in thin transparent films, such as soap bubbles. On the other hand, Newton favored the particle model for light and suggested that light has a dual nature and that it is a stream of particles that can induce oscillations in the aether. Newton, however, misunderstood how waves behave. He expected that if light were a wave, it should clearly spread out after passing through an opening, instead of producing the observed narrow beams. In his opinion, the particle model for light better explained how light propagates along straight lines and why shadows are sharp. The problem is that light does spread out as Newton expected, but this can be seen only if the opening is of the same approximate size as the wavelength of the light, which is extremely small (at least for visible light, which was what he used at the time).

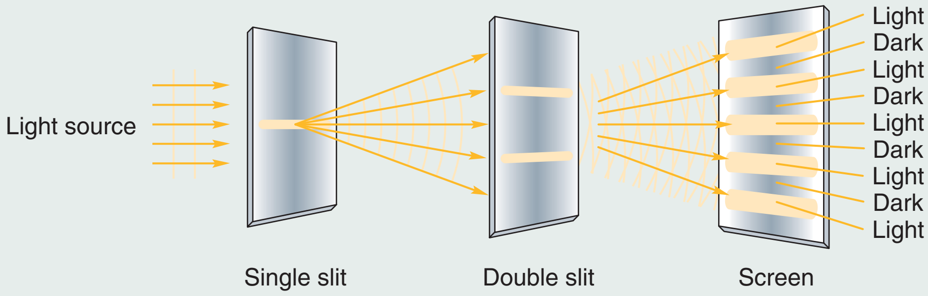


FIGURE B4-7 Young's double-slit experiment. The colors used for the light areas on the screen are for illustration purposes only and correspond to decreasing intensity of the light.

Both the particle and wave models for light explained two of the most common phenomena we observe. Light reflects—it bounces like a tennis ball off a flat surface. Also, light refracts—it changes direction when going from one medium (such as air) to another (such as water). The particle model of light, however, gained acceptance for more than a century, mainly because of Newton's reputation and authority.

Around 1801, Thomas Young first proposed a simple but convincing experimental test to distinguish between the two competing models. Young's experiment was to shine light of a specific wavelength (from a single source) through two narrow parallel slits, close to each other. The light then fell on a screen a certain distance away (**FIGURE B4-7**). Young observed a pattern of light and dark bands on the screen, called interference fringes, which he explained by assuming that light is a wave. As light waves go through the slits, they *diffract* (they spread out) in a series of crests and troughs. When the waves meet, they add up algebraically as shown in **FIGURE B4-8**. Bright (dark) fringes appear on the screen in places where the waves interfere constructively (destructively). Young used this ***double-slit experiment*** (actually he used pinholes instead of slits) to measure the wavelength for violet (400 nm) and red light (700 nm).

The experiments of the French physicist Augustin Fresnel (1788–1827) helped put the wave model of light on a firm mathematical basis. The interference of light clearly showed its wave nature, but what was the nature of the waves? In the early 1860s, the Scottish mathematical physicist James Clerk Maxwell (1831–1879) succeeded in unifying what was then known about electricity and magnetism into four equations, which today are named after him. He found that his equations described the existence of transverse waves (such as the up-and-down waves traveling on a stretched rope) that combine electromagnetic effects and move at a speed that is almost the same as the then known speed of light. To understand this, consider a small sphere carrying a uniform charge Q. If we place a tiny positive test-charge q_0 anywhere in the space around Q, it will experience a force of a specific direction and strength. We say that there is a ***field*** of force around charge Q. To represent visually this electric field, we draw continuous lines that are tangent to all of the "specific directions of force," as shown in **FIGURE B4-9a**. Now consider what will happen if we make charge Q oscillate; if you visualize the field lines as made of rubber bands, you can see that the oscillation will set up waves propagating outward. Indeed, the changes in the strength of the field that occur due

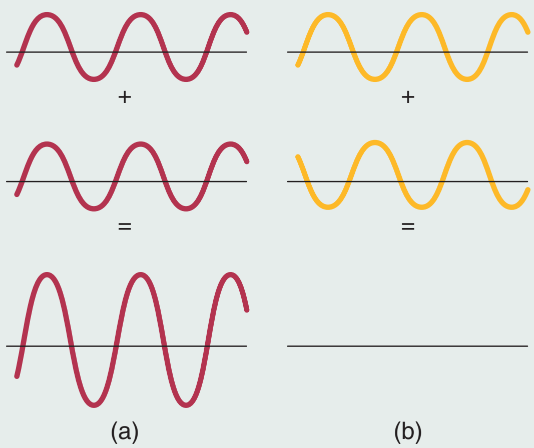


FIGURE B4-8 (a) Waves interfering constructively. (b) Waves interfering destructively.

Advancing the Model

Evidence for the Wave-Particle Duality of Light *(Cont'd)*

to the motion of charge Q propagate outward like waves with a speed equal to *c*. Maxwell found that magnetic fields can be formed not only by moving charges but also by changing electric fields, and that electric fields form not only by charges but also by changing magnetic fields (**FIGURE B4-9b**). Maxwell wrote that "we can scarcely avoid the inference that light consists in the transverse modulations of the same medium which is the cause of electric and magnetic phenomena." Nine years after Maxwell died, the German physicist Heinrich Hertz (1857–1894) produced radio waves in his lab, which confirmed all the properties of light known at the time. At the close of the 19th century, the wave model for light seemed to be very successful; however, some unanswered questions still remained. The most important ones dealt with the continuous spectrum of blackbody radiation and with the emission and absorption spectra.

In 1900, while trying to explain the continuous spectrum of blackbody radiation, the German physicist Max Planck (1858–1947) discovered an equation that fit the blackbody curve. In an effort to understand its meaning, Planck was forced to accept that electromagnetic waves can only have discrete (***quantized***) energy values that are integer multiples of a minimum energy value, called a ***quantum*** of energy. This quantum of energy is given by *hf*, where *f* is the frequency of the wave and *h* is Planck's constant. Today we consider *h* to be a fundamental constant of nature, like the gravitational constant G and the speed of light *c*. It is also the basis of ***Quantum Mechanics***, which is the modern description of matter and energy; however, the quantum idea did not fit at all with the prevailing wave model of light.

The quantum nature of light was taken seriously by Einstein, who in 1905 used it to explain a very puzzling phenomenon, known as the ***photoelectric effect***. When light of a certain frequency shines on a metal surface, electrons are ejected from it with a range of energies. (This is the basis of today's photocells in door openers, bar code scanners, and hundreds of other applications.) However, the maximum kinetic energy of these electrons does not depend on how bright the source of light is! According to the wave model of light, if we increase the rate of light energy falling on the surface, individual electrons will absorb more energy and will be emitted with larger kinetic energies. This is not what is observed. Increasing the brightness of the light source results in more electrons being emitted, but it doesn't affect their maximum kinetic energy. In addition, there is a minimum frequency that the light must have in order for any electrons to be emitted. This is also in contrast to the wave model for light, according to which if we wait long enough, the electrons will be able to absorb enough energy to be emitted, independent of the frequency of the light source.

Einstein's explanation was based on the assumption that light energy striking the metal surface is quantized in small bundles. These bundles behave as if they are a stream of massless particles that today we call ***photons***. The energy of each photon is equal to *hf*. Convincing evidence that light indeed shows its particle nature when it interacts with matter was provided by the American physicist Arthur Compton in 1922. He measured the change in the wavelength of X-ray photons as they were scattered by free electrons (an observation now called the ***Compton effect***) and found it to be exactly as predicted by the theory of a collision between two particles.

What, then, is the nature of light? It seems that light has a ***wave-particle duality***. When it propagates through space, light can be described by a wave model (as shown by the double-slit experiment). When it interacts with matter, light can be described by a particle model (as shown by the photoelectric effect and the Compton effect). We cannot say whether light is particle or wave. This is not an either/or situation; light seems to be both particles and waves and thus is probably neither.

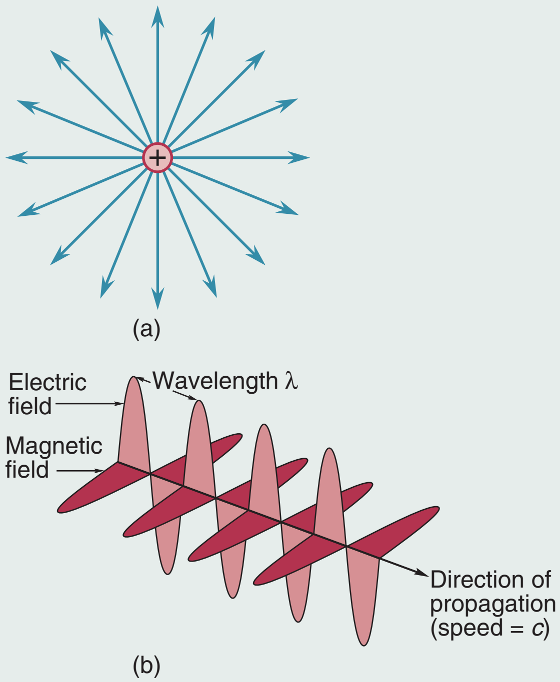


FIGURE B4-9 (a) Electric field lines around a positive charge. If the charge were negative, the lines would be pointing toward the charge. Keep in mind that this is a three-dimensional field. The field is stronger where the concentration of lines is denser. (b) Electromagnetic radiation (from radio waves to X-rays) consists of oscillating electric and magnetic fields, perpendicular to each other, moving through space at the speed of light.

FIGURE 4-14 (a) The emission spectrum of an element; (b) the absorption spectrum of the same element. The absorbed wavelengths in (b) are the same as the emission lines in (a).

photosphere The region of the Sun from which mostly visible radiation is emitted.

The visible surface (the ***photosphere***) of the Sun emits a continuous spectrum. Even though the Sun, in most ways, is more like a gas than a solid, it produces a continuous spectrum rather than an emission spectrum. This is because as atoms are pushed together, their energy levels are broadened (as if slightly different orbits are allowed). As atoms become more and more tightly pressed together, their energy levels begin to overlap so that a full range of orbital energies is possible. An entire range of photon energies thus is emitted by the atoms, and instead of separate, distinct spectral lines appearing in the spectrum, an entire range of frequencies appears.

Before the light from the Sun gets to us on Earth, it must pass through the relatively cooler atmosphere of the Sun as well as through the atmosphere of the Earth. The Sun does indeed have an atmosphere and, as we will see elsewhere in this text, its atmosphere is much deeper than Earth's. As the light passes through these gases, atoms of the gases absorb some of it. This absorption of energy raises an atom's energy level, but because only certain specific energy levels are possible, only certain amounts of energy can be absorbed by the atom. This results in the reverse of what we had before: instead of an atom emitting a photon as it releases energy, it absorbs a photon as it absorbs energy. Just as a hot, low-density gas emits photons of certain energies, the same gas when in a cooler atmosphere absorbs photons of the same energies.

absorption spectrum A spectrum that is continuous except for certain discrete frequencies (or wavelengths).

FIGURE 4-14a represents the emission spectrum of some element. **FIGURE 4-14b** shows the ***absorption spectrum*** that results when white light is passed through the cool gas of this same element. The dark lines of the absorption spectrum correspond exactly to the bright lines of the emission spectrum.

You might point out that after the cool gas has absorbed radiation, it must re-emit it. Shouldn't this then cancel out the absorption? No. As **FIGURE 4-15** shows, the re-emitted light is

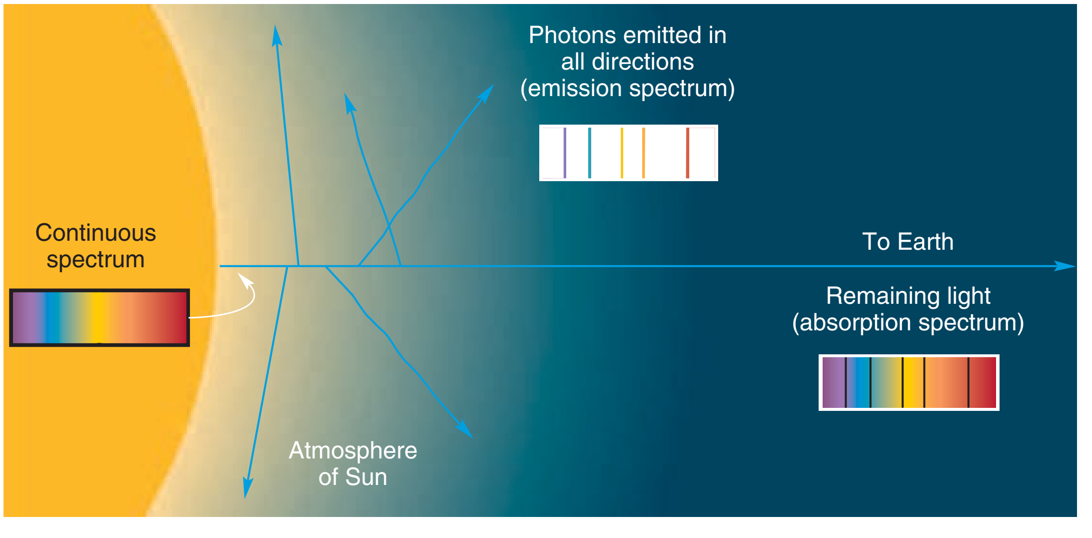


FIGURE 4-15 Consider a beam of light leaving a point on the Sun and moving toward the Earth. As it passes through the Sun's atmosphere, some wavelengths are absorbed and then re-emitted in random directions. This results in the solar spectrum being an absorption spectrum. Light from the Sun's atmosphere is an emission spectrum.

sent out in all directions. Certain frequencies of the light that was originally coming toward the Earth thus are scattered by the atmosphere of the Sun. This results in less light of those frequencies reaching us, and we observe an absorption spectrum.

◆ Absorption spectra are the dark line spectra of Kirchhoff's laws.

The spectrum of the light that is re-emitted is an emission spectrum. During a total eclipse of the Sun, light from the main body of the Sun is blocked out, and astronomers can see the light emitted by the Sun's atmosphere and examine its emission spectrum. It was by examining the emission spectrum from the gas near the Sun that astronomers first discovered the element helium (from the Greek *helios*, the Sun).

The Sun, and other stars as well, has various chemical elements in its atmosphere (that is, different kinds of atoms, each with its own pattern of electron orbits and spectral lines). As the white light passes through this gas, many frequencies are absorbed, corresponding to the various chemical elements of the gas. By examining the complicated absorption spectrum that results, we are able to deduce what elements are present in the star's atmosphere.

◆ The elements in the Earth's atmosphere also absorb radiation, the frequencies of which depend on what elements are in our atmosphere, but we know what those elements are and can take them into account.

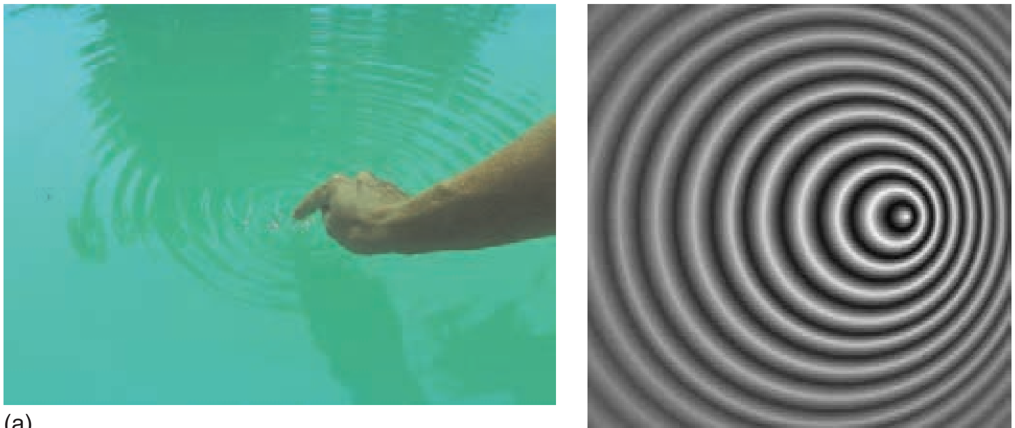
We thus answer a question that, just a century ago, was thought to be unanswerable. We now know what the surface layers of stars are made of! As you might appreciate from the complexity of the Sun's spectrum (look back at Figure 4-10), the analysis is fairly complicated, but it is now a common one in astronomy.

4-7 The Doppler Effect

Have you ever stood near a road and listened to the sound of a siren on a car as it sped by you? Recall how the sound changed when the siren passed, going from a higher pitch down to a lower pitch. This phenomenon has a very important parallel in astronomy. To understand it, we first consider water waves.

FIGURE 4-16a is a photo of waves spreading from a disturbance on the surface of water. The waves move away from the source in a regular way and appear the same in all directions from the source. **FIGURE 4-16b** was made by moving a vibrating object toward the right as it makes waves on water. Look at the difference between the waves in front of and behind the moving source. Four important points can be made about this case, although only one of them is apparent in the photo.

1. Even though the source of the waves is moving, the waves still travel at the same speed in all directions. The source's motion does not push or pull the waves. The source just disturbs the liquid, and the disturbance moves away at a speed that depends only on the liquid's characteristics—water, in this case.



(a) (b)

FIGURE 4-16 (a) Waves spread evenly from their source. Courtesy of Karl Kuhn. (b) If the source is moving to the right, the waves are compressed in front of the source and stretched behind it. Courtesy of Ryan Wilson.

2. The wavelengths of the waves in front of the moving source are shorter than they would be if the source was stationary, and the wavelengths behind the moving source are longer. For waves traveling at the same speed, the wavelength is inversely proportional to the frequency. This means that if there were corks on the water, the corks in front of the moving source would bounce up and down with a greater frequency than if the source were not moving, and corks behind the moving source would bounce with a lower frequency.

   This change in wavelength is the same effect that causes the sound frequency of a siren to change as the car passes. The siren emits sound waves just as the vibrating object produces water waves. When you are in front of the car, you are in the region of shorter wavelength and higher frequency. In the case of sound, high frequency means high pitch. After the siren has passed, its sound waves are stretched in wavelength, causing you to hear a lower pitch.

   This effect, which we see here both in water waves and in sound waves, is called the ***Doppler effect***, named after the Austrian physicist Christian Doppler (1803–1853), who first explained it. Before we apply it to light waves and astronomy, let's continue the list of important things to know about it.

Doppler effect The observed change in wavelength of waves from a source moving toward or away from an observer.

3. The sound does indeed get louder as a siren approaches (and the water waves get higher as the vibrating object approaches a bobbing cork), but this is *not* what the Doppler effect is about. The Doppler effect refers only to the *change in wavelength* (and therefore frequency) of the wave.
4. The frequency does *not* get higher and higher as the source approaches at a uniform speed. Rather, the frequency is observed to be higher than the source's (but constant in value) as the source approaches and lower than the source's (but constant in value) as it recedes.

The Doppler Effect in Astronomy

The Doppler effect also occurs for electromagnetic waves, which is what we receive from the stars. This means that if an object is coming toward us, the light we receive from it will have a shorter than normal wavelength, and from an object moving away we will receive a longer than normal wavelength. The reason you can't observe this for moving objects here on Earth is that the amount of the shortening and lengthening of the wave depends on the speed of the object *compared with the speed of the wave*.

◆ By *normal* we mean the wavelength of the emitted light as measured by someone traveling with the source.

For water waves, which move fairly slowly, you observe the Doppler effect even for a slow-moving wave source. In the case of sound, which has a speed much greater than water waves, you notice the Doppler effect only for fairly fast objects. A car going 70 miles/hour is moving at about 10% of the speed of sound.

In the case of light, you don't perceive the Doppler effect for a car traveling at 70 miles/hour because it is moving at only one ten-millionth the speed of light in vacuum. To describe the Doppler effect for light, consider a spaceship with a lamp emitting green light. If the spaceship is moving away from us at a great enough speed, the wavelength of the light we see from the lamp is stretched so that the light appears red. The light is ***redshifted***. If the spaceship is approaching, the light is ***blueshifted***.

redshift A change in wavelength toward longer wavelengths.

blueshift A change in wavelength toward shorter wavelengths.

The spaceship example does illustrate the Doppler effect, but it is very misleading in an important respect: Except for very distant galaxies, objects in the heavens do not move with speeds great enough to actually change their colors appreciably. The redshift or blueshift caused by the Doppler effect is very small in most cases. If the spectra of stars were continuous spectra, there would be few cases in which the Doppler effect could be used to detect motion. It is the spectral lines (usually the absorption lines) that make the Doppler effect such a powerful tool.

As an example, imagine that we record the spectrum of hydrogen gas in the laboratory (**FIGURE 4-17a**). **FIGURE 4-17b** represents the spectrum of a star having only hydrogen in its atmosphere (which is unrealistic, but this is a simplified example). The absorption lines in the star's spectrum do not align exactly with the emission lines of the laboratory spectrum. Instead, the absorption lines are shifted slightly toward the red. This indicates that the star is moving away from us.

FIGURE 4-17 (a) Emission spectrum of hydrogen when the source is stationary with respect to the observer. (b) Absorption spectrum of hydrogen for a receding source (at 0.7% of the speed of light in vacuum). Note the shift of all lines toward redder colors.

There are three major differences between our example and a measurement of a real star: First, a real star's spectrum has many more spectral lines. Second, the Doppler shift is almost always much smaller than that indicated in the example. When we later show photos of actual spectra, they usually will be a magnified portion of a small part of the visible spectrum. Third, astronomers do not normally use color film in recording the spectrum. This may seem odd, but color is not easy to describe accurately, whereas wavelength is. The wavelengths of absorption lines can be measured very accurately and compared with the lines from a laboratory spectrum to determine the existence and the precise amount of the Doppler shift.

The Doppler Effect as a Measurement Technique

◆ An object's velocity is a quantity that gives us the object's speed and its direction of motion.

radial velocity Velocity along the line of sight, toward or away from the observer.

tangential velocity Velocity perpendicular to the line of sight.

Thus far, we have described the Doppler effect as a method for detecting whether a star is moving toward or away from us, but it is more powerful than this. From measurements of the *amount* of the shifting of the spectral lines, we can determine the ***radial velocity*** of the star relative to Earth. The radial velocity is the star's velocity toward or away from us and must be distinguished from its ***tangential velocity***, which is its velocity across our line of sight.

FIGURE 4-18 distinguishes the two velocities. To measure tangential velocity, we must look for motion of the star across our line of sight (like the yellow car in Figure 4-18), and this motion can be detected only for relatively nearby stars. To measure radial velocity, we use Doppler shift data and the following equation:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\upsilon}{c},$$

where $\Delta\lambda = \lambda - \lambda_0$ = wavelength difference, λ = observed wavelength, λ_0 = wavelength of spectral line from stationary source, υ = radial velocity of object, and c = velocity of light in vacuum. If we solve this equation for what we are usually calculating—that is, the velocity of the object—we obtain

$$\upsilon = c\left(\frac{\Delta\lambda}{\lambda_0}\right).$$

When an object is approaching the observer, the wavelength difference is negative and so is the radial velocity. When an object is moving away from the observer, the wavelength difference is positive and so is the radial velocity.

◆ This equation applies if the object is moving much slower than the speed of light in vacuum, as is the case for most galaxies other than the very distant ones. For distant galaxies, a slightly more complex equation is needed, as relativistic effects become important.

EXAMPLE

The wavelength of one of the most prominent spectral lines of hydrogen is 656.285 nanometers (this is in the red portion of the spectrum). In the spectrum of Regulus (the brightest star in the constellation Leo), the wavelength of this line is observed to appear greater by 0.0077 nanometers. Calculate the speed of Regulus relative to Earth, and determine whether it is moving toward or away from us.

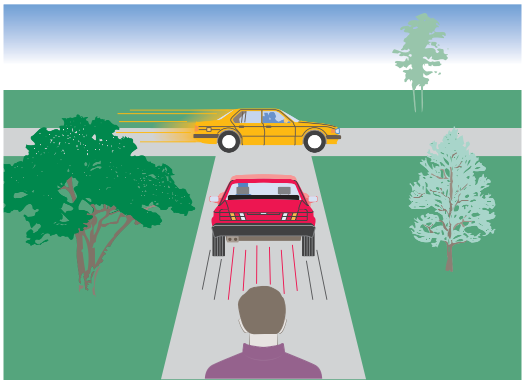


FIGURE 4-18 The red car has a radial (to-or-fro) velocity with respect to the observer, while the yellow car has a tangential (side-to-side) velocity. The Doppler effect cannot be used to detect tangential velocity.

SOLUTION

First, the data indicate that the wavelength of the line in the spectrum of Regulus is *longer* by

0.0077 nanometers. This means that the star is moving *away* from us. To determine its speed, we substitute the given values in the equation that relates Doppler shift and speed:

$$v = c\left(\frac{\Delta\lambda}{\lambda_0}\right) = (3.0 \times 10^8 \text{ m/s}) \times \left(\frac{0.0077 \text{ nm}}{656.285 \text{ nm}}\right)$$

$$= 3500 \text{ m/s} = 3.5 \text{ km/s}.$$

Regulus thus is moving away from the Earth at a speed of about 3.5 kilometers/second. This is about 2 miles/second, or 8000 miles/hour, a typical speed for nearby stars. Because the Earth's speed in its orbit around the Sun is about 30 kilometers/second, the Earth's motion would have to be taken into account in making the measurement. Our calculation assumed that the Earth was between the Sun and Regulus so that the Earth had no motion toward or away from the star.

TRY ONE YOURSELF

The nearest star to the Sun that is visible to the naked eye is Alpha Centauri. With Earth's motion removed, the 656.285-nanometers line of hydrogen has a wavelength of 656.237 nanometers in Alpha Centauri's spectrum. Calculate the radial velocity of this star relative to the Sun, and tell whether it is moving toward or away from the Sun.

Other Doppler Effect Measurements

◆ The annual variation in the Doppler shift observed in stellar spectra provides evidence for the Earth's motion around the Sun. The evidence was not available, of course, when the question was controversial.

The use of the Doppler effect is not limited to measuring the speeds of stars. Other applications include the following:

1. Measuring the rotation rate of the Sun. Galileo was the first to observe that sunspots move across the Sun, thus providing a method to measure the Sun's rotation rate. The Doppler effect gives a second method. The measurement is done by examining the light from opposite sides of the Sun. Light from the side moving toward us is blueshifted and light from the other side is redshifted.
2. In a similar manner, the rotation rates of distant stars, other galaxies, planets, and the rings of Saturn can be measured. The fact that the light in the case of planets has been reflected by the planet (or rings) rather than emitted by it does not matter; the light is still shifted by the Doppler effect. In fact, the rotations of Mercury and Venus were first revealed by reflected radar waves.
3. Many stars are part of a two (or more) star system in which the stars orbit one another. If their orbits happen to be aligned so that each star moves alternately toward and away from us, we can detect this motion by the blueshift and redshift of each star's spectrum. When we discuss such ***binary stars,*** we will see that they are very important in our quest to learn more about stars.

◆ Police radar measures motorists' speeds by bouncing waves from their cars and detecting the Doppler shift in the reflected waves.

binary star (system) A pair of stars gravitationally bound so that they orbit one another.

Relative or Real Speed?

The speed measured by the Doppler effect is the object's speed *relative to the speed of the Earth.* We, therefore, must take the Earth's speed into account in any calculation made with the Doppler effect, but even then we are only measuring the speed of the object with respect to the Sun. What about the object's *real* speed? There is no such thing because all speeds are relative to something. When you say that a car is moving at 50 miles/hour, you mean "relative to the surface of the Earth." When you walk up the aisle of a moving plane, you have one speed relative to the seated passengers, another relative to the Earth, another relative to the Sun, and so on.

Just as all motion is relative, all nonmotion is relative, too. When we say that something is at rest, we *usually* mean that it is at rest relative to the Earth. It is meaningless to say that something is absolutely at rest. Thus, there is no loss of meaning to our finding the velocity of an object relative to the Earth and then correcting for the Earth's motion around the Sun. All motion is relative.

◆ This understanding of the relativity of motion is called *Galilean relativity* (or *Newtonian relativity*). Einstein's theory of relativity goes much further than this.

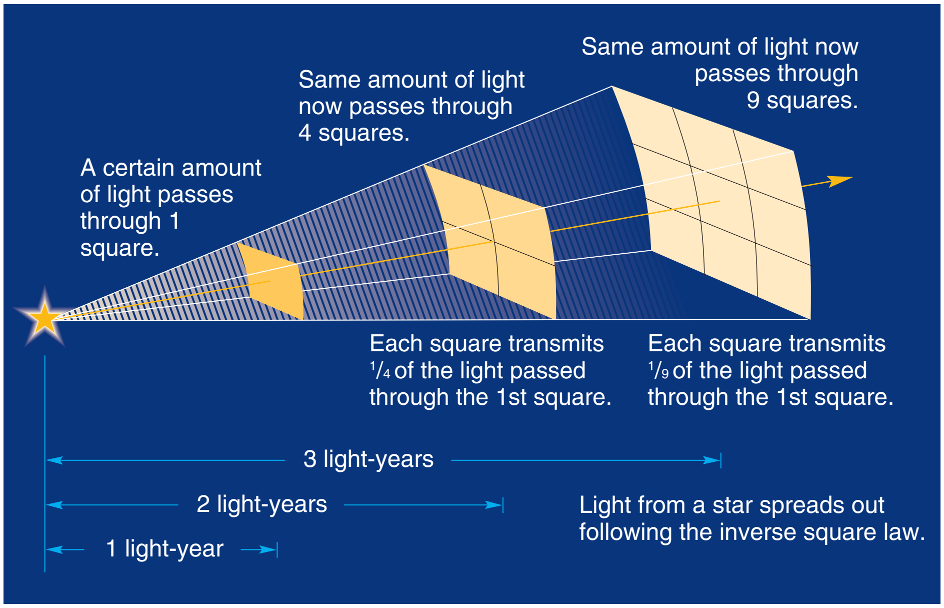


FIGURE 4-19 As light spreads from a star, its intensity decreases as the inverse square of the distance.

4-8 The Inverse Square Law of Radiation

Everyone has experienced the fact that the intensity—that is, the brightness—of light decreases when we move farther from its source. The decrease in intensity follows an ***inverse square law***, a relationship that states that radiation spreading from a small source decreases in intensity as the inverse square of the distance from the source.

inverse square law Any relationship in which some factor decreases as the square of the distance from its source.

We can reach the conclusion that light intensity (just like gravity) decreases inversely with the distance squared ($1/d^2$) if we assume that light "spreads out" from its source uniformly in all directions. Indeed, this outward diffusion has to pass through successive imaginary spheres centered on the source. Because the surface area of a sphere of radius d is $4\pi d^2$, as light spreads out from the source filling all space uniformly in all directions, it must become less "concentrated" by a factor of $1/d^2$ (**FIGURE 4-19**).

◆ The inverse square law applies only to small sources of light, but this requirement is easily met in most astronomical cases.

In our study of stellar properties, we discuss how we use this inverse square law to find how much energy a star really emits if we know its distance from us and its apparent brightness.

Conclusion

One of the major differences between Astronomy and other disciplines is that the subject of our studies—the universe—is beyond our control. Stars are born and die continually, galaxies collide and, most important of all, when we look at an object we see it as it was when it emitted the light we now see. One of the means to learn about the cosmos is by unlocking the information in the radiation we collect. In this chapter, we examined the evolution of our ideas on light since antiquity (**FIGURE 4-20**). We also discussed how the spectra of stars are used in two very different ways. First, the spectra are treated as continuous spectra, and we examine their graphs of intensity versus wavelength. By measuring the wavelength of the maximum intensity of radiation, we can determine the temperature of a star's surface. In doing this analysis, we ignore the absorption lines. Recall that these lines are very narrow, and their presence does not change the overall pattern of the blackbody curve.

Second, we examine the absorption lines within the spectrum. These lines allow us to determine the chemical composition of stars. In addition, when we measure the Doppler effect, the shift in the lines allows us to calculate the radial speeds of stars relative to Earth, as well as the speeds of rotation and revolution of celestial objects.

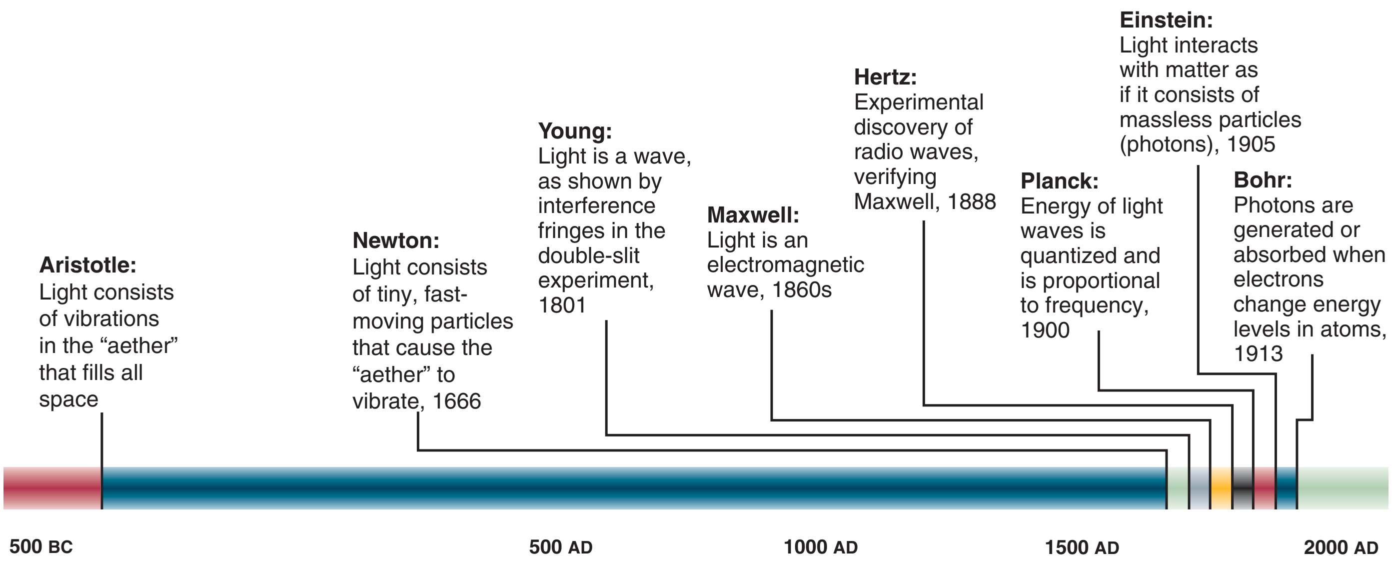


FIGURE 4-20 Over the years, explanations for the nature of light went back and forth between wave models and particle models. Today we talk about the wave-particle duality of light, as we saw in the corresponding Advancing the Model box; it propagates through space as a wave but interacts with matter as a stream of particles.

STUDY GUIDE

RECALL QUESTIONS

1. The frequency of visible light falls between that of
   - **A.** infrared waves and radio waves.
   - **B.** X-rays and cosmic rays.
   - **C.** ultraviolet waves and X-rays.
   - **D.** short radio waves and long radio waves.
   - **E.** ultraviolet waves and radio waves.
2. Infrared radiation differs from red light in
   - **A.** intensity.
   - **B.** wavelength.
   - **C.** its speed in a vacuum.
   - **D.** [All of the above.]
   - **E.** [None of the above.]
3. The frequency at which a star emits the most light depends on the star's
   - **A.** distance from us.
   - **B.** brightness.
   - **C.** temperature.
   - **D.** eccentricity.
   - **E.** velocity toward or away from us.
4. In an infrared photo taken on a cool night, your skin will appear brighter than your clothes.
   - **A.** Correct.
   - **B.** Wrong, it depends upon the color of your clothes.
   - **C.** Wrong, your clothes will appear brighter.
   - **D.** Wrong, they will be equally bright.
5. Light waves of greater frequency have
   - **A.** shorter wavelength.
   - **B.** longer wavelength.
   - **C.** [Either of the above; there is no direct connection between frequency and wavelength.]
6. Which of the following choices does not have the same fundamental nature as visible light?
   - **A.** X-rays.
   - **B.** Sound waves.
   - **C.** Ultraviolet radiation.
   - **D.** Infrared waves.
   - **E.** Radio waves.
7. As an electron of an atom changes from one energy level to a higher energy level by absorbing a photon, the total energy of the atom
   - **A.** increases.
   - **B.** decreases.
   - **C.** remains the same.
8. Which of the following choices is produced when white light is shined through a cool gas?
   - **A.** An absorption spectrum.
   - **B.** A continuous spectrum.
   - **C.** An emission spectrum.
   - **D.** [All of the above.]
   - **E.** [None of the above.]
9. The solar spectrum is which of the following?
   - **A.** An absorption spectrum.
   - **B.** A continuous spectrum.
   - **C.** An emission spectrum.
   - **D.** [All of the above.]
   - **E.** [None of the above.]
10. The spectrum of light from the Sun's atmosphere *seen during a total solar eclipse* is
    - **A.** an emission spectrum.
    - **B.** an absorption spectrum.
    - **C.** a combination of emission spectrum and absorption spectrum.
    - **D.** a continuous spectrum.
    - **E.** a combination of all three types of spectra.

11. Analysis of a star's spectrum *cannot* determine
    A. the star's radial velocity.
    B. the star's tangential velocity.
    C. the chemical elements present in the star's atmosphere.
    D. [More than one of the above.]
12. According to the Doppler effect,
    A. sound gets louder as its source approaches and softer as it recedes.
    B. sound gets higher and higher in pitch as its source approaches and lower and lower as its source recedes.
    C. sound is of constant higher pitch as its source approaches and of constant lower pitch as its source recedes.
    D. [Both A and B above.]
    E. [Both A and C above.]
13. The Doppler effect causes light from a source moving away to be
    A. shifted to shorter wavelengths.
    B. shifted to longer wavelengths.
    C. changed in velocity.
    D. [Both A and C above.]
    E. [Both B and C above.]
14. We can determine the elements in the atmosphere of a star by examining
    A. its color.
    B. its absorption spectrum.
    C. the frequency at which it emits the most energy.
    D. its temperature.
    E. its motion relative to us.
15. Which list shows the colors of stars from coolest to hottest?
    A. Red, white, blue.
    B. White, blue, red.
    C. Blue, white, red.
    D. Red, blue, white.
    E. Blue, red, white.
16. The Doppler effect is used to
    A. measure the radial velocity of a star.
    B. detect and study binary stars.
    C. measure the rotation of the Sun.
    D. [Two of the above.]
    E. [All of the above.]
17. Sound waves cannot travel in a vacuum. How, then, do radio waves travel through interstellar space?
    A. They are extra-powerful sound waves.
    B. They are very high frequency sound waves.
    C. Radio waves are not sound waves at all.
    D. The question is a trick, for radio waves do *not* travel through interstellar space.
    E. Interstellar space is not a vacuum.
18. The energy of a photon is directly proportional to the light's
    A. wavelength.
    B. frequency.
    C. velocity.
    D. brightness.
19. In the Bohr model of the atom, light is emitted from an atom when
    A. an electron moves from an inner to an outer orbit.
    B. an atom gains energy.
    C. an electron moves from an outer to an inner orbit.
    D. one element reacts with another.
    E. [Both A and B above.]
20. The intensity/wavelength graph of a "blue-hot" object peaks in the
    A. infrared region.
    B. red region.
    C. yellow region.
    D. ultraviolet region.
21. The emission spectrum produced by the excited atoms of an element contains wavelengths that are
    A. the same for all elements.
    B. characteristic of the particular element.
    C. evenly distributed throughout the entire visible spectrum.
    D. different from the wavelengths in its absorption spectrum.
    E. [Both A and D above.]
22. Each element has its own characteristic spectrum because
    A. the speed of light differs for each element.
    B. some elements are at a higher temperature than others.
    C. atoms combine to form molecules, releasing different wavelengths depending on the elements involved.
    D. electron energy levels are different for different elements.
    E. hot solids, such as tungsten, emit a continuous spectrum.
23. The speed of sound is 335 meters/second. What is the wavelength of a sound that has a frequency of 500 cycles/second?
    A. 0.67 meters.
    B. 1.49 meters.
    C. 165 meters.
    D. 835 meters.
24. Suppose the speed of a water wave is 12 inches/second and the wavelength is 4 inches. What is the frequency of the wave?
    A. 48 cycles/second.
    B. 18 cycles/second.
    C. 8 cycles/second.
    D. 3 cycles/second.
    E. 1/3 cycles/second.
25. Define *wavelength* and *frequency* in the case of a wave.
26. Which has the higher frequency, light of 400 nanometers or light of 450 nanometers?
27. Approximately what are the least and greatest wavelengths of visible light?
28. Name six regions of the electromagnetic spectrum in order from longest to shortest wavelength. (Do not list the colors of visible light as separate regions of the spectrum.)
29. Which parts of the electromagnetic spectrum penetrate the atmosphere?
30. Define the following terms: electron, nucleus, photon.
31. State the three postulates on which the Bohr model of the atom is based.

32. How is the energy of the photon related to the frequency of the light?
33. Why do the various elements each have different emission spectra?
34. Name the three different types of spectra, and explain how each is produced.
35. Explain how we know what elements are in the atmospheres of the stars.
36. Carefully explain what the Doppler effect is. For light waves, does the Doppler effect tell us anything about the intensity of the light in front of and behind a moving light source?
37. Distinguish between the way a spectrum is used to determine the temperature of a star and the way it is used to determine the star's composition and/or motion toward or away from us.

QUESTIONS TO PONDER

1. Why do we have three different temperature scales instead of one? What are the advantages (if any) of each?
2. Two people are having fun in the ocean. One is surfing, and the other is floating up and down. Their different motions could be used to illustrate two quantities in the equation $\upsilon = \lambda \times f$. Which two?
3. The period of a wave is defined as the amount of time required for the wave to complete one cycle. What, then, is the relationship between the period and the frequency of a wave?
4. It is especially easy to get a sunburn when skiing high in the mountains. How does the high altitude contribute to the danger of sunburn?
5. Why can't we hear radio waves without using the device that we call a "radio"?
6. Nowadays, radio waves (both for radio and TV) are striking your body all the time, but you are not allowed to get too many X-rays in one year. Why is this so? After all, both radio waves and X-rays are a part of the electromagnetic spectrum.
7. What does an object do to light to give the object its color? How does this differ from the color of an object that emits its own light?
8. Draw a graph of intensity versus wavelength for a red star and another for a white star. Describe two ways in which the graphs differ.
9. The text explains that cool stars are redder than hot ones. However, couldn't the red color result instead from the Doppler effect if the star is moving away from us? Explain.
10. If absorption lines were to be included in the graph of intensity versus wavelength for a star, how would this change the graph?
11. How would Figure 4-10 be different if it were the spectrum of a red star?
12. How do we know what chemical elements are in the atmosphere of the Sun? Explain.
13. What is the Doppler effect and why is it important to astronomers?
14. Figure 4-18 greatly exaggerates color differences for the two cars. If it showed a car coming toward you, what color would the car be, using the same exaggeration?

CALCULATIONS

1. If the speed of a particular water wave is 12 meters/second and its wavelength is 3 meters, what is its frequency?
2. The speed of sound in air at room temperature is about 344 meters/second. What is the wavelength of a sound wave with a frequency of 256 Hz?
3. Express 500 nanometers in meters.
4. The 656.285-nanometers line of hydrogen is measured to be 656.305-nanometers in the spectrum of a certain star. Is this star approaching or receding from the Earth? Calculate its radial speed relative to the Earth.
5. If a certain star is moving away from Earth at 25 km/s, what will be the measured wavelength of a spectral line that has a wavelength of 500 nm for a stationary source?
6. Suppose the Kelvin temperature of blackbody X is three times as great as that of blackbody Y. Compare the energy released by equal areas of the two objects.
7. Use Wien's law to determine the wavelength at which an object at body temperature (98.6°F) emits most of its energy. (*Hint*: Make sure you find the corresponding temperature in kelvin.) What kind of radiation is this? Can you see it?
8. Two thermometers, one marked in °F and the other in °C, are placed in the same container. At what temperature will both thermometers read the same?
9. Matter falling toward a black hole gets compressed and heated to about 10^6 K. In what part of the electromagnetic spectrum would you search for black holes?
10. A star has five times the surface area of the Sun, but its surface temperature is smaller by a factor of three. Does this star emit more energy than the Sun or less? Explain.
11. (a) We said that light takes 8.3 minutes to reach us from the Sun. Show that this is the case. (b) When we are observing an object that is 5000 light years away, do we see it as it is now? Explain.
12. Compare the light we receive from a 100-watt lightbulb that is 30 feet away with the light from a similar bulb that is 10 feet away.

ACTIVITIES

Doppler Effect Measurement

Figure 4-17a shows a hydrogen emission spectrum (in the visible part of the spectrum) when the source is stationary with respect to the observer, whereas Figure 4-17b shows a corresponding hydrogen absorption spectrum for a receding source. In general, spectra are much more complicated, including many lines from different elements; however, let us imagine that we have isolated the hydrogen lines in this spectrum. In addition, consider the spectrum as a "map," exactly as is. We would like to calculate the speed of the source, using the Doppler effect.

For a map to be useful, it must include the correct scale. The lines in Figure 4-17a correspond to the following wavelengths from right to left: 656.3 nm (red), 486.1 nm (blue-green), 434.0 nm (violet), and 410.1 nm (violet). Measure the distances between the lines in millimeters (mm), and calculate the scale with units nm/mm.

Now compare the position of the lines between the two spectra. For example, by how many millimeters has the 656.3-nanometer line shifted to the right (toward longer wavelengths)? Using the scale you found in the previous step, translate this shift (redshift) into nanometers. This is the change between the observed and laboratory-based wavelength for this hydrogen line ($\Delta\lambda$). Using $\lambda_0 = 656.3$ nanometers and the Doppler equation, show that the speed of the receding source is 0.7% of the speed of light in vacuum.

EXPANDING THE QUEST

1. "The Duality in Matter and Light," by B. G. Englert, M. O. Scully, and H. Walther, in *Scientific American* (December 1994).
2. "The Truth About Star Colors," by P. C. Steffy, in *Sky & Telescope* (September 1992, p. 266).
3. "Unlocking the Chemical Secrets of the Cosmos," by O. Gingerich, in *Sky & Telescope* (July 1981).
4. "The Electromagnetic Spectrum," by H. Augensen and J. Woodbury, in *Astronomy* (June 1982).
5. "Beyond the Rainbow," by J. B. Kaler, in *Astronomy* (September 2000).
6. "Starlight Detectives," by A. W. Hirshfeld, in *Sky & Telescope* (August 2004).
7. "On the Solar Spectrum and the Color Sensitivity of the Eye," by D. L. Lynch and B. H. Soffer, in *Optics & Photonics News* (March 1999).

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Query:

PE1: Reconcile use of “degree” (text vs symbol) throughout text.