bright stars in our sky, such as Betelgeuse (in Orion) and Antares (in Scorpius), appear reddish in color. The Sun's 5800 K surface emits most strongly in green light (around 500 nm), but the Sun looks yellow or white to our eyes because it also emits other colors throughout the visible spectrum. Hotter stars emit mostly in the ultraviolet but appear blue-white in color because our eyes cannot see their ultraviolet light. If an object were heated to a temperature of millions of degrees, it would radiate mostly X rays. Some astronomical objects are indeed hot enough to emit X rays, such as disks of gas encircling exotic objects like neutron stars and black holes (see Chapter 18).

How do we interpret an actual spectrum?

The spectra of real astronomical objects are usually combinations of the three idealized types of spectra (continuous or thermal, absorption line, and emission line). They may also show features produced by reflection or scattering.

Reflected Light Spectra An object that reflects light will have the spectrum of the light shining on it, minus the light it absorbs. For example, a red sweatshirt absorbs blue light and reflects red light, so its visible spectrum looks like the spectrum of sunlight (or lamp light) but with blue light missing. In the same way that we can distinguish lemons from limes, we can use color information in reflected light to learn about celestial objects. Different fruits, different rocks, and even different atmospheric gases reflect and absorb light at different wavelengths. Although the absorption features that show up in spectra of reflected light are not as distinct as the emission and absorption lines for thin gases, they still provide useful information. For example, the surface materials of a planet determine how much light of different colors is reflected or absorbed. The reflected light gives the planet its color, while the absorbed light heats the surface and helps determine its temperature.

Putting It All Together Figure 5.21 shows the same spectrum we began with in Figure 5.13, but this time with labels indicating the processes responsible for its various features. The thermal emission peaks in the infrared, showing a surface temperature of about 225 K, well below the 273 K freezing point of water. The absorption bands in the infrared come mainly from carbon dioxide, indicating a carbon dioxide atmosphere. The emission lines in the ultraviolet come from hot gas in a high, thin layer of the object's atmosphere. The reflected light looks like the Sun's 5800 K thermal radiation except that much of the blue light is missing, so the object must be reflecting sunlight and must look red in color. Perhaps by now you have guessed that this figure represents the spectrum of the planet Mars. Note that the figure includes the Doppler effect (as item 6), which we discuss next.

MA™ **The Doppler Effect Tutorial, Lessons 1, 2**

5.5 THE DOPPLER EFFECT

You're probably already amazed at the volume of information contained in light, but there is still more. In particular, we can learn about the motion of distant objects (relative to us) from changes in their spectra caused by the **Doppler effect.**

MATHEMATICAL INSIGHT 5.2

Laws of Thermal Radiation

The two rules of thermal radiation have simple mathematical formulas. The *Stefan-Boltzmann law* (Law 1) is expressed as

$$\text{emitted power (per square meter of surface)} = \sigma T^4$$

where σ (Greek letter *sigma*) is a constant with a measured value of $\sigma = 5.7 \times 10^{-8}$ watt/($\text{m}^2 \times \text{K}^4$) and T is on the Kelvin scale (K).

Wien's law (Law 2) is expressed approximately as

$$\lambda_{\text{max}} \approx \frac{2{,}900{,}000}{T\ (\text{Kelvin scale})}\ \text{nm}$$

where λ_{max} (read as "lambda-max") is the wavelength (in nanometers) of maximum intensity, which is the peak of a thermal radiation spectrum.

EXAMPLE: Consider a 15,000 K object that emits thermal radiation. How much power does it emit per square meter? What is its wavelength of peak intensity?

SOLUTION:

Step 1 Understand: We can calculate the total emitted power per square meter from the Stefan-Boltzmann law and the wavelength of maximum intensity from Wien's law.

Step 2 Solve: We plug the object's temperature ($T = 15{,}000$ K) into the Stefan-Boltzmann law to find the emitted power per square meter:

$$\begin{aligned}\sigma T^4 &= 5.7 \times 10^{-8} \frac{\text{watt}}{\text{m}^2 \times \text{K}^4} \times (15{,}000\ \text{K})^4 \\ &= 2.9 \times 10^9\ \text{watt/m}^2\end{aligned}$$

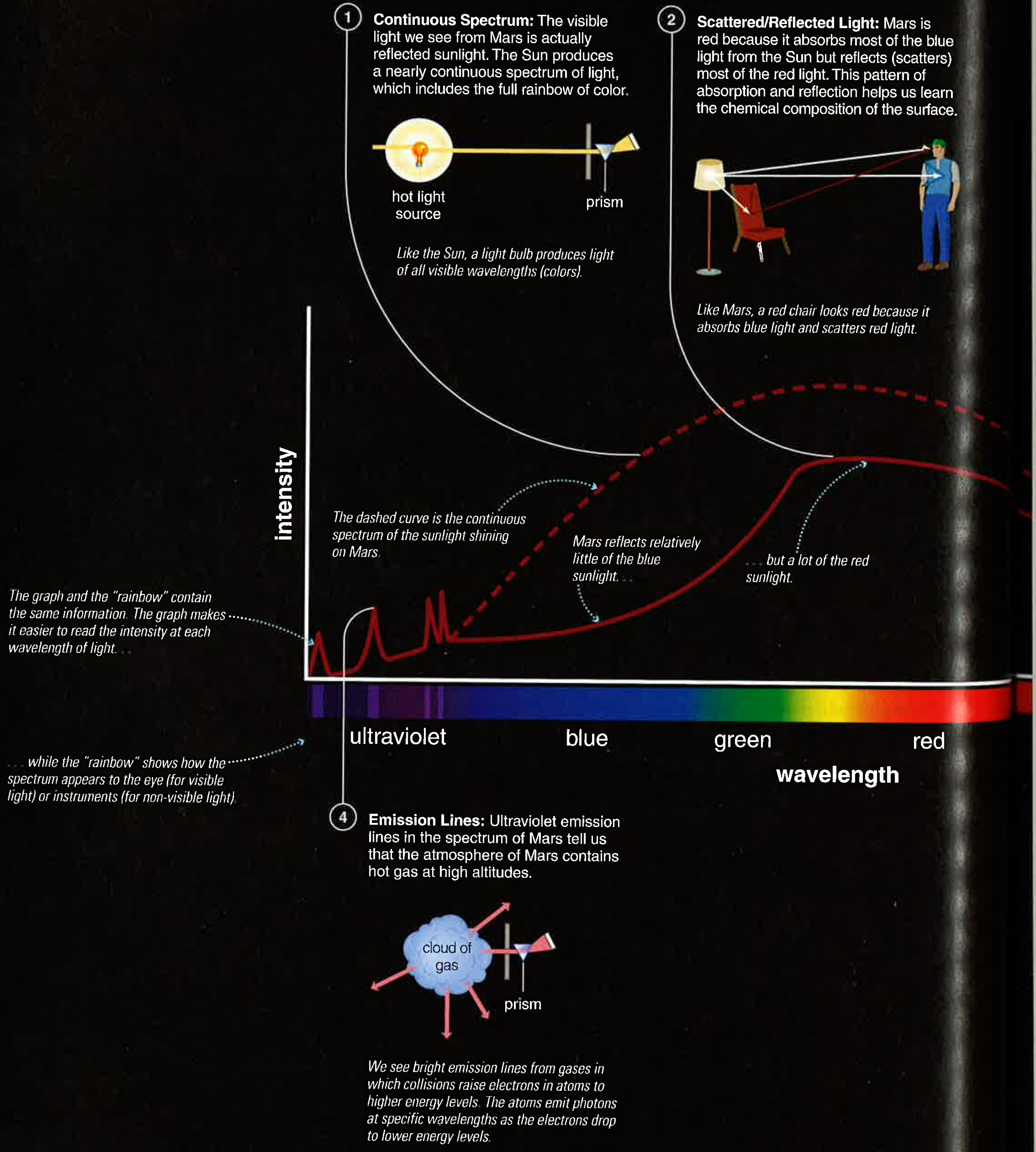
We find the wavelength of maximum intensity with Wien's law:

$$\lambda_{\text{max}} \approx \frac{2{,}900{,}000}{15{,}000\ (\text{Kelvin scale})}\ \text{nm} \approx 190\ \text{nm}$$

Step 3 Explain: A 15,000 K object emits a total power of 2.9 billion watts per square meter. Its wavelength of maximum intensity is 190 nm, which is in the ultraviolet portion of the electromagnetic spectrum. By using these facts in reverse, we can learn about astronomical objects. For example, if an object has a thermal radiation spectrum that peaks at a wavelength of 190 nm, we know that its surface temperature is about 15,000 K. And because the temperature tells us how much power the object emits per square meter of surface, we can calculate its total size from its total radiated power.

COSMIC CONTEXT FIGURE 5.21 *Interpreting a Spectrum*

An astronomical spectrum contains an enormous amount of information. This figure shows a schematic spectrum of Mars. It is the same spectrum shown in Figure 5.13, but this time describing what we can learn from it.



① **Continuous Spectrum:** The visible light we see from Mars is actually reflected sunlight. The Sun produces a nearly continuous spectrum of light, which includes the full rainbow of color.

Like the Sun, a light bulb produces light of all visible wavelengths (colors).

② **Scattered/Reflected Light:** Mars is red because it absorbs most of the blue light from the Sun but reflects (scatters) most of the red light. This pattern of absorption and reflection helps us learn the chemical composition of the surface.

Like Mars, a red chair looks red because it absorbs blue light and scatters red light.

The dashed curve is the continuous spectrum of the sunlight shining on Mars.

Mars reflects relatively little of the blue sunlight . . .

. . . but a lot of the red sunlight.

The graph and the "rainbow" contain the same information. The graph makes it easier to read the intensity at each wavelength of light . . .

. . . while the "rainbow" shows how the spectrum appears to the eye (for visible light) or instruments (for non-visible light).

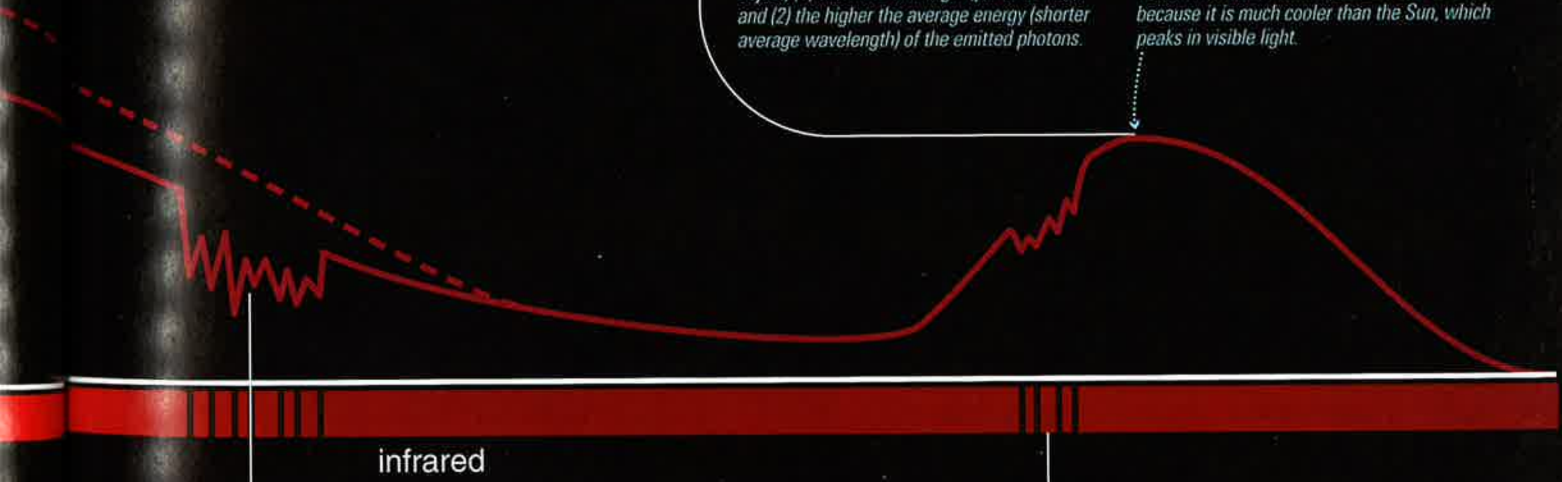
④ **Emission Lines:** Ultraviolet emission lines in the spectrum of Mars tell us that the atmosphere of Mars contains hot gas at high altitudes.

We see bright emission lines from gases in which collisions raise electrons in atoms to higher energy levels. The atoms emit photons at specific wavelengths as the electrons drop to lower energy levels.

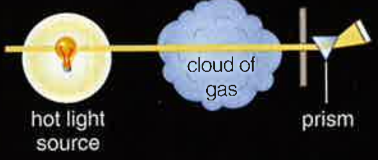
③ **Thermal Radiation:** Objects emit a continuous spectrum of thermal radiation that peaks at a wavelength determined by temperature. Thermal radiation from Mars produces a broad hump in the infrared, with a peak indicating a surface temperature of about 225 K.

All objects—whether a fireplace poker, planet, or star—emit thermal radiation. The hotter the object, (1) the more total light (per unit area), and (2) the higher the average energy (shorter average wavelength) of the emitted photons.

Mars's thermal radiation peaks in the infrared because it is much cooler than the Sun, which peaks in visible light.



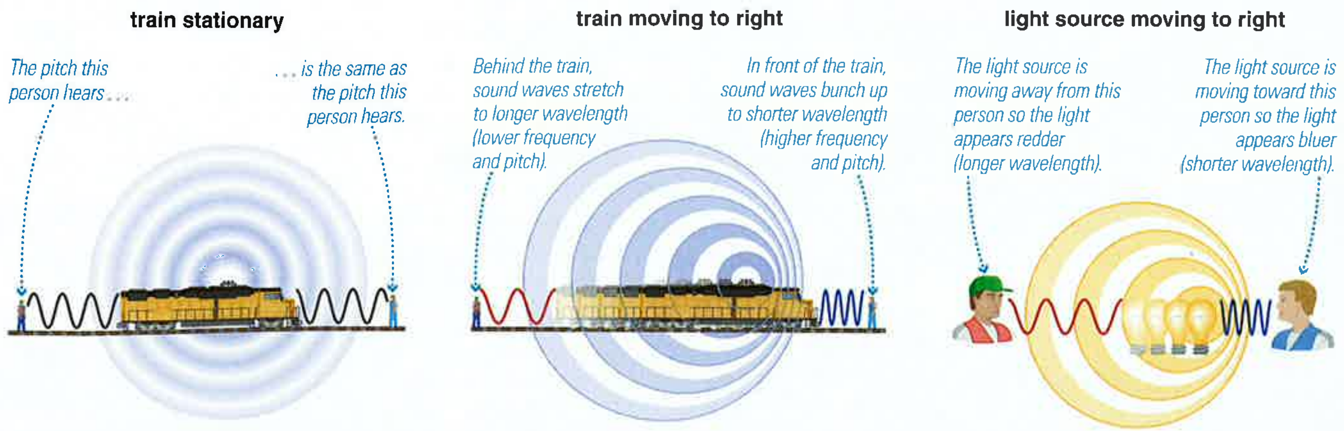
⑤ **Absorption Lines:** These absorption lines reveal the presence of carbon dioxide in Mars's atmosphere.



When light from a hot source passes through a cooler gas, the gas absorbs light at specific wavelengths that raise electrons to higher energy levels. Every different element, ion, and molecule has unique energy levels and hence its own spectral "fingerprint."

⑥ **Doppler Effect:** The wavelengths of the spectral lines from Mars are slightly shifted by an amount that depends on the velocity of Mars toward or away from us as it moves in its orbit around the Sun.

A Doppler shift toward the red side of the spectrum tells us the object is moving away from us. A shift toward the blue side of the spectrum tells us the object is moving toward us.



a The whistle sounds the same no matter where you stand near a stationary train.

b For a moving train, the sound you hear depends on whether the train is moving toward you or away from you.

c We get the same basic effect from a moving light source (although the shifts are usually too small to notice with our eyes).

FIGURE 5.22 The Doppler effect. Each circle represents the crests of sound (or light) waves going in all directions from the source. For example, the circles from the train might represent waves emitted 0.001 second apart.

How does light tell us the speed of a distant object?

You've probably noticed the Doppler effect on the *sound* of a train whistle near train tracks. If the train is stationary, the pitch of its whistle sounds the same no matter where you stand (Figure 5.22a). But if the train is moving, the pitch sounds higher when the train is coming toward you and lower when it's moving away from you. Just as the train passes by, you can hear the dramatic change from high to low pitch—a sort of "weeeeeeee–ooooooooooh" sound. To understand why, we have to think about what happens to the sound waves coming from the train (Figure 5.22b). When the train is moving toward you, each pulse of a sound wave is emitted a little closer to you. The result is that waves are bunched up between you and the train, giving them a shorter wavelength and higher frequency (pitch). After the train passes you by, each pulse comes from farther away, stretching out the wavelengths and giving the sound a lower frequency.

The Doppler effect causes similar shifts in the wavelengths of light (Figure 5.22c). If an object is moving toward us, the light waves bunch up between us and the object, so that its entire spectrum is shifted to shorter wavelengths. Because shorter wavelengths of visible light are bluer, the Doppler shift of an object coming toward us is called a **blueshift**. If an object is moving away from us, its light is shifted to longer wavelengths. We call this a **redshift** because longer wavelengths of visible light are redder. For convenience, astronomers use the terms *blueshift* and *redshift* even when they aren't talking about visible light.

Spectral lines provide the reference points we use to identify and measure Doppler shifts (Figure 5.23). For example, suppose we recognize the pattern of hydrogen lines in the spectrum of a distant object. We know the **rest wavelengths** of the hydrogen lines—that is, their wavelengths in stationary clouds of hydrogen gas—from laboratory experiments in which a tube of hydrogen gas is heated so that the wavelengths of the spectral lines can be measured. If the hydrogen lines from the object appear at longer wavelengths, then we know they are redshifted and the object is moving away from us. The larger the shift, the faster the object is moving. If the lines appear at shorter wavelengths, then we know they are blueshifted and the object is moving toward us.

THINK ABOUT IT

Suppose the hydrogen emission line with a rest wavelength of 121.6 nm (the transition from level 2 to level 1) appears at a wavelength of 120.5 nm in the spectrum of a particular star. Given that these wavelengths are in the ultraviolet, is the shifted wavelength closer to or farther from blue visible light? Why, then, do we say that this spectral line is *blueshifted?*

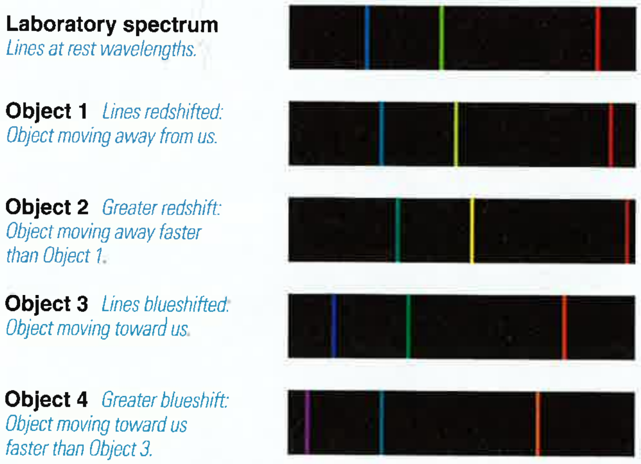
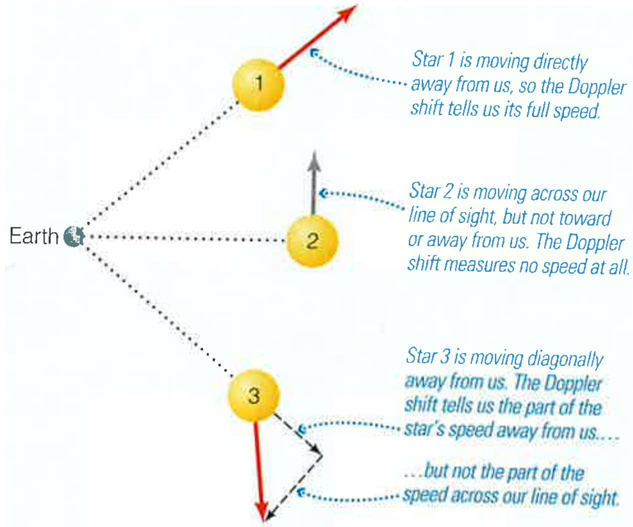


FIGURE 5.23 Interactive Figure Spectral lines provide the crucial reference points for measuring Doppler shifts.



Star 1 is moving directly away from us, so the Doppler shift tells us its full speed.

Star 2 is moving across our line of sight, but not toward or away from us. The Doppler shift measures no speed at all.

Star 3 is moving diagonally away from us. The Doppler shift tells us the part of the star's speed away from us. . .

. . .but not the part of the speed across our line of sight.

FIGURE 5.24 Interactive Figure The Doppler shift tells us only the portion of an object's speed that is directed toward or away from us. It does not give us any information about how fast an object is moving across our line of sight.

Notice that the Doppler shift tells us only the part of an object's full motion that is directed toward or away from us (the object's *radial* component of motion). Doppler shifts do not give us any information about how fast an object is moving across our line of sight (the object's *tangential* component of motion). For example, consider three stars all moving at the same speed, with one moving directly away from us, one moving across our line of sight, and one moving diagonally away from us (Figure 5.24). The Doppler shift will tell us the full speed of only the first star. It will not indicate any speed for the second star, because none of this star's motion is directed toward or away from us. For the third star, the Doppler shift will tell us only the part of the star's velocity that is directed away from us. To measure how fast an object is moving across our line of sight, we must observe it long enough to notice how its position gradually shifts across our sky.

How does light tell us the rotation rate of a distant object?

The Doppler effect not only tells us how fast a distant object is moving toward or away from us but also can reveal information about motion *within* the object. For example, suppose we look at spectral lines of a planet or star that happens to be rotating (Figure 5.25). As the object rotates, light from the part of the object rotating toward us will be blueshifted, light from the part rotating away from us will be redshifted, and light from the center of the object won't be shifted at all. The net effect, if we look at the whole object at once, is to make each spectral line appear *wider* than it would if the object were not rotating. The faster the object is rotating, the broader in wavelength the spectral lines become. We can therefore determine the rotation rate of a distant object by measuring the width of its spectral lines. We will see later that the Doppler effect on the spectra of celestial objects reveals even more information.

MATHEMATICAL INSIGHT 5.3

The Doppler Shift

As long as an object's radial velocity is small compared to the speed of light (less than a few percent of c), we can use a simple formula to calculate the radial velocity (toward or away from us) of an object from its Doppler shift:

$$\frac{v_{\text{rad}}}{c} = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}}$$

where v_{rad} is the radial velocity of the object, λ_{rest} is the rest wavelength of a particular spectral line, and λ_{shift} is the shifted wavelength of the same line. (And, as always, c is the speed of light.)

If the result is positive, the object has a redshift and is moving away from us. A negative result means that the object has a blueshift and is moving toward us.

EXAMPLE: The rest wavelength of one of the visible lines of hydrogen is 656.285 nm. This line is easily identifiable in the spectrum of the bright star Vega, but it appears at a wavelength of 656.255 nm. What is the radial velocity of Vega?

SOLUTION:

Step 1 Understand: We notice that the line's wavelength in Vega's spectrum is slightly shorter than its rest wavelength. Thus, the line is blueshifted and Vega's radial motion is *toward* us. We can calculate the radial velocity from the given formula.

Step 2 Solve: In the radial velocity formula, the rest wavelength is $\lambda_{\text{rest}} = 656.285$ nm. The shifted wavelength is the wavelength in Vega's spectrum, $\lambda_{\text{shift}} = 656.255$ nm. We find

$$\begin{aligned}\frac{v_{\text{rad}}}{c} &= \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}}\\ &= \frac{656.255\text{ nm} - 656.285\text{ nm}}{656.285\text{ nm}}\\ &= -4.5712 \times 10^{-5}\end{aligned}$$

Step 3 Explain: The answer we have found tells us Vega's radial velocity as a fraction of the speed of light; it is negative because Vega is moving toward us. To convert our answer to a velocity in km/s, we multiply by the speed of light:

$$\begin{aligned}v_{\text{rad}} &= -4.5712 \times 10^{-5} \times c\\ &= -4.5712 \times 10^{-5} \times (3 \times 10^{5}\text{ km/s})\\ &= -13.7\text{ km/s}\end{aligned}$$

Vega is moving *toward* us at 13.7 km/s. This speed is typical of stars in our neighborhood of the galaxy.

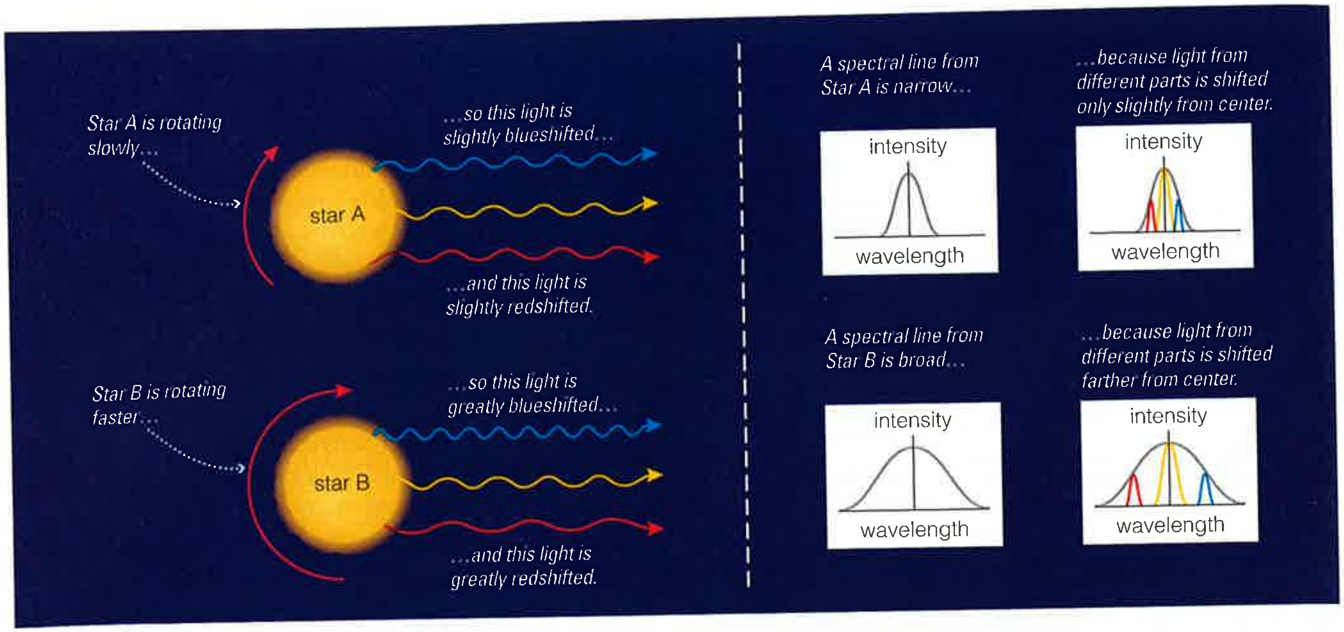


FIGURE 5.25 This diagram shows how the Doppler effect can tell us the rotation rate even of stars that appear as points of light to our telescopes. Rotation spreads the light of any spectral line over a range of wavelengths, so faster-rotating stars have broader spectral lines.

THE BIG PICTURE

Putting Chapter 5 into Context

This chapter was devoted to one essential purpose: understanding how we learn about the universe by observing the light of distant objects. "Big picture" ideas that will help you keep your understanding in perspective include the following:

- Light and matter interact in ways that allow matter to leave "fingerprints" on light. We can therefore learn a great deal about the objects we observe by carefully analyzing their light. Most of what we know about the universe comes from information that we receive from light.
- The visible light that our eyes can see is only a small portion of the complete electromagnetic spectrum. Different portions of the spectrum may contain different pieces of the story of a distant object, so it is important to study all forms of light.
- There is far more to light than meets the eye. By dispersing the light of a distant object into a spectrum, we can determine the object's composition, surface temperature, motion toward or away from us, rotation rate, and more.

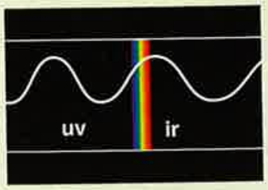
SUMMARY OF KEY CONCEPTS

5.1 LIGHT IN EVERYDAY LIFE

- **How do we experience light?** Light carries radiative energy that it can exchange with matter. **Power** is the *rate* of energy transfer, measured in **watts**: 1 watt = 1 joule/s. The colors of light contain a great deal of information about the matter with which it has interacted.
- **How do light and matter interact?** Matter can emit, absorb, transmit, or reflect (or scatter) light.

5.2 PROPERTIES OF LIGHT

- **What is light?** Light is an **electromagnetic wave**, but also comes in individual "pieces" called **photons**. Each photon has a precise wavelength, frequency, and energy: The shorter the wavelength, the higher the frequency and energy.
- **What is the electromagnetic spectrum?** In order of decreasing wavelength (increasing frequency and energy), the forms of light are **radio waves, microwaves, infrared, visible light, ultraviolet, X rays,** and **gamma rays.**



5.3 PROPERTIES OF MATTER

- **What is the structure of matter?** Ordinary matter made of **atoms**, which are made of **protons, neutrons,** and **electrons.** Atoms of different **chemical elements** have different numbers of protons. **Isotopes** of a particular chemical