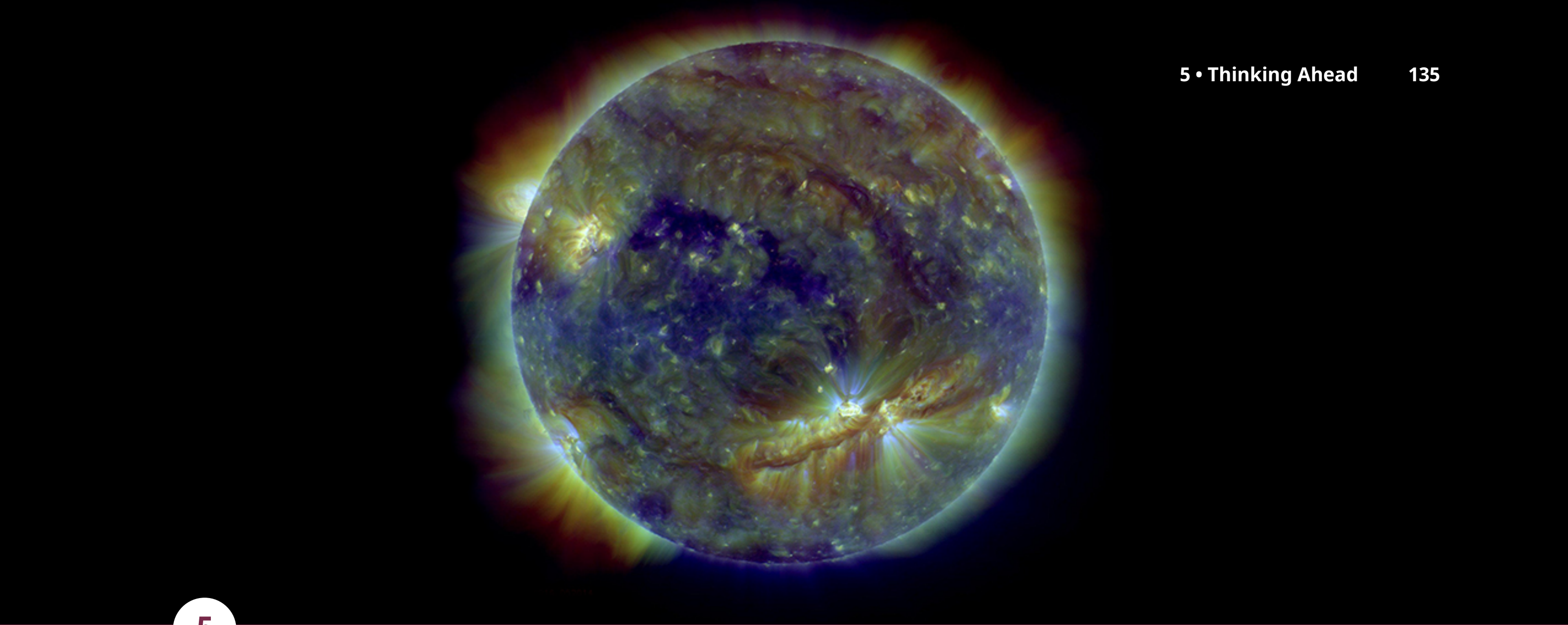

5

Radiation and Spectra

Figure 5.1 Our Sun in Ultraviolet Light. This photograph of the Sun was taken at several different wavelengths of ultraviolet, which our eyes cannot see, and then color coded so it reveals activity in our Sun’s atmosphere that cannot be observed in visible light. This is why it is important to observe the Sun and other astronomical objects in wavelengths other than the visible band of the spectrum. This image was taken by a satellite from above Earth’s atmosphere, which is necessary since Earth’s atmosphere absorbs much of the ultraviolet light coming from space. (credit: modification of work by NASA)

Chapter Outline

Thinking Ahead

The nearest star is so far away that the fastest spacecraft humans have built would take almost 100,000 years to get there. Yet we very much want to know what material this neighbor star is composed of and how it differs from our own Sun. How can we learn about the chemical makeup of stars that we cannot hope to visit or sample?

In astronomy, most of the objects that we study are completely beyond our reach. The temperature of the Sun is so high that a spacecraft would be fried long before it reached it, and the stars are much too far away to visit in our lifetimes with the technology now available. Even light, which travels at a speed of 300,000 kilometers per second (km/s), takes more than 4 years to reach us from the nearest star. If we want to learn about the Sun and stars, we must rely on techniques that allow us to analyze them from a distance.

5.1 The Behavior of Light

Learning Objectives

By the end of this section, you will be able to:

- Explain the evidence for Maxwell’s electromagnetic model of light
- Describe the relationship between wavelength, frequency, and speed of light
- Discuss the particle model of light and the definition of photon
- Explain how and why the amount of light we see from an object depends upon its distance

Coded into the light and other kinds of radiation that reach us from objects in the universe is a wide range of information about what those objects are like and how they work. If we can decipher this code and read the messages it contains, we can learn an enormous amount about the cosmos without ever having to leave Earth or its immediate environment.

The visible light and other radiation we receive from the stars and planets is generated by processes at the atomic level—by changes in the way the parts of an atom interact and move. Thus, to appreciate how light is generated, we must explore how atoms work. There is a bit of irony in the fact that in order to understand some of the largest structures in the universe, we must become acquainted with some of the smallest.

Notice that we have twice used the phrase “light and other radiation.” One of the key ideas explored in this chapter is that visible light is not unique; it is merely the most familiar example of a much larger family of radiation that can carry information to us.

The word “radiation” will be used frequently in this book, so it is important to understand what it means. In everyday language, “radiation” is often used to describe certain kinds of energetic subatomic particles released by radioactive materials in our environment. (An example is the kind of radiation used to treat some cancers.) But this is not what we mean when we use the word “radiation” in an astronomy text. *Radiation*, as used in this book, is a general term for waves (including light waves) that *radiate* outward from a source.

As we saw in Orbits and Gravity, Newton’s theory of gravity accounts for the motions of planets as well as objects on Earth. Application of this theory to a variety of problems dominated the work of scientists for nearly two centuries. In the nineteenth century, many physicists turned to the study of electricity and magnetism, which are intimately connected with the production of light.

The scientist who played a role in this field comparable to Newton’s role in the study of gravity was physicist James Clerk Maxwell, born and educated in Scotland (Figure 5.2). Inspired by a number of ingenious experiments that showed an intimate relationship between electricity and magnetism, Maxwell developed a theory that describes both electricity and magnetism with only a small number of elegant equations. It is this theory that gives us important insights into the nature and behavior of light.

Figure 5.2 James Clerk Maxwell (1831–1879). Maxwell unified the rules governing electricity and magnetism into a coherent theory.

Maxwell’s Theory of Electromagnetism

We will look at the structure of the atom in more detail later, but we begin by noting that the typical atom consists of several types of particles, a number of which have not only mass but an additional property called electric charge. In the nucleus (central part) of every atom are *protons*, which are positively charged; outside the nucleus are electrons, which have a negative charge.

Maxwell’s theory deals with these electric charges and their effects, especially when they are moving. In the vicinity of an electron charge, another charge feels a force of attraction or repulsion: opposite charges attract; like charges repel. When charges are not in motion, we observe only this electric attraction or repulsion. If charges are in motion, however (as they are inside every atom and in a wire carrying a current), then we measure another force called *magnetism*.

Magnetism was well known for much of recorded human history, but its cause was not understood until the nineteenth century. Experiments with electric charges demonstrated that magnetism was the result of moving charged particles. Sometimes, the motion is clear, as in the coils of heavy wire that make an industrial electromagnet. Other times, it is more subtle, as in the kind of magnet you buy in a hardware store, in which many of the electrons inside the atoms are spinning in roughly the same direction; it is the alignment of their motion that causes the material to become magnetic.

Physicists use the word *field* to describe the action of forces that one object exerts on other distant objects. For example, we say the Sun produces a *gravitational field* that controls Earth’s orbit, even though the Sun and Earth do not come directly into contact. Using this terminology, we can say that stationary electric charges produce *electric fields*, and moving electric charges also produce *magnetic fields*.

Actually, the relationship between electric and magnetic phenomena is even more profound. Experiments showed that changing magnetic fields could produce electric currents (and thus changing electric fields), and changing electric currents could in turn produce changing magnetic fields. So once begun, electric and magnetic field changes could continue to trigger each other.

Maxwell analyzed what would happen if electric charges were oscillating (moving constantly back and forth) and found that the resulting pattern of electric and magnetic fields would spread out and travel rapidly through space. Something similar happens when a raindrop strikes the surface of water or a frog jumps into a pond. The disturbance moves outward and creates a pattern we call a *wave* in the water (Figure 5.3). You might, at first, think that there must be very few situations in nature where electric charges oscillate, but this is not at all the case. As we shall see, atoms and molecules (which consist of charged particles) oscillate back and forth all the time. The resulting electromagnetic disturbances are among the most common phenomena in the universe.

Figure 5.3 Making Waves. An oscillation in a pool of water creates an expanding disturbance called a wave. (credit: modification of work by "vastateparksstaff"/Flickr)

Maxwell was able to calculate the speed at which an electromagnetic disturbance moves through space; he found that it is equal to the speed of light, which had been measured experimentally. On that basis, he speculated that light was one form of a family of possible electromagnetic disturbances called **electromagnetic radiation**, a conclusion that was again confirmed in laboratory experiments. When light (reflected from the pages of an astronomy textbook, for example) enters a human eye, its changing electric and magnetic fields stimulate nerve endings, which then transmit the information contained in these changing fields to the brain. The science of astronomy is primarily about analyzing radiation from distant objects to understand what they are and how they work.

The Wave-Like Characteristics of Light

The changing electric and magnetic fields in light are similar to the waves that can be set up in a quiet pool of water. In both cases, the disturbance travels rapidly outward from the point of origin and can use its energy to disturb other things farther away. (For example, in water, the expanding ripples moving away from our frog could disturb the peace of a dragonfly resting on a leaf in the same pool.) In the case of electromagnetic waves, the radiation generated by a transmitting antenna full of charged particles and moving electrons at your local radio station can, sometime later, disturb a group of electrons in your car radio antenna and bring you the news and weather while you are driving to class or work in the morning.

The waves generated by charged particles differ from water waves in some profound ways, however. Water waves require water to travel in. The sound waves we hear, to give another example, are pressure disturbances that require air to travel though. But electromagnetic waves do not require water or air: the fields generate each other and so can move through a vacuum (such as outer space). This was such a disturbing idea to nineteenth-century scientists that they actually made up a substance to fill all of space—one for which there was not a single shred of evidence—just so light waves could have something to travel through: they called it the *aether*. Today, we know that there is no aether and that electromagnetic waves have no trouble at all moving through empty space (as all the starlight visible on a clear night must surely be doing).

The other difference is that *all* electromagnetic waves move at the same speed in empty space (the speed of light—approximately 300,000 kilometers per second, or 300,000,000 meters per second, which can also be written as 3×10^8 m/s), which turns out to be the fastest possible speed in the universe. No matter where electromagnetic waves are generated from and no matter what other properties they have, when they are moving (and not interacting with matter), they move at the speed of light. Yet you know from everyday experience that there are different kinds of light. For example, we perceive that light waves differ from one another in a property we call color. Let’s see how we can denote the differences among the whole broad family of electromagnetic waves.

The nice thing about a wave is that it is a repeating phenomenon. Whether it is the up-and-down motion of a water wave or the changing electric and magnetic fields in a wave of light, the pattern of disturbance repeats in a cyclical way. Thus, any wave motion can be characterized by a series of crests and troughs (Figure 5.4). Moving from one crest through a trough to the next crest completes one cycle. The horizontal length covered by one cycle is called the **wavelength**. Ocean waves provide an analogy: the wavelength is the distance that separates successive wave crests.

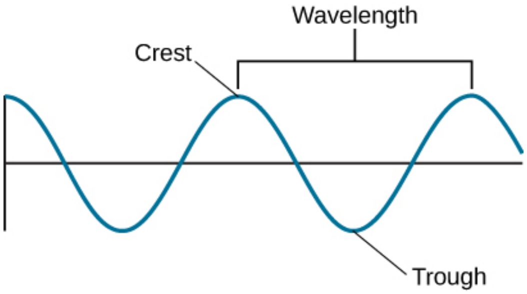

Figure 5.4 Characterizing Waves. Electromagnetic radiation has wave-like characteristics. The wavelength (λ) is the distance between crests, the frequency (*f*) is the number of cycles per second, and the speed (*c*) is the distance the wave covers during a specified period of time (e.g., kilometers per second).

For visible light, our eyes perceive different wavelengths as different colors: red, for example, is the longest visible wavelength, and violet is the shortest. The main colors of visible light from longest to shortest wavelength can be remembered using the mnemonic ROY G BIV—for Red, Orange, Yellow, Green, Blue, Indigo, and Violet. Other invisible forms of electromagnetic radiation have different wavelengths, as we will see in the next section.

We can also characterize different waves by their **frequency**, the number of wave cycles that pass by per second. If you count 10 crests moving by each second, for example, then the frequency is 10 cycles per second (cps). In honor of Heinrich Hertz, the physicist who—inspired by Maxwell’s work—discovered radio waves, a cps is also called a *hertz* (Hz). Take a look at your radio, for example, and you will see the channel assigned to each radio station is characterized by its frequency, usually in units of KHz (kilohertz, or thousands of hertz) or MHz (megahertz, or millions of hertz).

Wavelength (λ) and frequency (*f*) are related because all electromagnetic waves travel at the same speed. To see how this works, imagine a parade in which everyone is forced by prevailing traffic conditions to move at exactly the same speed. You stand on a corner and watch the waves of marchers come by. First you see row after row of miniature ponies. Because they are not very large and, therefore, have a shorter wavelength, a good number of the ponies can move past you each minute; we can say they have a high frequency. Next, however, come several rows of circus elephants. The elephants are large and marching at the same speed as the ponies, so far fewer of them can march past you per minute: Because they have a wider spacing (longer wavelength), they represent a lower frequency.

The formula for this relationship can be expressed as follows: for any wave motion, the speed at which a wave moves equals the frequency times the wavelength. Waves with longer wavelengths have lower frequencies. Mathematically, we can express this as

$$c = \lambda f$$

where the Greek letter for “l”—lambda, λ—is used to denote wavelength and *c* is the scientific symbol for the speed of light. Solving for the wavelength, this is expressed as:

$$\lambda = \frac{c}{f}.$$

EXAMPLE 5.1

Deriving and Using the Wave Equation

The equation for the relationship between the speed and other characteristics of a wave can be derived from our basic understanding of motion. The average speed of anything that is moving is:

$$\text{average speed} = \frac{\text{distance}}{\text{time}}$$

(So, for example, a car on the highway traveling at a speed of 100 km/h covers 100 km during the time of 1 h.) For an electromagnetic wave to travel the distance of one of its wavelengths, λ, at the speed of light, *c*, we have $c = \lambda / t$. The frequency of a wave is the number of cycles per second. If a wave has a frequency of a million cycles per second, then the time for each cycle to go by is a millionth of a second. So, in general, $t = 1/f$. Substituting into our wave equation, we get $c = \lambda \times f$. Now let's use this to calculate an example. What is the wavelength of visible light that has a frequency of 5.66×10^{14} Hz?

Solution

Solving the wave equation for wavelength, we find:

$$\lambda = \frac{c}{f}$$

Substituting our values gives:

$$\lambda = \frac{3.00 \times 10^{8}\ \text{m/s}}{5.66 \times 10^{14}\ \text{Hz}} = 5.30 \times 10^{-7}\ \text{m}$$

This answer can also be written as 530 nm, which is in the yellow-green part of the visible spectrum (nm stands for nanometers, where the term "nano" means "billionths").

Check Your Learning

"Tidal waves," or tsunamis, are waves caused by earthquakes that travel rapidly through the ocean. If a tsunami travels at the speed of 600 km/h and approaches a shore at a rate of one wave crest every 15 min (4 waves/h), what would be the distance between those wave crests at sea?

Answer:

$$\lambda = \frac{600\ \text{km/h}}{4\ \text{waves/h}} = 150\ \text{km}$$

Light as a Photon

The electromagnetic wave model of light (as formulated by Maxwell) was one of the great triumphs of nineteenth-century science. In 1887, when Heinrich Hertz actually made invisible electromagnetic waves (what today are called radio waves) on one side of a room and detected them on the other side, it ushered in a new era that led to the modern age of telecommunications. His experiment ultimately led to the technologies of television, cell phones, and today's wireless networks around the globe.

However, by the beginning of the twentieth century, more sophisticated experiments had revealed that light behaves in certain ways that cannot be explained by the wave model. Reluctantly, physicists had to accept that sometimes light behaves more like a "particle"—or at least a self-contained packet of energy—than a wave. We call such a packet of electromagnetic energy a **photon**.

The fact that light behaves like a wave in certain experiments and like a particle in others was a very surprising and unlikely idea. After all, our common sense says that waves and particles are opposite concepts. On one hand, a wave is a repeating disturbance that, by its very nature, is not in only one place, but spreads out. A particle, on the other hand, is something that can be in only one place at any given time. Strange as it sounds, though, countless experiments now confirm that electromagnetic radiation can sometimes behave like a wave and at other times like a particle.

Then, again, perhaps we shouldn’t be surprised that something that always travels at the “speed limit” of the universe and doesn’t need a medium to travel through might not obey our everyday common sense ideas. The confusion that this wave-particle duality of light caused in physics was eventually resolved by the introduction of a more complicated theory of waves and particles, now called quantum mechanics. (This is one of the most interesting fields of modern science, but it is mostly beyond the scope of our book. If you are interested in it, see some of the suggested resources at the end of this chapter.)

In any case, you should now be prepared when scientists (or the authors of this book) sometimes discuss electromagnetic radiation as if it consisted of waves and at other times refer to it as a stream of photons. A photon (being a packet of energy) carries a specific amount of energy. We can use the idea of energy to connect the photon and wave models. How much energy a photon has depends on its frequency when you think about it as a wave. A low-energy radio wave has a low frequency as a wave, while a high-energy X-ray at your dentist’s office is a high-frequency wave. Among the colors of visible light, violet-light photons have the highest energy and red-light photons have the lowest.

Test whether the connection between photons and waves is clear to you. In the above example, which photon would have the longer wavelength as a wave: the radio wave or the X-ray? If you answered the radio wave, you are correct. Radio waves have a lower frequency, so the wave cycles are longer (they are elephants, not miniature ponies).

Propagation of Light

Let’s think for a moment about how light from a lightbulb moves through space. As waves expand, they travel away from the bulb, not just toward your eyes but in all directions. They must therefore cover an ever-widening space. Yet the total amount of light available can’t change once the light has left the bulb. This means that, as the same expanding shell of light covers a larger and larger area, there must be less and less of it in any given place. Light (and all other electromagnetic radiation) gets weaker and weaker as it gets farther from its source.

The increase in the area that the light must cover is proportional to the square of the distance that the light has traveled (Figure 5.5). If we stand twice as far from the source, our eyes will intercept two-squared (2 × 2), or four times less light. If we stand 10 times farther from the source, we get 10-squared, or 100 times less light. You can see how this weakening means trouble for sources of light at astronomical distances. One of the nearest stars, Alpha Centauri A, emits about the same total energy as the Sun. But it is about 270,000 times farther away, and so it appears about 73 billion times fainter. No wonder the stars, which close-up would look more or less like the Sun, look like faint pinpoints of light from far away.

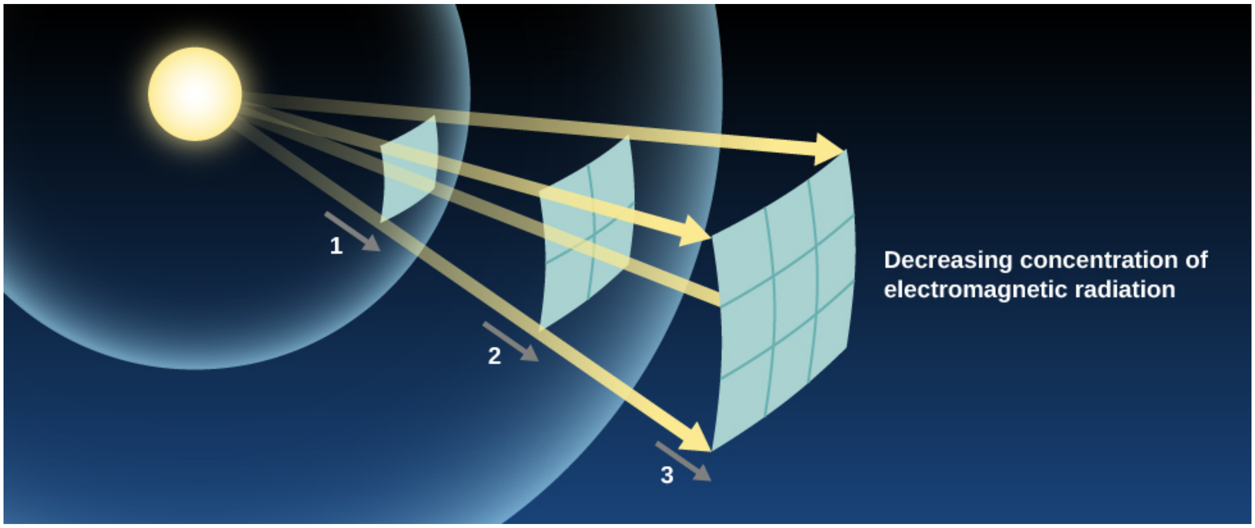

Figure 5.5 Inverse Square Law for Light. As light radiates away from its source, it spreads out in such a way that the energy per unit area (the amount of energy passing through one of the small squares) decreases as the square of the distance from its source.

This idea—that the apparent brightness of a source (how bright it looks to us) gets weaker with distance in the way we have described—is known as the **inverse square law** for light propagation. In this respect, the propagation of light is similar to the effects of gravity. Remember that the force of gravity between two attracting masses is also inversely proportional to the square of their separation.

EXAMPLE 5.2

The Inverse Square Law for Light

The intensity of a 120-W lightbulb observed from a distance 2 m away is 2.4 W/m^2. What would be the intensity if this distance was doubled?

Solution

If we move twice as far away, then the answer will change according to the inverse square of the distance, so the new intensity will be $(1/2)^2 = 1/4$ of the original intensity, or 0.6 W/m^2.

Check Your Learning

How many times brighter or fainter would a star appear if it were moved to:

a. twice its present distance?
b. ten times its present distance?
c. half its present distance?

Answer:

a. $\left(\frac{1}{2}\right)^2 = \frac{1}{4}$; b. $\left(\frac{1}{10}\right)^2 = \frac{1}{100}$; c. $\left(\frac{1}{1/2}\right)^2 = 4$

5.2 The Electromagnetic Spectrum

Learning Objectives

By the end of this section, you will be able to:

- Understand the bands of the electromagnetic spectrum and how they differ from one another
- Understand how each part of the spectrum interacts with Earth’s atmosphere
- Explain how and why the light emitted by an object depends on its temperature

Objects in the universe send out an enormous range of electromagnetic radiation. Scientists call this range the **electromagnetic spectrum**, which they have divided into a number of categories. The spectrum is shown in Figure 5.6, with some information about the waves in each part or band.

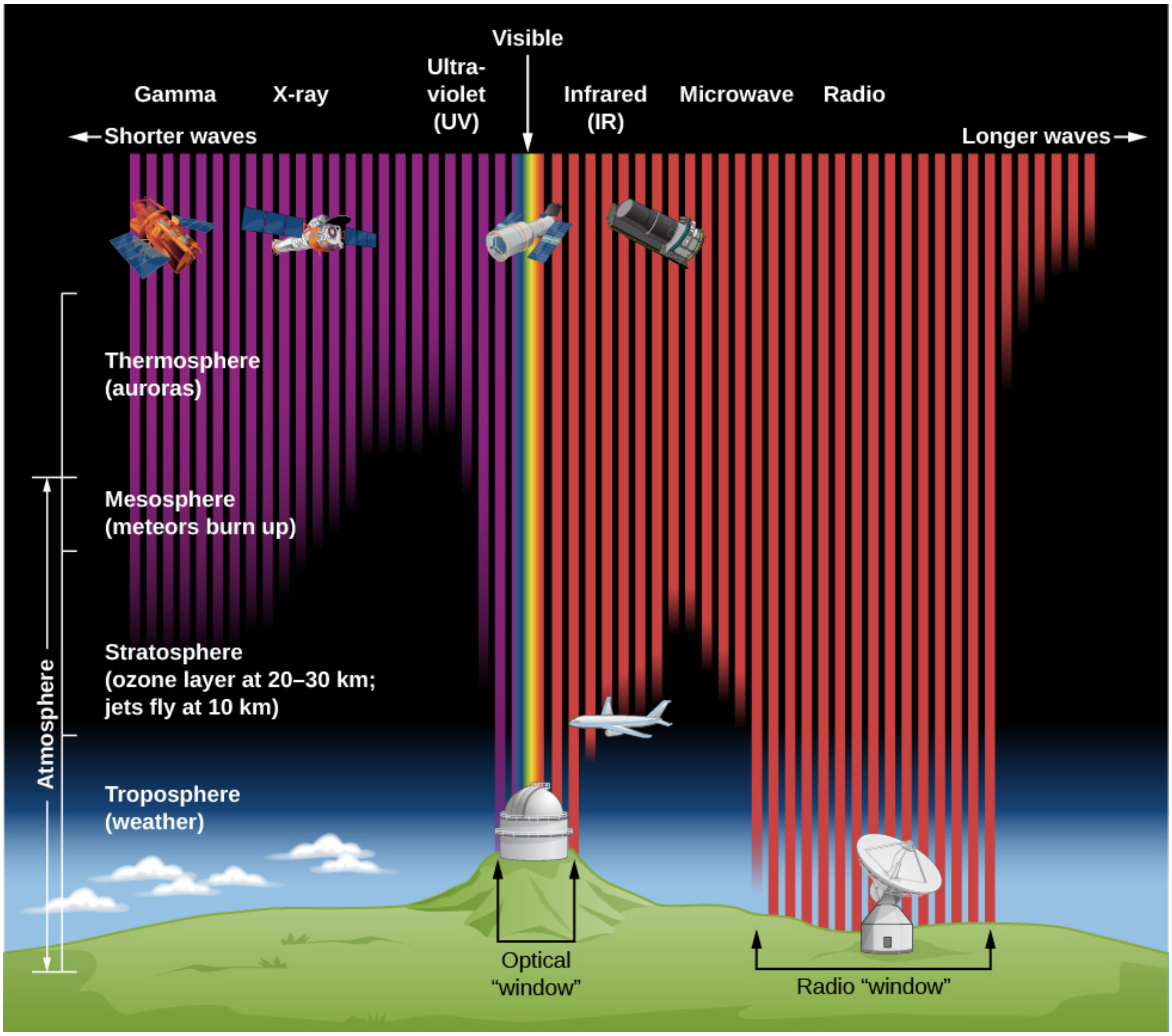

Figure 5.6 Radiation and Earth's Atmosphere. This figure shows the bands of the electromagnetic spectrum and how well Earth's atmosphere transmits them. Note that high-frequency waves from space do not make it to the surface and must therefore be observed from space. Some infrared and microwaves are absorbed by water and thus are best observed from high altitudes. Low-frequency radio waves are blocked by Earth's ionosphere. (credit: modification of work by STScI/JHU/NASA)

Types of Electromagnetic Radiation

Electromagnetic radiation with the shortest wavelengths, no longer than 0.01 nanometer, is categorized as **gamma rays** (1 nanometer = 10^{-9} meters; see Appendix D). The name *gamma* comes from the third letter of the Greek alphabet: gamma rays were the third kind of radiation discovered coming from radioactive atoms when physicists first investigated their behavior. Because gamma rays carry a lot of energy, they can be dangerous for living tissues. Gamma radiation is generated deep in the interior of stars, as well as by some of the most violent phenomena in the universe, such as the deaths of stars and the merging of stellar corpses. Gamma rays coming to Earth are absorbed by our atmosphere before they reach the ground (which is a good thing for our health); thus, they can only be studied using instruments in space.

Electromagnetic radiation with wavelengths between 0.01 nanometer and 20 nanometers is referred to as **X-rays**. Being more energetic than visible light, X-rays are able to penetrate soft tissues but not bones, and so allow us to make images of the shadows of the bones inside us. While X-rays can penetrate a short length of human flesh, they are stopped by the large numbers of atoms in Earth’s atmosphere with which they interact. Thus, X-ray astronomy (like gamma-ray astronomy) could not develop until we invented ways of sending instruments above our atmosphere (Figure 5.7).

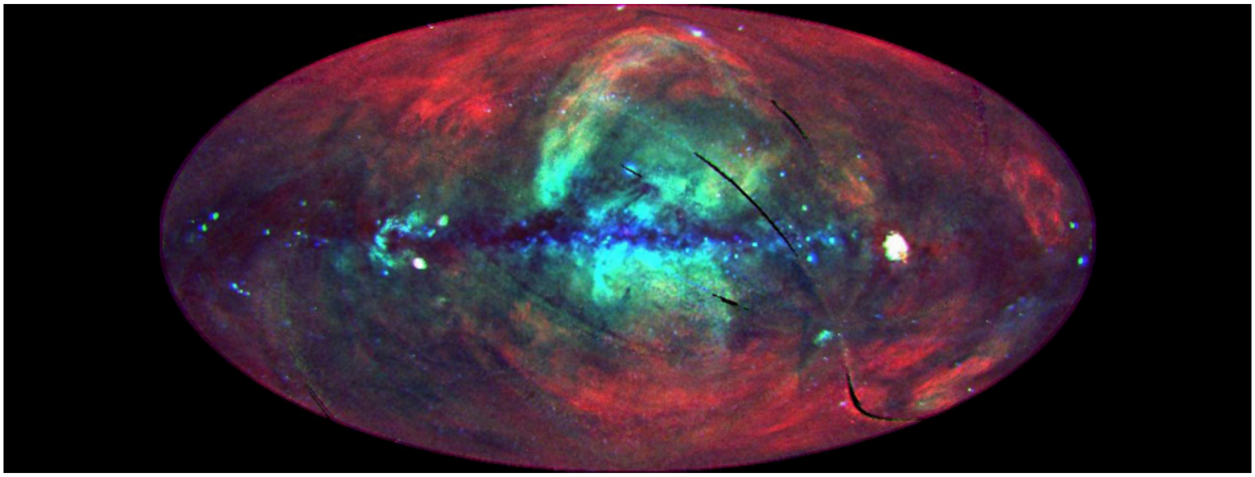

Figure 5.7 X-Ray Sky. This is a map of the sky tuned to certain types of X-rays (seen from above Earth’s atmosphere). The map tilts the sky so that the disk of our Milky Way Galaxy runs across its center. It was constructed and artificially colored from data gathered by the European ROSAT satellite. Each color (red, yellow, and blue) shows X-rays of different frequencies or energies. For example, red outlines the glow from a hot local bubble of gas all around us, blown by one or more exploding stars in our cosmic vicinity. Yellow and blue show more distant sources of X-rays, such as remnants of other exploded stars or the active center of our Galaxy (in the middle of the picture). (credit: modification of work by NASA)

Radiation intermediate between X-rays and visible light is **ultraviolet** (meaning higher energy than violet). Outside the world of science, ultraviolet light is sometimes called “black light” because our eyes cannot see it. Ultraviolet radiation is mostly blocked by the ozone layer of Earth’s atmosphere, but a small fraction of ultraviolet rays from our Sun do penetrate to cause sunburn or, in extreme cases of overexposure, skin cancer in human beings. Ultraviolet astronomy is also best done from space.

Electromagnetic radiation with wavelengths between roughly 400 and 700 nm is called **visible light** because these are the waves that human vision can perceive. This is also the band of the electromagnetic spectrum that most readily reaches Earth’s surface. These two observations are not coincidental: human eyes evolved to see the kinds of waves that arrive from the Sun most effectively. Visible light penetrates Earth’s atmosphere effectively, except when it is temporarily blocked by clouds.

Between visible light and radio waves are the wavelengths of **infrared** or heat radiation. Astronomer William Herschel first discovered infrared in 1800 while trying to measure the temperatures of different colors of sunlight spread out into a spectrum. He noticed that when he accidently positioned his thermometer beyond the reddest color, it still registered heating due to some invisible energy coming from the Sun. This was the first hint about the existence of the other (invisible) bands of the electromagnetic spectrum, although it would take many decades for our full understanding to develop.

A heat lamp radiates mostly infrared radiation, and the nerve endings in our skin are sensitive to this band of the electromagnetic spectrum. Infrared waves are absorbed by water and carbon dioxide molecules, which are more concentrated low in Earth’s atmosphere. For this reason, infrared astronomy is best done from high mountaintops, high-flying airplanes, and spacecraft.

After infrared comes the familiar **microwave**, used in short-wave communication and microwave ovens. (Wavelengths vary from 1 millimeter to 1 meter and are absorbed by water vapor, which makes them effective in heating foods.) The “micro-” prefix refers to the fact that microwaves are small in comparison to radio waves, the next on the spectrum. You may remember that tea—which is full of water—heats up quickly in your microwave oven, while a ceramic cup—from which water has been removed by baking—stays cool in comparison.

All electromagnetic waves longer than microwaves are called **radio waves**, but this is so broad a category that we generally divide it into several subsections. Among the most familiar of these are radar waves, which are used in radar guns by traffic officers to determine vehicle speeds, and AM radio waves, which were the first to be developed for broadcasting. The wavelengths of these different categories range from over a meter to hundreds of meters, and other radio radiation can have wavelengths as long as several kilometers.

With such a wide range of wavelengths, not all radio waves interact with Earth's atmosphere in the same way. FM and TV waves are not absorbed and can travel easily through our atmosphere. AM radio waves are absorbed or reflected by a layer in Earth's atmosphere called the ionosphere (the ionosphere is a layer of charged particles at the top of our atmosphere, produced by interactions with sunlight and charged particles that are ejected from the Sun).

We hope this brief survey has left you with one strong impression: although visible light is what most people associate with astronomy, the light that our eyes can see is only a tiny fraction of the broad range of waves generated in the universe. Today, we understand that judging some astronomical phenomenon by using only the light we can see is like hiding under the table at a big dinner party and judging all the guests by nothing but their shoes. There's a lot more to each person than meets our eye under the table. It is very important for those who study astronomy today to avoid being "visible light chauvinists"—to respect only the information seen by their eyes while ignoring the information gathered by instruments sensitive to other bands of the electromagnetic spectrum.

Table 5.1 summarizes the bands of the electromagnetic spectrum and indicates the temperatures and typical astronomical objects that emit each kind of electromagnetic radiation. While at first, some of the types of radiation listed in the table may seem unfamiliar, you will get to know them better as your astronomy course continues. You can return to this table as you learn more about the types of objects astronomers study.

Types of Electromagnetic Radiation

Type of Radiation	Wavelength Range (nm)	Radiated by Objects at This Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Produced in nuclear reactions; require very high-energy processes
X-rays	0.01–20	10^6–10^8 K	Gas in clusters of galaxies, supernova remnants, solar corona
Ultraviolet	20–400	10^4–10^6 K	Supernova remnants, very hot stars
Visible	400–700	10^3–10^4 K	Stars
Infrared	10^3–10^6	10–10^3 K	Cool clouds of dust and gas, planets, moons
Microwave	10^6–10^9	Less than 10 K	Active galaxies, pulsars, cosmic background radiation
Radio	More than 10^9	Less than 10 K	Supernova remnants, pulsars, cold gas

Table 5.1

Radiation and Temperature

Some astronomical objects emit mostly infrared radiation, others mostly visible light, and still others mostly ultraviolet radiation. What determines the type of electromagnetic radiation emitted by the Sun, stars, and other dense astronomical objects? The answer often turns out to be their *temperature*.

At the microscopic level, everything in nature is in motion. A solid is composed of molecules and atoms in continuous vibration: they move back and forth in place, but their motion is much too small for our eyes to make out. A gas consists of atoms and/or molecules that are flying about freely at high speed, continually bumping into one another and bombarding the surrounding matter. The hotter the solid or gas, the more rapid the motion of its molecules or atoms. The temperature of something is thus a measure of the average motion energy of the particles that make it up.

This motion at the microscopic level is responsible for much of the electromagnetic radiation on Earth and in the universe. As atoms and molecules move about and collide, or vibrate in place, their electrons give off electromagnetic radiation. The characteristics of this radiation are determined by the temperature of those atoms and molecules. In a hot material, for example, the individual particles vibrate in place or move rapidly from collisions, so the emitted waves are, on average, more energetic. And recall that higher energy waves have a higher frequency. In very cool material, the particles have low-energy atomic and molecular motions and thus generate lower-energy waves.

LINK TO LEARNING

Check out the NASA briefing (https://openstax.org/l/30elmagsp1) or NASA's 5-minute introductory video (https://openstax.org/l/30elmagsp2) to learn more about the electromagnetic spectrum.

Radiation Laws

To understand, in more quantitative detail, the relationship between temperature and electromagnetic radiation, we imagine an idealized object called a **blackbody**. Such an object (unlike your sweater or your astronomy instructor's head) does not reflect or scatter any radiation, but absorbs all the electromagnetic energy that falls onto it. The energy that is absorbed causes the atoms and molecules in it to vibrate or move around at increasing speeds. As it gets hotter, this object will radiate electromagnetic waves until absorption and radiation are in balance. We want to discuss such an idealized object because, as you will see, stars behave in very nearly the same way.

The radiation from a blackbody has several characteristics, as illustrated in Figure 5.8. The graph shows the power emitted at each wavelength by objects of different temperatures. In science, the word *power* means the energy coming off per second (and it is typically measured in *watts*, which you are probably familiar with from buying lightbulbs).

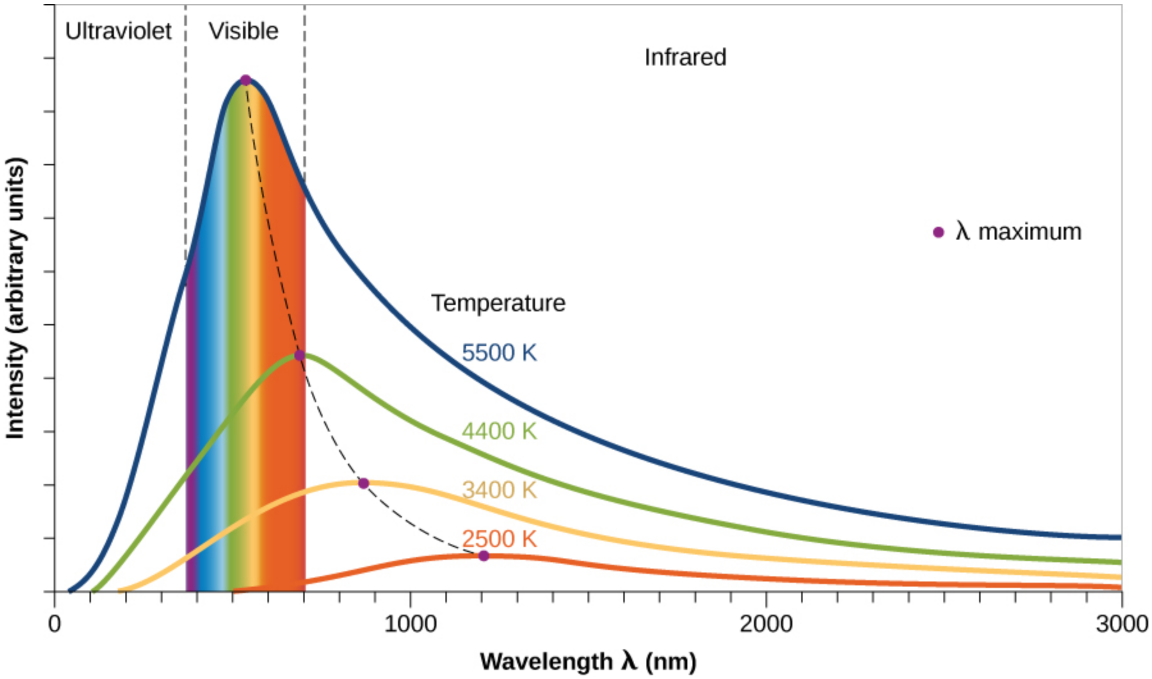

Figure 5.8 Radiation Laws Illustrated. This graph shows in arbitrary units how many photons are given off at each wavelength for objects at four different temperatures. The wavelengths corresponding to visible light are shown by the colored bands. Note that at hotter temperatures, more energy (in the form of photons) is emitted at all wavelengths. The higher the temperature, the shorter the wavelength at which the peak amount of energy is radiated (this is known as Wien's law).

First of all, notice that the curves show that, at each temperature, our blackbody object emits radiation (photons) at all wavelengths (all colors). This is because in any solid or denser gas, some molecules or atoms vibrate or move between collisions slower than average and some move faster than average. So when we look at the electromagnetic waves emitted, we find a broad range, or spectrum, of energies and wavelengths. More energy is emitted at the average vibration or motion rate (the highest part of each curve), but if we have a large number of atoms or molecules, some energy will be detected at each wavelength.

Second, note that an object at a higher temperature emits more power at all wavelengths than does a cooler one. In a hot gas (the taller curves in Figure 5.8), for example, the atoms have more collisions and give off more energy. In the real world of stars, this means that hotter stars give off more energy at every wavelength than do cooler stars.

Third, the graph shows us that the higher the temperature, the shorter the wavelength at which the maximum power is emitted. Remember that a shorter wavelength means a higher frequency and energy. It makes sense, then, that hot objects give off a larger fraction of their energy at shorter wavelengths (higher energies) than do cool objects. You may have observed examples of this rule in everyday life. When a burner on an electric stove is turned on low, it emits only heat, which is infrared radiation, but does not glow with visible light. If the burner is set to a higher temperature, it starts to glow a dull red. At a still-higher setting, it glows a brighter orange-red (shorter wavelength). At even higher temperatures, which cannot be reached with ordinary stoves, metal can appear brilliant yellow or even blue-white.

We can use these ideas to come up with a rough sort of "thermometer" for measuring the temperatures of stars. Because many stars give off most of their energy in visible light, the color of light that dominates a star's appearance is a rough indicator of its temperature. If one star looks red and another looks blue, which one has the higher temperature? Because blue is the shorter-wavelength color, it is the sign of a hotter star. (Note that the temperatures we associate with different colors in science are not the same as the ones artists use. In art, red is often called a "hot" color and blue a "cool" color. Likewise, we commonly see red on faucet or air conditioning controls to indicate hot temperatures and blue to indicate cold temperatures. Although these are common uses to us in daily life, in nature, it's the other way around.)

We can develop a more precise star thermometer by measuring how much energy a star gives off at each wavelength and by constructing diagrams like Figure 5.8. The location of the peak (or maximum) in the power curve of each star can tell us its temperature. The average temperature at the surface of the Sun, which is where the radiation that we see is emitted, turns out to be 5800 K. (Throughout this text, we use the kelvin or absolute temperature scale. On this scale, water freezes at 273 K and boils at 373 K. All molecular motion ceases at 0 K. The various temperature scales are described in Appendix D.) There are stars cooler than the Sun and stars hotter than the Sun.

The wavelength at which maximum power is emitted can be calculated according to the equation

$$\lambda_{\text{max}} = \frac{3 \times 10^6}{T}$$

where the wavelength is in nanometers (one billionth of a meter) and the temperature is in K (the constant 3 x 10^6 has units of nm × K). This relationship is called **Wien’s law**. For the Sun, the wavelength at which the maximum energy is emitted is 520 nanometers, which is near the middle of that portion of the electromagnetic spectrum called visible light. Characteristic temperatures of other astronomical objects, and the wavelengths at which they emit most of their power, are listed in Table 5.1.

EXAMPLE 5.3

Calculating the Temperature of a Blackbody

We can use Wien’s law to calculate the temperature of a star provided we know the wavelength of peak intensity for its spectrum. If the emitted radiation from a red dwarf star has a wavelength of maximum power at 1200 nm, what is the temperature of this star, assuming it is a blackbody?

Solution

Solving Wien’s law for temperature gives:

$$T = \frac{3 \times 10^6 \text{ nm K}}{\lambda_{\text{max}}} = \frac{3 \times 10^6 \text{ nm K}}{1200 \text{ nm}} = 2500 \text{ K}$$

Check Your Learning

What is the temperature of a star whose maximum light is emitted at a much shorter wavelength of 290 nm?

Answer:

$$T = \frac{3 \times 10^6 \text{ nm K}}{\lambda_{\text{max}}} = \frac{3 \times 10^6 \text{ nm K}}{290 \text{ nm}} = 10{,}300 \text{ K}$$

Since this star has a peak wavelength that is at a shorter wavelength (in the ultraviolet part of the spectrum) than that of our Sun (in the visible part of the spectrum), it should come as no surprise that its surface temperature is much hotter than our Sun’s.

We can also describe our observation that hotter objects radiate more power at all wavelengths in a mathematical form. If we sum up the contributions from all parts of the electromagnetic spectrum, we obtain the total energy emitted by a blackbody. What we usually measure from a large object like a star is the **energy flux**, the power emitted per square meter. The word *flux* means “flow” here: we are interested in the flow of power into an area (like the area of a telescope mirror). It turns out that the energy flux from a blackbody at temperature *T* is proportional to the fourth power of its absolute temperature. This relationship is known as the **Stefan-Boltzmann law** and can be written in the form of an equation as

$$F = \sigma T^4$$

where *F* stands for the energy flux (in units of watts per square meter), T is given in Kelvins, and σ (Greek letter sigma) is a constant number (5.67×10^{-8}).

Notice how impressive this result is. Increasing the temperature of a star would have a tremendous effect on the power it radiates. If the Sun, for example, were twice as hot—that is, if it had a temperature of 11,600 K—it would radiate 2^4, or 16 times more power than it does now. Tripling the temperature would raise the power output 81 times. Hot stars really shine away a tremendous amount of energy.

EXAMPLE 5.4

Calculating the Power of a Star

While energy flux tells us how much power a star emits per square meter, we would often like to know how much total power is emitted by the star. We can determine that by multiplying the energy flux by the number of square meters on the surface of the star. Stars are mostly spherical, so we can use the formula $4\pi R^2$ for the surface area, where *R* is the radius of the star. The total power emitted by the star (which we call the star's "absolute luminosity") can be found by multiplying the formula for energy flux and the formula for the surface area:

$$L = 4\pi R^2 \sigma T^4$$

Two stars have the same size and are the same distance from us. Star A has a surface temperature of 6000 K, and star B has a surface temperature twice as high, 12,000 K. How much more luminous is star B compared to star A?

Solution

$$L_A = 4\pi {R_A}^2 \sigma {T_A}^4 \text{ and } L_B = 4\pi {R_B}^2 \sigma {T_B}^4$$

Take the ratio of the luminosity of Star A to Star B:

$$\frac{L_B}{L_A} = \frac{4\pi {R_B}^2 \sigma {T_B}^4}{4\pi {R_A}^2 \sigma {T_A}^4} = \frac{{R_B}^2 {T_B}^4}{{R_A}^2 {T_A}^4}$$

Because the two stars are the same size, $R_A = R_B$, leaving

$$\frac{{T_B}^4}{{T_A}^4} = \frac{(12{,}000 \text{ K})^4}{(6000 \text{ K})^4} = 2^4 = 16$$

Check Your Learning

Two stars with identical diameters are the same distance away. One has a temperature of 8700 K and the other has a temperature of 2900 K. Which is brighter? How much brighter is it?

Answer:

The 8700 K star has triple the temperature, so it is $3^4 = 81$ times brighter.

LINK TO LEARNING

You can use the Blackbody Spectrum simulator (https://openstax.org/l/30blackbodysim) to explore the relationship between an object's temperature, peak wavelength, overall brightness, and apparent color.

5.3 Spectroscopy in Astronomy

Learning Objectives

By the end of this section, you will be able to:

- Describe the properties of light
- Explain how astronomers learn the composition of a gas by examining its spectral lines
- Discuss the various types of spectra

Electromagnetic radiation carries a lot of information about the nature of stars and other astronomical objects. To extract this information, however, astronomers must be able to study the amounts of energy we receive at different wavelengths of light in fine detail. Let’s examine how we can do this and what we can learn.

Properties of Light

Light exhibits certain behaviors that are important to the design of telescopes and other instruments. For example, light can be *reflected* from a surface. If the surface is smooth and shiny, as with a mirror, the direction of the reflected light beam can be calculated accurately from knowledge of the shape of the reflecting surface. Light is also bent, or *refracted*, when it passes from one kind of transparent material into another—say, from the air into a glass lens.

Reflection and refraction of light are the basic properties that make possible all *optical* instruments (devices that help us to see things better)—from eyeglasses to giant astronomical telescopes. Such instruments are generally combinations of glass lenses, which bend light according to the principles of refraction, and curved mirrors, which depend on the properties of reflection. Small optical devices, such as eyeglasses or binoculars, generally use lenses, whereas large telescopes depend almost entirely on mirrors for their main optical elements. We will discuss astronomical instruments and their uses more fully in Astronomical Instruments. For now, we turn to another behavior of light, one that is essential for the decoding of light.

In 1672, in the first paper that he submitted to the Royal Society, Sir Isaac Newton described an experiment in which he permitted sunlight to pass through a small hole and then through a prism. Newton found that sunlight, which looks white to us, is actually made up of a mixture of all the colors of the rainbow (Figure 5.9).

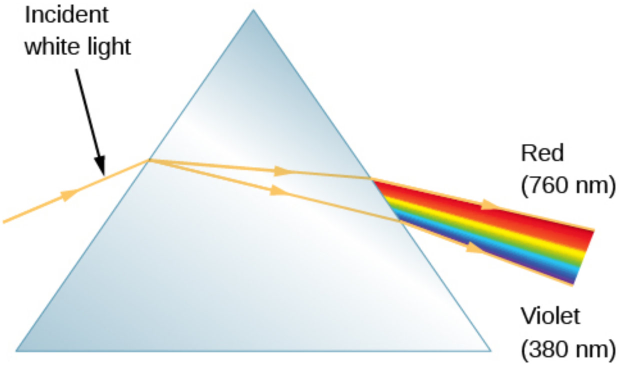

Figure 5.9 Action of a Prism. When we pass a beam of white sunlight through a prism, we see a rainbow-colored band of light that we call a continuous spectrum.

Figure 5.9 shows how light is separated into different colors with a prism—a piece of glass in the shape of a triangle with refracting surfaces. Upon entering one face of the prism, the path of the light is refracted (bent), but not all of the colors are bent by the same amount. The bending of the beam depends on the wavelength of the light as well as the properties of the material, and as a result, different wavelengths (or colors of light) are bent by different amounts and therefore follow slightly different paths through the prism. The violet light is bent more than the red. This phenomenon is called **dispersion** and explains Newton’s rainbow experiment.

Upon leaving the opposite face of the prism, the light is bent again and further dispersed. If the light leaving the prism is focused on a screen, the different wavelengths or colors that make up white light are lined up side by side just like a rainbow (Figure 5.10). (In fact, a rainbow is formed by the dispersion of light though raindrops; see The Rainbow feature box.) Because this array of colors is a spectrum of light, the instrument used to disperse the light and form the spectrum is called a **spectrometer**.

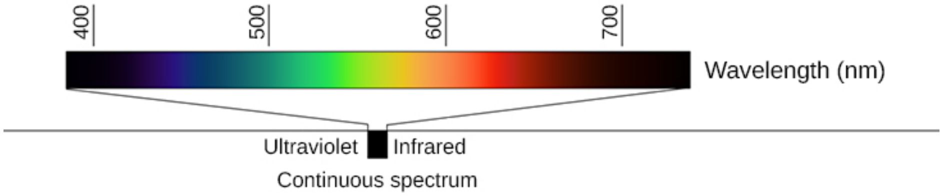

Figure 5.10 Continuous Spectrum. When white light passes through a prism, it is dispersed and forms a continuous spectrum of all the colors. Although it is hard to see in this printed version, in a well-dispersed spectrum, many subtle gradations in color are visible as your eye scans from one end (violet) to the other (red).

The Value of Stellar Spectra

When Newton described the laws of refraction and dispersion in optics, and observed the solar spectrum, all he could see was a continuous band of colors. If the spectrum of the white light from the Sun and stars were simply a continuous rainbow of colors, astronomers would have little interest in the detailed study of a star's spectrum once they had learned its average surface temperature. In 1802, however, William Wollaston built an improved spectrometer that included a lens to focus the Sun's spectrum on a screen. With this device, Wollaston saw that the colors were not spread out uniformly, but instead, some ranges of color were missing, appearing as dark bands in the solar spectrum. He mistakenly attributed these lines to natural boundaries between the colors. In 1815, German physicist Joseph Fraunhofer, upon a more careful examination of the solar spectrum, found about 600 such dark lines (missing colors), which led scientists to rule out the boundary hypothesis (Figure 5.11).

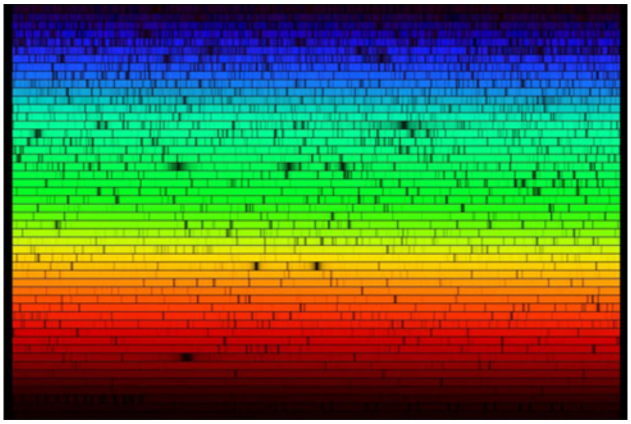

Figure 5.11 Visible Spectrum of the Sun. Our star's spectrum is crossed by dark lines produced by atoms in the solar atmosphere that absorb light at certain wavelengths. (credit: modification of work by Nigel Sharp, NOAO/National Solar Observatory at Kitt Peak/AURA, and the National Science Foundation)

Later, researchers found that similar dark lines could be produced in the spectra ("spectra" is the plural of "spectrum") of artificial light sources. They did this by passing their light through various apparently transparent substances—usually containers with just a bit of thin gas in them.

These gases turned out not to be transparent at *all* colors: they were quite opaque at a few sharply defined wavelengths. Something in each gas had to be absorbing just a few colors of light and no others. All gases did this, but each different element absorbed a different set of colors and thus showed different dark lines. If the gas in a container consisted of two elements, then light passing through it was missing the colors (showing dark lines) for both of the elements. So it became clear that certain lines in the spectrum "go with" certain elements. This discovery was one of the most important steps forward in the history of astronomy.

What would happen if there were no continuous spectrum for our gases to remove light from? What if, instead, we heated the same thin gases until they were hot enough to glow with their own light? When the gases were heated, a spectrometer revealed no continuous spectrum, but several separate bright lines. That is, these hot gases emitted light only at certain specific wavelengths or colors.

When the gas was pure hydrogen, it would emit one pattern of colors; when it was pure sodium, it would emit a different pattern. A mixture of hydrogen and sodium emitted both sets of spectral lines. The colors the gases emitted when they were heated were the very same colors as those they had absorbed when a continuous source of light was behind them. From such experiments, scientists began to see that different substances showed distinctive *spectral signatures* by which their presence could be detected (Figure 5.12). Just as your signature allows the bank to identify you, the unique pattern of colors for each type of atom (its spectrum) can help us identify which element or elements are in a gas.

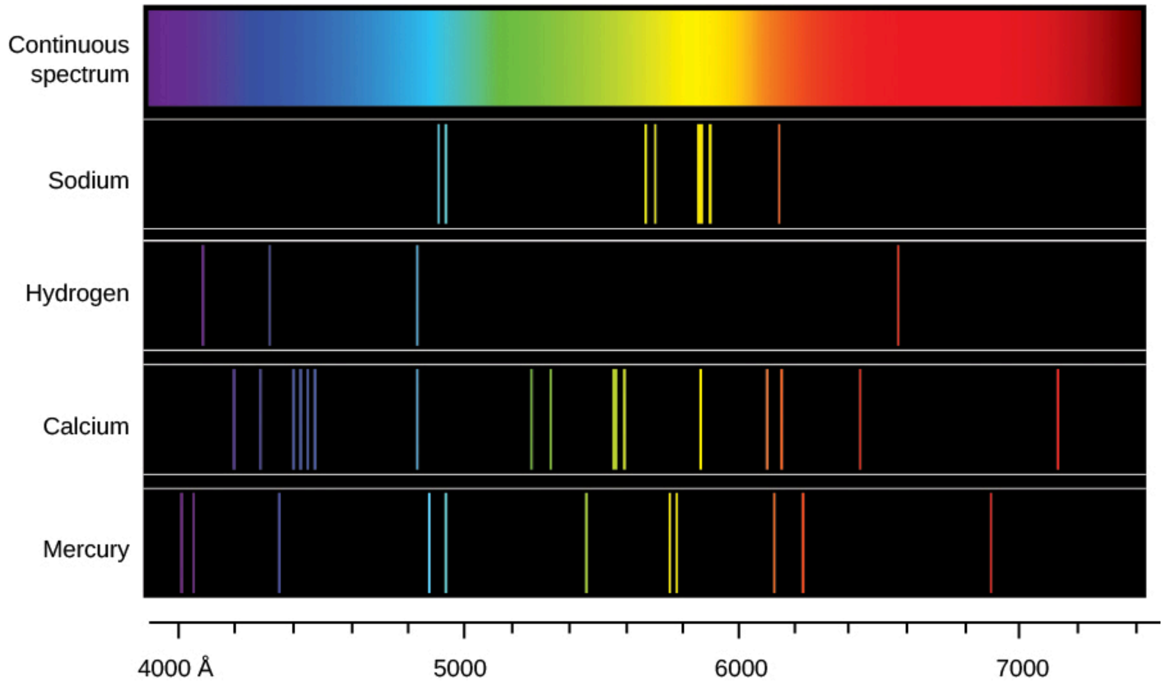

Figure 5.12 Continuous Spectrum and Line Spectra from Different Elements. Each type of glowing gas (each element) produces its own unique pattern of lines, so the composition of a gas can be identified by its spectrum. The spectra of sodium, hydrogen, calcium, and mercury gases are shown here.

Types of Spectra

In these experiments, then, there were three different types of spectra. A **continuous spectrum** (formed when a solid or very dense gas gives off radiation) is an array of all wavelengths or colors of the rainbow. A continuous spectrum can serve as a backdrop from which the atoms of much less dense gas can absorb light. A dark line, or **absorption spectrum**, consists of a series or pattern of dark lines—missing colors—superimposed upon the continuous spectrum of a source. A bright line, or **emission spectrum**, appears as a pattern or series of bright lines; it consists of light in which only certain discrete wavelengths are present. (Figure 5.11 shows an absorption spectrum, whereas Figure 5.12 shows the emission spectrum of a number of common elements along with an example of a continuous spectrum.)

When we have a hot, thin gas, each particular chemical element or compound produces its own characteristic pattern of spectral lines—its spectral signature. No two types of atoms or molecules give the same patterns. In other words, each particular gas can absorb or emit only certain wavelengths of the light peculiar to that gas. In contrast, absorption spectra occur when passing white light through a cool, thin gas. The temperature and other conditions determine whether the lines are bright or dark (whether light is absorbed or emitted), but the wavelengths of the lines for any element are the same in either case. It is the precise pattern of wavelengths that makes the signature of each element unique. Liquids and solids can also generate spectral lines or bands, but they are broader and less well defined—and hence, more difficult to interpret. Spectral analysis, however, can be quite useful. It can, for example, be applied to light reflected off the surface of a nearby asteroid as well as to light from a distant galaxy.

The dark lines in the solar spectrum thus give evidence of certain chemical elements between us and the Sun absorbing those wavelengths of sunlight. Because the space between us and the Sun is pretty empty, astronomers realized that the atoms doing the absorbing must be in a thin atmosphere of cooler gas around the Sun. This outer atmosphere is not all that different from the rest of the Sun, just thinner and cooler. Thus, we can use what we learn about its composition as an indicator of what the whole Sun is made of. Similarly, we can use the presence of absorption and emission lines to analyze the composition of other stars and clouds of gas in space.

Such analysis of spectra is the key to modern astronomy. Only in this way can we “sample” the stars, which are too far away for us to visit. Encoded in the electromagnetic radiation from celestial objects is clear information about the chemical makeup of these objects. Only by understanding what the stars were made of could astronomers begin to form theories about what made them shine and how they evolved.

In 1860, German physicist Gustav Kirchhoff became the first person to use spectroscopy to identify an element in the Sun when he found the spectral signature of sodium gas. In the years that followed, astronomers found many other chemical elements in the Sun and stars. In fact, the element helium was found first in the Sun from its spectrum and only later identified on Earth. (The word “helium” comes from *helios*, the Greek name for the Sun.)

Why are there specific lines for each element? The answer to that question was not found until the twentieth century; it required the development of a model for the atom. We therefore turn next to a closer examination of the atoms that make up all matter.

LINK TO LEARNING

You can use the Spectrum Constructor (https://openstax.org/l/30spectcoord) to explore the three types of spectra and how they appear through a diffraction grating when the brightness of each wavelength is measured with a spectrometer.

MAKING CONNECTIONS

The Rainbow

Rainbows are an excellent illustration of the dispersion of sunlight. You have a good chance of seeing a rainbow any time you are between the Sun and a rain shower, as illustrated in Figure 5.13. The raindrops act like little prisms and break white light into the spectrum of colors. Suppose a ray of sunlight encounters a raindrop and passes into it. The light changes direction—is refracted—when it passes from air to water; the blue and violet light are refracted more than the red. Some of the light is then reflected at the backside of the drop and reemerges from the front, where it is again refracted. As a result, the white light is spread out into a rainbow of colors.

Figure 5.13 Rainbow Refraction. (a) This diagram shows how light from the Sun, which is located behind the observer, can be refracted by raindrops to produce (b) a rainbow. (c) Refraction separates white light into its component colors.

Note that violet light lies above the red light after it emerges from the raindrop. When you look at a rainbow, however, the red light is higher in the sky. Why? Look again at Figure 5.13. If the observer looks at a raindrop that is high in the sky, the violet light passes over her head and the red light enters her eye. Similarly, if the observer looks at a raindrop that is low in the sky, the violet light reaches her eye and the drop appears violet, whereas the red light from that same drop strikes the ground and is not seen. Colors of intermediate wavelengths are refracted to the eye by drops that are intermediate in altitude between the drops that appear violet and the ones that appear red. Thus, a single rainbow always has red on the outside and violet on the inside.

5.4 The Structure of the Atom

Learning Objectives

By the end of this section, you will be able to:

- Describe the structure of atoms and the components of nuclei
- Explain the behavior of electrons within atoms and how electrons interact with light to move among energy levels

The idea that matter is composed of tiny particles called atoms is at least 25 centuries old. It took until the twentieth century, however, for scientists to invent instruments that permitted them to probe inside an atom and find that it is not, as had been thought, hard and indivisible. Instead, the atom is a complex structure composed of still smaller particles.

Probing the Atom

The first of these smaller particles was discovered by British physicist James (J. J.) Thomson in 1897. Named the *electron*, this particle is negatively charged. (It is the flow of these particles that produces currents of electricity, whether in lightning bolts or in the wires leading to your lamp.) Because an atom in its normal state is electrically neutral, each electron in an atom must be balanced by the same amount of positive charge.

The next step was to determine where in the atom the positive and negative charges are located. In 1911, British physicist Ernest Rutherford devised an experiment that provided part of the answer to this question. He bombarded an extremely thin piece of gold foil, only about 400 atoms thick, with a beam of alpha particles (Figure 5.14). *Alpha particles* (α particles) are helium atoms that have lost their electrons and thus are positively charged. Most of these particles passed though the gold foil just as if it and the atoms in it were nearly empty space. About 1 in 8000 of the alpha particles, however, completely reversed direction and bounced backward from the foil. Rutherford wrote, “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

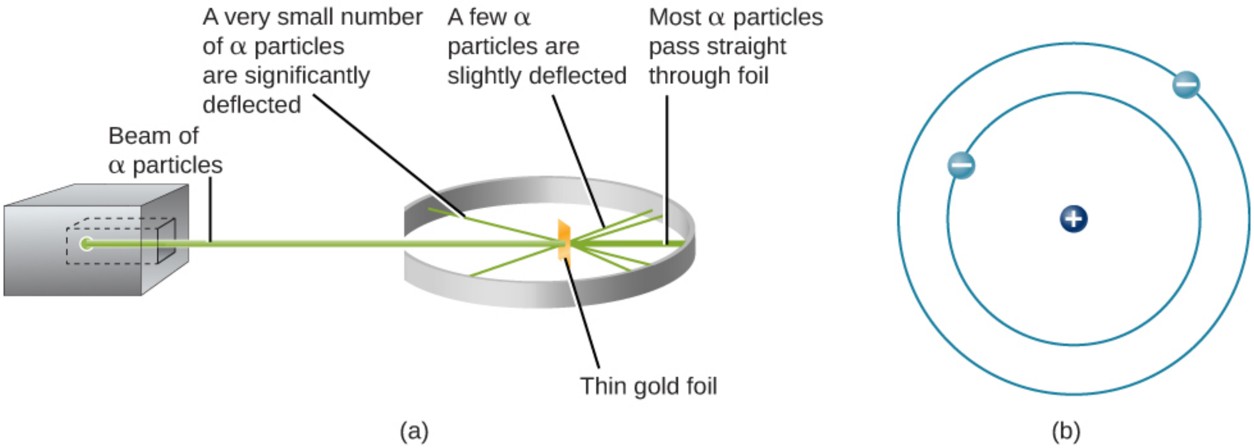

Figure 5.14 Rutherford's Experiment. (a) When Rutherford allowed α particles from a radioactive source to strike a target of gold foil, he found that, although most of them went straight through, some rebounded back in the direction from which they came. (b) From this experiment, he concluded that the atom must be constructed like a miniature solar system, with the positive charge concentrated in the nucleus and the negative charge orbiting in the large volume around the nucleus. Note that this drawing is not to scale; the electron orbits are much larger relative to the size of the nucleus.

The only way to account for the particles that reversed direction when they hit the gold foil was to assume that nearly all of the mass, as well as all of the positive charge in each individual gold atom, is concentrated in a tiny center or **nucleus**. When a positively charged alpha particle strikes a nucleus, it reverses direction, much as a cue ball reverses direction when it strikes another billiard ball. Rutherford's model placed the other type of charge—the negative electrons—in orbit around this nucleus.

Rutherford's model required that the electrons be in motion. Positive and negative charges attract each other, so stationary electrons would fall into the positive nucleus. Also, because both the electrons and the nucleus are extremely small, most of the atom is empty, which is why nearly all of Rutherford's particles were able to pass right through the gold foil without colliding with anything. Rutherford's model was a very successful explanation of the experiments he conducted, although eventually scientists would discover that even the nucleus itself has structure.

The Atomic Nucleus

The simplest possible atom (and the most common one in the Sun and stars) is hydrogen. The nucleus of ordinary hydrogen contains a single proton. Moving around this proton is a single electron. The mass of an electron is nearly 2000 times smaller than the mass of a proton; the electron carries an amount of charge exactly equal to that of the proton but opposite in sign (Figure 5.15). Opposite charges attract each other, so it is an electromagnetic force that holds the proton and electron together, just as gravity is the force that keeps planets in orbit around the Sun.

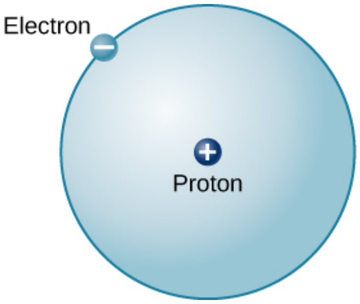

Figure 5.15 Hydrogen Atom. This is a schematic diagram of a hydrogen atom in its lowest energy state, also called the ground state. The proton and electron have equal but opposite charges, which exert an electromagnetic force that binds the hydrogen atom together. In the illustration, the size of the particles is exaggerated so that you can see them; they are not to scale. They are also shown much closer than they would actually be as it would take more than an entire page to show their actual distance to scale.

There are many other types of atoms in nature. Helium, for example, is the second-most abundant element in the Sun. Helium has two protons in its nucleus instead of the single proton that characterizes hydrogen. In addition, the helium nucleus contains two neutrons, particles with a mass comparable to that of the proton but with no electric charge. Moving around this nucleus are two electrons, so the total net charge of the helium atom is also zero (Figure 5.16).

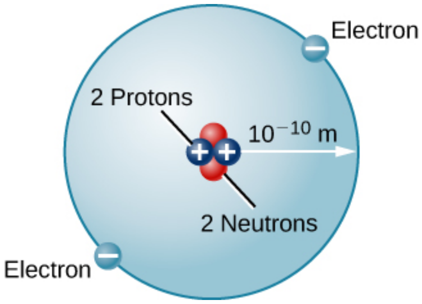

Figure 5.16 Helium Atom. Here we see a schematic diagram of a helium atom in its lowest energy state. Two protons are present in the nucleus of all helium atoms. In the most common variety of helium, the nucleus also contains two neutrons, which have nearly the same mass as the proton but carry no charge. Two electrons orbit the nucleus.

From this description of hydrogen and helium, perhaps you have guessed the pattern for building up all the elements (different types of atoms) that we find in the universe. The type of element is determined by the number of protons in the nucleus of the atom. For example, any atom with six protons is the element carbon, with eight protons is oxygen, with 26 is iron, and with 92 is uranium. On Earth, a typical atom has the same number of electrons as protons, and these electrons follow complex orbital patterns around the nucleus. Deep inside stars, however, it is so hot that the electrons get loose from the nucleus and (as we shall see) lead separate yet productive lives.

The ratio of neutrons to protons increases as the number of protons increases, but each element is unique. The number of neutrons is not necessarily the same for all atoms of a given element. For example, most hydrogen atoms contain no neutrons at all. There are, however, hydrogen atoms that contain one proton and one neutron, and others that contain one proton and two neutrons. The various types of hydrogen nuclei with different numbers of neutrons are called **isotopes** of hydrogen (Figure 5.17), and all other elements have isotopes as well. You can think of isotopes as siblings in the same element "family"—closely related but with different characteristics and behaviors.

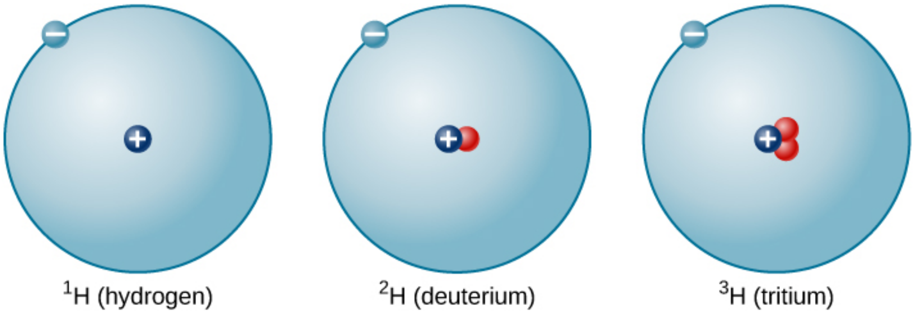

Figure 5.17 Isotopes of Hydrogen. A single proton in the nucleus defines the atom to be hydrogen, but there may be zero, one, or two neutrons. The most common isotope of hydrogen is the one with only a single proton and no neutrons.

LINK TO LEARNING

To explore the structure of atoms, go to the PhET Build an Atom website (https://openstax.org/l/30atombld) where you can add protons, neutrons, or electrons to a model and the name of the element you have created will appear. You can also see the net charge, the mass number, whether it is stable or unstable, and whether it is an ion or a neutral atom.

The Bohr Atom

Rutherford's model for atoms has one serious problem. Maxwell's theory of electromagnetic radiation says that when electrons change either speed or the direction of motion, they must emit energy. Orbiting electrons constantly change their direction of motion, so they should emit a constant stream of energy. Applying Maxwell's theory to Rutherford's model, all electrons should spiral into the nucleus of the atom as they lose energy, and this collapse should happen very quickly—in about 10^{-16} seconds.

It was Danish physicist Niels Bohr (1885–1962) who solved the mystery of how electrons remain in orbit. He was trying to develop a model of the atom that would also explain certain regularities observed in the spectrum of hydrogen. He suggested that the spectrum of hydrogen can be understood if we assume that orbits of only certain sizes are possible for the electron. Bohr further assumed that as long as the electron moves in only one of these allowed orbits, it radiates no energy: its energy would change only if it moved from one orbit to another.

This suggestion, in the words of science historian Abraham Pais, was "one of the most audacious hypotheses ever introduced in physics." If something equivalent were at work in the everyday world, you might find that, as you went for a walk after astronomy class, nature permitted you to walk two steps per minute, five steps per minute, and 12 steps per minute, but no speeds in between. No matter how you tried to move your legs, only certain walking speeds would be permitted. To make things more bizarre, it would take no effort to walk at any one of the allowed speeds, but it would be difficult to change from one speed to another. Luckily, no such rules apply at the level of human behavior. But at the microscopic level of the atom, experiment after experiment has confirmed the validity of Bohr's strange idea. Bohr's suggestions became one of the foundations of the new (and much more sophisticated) model of the subatomic world called quantum mechanics.

In Bohr's model, if the electron moves from one orbit to another closer to the atomic nucleus, it must give up some energy in the form of electromagnetic radiation. If the electron goes from an inner orbit to one farther from the nucleus, however, it requires some additional energy. One way to obtain the necessary energy is to absorb electromagnetic radiation that may be streaming past the atom from an outside source.

A key feature of Bohr's model is that each of the permitted electron orbits around a given atom has a certain energy value; we therefore can think of each orbit as an **energy level**. To move from one orbit to another (which will have its own specific energy value) requires a change in the electron's energy—a change determined by the difference between the two energy values. If the electron goes to a lower level, the energy difference will be given off; if the electron goes to a higher level, the energy difference must be obtained from somewhere else. Each jump (or transition) to a different level has a fixed and definite energy change associated with it.

A crude analogy for this situation might be life in a tower of luxury apartments where the rent is determined by the quality of the view. Such a building has certain, definite numbered levels or floors on which apartments are located. No one can live on floor 5.37 or 22.5. In addition, the rent gets higher as you go up to higher floors. If you want to exchange an apartment on the twentieth floor for one on the second floor, you will not owe as much rent. However, if you want to move from the third floor to the twenty-fifth floor, your rent will increase. In an atom, too, the "cheapest" place for an electron to live is the lowest possible level, and energy is required to move to a higher level.

Here we have one of the situations where it is easier to think of electromagnetic radiation as particles (photons) rather than as waves. As electrons move from one level to another, they give off or absorb little packets of energy. When an electron moves to a higher level, it absorbs a photon of just the right energy (provided one is available). When it moves to a lower level, it emits a photon with the exact amount of energy it no longer needs in its "lower-cost living situation."

The photon and wave perspectives must be equivalent: light is light, no matter how we look at it. Thus, each photon carries a certain amount of energy that is proportional to the frequency (f) of the wave it represents. The value of its energy (E) is given by the formula

$$E = hf$$

where the constant of proportionality, h, is called Planck's constant.

The constant is named for Max Planck, the German physicist who was one of the originators of the quantum theory (Figure 5.18). If metric units are used (that is, if energy is measured in joules and frequency in hertz), then Planck's constant has the value $h = 6.626 \times 10^{-34}$ joule-seconds (J-s). Higher-energy photons correspond to higher-frequency waves (which have a shorter wavelength); lower-energy photons are waves of lower frequency.

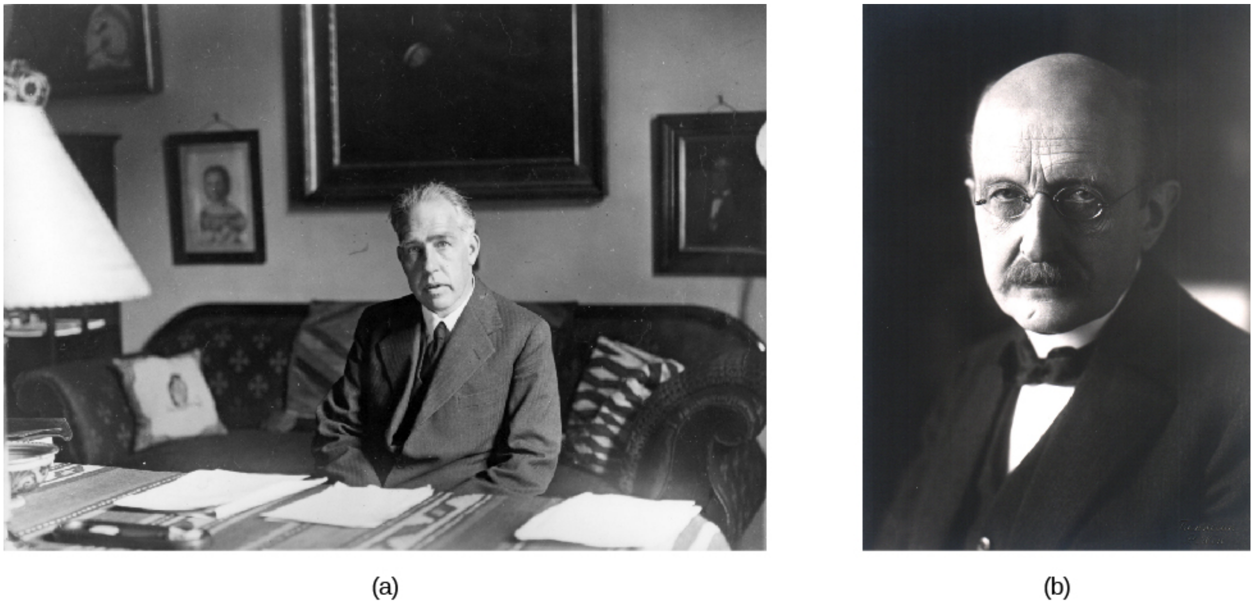
(a) (b)

Figure 5.18 Niels Bohr (1885–1962) and Max Planck (1858–1947). (a) Bohr, shown at his desk in this 1935 photograph, and (b) Planck helped us understand the energy behavior of photons.

To take a specific example, consider a calcium atom inside the Sun's atmosphere in which an electron jumps from a lower level to a higher level. To do this, it needs about 5×10^{-19} joules of energy, which it can conveniently obtain by absorbing a passing photon of that energy coming from deeper inside the Sun. This photon is equivalent to a wave of light whose frequency is about 7.5×10^{14} hertz and whose wavelength is about 3.9×10^{-7} meters (393 nanometers), in the deep violet part of the visible light spectrum. Although it may seem strange at first to switch from picturing light as a photon (or energy packet) to picturing it as a wave, such switching has become second nature to astronomers and can be a handy tool for doing calculations about spectra.

EXAMPLE 5.5

The Energy of a Photon

Now that we know how to calculate the wavelength and frequency of a photon, we can use this information, along with Planck's constant, to determine how much energy each photon carries. How much energy does a red photon of wavelength 630 nm have?

Solution

First, as we learned earlier, we can find the frequency of the photon:

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8} \text{ m/s}}{630 \times 10^{-9} \text{ m}} = 4.8 \times 10^{14} \text{ Hz}$$

Next, we can use Planck's constant to determine the energy (remember that a Hz is the same as 1/s):

$$E = hf = \left(6.626 \times 10^{-34} \text{ J-s}\right)\left(4.8 \times 10^{14} \text{ Hz(1/s)}\right) = 3.2 \times 10^{-19} \text{ J}$$

Check Your Learning

What is the energy of a yellow photon with a frequency of 5.5×10^{14} Hz?

Answer:

$E = hf = \left(6.626 \times 10^{-34}\text{J-s}\right)\left(5.5 \times 10^{14}\text{Hz}\right) = 3.6 \times 10^{-19}$ J

5.5 Formation of Spectral Lines

Learning Objectives

By the end of this section, you will be able to:

- Explain how emission line spectra and absorption line spectra are formed
- Describe what ions are and how they are formed
- Explain how spectral lines and ionization levels in a gas can help us determine its temperature

We can use Bohr's model of the atom to understand how spectral lines are formed. The concept of energy levels for the electron orbits in an atom leads naturally to an explanation of why atoms absorb or emit only specific energies or wavelengths of light.

The Hydrogen Spectrum

Let's look at the hydrogen atom from the perspective of the Bohr model. Suppose a beam of white light (which consists of photons of all visible wavelengths) shines through a gas of atomic hydrogen. A photon of wavelength 656 nanometers has just the right energy to raise an electron in a hydrogen atom from the second to the third orbit. Thus, as all the photons of different energies (or wavelengths or colors) stream by the hydrogen atoms, photons with *this* particular wavelength can be absorbed by those atoms whose electrons are orbiting on the second level. When they are absorbed, the electrons on the second level will move to the third level, and a number of the photons of this wavelength and energy will be missing from the general stream of white light.

Other photons will have the right energies to raise electrons from the second to the fourth orbit, or from the first to the fifth orbit, and so on. Only photons with these exact energies can be absorbed. All of the other photons will stream past the atoms untouched. Thus, hydrogen atoms absorb light at only certain wavelengths and produce dark lines at those wavelengths in the spectrum we see.

Suppose we have a container of hydrogen gas through which a whole series of photons is passing, allowing many electrons to move up to higher levels. When we turn off the light source, these electrons "fall" back down from larger to smaller orbits and emit photons of light—but, again, only light of those energies or wavelengths that correspond to the energy difference between permissible orbits. The orbital changes of hydrogen electrons that give rise to some spectral lines are shown in Figure 5.19.

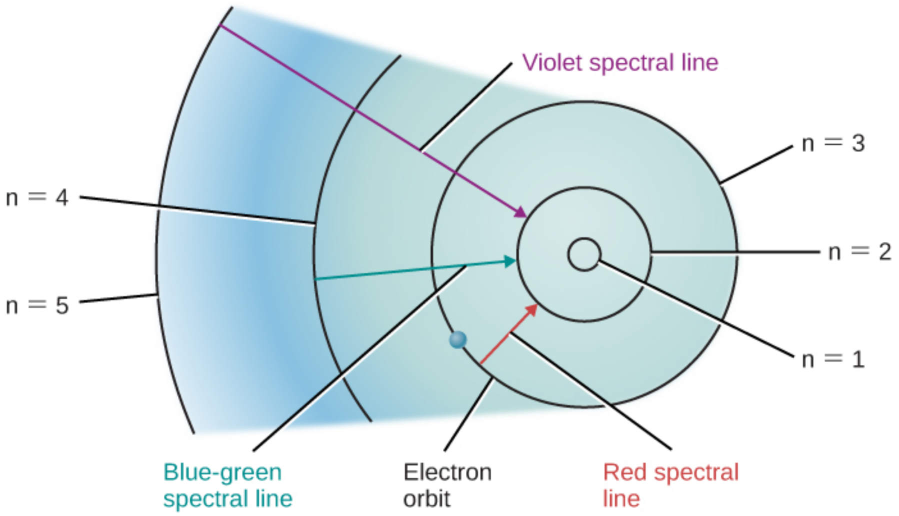

Figure 5.19 Bohr Model for Hydrogen. In this simplified model of a hydrogen atom, the concentric circles shown represent permitted orbits or energy levels. An electron in a hydrogen atom can only exist in one of these energy levels (or states). The closer the electron is to the nucleus, the more tightly bound the electron is to the nucleus. By absorbing energy, the electron can move to energy levels farther from the nucleus (and even escape if enough energy is absorbed).

Similar pictures can be drawn for atoms other than hydrogen. However, because these other atoms ordinarily have more than one electron each, the orbits of their electrons are much more complicated, and the spectra are more complex as well. For our purposes, the key conclusion is this: *each type of atom has its own unique pattern of electron orbits, and no two sets of orbits are exactly alike*. This means that each type of atom shows its own unique set of spectral lines, produced by electrons moving between its unique set of orbits.

Astronomers and physicists have worked hard to learn the lines that go with each element by studying the way atoms absorb and emit light in laboratories here on Earth. Then they can use this knowledge to identify the elements in celestial bodies. In this way, we now know the chemical makeup of not just any star, but even galaxies of stars so distant that their light started on its way to us long before Earth had even formed.

Energy Levels and Excitation

Bohr's model of the hydrogen atom was a great step forward in our understanding of the atom. However, we know today that atoms cannot be represented by quite so simple a picture. For example, the concept of sharply defined electron orbits is not really correct; however, at the level of this introductory course, the notion that only certain discrete energies are allowable for an atom is very useful. The energy levels we have been discussing can be thought of as representing certain average distances of the electron's possible orbits from the atomic nucleus.

Ordinarily, an atom is in the state of lowest possible energy, its **ground state**. In the Bohr model of the hydrogen atom, the ground state corresponds to the electron being in the innermost orbit. An atom can absorb energy, which raises it to a higher energy level (corresponding, in the simple Bohr picture, to an electron's movement to a larger orbit)—this is referred to as **excitation**. The atom is then said to be in an *excited state*. Generally, an atom remains excited for only a very brief time. After a short interval, typically a hundred-millionth of a second or so, it drops back spontaneously to its ground state, with the simultaneous emission of light. The atom may return to its lowest state in one jump, or it may make the transition in steps of two or more jumps, stopping at intermediate levels on the way down. With each jump, it emits a photon of the wavelength that corresponds to the energy difference between the levels at the beginning and end of that jump.

An energy-level diagram for a hydrogen atom and several possible atomic transitions are shown in Figure 5.20. When we measure the energies involved as the atom jumps between levels, we find that the transitions to or from the ground state, called the *Lyman series* of lines, result in the emission or absorption of ultraviolet photons. But the transitions to or from the first excited state (labeled n = 2 in part (a) of Figure 5.20), called the Balmer series, produce emission or absorption in visible light. In fact, it was to explain this Balmer series that Bohr first suggested his model of the atom.

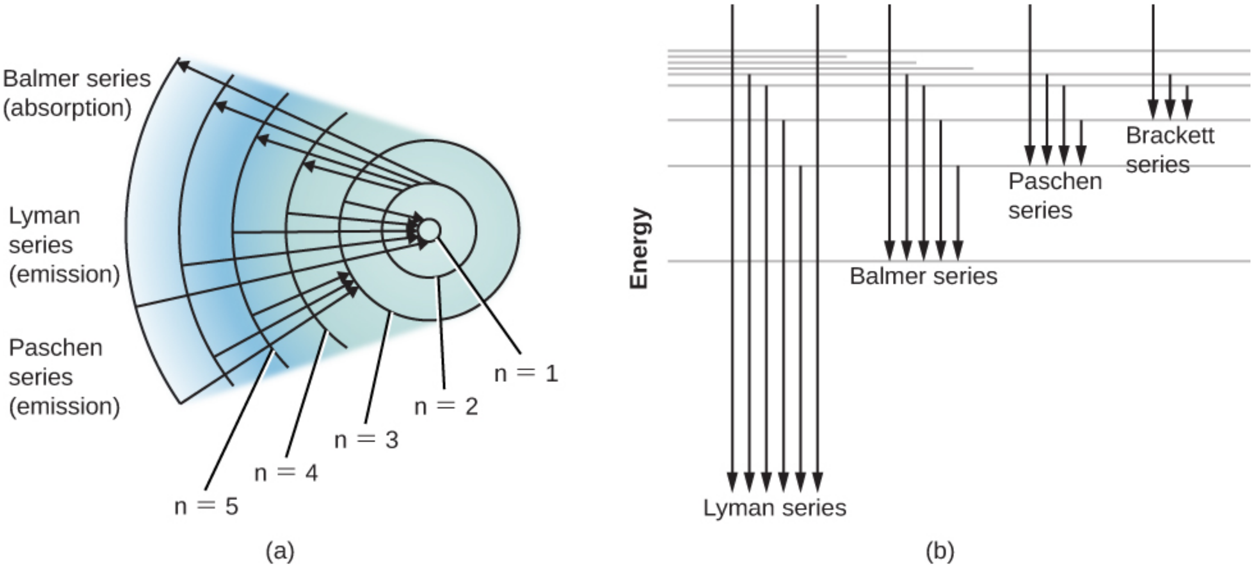

Figure 5.20 Energy-Level Diagrams for Hydrogen. (a) Here we follow the emission or absorption of photons by a hydrogen atom according to the Bohr model. Several different series of spectral lines are shown, corresponding to transitions of electrons from or to certain allowed orbits. Each series of lines that terminates on a specific inner orbit is named for the physicist who studied it. At the top, for example, you see the Balmer series, and arrows show electrons jumping from the second orbit ($n = 2$) to the third, fourth, fifth, and sixth orbits. Each time a “poor” electron from a lower level wants to rise to a higher position in life, it must absorb energy to do so. It can absorb the energy it needs from passing waves (or photons) of light. The next set of arrows (Lyman series) show electrons falling down to the first orbit from different (higher) levels. Each time a “rich” electron goes downward toward the nucleus, it can afford to give off (emit) some energy it no longer needs. (In this idealized diagram, the energy levels are shown equally spaced; in real life, they are not.) (b) At higher and higher energy levels, the levels become more and more crowded together, approaching a limit. The region above the top line represents energies at which the atom is ionized (the electron is no longer attached to the atom). Each series of arrows represents electrons falling from higher levels to lower ones, releasing photons or waves of energy in the process.

Atoms that have absorbed specific photons from a passing beam of white light and have thus become excited generally de-excite themselves and emit that light again in a very short time. You might wonder, then, why *dark* spectral lines are ever produced. In other words, why doesn’t this reemitted light quickly “fill in” the darker absorption lines?

Imagine a beam of white light coming toward you through some cooler gas. Some of the reemitted light *is* actually returned to the beam of white light you see, but this fills in the absorption lines only to a slight extent. The reason is that the atoms in the gas reemit light *in all directions*, and only a small fraction of the reemitted light is in the direction of the original beam (toward you). In a star, much of the reemitted light actually goes in directions leading back into the star, which does observers outside the star no good whatsoever.

Figure 5.21 summarizes the different kinds of spectra we have discussed. An incandescent lightbulb produces a continuous spectrum. When that continuous spectrum is viewed through a thinner cloud of gas, an absorption line spectrum can be seen superimposed on the continuous spectrum. If we look only at a cloud of excited gas atoms (with no continuous source seen behind it), we see that the excited atoms give off an emission line spectrum.

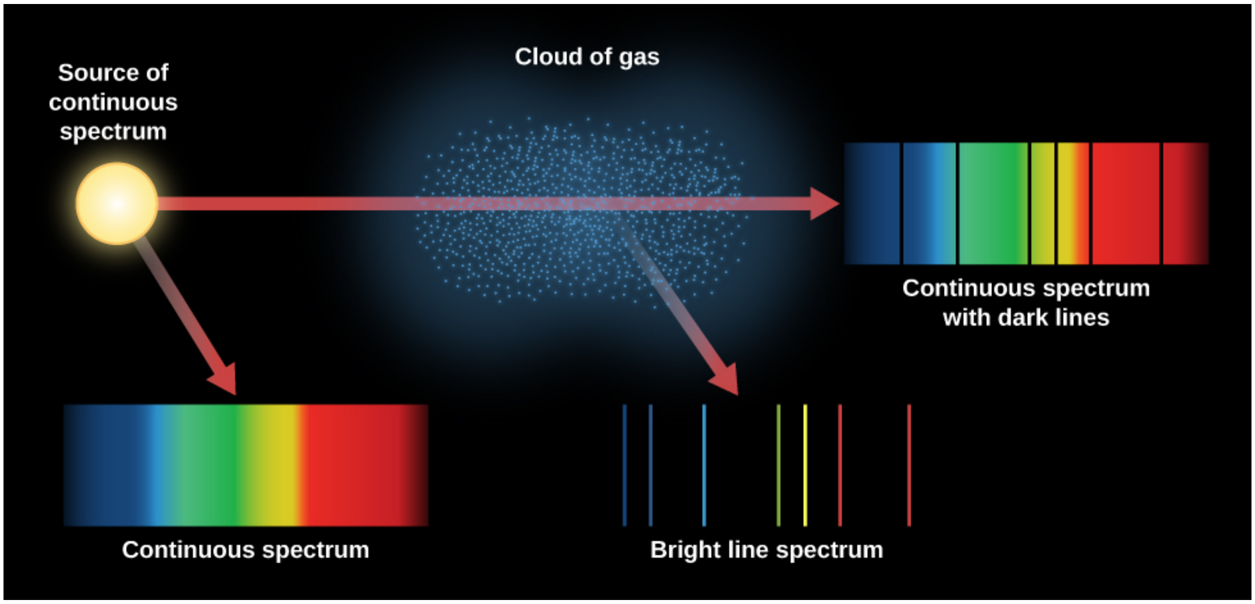

Figure 5.21 Three Kinds of Spectra. When we see a lightbulb or other source of continuous radiation, all the colors are present. When the continuous spectrum is seen through a thinner gas cloud, the cloud's atoms produce absorption lines in the continuous spectrum. When the excited cloud is seen without the continuous source behind it, its atoms produce emission lines. We can learn which types of atoms are in the gas cloud from the pattern of absorption or emission lines.

Atoms in a hot gas are moving at high speeds and continually colliding with one another and with any loose electrons. They can be excited (electrons moving to a higher level) and de-excited (electrons moving to a lower level) by these collisions as well as by absorbing and emitting light. The speed of atoms in a gas depends on the temperature. When the temperature is higher, so are the speed and energy of the collisions. The hotter the gas, therefore, the more likely that electrons will occupy the outermost orbits, which correspond to the highest energy levels. This means that the level where electrons *start* their upward jumps in a gas can serve as an indicator of how hot that gas is. In this way, the absorption lines in a spectrum give astronomers information about the temperature of the regions where the lines originate.

LINK TO LEARNING

Use this simulation (https://openstax.org/l/30Hatom) to play with a hydrogen atom and see what happens when electrons move to higher levels and then give off photons as they go to a lower level.

Ionization

We have described how certain discrete amounts of energy can be absorbed by an atom, raising it to an excited state and moving one of its electrons farther from its nucleus. If enough energy is absorbed, the electron can be completely removed from the atom—this is called **ionization**. The atom is then said to be ionized. The minimum amount of energy required to remove one electron from an atom in its ground state is called its ionization energy.

Still-greater amounts of energy must be absorbed by the now-ionized atom (called an **ion**) to remove an additional electron deeper in the structure of the atom. Successively greater energies are needed to remove the third, fourth, fifth—and so on—electrons from the atom. If enough energy is available, an atom can become completely ionized, losing all of its electrons. A hydrogen atom, having only one electron to lose, can be ionized only once; a helium atom can be ionized twice; and an oxygen atom up to eight times. When we examine regions of the cosmos where there is a great deal of energetic radiation, such as the neighborhoods where hot young stars have recently formed, we see a lot of ionization going on.

An atom that has become positively ionized has lost a negative charge—the missing electron—and thus is left with a net positive charge. It therefore exerts a strong attraction on any free electron. Eventually, one or more electrons will be captured and the atom will become neutral (or ionized to one less degree) again. During the electron-capture process, the atom emits one or more photons. Which photons are emitted depends on whether the electron is captured at once to the lowest energy level of the atom or stops at one or more intermediate levels on its way to the lowest available level.

Just as the excitation of an atom can result from a collision with another atom, ion, or electron (collisions with electrons are usually most important), so can ionization. The rate at which such collisional ionizations occur depends on the speeds of the atoms and hence on the temperature of the gas—the hotter the gas, the more of its atoms will be ionized.

The rate at which ions and electrons recombine also depends on their relative speeds—that is, on the temperature. In addition, it depends on the density of the gas: the higher the density, the greater the chance for recapture, because the different kinds of particles are crowded more closely together. From a knowledge of the temperature and density of a gas, it is possible to calculate the fraction of atoms that have been ionized once, twice, and so on. In the Sun, for example, we find that most of the hydrogen and helium atoms in its atmosphere are neutral, whereas most of the calcium atoms, as well as many other heavier atoms, are ionized once.

The energy levels of an ionized atom are entirely different from those of the same atom when it is neutral. Each time an electron is removed from the atom, the energy levels of the ion, and thus the wavelengths of the spectral lines it can produce, change. This helps astronomers differentiate the ions of a given element. Ionized hydrogen, having no electron, can produce no absorption lines.

5.6 The Doppler Effect

Learning Objectives

By the end of this section, you will be able to:

- Explain why the spectral lines of photons we observe from an object will change as a result of the object's motion toward or away from us
- Describe how we can use the Doppler effect to deduce how fast astronomical objects are moving through space

The last two sections introduced you to many new concepts, and we hope that through those, you have seen one major idea emerge. Astronomers can learn about the elements in stars and galaxies by decoding the information in their spectral lines. There is a complicating factor in learning how to decode the message of starlight, however. If a star is moving toward or away from us, its lines will be in a slightly different place in the spectrum from where they would be in a star at rest. And most objects in the universe do have some motion relative to the Sun.

Motion Affects Waves

In 1842, Christian Doppler first measured the effect of motion on waves by hiring a group of musicians to play on an open railroad car as it was moving along the track. He then applied what he learned to all waves, including light, and pointed out that if a light source is approaching or receding from the observer, the light waves will be, respectively, crowded more closely together or spread out. The general principle, now known as the **Doppler effect**, is illustrated in Figure 5.22.

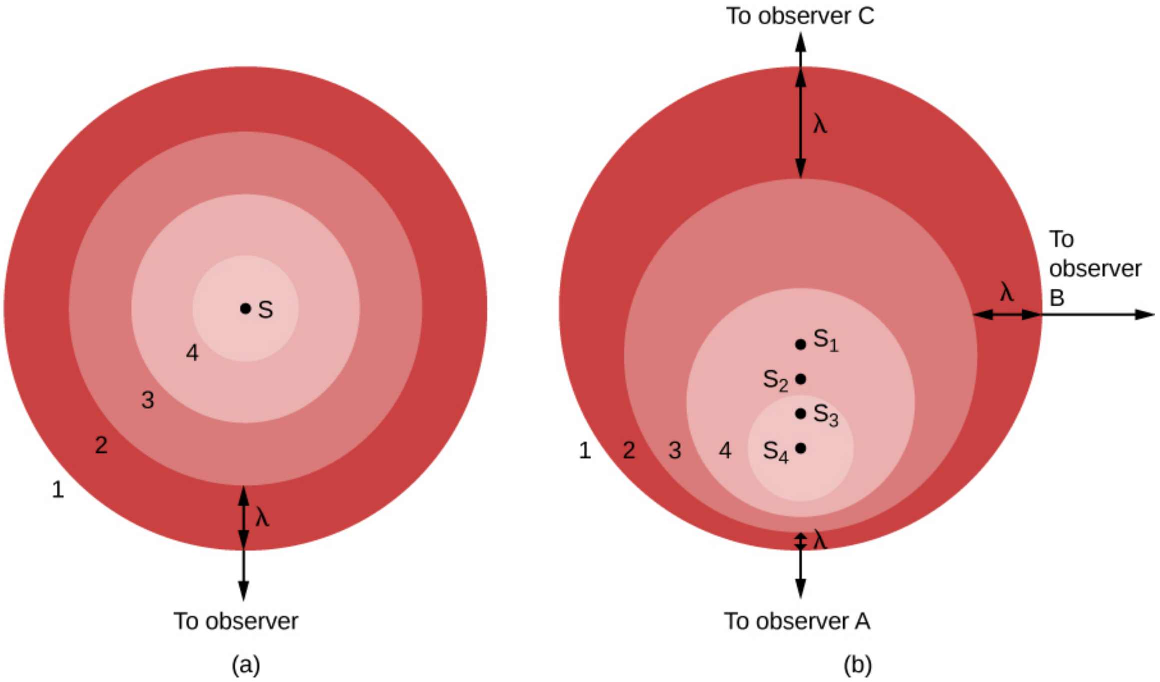

Figure 5.22 Doppler Effect. (a) A source, S, makes waves whose numbered crests (1, 2, 3, and 4) wash over a stationary observer. (b) The source S now moves toward observer *A* and away from observer *C*. Wave crest 1 was emitted when the source was at position S1, crest 2 at position S2, and so forth. Observer *A* sees waves compressed by this motion and sees a blueshift (if the waves are light). Observer *C* sees the waves stretched out by the motion and sees a redshift. Observer *B*, whose line of sight is perpendicular to the source's motion, sees no change in the waves (and feels left out).

In part (a) of the figure, the light source (S) is at rest with respect to the observer. The source gives off a series of waves, whose crests we have labeled 1, 2, 3, and 4. The light waves spread out evenly in all directions, like the ripples from a splash in a pond. The crests are separated by a distance, λ, where λ is the wavelength. The observer, who happens to be located in the direction of the bottom of the image, sees the light waves coming nice and evenly, one wavelength apart. Observers located anywhere else would see the same thing.

On the other hand, if the source of light is moving with respect to the observer, as seen in part (b), the situation is more complicated. Between the time one crest is emitted and the next one is ready to come out, the source has moved a bit, toward the bottom of the page. From the point of view of observer *A*, this motion of the source has decreased the distance between crests—it's squeezing the crests together, this observer might say.

In part (b), we show the situation from the perspective of three observers. The source is seen in four positions, S_1, S_2, S_3, and S_4, each corresponding to the emission of one wave crest. To observer *A*, the waves seem to follow one another more closely, at a decreased wavelength and thus increased frequency. (Remember, all light waves travel at the speed of light through empty space, no matter what. This means that motion cannot affect the speed, but only the wavelength and the frequency. As the wavelength decreases, the frequency must increase. If the waves are shorter, more will be able to move by during each second.)

The situation is not the same for other observers. Let's look at the situation from the point of view of observer *C*, located opposite observer *A* in the figure. For her, the source is moving away from her location. As a result, the waves are not squeezed together but instead are spread out by the motion of the source. The crests arrive with an increased wavelength and decreased frequency. To observer *B*, in a direction at right angles to the motion of the source, no effect is observed. The wavelength and frequency remain the same as they were in part (a) of the figure.

We can see from this illustration that the Doppler effect is produced only by a motion toward or away from the observer, a motion called **radial velocity**. Sideways motion does not produce such an effect. Observers between *A* and *B* would observe some shortening of the light waves for that part of the motion of the source that is along their line of sight. Observers between *B* and *C* would observe lengthening of the light waves that are along their line of sight.

You may have heard the Doppler effect with sound waves. When a train whistle or police siren approaches you and then moves away, you will notice a decrease in the pitch (which is how human senses interpret sound wave frequency) of the sound waves. Compared to the waves at rest, they have changed from slightly more frequent when coming toward you, to slightly less frequent when moving away from you.

LINK TO LEARNING

A nice example of this change in the sound of a train whistle can be heard at the end of the classic Beach Boys song “Caroline, No” on their album *Pet Sounds*. To hear this sound, go to this YouTube (https://openstax.org/l/30BBtrain) version of the song. The sound of the train begins at approximately 2:20.

Color Shifts

When the source of waves moves toward you, the wavelength decreases a bit. If the waves involved are visible light, then the colors of the light change slightly. As wavelength decreases, they shift toward the blue end of the spectrum: astronomers call this a *blueshift* (since the end of the spectrum is really violet, the term should probably be *violetshift*, but blue is a more common color). When the source moves away from you and the wavelength gets longer, we call the change in colors a *redshift*. Because the Doppler effect was first used with visible light in astronomy, the terms “blueshift” and “redshift” became well established. Today, astronomers use these words to describe changes in the wavelengths of radio waves or X-rays as comfortably as they use them to describe changes in visible light.

The greater the motion toward or away from us, the greater the Doppler shift. If the relative motion is entirely along the line of sight, the formula for the Doppler shift of light is

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where λ is the wavelength emitted by the source, $\Delta\lambda$ is the difference between λ and the wavelength measured by the observer, c is the speed of light, and v is the relative speed of the observer and the source in the line of sight. The variable v is counted as positive if the velocity is one of recession, and negative if it is one of approach. Solving this equation for the velocity, we find $v = c \times \Delta\lambda/\lambda$.

LINK TO LEARNING

Click-and-drag the object emitting waves or the object receiving waves in this simulator (https://openstax.org/l/30doppsim) to experiment with the Doppler effect yourself. The plots along the top show how the detected wavelengths change if the objects are approaching each other or moving further apart.

If a star approaches or recedes from us, the wavelengths of light in its continuous spectrum appear shortened or lengthened, respectively, as do those of the dark lines. However, unless its speed is tens of thousands of kilometers per second, the star does not appear noticeably bluer or redder than normal. The Doppler shift is thus not easily detected in a continuous spectrum and cannot be measured accurately in such a spectrum. The wavelengths of the absorption lines can be measured accurately, however, and their Doppler shift is relatively simple to detect.

EXAMPLE 5.6

The Doppler Effect

We can use the Doppler effect equation to calculate the radial velocity of an object if we know three things: the speed of light, the original (unshifted) wavelength of the light emitted, and the difference between the wavelength of the emitted light and the wavelength we observe. For particular absorption or emission lines, we usually know exactly what wavelength the line has in our laboratories on Earth, where the source of light is not moving. We can measure the new wavelength with our instruments at the telescope, and so we know the difference in wavelength due to Doppler shifting. Since the speed of light is a universal constant, we can then calculate the radial velocity of the star.

A particular emission line of hydrogen is originally emitted with a wavelength of 656.3 nm from a gas cloud. At our telescope, we observe the wavelength of the emission line to be 656.6 nm. How fast is this gas cloud moving toward or away from Earth?

Solution

Because the light is shifted to a longer wavelength (redshifted), we know this gas cloud is moving away from us. The speed can be calculated using the Doppler shift formula:

$$\begin{aligned} v &= c \times \frac{\Delta\lambda}{\lambda} = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.3 \text{ nm}}{656.3 \text{ nm}}\right) = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.3 \times 10^{-9} \text{ m}}{656.3 \times 10^{-9} \text{ m}}\right) \\ &= 140{,}000 \text{ m/s} = 140 \text{ km/s} \end{aligned}$$

Check Your Learning

Suppose a spectral line of hydrogen, normally at 500 nm, is observed in the spectrum of a star to be at 500.1 nm. How fast is the star moving toward or away from Earth?

Answer:

Because the light is shifted to a longer wavelength, the star is moving away from us:

$v = c \times \frac{\Delta\lambda}{\lambda} = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.1 \text{ nm}}{500 \text{ nm}}\right) = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.1 \times 10^{-9} \text{ m}}{500 \times 10^{-9} \text{ m}}\right) = 60{,}000 \text{ m/s}$. Its speed is 60,000 m/s.

You may now be asking: if all the stars are moving and motion changes the wavelength of each spectral line, won't this be a disaster for astronomers trying to figure out what elements are present in the stars? After all, it is the precise wavelength (or color) that tells astronomers which lines belong to which element. And we first measure these wavelengths in containers of gas in our laboratories, which are not moving. If every line in a star's spectrum is now shifted by its motion to a different wavelength (color), how can we be sure which lines and which elements we are looking at in a star whose speed we do not know?

Take heart. This situation sounds worse than it really is. Astronomers rarely judge the presence of an element in an astronomical object by a single line. It is the *pattern* of lines unique to hydrogen or calcium that enables us to determine that those elements are part of the star or galaxy we are observing. The Doppler effect does not change the pattern of lines from a given element—it only shifts the whole pattern slightly toward redder or bluer wavelengths. The shifted pattern is still quite easy to recognize. Best of all, when we do recognize a familiar element's pattern, we get a bonus: the amount the pattern is shifted can enable us to determine the speed of the objects in our line of sight.

The training of astronomers includes much work on learning to decode light (and other electromagnetic radiation). A skillful "decoder" can learn the temperature of a star, what elements are in it, and even its speed in a direction toward us or away from us. That's really an impressive amount of information for stars that are light-years away.

Key Terms

absorption spectrum a series or pattern of dark lines superimposed on a continuous spectrum

blackbody an idealized object that absorbs all electromagnetic energy that falls onto it

continuous spectrum a spectrum of light composed of radiation of a continuous range of wavelengths or colors, rather than only certain discrete wavelengths

dispersion separation of different wavelengths of white light through refraction of different amounts

Doppler effect the apparent change in wavelength or frequency of the radiation from a source due to its relative motion away from or toward the observer

electromagnetic radiation radiation consisting of waves propagated through regularly varying electric and magnetic fields and traveling at the speed of light

electromagnetic spectrum the whole array or family of electromagnetic waves, from radio to gamma rays

emission spectrum a series or pattern of bright lines superimposed on a continuous spectrum

energy flux the amount of energy passing through a unit area (for example, 1 square meter) per second; the units of flux are watts per square meter

energy level a particular level, or amount, of energy possessed by an atom or ion above the energy it possesses in its least energetic state; also used to refer to the states of energy an electron can have in an atom

excitation the process of giving an atom or an ion an amount of energy greater than it has in its lowest energy (ground) state

frequency the number of waves that cross a given point per unit time (in radiation)

gamma rays photons (of electromagnetic radiation) of energy with wavelengths no longer than 0.01 nanometer; the most energetic form of electromagnetic radiation

ground state the lowest energy state of an atom

infrared electromagnetic radiation of wavelength 10^3–10^6 nanometers; longer than the longest (red) wavelengths that can be perceived by the eye, but shorter than radio wavelengths

inverse square law (for light) the amount of energy (light) flowing through a given area in a given time decreases in proportion to the square of the distance from the source of energy or light

ion an atom that has become electrically charged by the addition or loss of one or more electrons

ionization the process by which an atom gains or loses electrons

isotope any of two or more forms of the same element whose atoms have the same number of protons but different numbers of neutrons

microwave electromagnetic radiation of wavelengths from 1 millimeter to 1 meter; longer than infrared but shorter than radio waves

nucleus (of an atom) the massive part of an atom, composed mostly of protons and neutrons, and about which the electrons revolve

photon a discrete unit (or “packet”) of electromagnetic energy

radial velocity motion toward or away from the observer; the component of relative velocity that lies in the line of sight

radio waves all electromagnetic waves longer than microwaves, including radar waves and AM radio waves

spectrometer an instrument for obtaining a spectrum; in astronomy, usually attached to a telescope to record the spectrum of a star, galaxy, or other astronomical object

Stefan-Boltzmann law a formula from which the rate at which a blackbody radiates energy can be computed; the total rate of energy emission from a unit area of a blackbody is proportional to the fourth power of its absolute temperature: $F = \sigma T^4$

ultraviolet electromagnetic radiation of wavelengths 10 to 400 nanometers; shorter than the shortest visible wavelengths

visible light electromagnetic radiation with wavelengths of roughly 400–700 nanometers; visible to the human eye

wavelength the distance from crest to crest or trough to trough in a wave

Wien's law formula that relates the temperature of a blackbody to the wavelength at which it emits the greatest intensity of radiation

X-rays electromagnetic radiation with wavelengths between 0.01 nanometer and 20 nanometers; intermediate between those of ultraviolet radiation and gamma rays

Summary

5.1 The Behavior of Light

James Clerk Maxwell showed that whenever charged particles change their motion, as they do in every atom and molecule, they give off waves of energy. Light is one form of this electromagnetic radiation. The wavelength of light determines the color of visible radiation. Wavelength (λ) is related to frequency (f) and the speed of light (c) by the equation $c = \lambda f$. Electromagnetic radiation sometimes behaves like waves, but at other times, it behaves as if it were a particle—a little packet of energy, called a photon. The apparent brightness of a source of electromagnetic energy decreases with increasing distance from that source in proportion to the square of the distance—a relationship known as the inverse square law.

5.2 The Electromagnetic Spectrum

The electromagnetic spectrum consists of gamma rays, X-rays, ultraviolet radiation, visible light, infrared, and radio radiation. Many of these wavelengths cannot penetrate the layers of Earth's atmosphere and must be observed from space, whereas others—such as visible light, FM radio and TV—can penetrate to Earth's surface. The emission of electromagnetic radiation is intimately connected to the temperature of the source. The higher the temperature of an idealized emitter of electromagnetic radiation, the shorter is the wavelength at which the maximum amount of radiation is emitted. The mathematical equation describing this relationship is known as Wien's law: $\lambda_{\max} = (3 \times 10^6)/T$. The total power emitted per square meter increases with increasing temperature. The relationship between emitted energy flux and temperature is known as the Stefan-Boltzmann law: $F = \sigma T^4$.

5.3 Spectroscopy in Astronomy

A spectrometer is a device that forms a spectrum, often utilizing the phenomenon of dispersion. The light from an astronomical source can consist of a continuous spectrum, an emission (bright line) spectrum, or an absorption (dark line) spectrum. Because each element leaves its spectral signature in the pattern of lines we observe, spectral analyses reveal the composition of the Sun and stars.

5.4 The Structure of the Atom

Atoms consist of a nucleus containing one or more positively charged protons. All atoms except hydrogen can also contain one or more neutrons in the nucleus. Negatively charged electrons orbit the nucleus. The number of protons defines an element (hydrogen has one proton, helium has two, and so on) of the atom. Nuclei with the same number of protons but different numbers of neutrons are different isotopes of the same element. In the Bohr model of the atom, electrons on permitted orbits (or energy levels) don't give off any electromagnetic radiation. But when electrons go from lower levels to higher ones, they must absorb a photon of just the right energy, and when they go from higher levels to lower ones, they give off a photon of just the right energy. The energy of a photon is connected to the frequency of the electromagnetic wave it represents by Planck's formula, $E = hf$.

5.5 Formation of Spectral Lines

When electrons move from a higher energy level to a lower one, photons are emitted, and an emission line can be seen in the spectrum. Absorption lines are seen when electrons absorb photons and move to higher energy levels. Since each atom has its own characteristic set of energy levels, each is associated with a unique pattern of spectral lines. This allows astronomers to determine what elements are present in the stars and in the clouds of gas and dust among the stars. An atom in its lowest energy level is in the ground state. If an electron is in an orbit other than the least energetic one possible, the atom is said to be excited. If an atom has lost one or more electrons, it is called an ion and is said to be ionized. The spectra of different ions look different and can tell astronomers about the temperatures of the sources they are observing.

5.6 The Doppler Effect

If an atom is moving toward us when an electron changes orbits and produces a spectral line, we see that line shifted slightly toward the blue of its normal wavelength in a spectrum. If the atom is moving away, we see the line shifted toward the red. This shift is known as the Doppler effect and can be used to measure the radial velocities of distant objects.

For Further Exploration

Articles

Augensen, H. & Woodbury, J. “The Electromagnetic Spectrum.” *Astronomy* (June 1982): 6.

Darling, D. “Spectral Visions: The Long Wavelengths.” *Astronomy* (August 1984): 16; “The Short Wavelengths.” *Astronomy* (September 1984): 14.

Gingerich, O. “Unlocking the Chemical Secrets of the Cosmos.” *Sky & Telescope* (July 1981): 13.

Stencil, R. et al. “Astronomical Spectroscopy.” *Astronomy* (June 1978): 6.

Websites

Doppler Effect: http://www.physicsclassroom.com/class/waves/Lesson-3/The-Doppler-Effect (http://www.physicsclassroom.com/class/waves/Lesson-3/The-Doppler-Effect). A shaking bug and the Doppler Effect explained.

Electromagnetic Spectrum: http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html (http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html). An introduction to the electromagnetic spectrum from NASA’s *Imagine the Universe*; note that you can click the “Advanced” button near the top and get a more detailed discussion.

Rainbows: How They Form and How to See Them: http://www.livescience.com/30235-rainbows-formation-explainer.html (http://www.livescience.com/30235-rainbows-formation-explainer.html). By meteorologist and amateur astronomer Joe Rao.

Videos

Doppler Effect: http://www.esa.int/spaceinvideos/Videos/2014/07/Doppler_effect_-_classroom_demonstration_video_VP05 (http://www.esa.int/spaceinvideos/Videos/2014/07/Doppler_effect_-_classroom_demonstration_video_VP05). ESA video with Doppler ball demonstration and Doppler effect and satellites (4:48).

How a Prism Works to Make Rainbow Colors: https://www.youtube.com/watch?v=JGqsi_LDUn0 (https://www.youtube.com/watch?v=JGqsi_LDUn0). Short video on how a prism bends light to make a rainbow of colors (2:44).

Tour of the Electromagnetic Spectrum: https://www.youtube.com/watch?v=HPcAWNlVl-8 (https://www.youtube.com/watch?v=HPcAWNlVl-8). *NASA Mission Science* video tour of the bands of the electromagnetic spectrum (eight short videos).

Introductions to Quantum Mechanics

Ford, Kenneth. *The Quantum World.* 2004. A well-written recent introduction by a physicist/educator.

Gribbin, John. *In Search of Schroedinger’s Cat.* 1984. Clear, very basic introduction to the fundamental ideas of

quantum mechanics, by a British physicist and science writer.

Rae, Alastair. *Quantum Physics: A Beginner's Guide.* 2005. Widely praised introduction by a British physicist.

Collaborative Group Activities

A. Have your group make a list of all the electromagnetic wave technology you use during a typical day.

B. How many applications of the Doppler effect can your group think of in everyday life? For example, why would the highway patrol find it useful?

C. Have members of your group go home and "read" the face of your radio set and then compare notes. If you do not have a radio, research "broadcast radio frequencies" to find answers to the following questions. What do all the words and symbols mean? What frequencies can your radio tune to? What is the frequency of your favorite radio station? What is its wavelength?

D. If your instructor were to give you a spectrometer, what kind of spectra does your group think you would see from each of the following: (1) a household lightbulb, (2) the Sun, (3) the "neon lights of Broadway," (4) an ordinary household flashlight, and (5) a streetlight on a busy shopping street?

E. Suppose astronomers want to send a message to an alien civilization that is living on a planet with an atmosphere very similar to that of Earth's. This message must travel through space, make it through the other planet's atmosphere, and be noticeable to the residents of that planet. Have your group discuss what band of the electromagnetic spectrum might be best for this message and why. (Some people, including noted physicist Stephen Hawking, have warned scientists not to send such messages and reveal the presence of our civilization to a possible hostile cosmos. Do you agree with this concern?)

Exercises

Review Questions

1. What distinguishes one type of electromagnetic radiation from another? What are the main categories (or bands) of the electromagnetic spectrum?

2. What is a wave? Use the terms *wavelength* and *frequency* in your definition.

3. Is your textbook the kind of idealized object (described in section on radiation laws) that absorbs all the radiation falling on it? Explain. How about the black sweater worn by one of your classmates?

4. Where in an atom would you expect to find electrons? Protons? Neutrons?

5. Explain how emission lines and absorption lines are formed. In what sorts of cosmic objects would you expect to see each?

6. Explain how the Doppler effect works for sound waves and give some familiar examples.

7. What kind of motion for a star does not produce a Doppler effect? Explain.

8. Describe how Bohr's model used the work of Maxwell.

9. Explain why light is referred to as electromagnetic radiation.

10. Explain the difference between radiation as it is used in most everyday language and radiation as it is used in an astronomical context.

11. What are the differences between light waves and sound waves?

12. Which type of wave has a longer wavelength: AM radio waves (with frequencies in the kilohertz range) or FM radio waves (with frequencies in the megahertz range)? Explain.

13. Explain why astronomers long ago believed that space must be filled with some kind of substance (the “aether”) instead of the vacuum we know it is today.
14. Explain what the ionosphere is and how it interacts with some radio waves.
15. Which is more dangerous to living things, gamma rays or X-rays? Explain.
16. Explain why we have to observe stars and other astronomical objects from above Earth’s atmosphere in order to fully learn about their properties.
17. Explain why hotter objects tend to radiate more energetic photons compared to cooler objects.
18. Explain how we can deduce the temperature of a star by determining its color.
19. Explain what dispersion is and how astronomers use this phenomenon to study a star’s light.
20. Explain why glass prisms disperse light.
21. Explain what Joseph Fraunhofer discovered about stellar spectra.
22. Explain how we use spectral absorption and emission lines to determine the composition of a gas.
23. Explain the results of Rutherford’s gold foil experiment and how they changed our model of the atom.
24. Is it possible for two different atoms of carbon to have different numbers of neutrons in their nuclei? Explain.
25. What are the three isotopes of hydrogen, and how do they differ?
26. Explain how electrons use light energy to move among energy levels within an atom.
27. Explain why astronomers use the term “blueshifted” for objects moving toward us and “redshifted” for objects moving away from us.
28. If spectral line wavelengths are changing for objects based on the radial velocities of those objects, how can we deduce which type of atom is responsible for a particular absorption or emission line?

Thought Questions

29. Make a list of some of the many practical consequences of Maxwell’s theory of electromagnetic waves (television is one example).
30. With what type of electromagnetic radiation would you observe:
    - A. A star with a temperature of 5800 K?
    - B. A gas heated to a temperature of one million K?
    - C. A person on a dark night?
31. Why is it dangerous to be exposed to X-rays but not (or at least much less) dangerous to be exposed to radio waves?
32. Go outside on a clear night, wait 15 minutes for your eyes to adjust to the dark, and look carefully at the brightest stars. Some should look slightly red and others slightly blue. The primary factor that determines the color of a star is its temperature. Which is hotter: a blue star or a red one? Explain
33. Water faucets are often labeled with a red dot for hot water and a blue dot for cold. Given Wien’s law, does this labeling make sense?
34. Suppose you are standing at the exact center of a park surrounded by a circular road. An ambulance drives completely around this road, with siren blaring. How does the pitch of the siren change as it circles around you?

35. How could you measure Earth’s orbital speed by photographing the spectrum of a star at various times throughout the year? (Hint: Suppose the star lies in the plane of Earth’s orbit.)

36. Astronomers want to make maps of the sky showing sources of X-rays or gamma rays. Explain why those X-rays and gamma rays must be observed from above Earth’s atmosphere.

37. The greenhouse effect can be explained easily if you understand the laws of blackbody radiation. A greenhouse gas blocks the transmission of infrared light. Given that the incoming light to Earth is sunlight with a characteristic temperature of 5800 K (which peaks in the visible part of the spectrum) and the outgoing light from Earth has a characteristic temperature of about 300 K (which peaks in the infrared part of the spectrum), explain how greenhouse gases cause Earth to warm up. As part of your answer, discuss that greenhouse gases block both incoming and outgoing infrared light. Explain why these two effects don’t simply cancel each other, leading to no net temperature change.

38. An idealized radiating object does not reflect or scatter any radiation but instead absorbs all of the electromagnetic energy that falls on it. Can you explain why astronomers call such an object a blackbody? Keep in mind that even stars, which shine brightly in a variety of colors, are considered blackbodies. Explain why.

39. Why are ionized gases typically only found in very high-temperature environments?

40. Explain why each element has a unique spectrum of absorption or emission lines.

Figuring for Yourself

41. What is the wavelength of the carrier wave of a campus radio station, broadcasting at a frequency of 97.2 MHz (million cycles per second or million hertz)?

42. What is the frequency of a red laser beam, with a wavelength of 670 nm, which your astronomy instructor might use to point to slides during a lecture on galaxies?

43. You go to a dance club to forget how hard your astronomy midterm was. What is the frequency of a wave of ultraviolet light coming from a blacklight in the club, if its wavelength is 150 nm?

44. What is the energy of the photon with the frequency you calculated in Exercise 5.43?

45. If the emitted infrared radiation from Pluto, has a wavelength of maximum intensity at 75,000 nm, what is the temperature of Pluto assuming it follows Wien’s law?

46. What is the temperature of a star whose maximum light is emitted at a wavelength of 290 nm?