*Chapter Three*

# Light and Atoms

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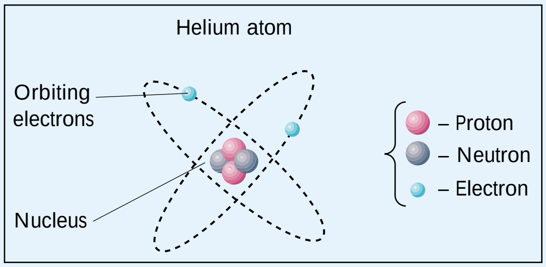
Newton studies the Sun's spectrum.
(Courtesy of Bausch and Lomb Optical Co.)




Sketch of an atom.

Our home planet is separated from other astronomical bodies by such vast distances that, with few exceptions, we cannot learn about them by direct measurements of their properties. For example, if we want to know how hot the Sun is, we cannot stick a thermometer into it. Similarly, we cannot directly sample the composition of the atmosphere of Saturn or a distant star. However, we can sample such remote bodies indirectly by analyzing their light. Light from a distant star or planet can tell us what the body is made of, its temperature, and many of its other properties. Light, therefore, is our key to studying the Universe. To use the key, however, we need to understand some of its properties.

In this chapter, we will discover that light is a form of energy that can be thought of either as a wave or as a stream of particles. Furthermore, we will discover that the light we see is just part of the radiation emitted by astronomical objects. We will also learn that light can be produced within an atom by changes in its electrons' energies. These changes imprint on the light the atom's "signature." However, the light may also bear unwanted messages. For example, when light reaches our atmosphere, gases there alter its properties, blocking some rays, and bending and blurring others. These distortions place severe limits on what astronomers can learn from the ground.

The goal of this chapter is to explain the nature of light, how it is produced, and how it interacts with our atmosphere. Our first step toward this goal is to better understand what light is.

## 3.1 PROPERTIES OF LIGHT

**Light** is radiant energy; that is, it is energy that can travel through space from one point to another without the need of a direct physical link. Therefore, light is very different in its basic nature from, for example, sound. Sound can reach us only if it is carried by a medium such as air or water, whereas light can reach us even across empty space. In empty space, we can see the burst of light of an explosion, but we will hear no sound from it at all.

Light's capacity to travel through the vacuum of space is paralleled by another very special property: its high speed. In fact, the speed of light is an upper limit to all motion. In empty space, light travels at the incredible speed of 299,792.458 kilometers per second. An object traveling that fast could circle the Earth in a mere seventh of a second.

The speed of light in empty space is a constant and is denoted by "c." However, in transparent materials, such as glass, water, and gases, the speed of light is reduced. Furthermore, different colors of light are slowed differently. For example, in nearly all materials, blue light travels slightly more slowly than red light. As we will see in chapter 4, lenses and prisms work because they slow the light as it travels through them.

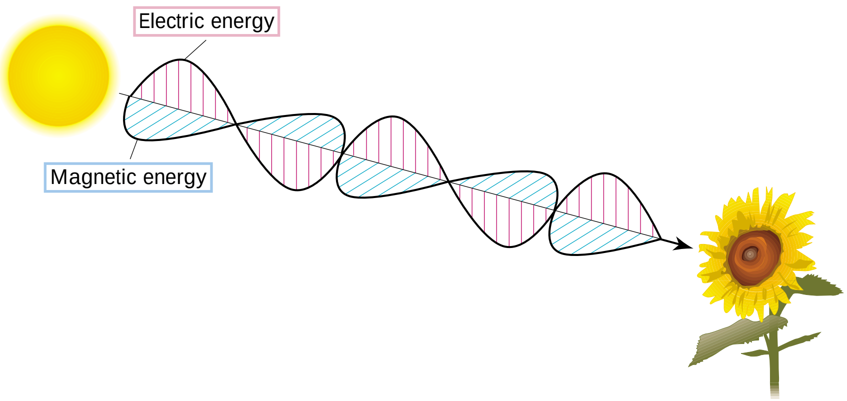
### The Nature of Light—Waves or Particles?

Animation 3.1
*An electromagnetic wave.*

Observation and experimentation on light throughout the last few centuries have produced two very different models of what it is and how it works. According to one model, light is an **electromagnetic wave** that is an alternation of electric and magnetic energy, changing in synchrony, as depicted in figure 3.1. The ability of such a wave to travel through empty space comes from the interrelatedness of electricity and magnetism.

You can see this relationship between electricity and magnetism in everyday life. For example, when you start your car, turning the ignition key sends an electric current from the battery to the starter. There, the current generates a magnetic force that turns over the engine. Similarly, when you pull the cord on a lawn mower, you spin a magnet that generates an electric current that creates the spark to start its engine.

This interrelatedness between electricity and magnetism is what allows light to travel through empty space. A small disturbance of an electric field creates a magnetic disturbance in the adjacent space, which in turn creates a new electric disturbance in the space adjacent to it, and so on. Thus, a fluctuation of electric and magnetic field



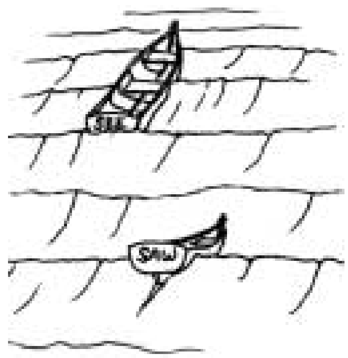



**FIGURE 3.1**
A wave of electromagnetic energy moves through empty space at the speed of light, 299,792.5 kilometers per second. The wave carries itself along by continually changing its electric energy into magnetic energy and vice versa.

spreads out from its source carried by the fields. In this fashion, light can move through empty space "carrying itself by its own bootstraps."

As the electromagnetic wave travels through matter, it may disturb the atoms, causing them to vibrate the way a water wave makes a boat rock. It is from such disturbances in our eyes, a piece of film, or an electronic sensor that we detect the light.

The model of light as a wave works well to explain many phenomena, but it fails to explain some of light's properties. In those circumstances, it is necessary (and easier!) to use a different model.

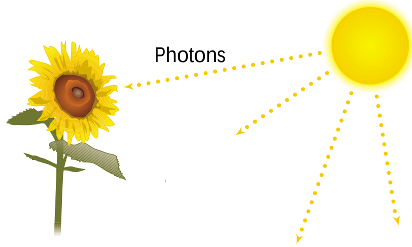
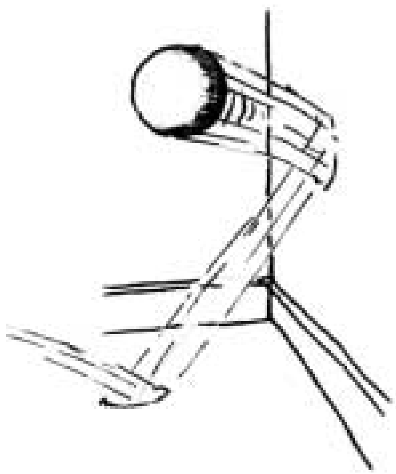



**FIGURE 3.2**
Photons—particles of energy—stream away from a light source at the speed of light.

In this model, light is a stream of particles called **photons** (fig. 3.2). The photons are packets of energy, and when they enter your eye, they produce the sensation of light.

In empty space, photons move in a straight line at the speed of light. Although they are described as particles, photons can behave as waves, but they are not unique in this respect. According to the laws of quantum physics, subatomic particles such as electrons and protons can also behave like waves. For this reason, scientists often speak of light and sub-atomic particles as having a **wave-particle duality** and they use whichever model—wave or particle—that best describes a particular phenomenon. For example, reflection of light off a mirror is easily understood if you imagine photons striking the mirror and bouncing back just the way a ball rebounds when thrown at a wall. On the other hand, the focusing of light by a lens is best explained by the wave model.



Brightness or intensity of light can be described conveniently by either model. Both brightness and intensity measure the amount of energy carried by the wave. If we imagine light as photons, intensity is proportional to the number of photons traveling in a given direction. If we think of light as a wave, intensity is related to the strength of the wave's vibrating electric and magnetic energy.

In most of the rest of this chapter, we will explain light using the wave model, so that we do not have to constantly refer first to photons and then to waves.

## Light and Color

Regardless of whether we consider light to be a wave or a stream of photons, our eyes perceive one of its most fundamental properties as color. Human beings can see colors ranging from deep red through orange and yellow into green, blue, and violet. The colors to which the human eye is sensitive define what is called the **visible spectrum.** But what property of photons or electromagnetic waves corresponds to light's different colors?

According to the wave theory, the color of light is determined by the light's **wavelength,** which is the spacing between wave crests (fig. 3.3). That is, instead of

**FIGURE 3.3**

The distance between crests defines the wavelength, $\lambda$, for any kind of wave, be it water or electromagnetic.

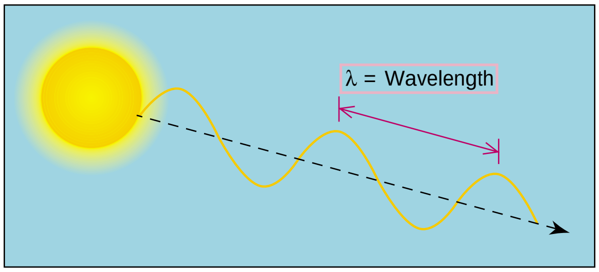



**TABLE 3.1**

**Colors and Wavelengths***

| | | |
|---|---|---|
| Red | 700 nm | 0.7 micrometers |
| Yellow | 580 | 0.58 |
| Blue | 480 | 0.48 |
| Violet | 400 | 0.40 |

*These color equivalences are only approximate.

describing a quality, light's color, we can specify a quantity, its wavelength, usually denoted by the Greek letter lambda, $\lambda$. For example, the wavelength of deep red light is about $7 \times 10^{-7}$ meters. The wavelength of violet light is about $4 \times 10^{-7}$ meters. Intermediate colors have intermediate wavelengths. The wave-particle duality model allows us to make a similar connection between wavelength and color for photons. Thus, we can also characterize photons by their wavelength.

Be sure to remember that shorter wavelengths of visible light correspond to bluer colors. We will use that information *many* times in later chapters.

The wavelengths of visible light are very small (roughly the size of a bacterium). They are therefore usually measured not in meters but in billionths of a meter, a unit called the **nanometer,** abbreviated nm. Thus, the wavelength of red light is about 700 nanometers, but that of violet light is about 400 nanometers.* Table 3.1 lists the wavelengths of the primary colors in nm and some other units sometimes used to measure wavelengths.

*Scientists sometimes use other units of length to measure wavelengths. For example, astronomers have traditionally used angstrom units and micrometers. One angstrom unit is $10^{-10}$ meters (1 ten-billionth of a meter) and is thus the same as 1/10 of a nanometer. The wavelength of red light is thus about 7000 angstroms. The micrometer (also called a micron and abbreviated $\mu$m) is used especially at infrared wavelengths (wavelengths longer than visible light that we perceive as heat). One micrometer is $10^{-6}$ meters. The wavelength of red light is about 0.7 micrometers.

## Characterizing Electromagnetic Waves by Their Frequency

Sometimes it is useful to describe electromagnetic waves by their frequency rather than their wavelength. You can see an everyday example of this on a radio dial, where you tune in a station by its frequency rather than its wavelength. **Frequency** is the number of wave crests that pass a given point in 1 second. It is measured in hertz (abbreviated as Hz) and is usually denoted by the Greek letter nu, $\nu$. Frequency and wavelength are related to the wave speed because in one vibration, a wave must travel a distance equal to one wavelength. This implies that for light, the product of the wavelength and the wave frequency is the speed of light, that is, $\lambda\nu = c$. Because all light travels at the same speed (in empty space), we can treat c as a constant. Thus, specifying $\lambda$ determines $\nu$ and vice versa. We will generally use $\lambda$ to characterize electromagnetic waves, but $\nu$ is just as good.

## White Light

Although wavelength is an excellent way to specify most colors of light, some light seems to have no color. For example, the Sun when it is seen high in the sky and an ordinary lightbulb appear to have no dominant color. Light from such sources is called **white light.**

White light is not a special color of light; rather it is a mixture of all colors. That is, the sunlight we see is made up of all the wavelengths of visible light—a blend of red, yellow, green, blue, and so on—and our eyes perceive these as white. Newton demonstrated this property of sunlight by a very simple but elegant experiment. He passed sunlight through a prism (fig. 3.4) so that the light was spread out into the visible spectrum (or rainbow of colors). He then recombined the separated colors with a lens and reformed the beam of white light.

Why do we see sunlight as white? Presumably because our senses have evolved to make us aware of *changes* in our surrounding. Thus, we ignore the ambient "color" of sunlight just as we come in time to ignore a steady background sound or smell.

But there is more to light than what meets the eye. Just as red is but one part of the visible spectrum, so too the visible spectrum itself is but one part of a much wider spectrum of electromagnetic radiation.

You can see how colors of light mix if you look at a color television screen close up. You will notice that the screen is covered with tiny red, green, and blue dots. In a red object, only the red spots are lit. In a blue one, only the blue spots. In a white object, all three are lit, and the brain mixes these three colors to form white. Other colors are made by appropriate blending of red, green, and blue. Notice this is very different from the way that pigments of paint mix. Red, green, and blue paint when mixed give a brownish color.

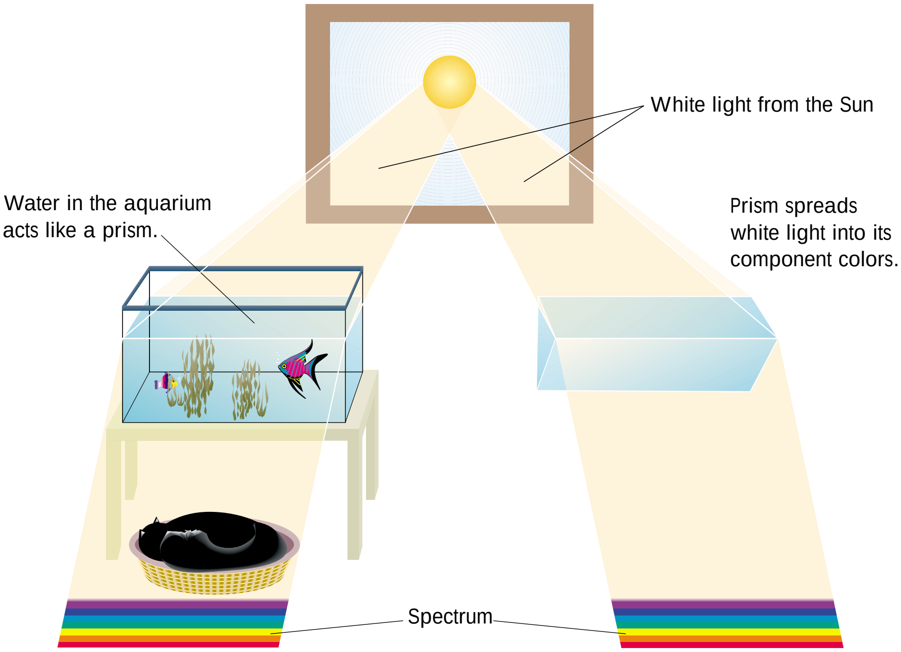



FIGURE 3.4
White light is spread into a spectrum by a prism.

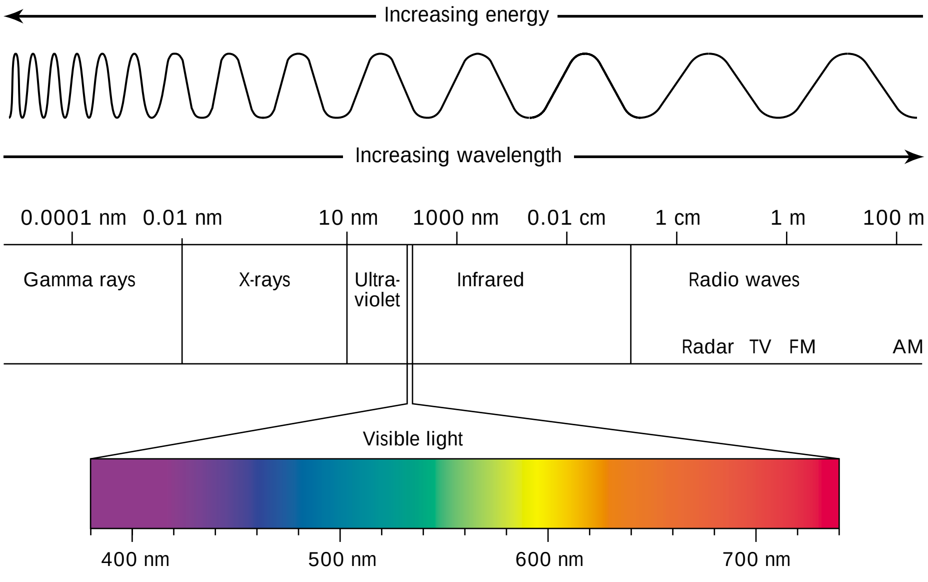



**FIGURE 3.5**
The electromagnetic spectrum.

**TABLE 3.2**
Electromagnetic Spectrum

| Wavelength | Kind of Radiation | Astronomical Sources |
|---|---|---|
| 100–500 meters | Radio (AM broadcast) | Pulsars (remnants of exploded stars) |
| 10–100 meters | Short-wave radio | Active galaxies |
| 1–10 meters | TV, FM radio | |
| 1–100 centimeters | Radar | Planets, active galaxies |
| 1–10 millimeters | Microwaves | Interstellar clouds, cosmic background radiation |
| 1000–$10^6$ nanometers | Infrared (heat) | Young stars, planets, interstellar dust |
| 400–700 nanometers | Visible light | Stars, Sun |
| 1–300 nanometers | Ultraviolet | Stars |
| 0.01–1 nanometers | X rays | Collapsed stars, hot gas in galaxy clusters |
| $10^{-7}$–0.01 nanometers | Gamma rays | Active galaxies and gamma-ray bursters |

## 3.2 THE ELECTROMAGNETIC SPECTRUM: BEYOND VISIBLE LIGHT

You are already familiar with many other forms of electromagnetic radiation from many different sources. Radio waves, X rays, and ultraviolet light are all electromagnetic waves that differ from visible light only in their wavelengths. To indicate the fundamental unity of all these kinds of radiation, they are referred to as parts of the **electromagnetic spectrum.** The electromagnetic spectrum is the assemblage of all types of electromagnetic waves arranged according to their wavelength. The longest electromagnetic waves yet detected have wavelengths thousands of kilometers long.* The shortest have wavelengths of $10^{-18}$ meters or less. Ordinary visible light falls in a very narrow section in about the middle of the known spectral range (see table 3.2 and fig. 3.5).

As you can see in figure 3.5, there is a vast range of wavelengths in the electromagnetic spectrum that we cannot see with our eyes. Nevertheless, the development of

*Such long waves have not been detected from astronomical sources, however, and cannot pass through our atmosphere.

various instruments allows these wavelength regions to be explored. In fact, new instruments allow astronomers to "see" such astronomically important events as the formation of stars, the remnants left behind when stars die, and, indirectly, black holes.

## Infrared Radiation

The exploration of the electromagnetic spectrum began in 1800, when Sir William Herschel (discoverer of the planet Uranus) showed that heat radiation, such as you feel from the Sun or from a warm radiator, though invisible, was related to visible light.

Herschel was trying to measure heat radiated by astronomical sources. He projected a spectrum of sunlight onto a table top and placed a thermometer in each color to measure its energy. He was surprised that when he put a thermometer just off the red end of the visible spectrum, the thermometer registered an elevated temperature there just as it did in the red part of the spectrum. He concluded that some form of invisible energy perceptible as heat existed beyond the red end of the spectrum and therefore called it **infrared.** Even though our eyes cannot see infrared light, nerves in our skin can feel it as heat.

Although humans cannot see infrared radiation, several kinds of snakes, including the rattlesnake, have special infrared sensors located just below their eyes. These allow the snake to "see" in total darkness, helping it to find warm-blooded prey such as rats.

## Ultraviolet Light

Another important part of the electromagnetic spectrum, **ultraviolet** radiation, was discovered in 1801 by J. Ritter while he was experimenting with chemicals that might be sensitive to light. Ritter noted that when he shined a spectrum of sunlight on a layer of silver chloride, the chemical blackened most strongly in the region just beyond the violet end of the spectrum.

Infrared and ultraviolet radiation differ in no physical way from visible light except in their wavelength. Infrared has longer wavelengths and ultraviolet shorter wavelengths than visible light (see table 3.2). Exploration of those parts of the electromagnetic spectrum with wavelengths much larger and much smaller than visible light had to await the growth of new technology, as the development of radio astronomy demonstrates.

## Radio Waves

James Clerk Maxwell, a Scottish physicist, predicted the existence of radio waves in the mid-1800s. It was some 20 years later, however, before Heinrich Hertz produced them experimentally in 1888, and another 50 years had to pass before Karl Jansky discovered naturally occurring radio waves coming from cosmic sources. Jansky's discovery in the 1930s that the center of the Milky Way was a strong source of radio emission was the birth of radio astronomy.

Radio waves range in length from millimeters to hundreds of meters, making them much longer than visible and infrared waves. Today we can generate radio waves and use them in many ways, ranging from communication to radar to microwave ovens. Astronomers too use radio waves, detecting them with radio telescopes. Such signals, generated by natural processes, allow astronomers to obtain radio "views" of forming stars, exploding stars, active galaxies, and interstellar gas clouds. Radio wavelengths are even being searched for signals that might hint at the existence of extraterrestrial civilizations (see essay 3).

## Other Wavelength Regions

Many decades also passed between the discovery of X rays by Wilhelm Roentgen in 1895 and detection in the late l940s of X rays coming from the Sun. X-ray wavelengths turn out to be far shorter than those of visible light, typically between 0.01 and 10 nanometers, but they too are important. Doctors and dentists use X rays to probe our bones and organs. Astronomers use X-ray telescopes to detect X rays emitted by the hot gas surrounding black holes and the tenuous gas in distant groups of galaxies.

Two parts of the electromagnetic spectrum remain relatively unexplored: the region between infrared and radio waves and the region of gamma rays, which are the shortest wavelengths known. Both these wavelength regions are difficult to study from the ground because, as we will see in section 3.7, they fall in wavelength bands that are strongly blocked by the Earth's atmosphere.

In the photon picture of electromagnetic radiation, a similar unity exists. Scientists refer to radio photons, visible photons, ultraviolet photons, etc.

Despite the enormous variety of electromagnetic waves, they are all the same physical phenomenon: the vibration of electric and magnetic energy traveling at the speed of light. The essential difference between kinds of electromagnetic radiation is merely their wavelength (or frequency). This difference alters not only how we perceive them but also how much energy they can carry.

## Energy Carried by Electromagnetic Radiation

The warmth we feel on our face from a beam of sunlight demonstrates that light carries energy, but not all wavelengths carry the same amount of energy. It turns out that the amount of energy, $E$, carried by electromagnetic radiation depends on its wavelength, $\lambda$. Each photon of wavelength $\lambda$ carries an energy, $E$, given by

$E$ = Energy carried by a photon of wavelength = $\lambda$
h = Constant
c = Speed of light (constant)

$$E = \frac{\mathrm{hc}}{\lambda}$$

The speed of light c, and the constant, h, are unchanging,* so if the wavelength of the light decreases, the energy it carries increases. Thus

**Short wavelength radiation carries proportionally more energy than long wavelength radiation.**

In the photon model of electromagnetic radiation, each photon is a bundle of energy, or "energy-packet."

Ultraviolet light with its short wavelength therefore carries proportionally more energy than infrared light with its longer wavelength. In fact, ultraviolet light of sufficiently short wavelengths can carry so much energy that it can break apart atomic and molecular bonds. As we will see in chapter 13, this may cause intense heating of gas near stars. Nearer to home, it is the reason ultraviolet light gives you a sunburn while an infrared heat lamp does not.

## Wien's Law: A Wavelength-Temperature Relation

Heated bodies generally radiate across a range of wavelengths, but there is usually a particular wavelength at which their radiation is most intense. That wavelength, which for visible wavelengths affects the color of the body's light, is given by a relation called **Wien's law.**

Wien's law states that the wavelength at which a body radiates most strongly is inversely proportional to the body's temperature. That is,

**Hotter bodies radiate more strongly at shorter wavelengths.**

As a body is heated, the color of the visible light it emits shifts gradually from red to orange to yellow. At sufficiently high temperatures, its light would look bluish white. This does *not* mean that a very hot body emits only blue light and no red light. Rather, it means that it emits *more* blue than red.

You have almost certainly used Wien's law instinctively and subconsciously when you cook on an electric stove. When the burner of an electric stove first is turned on, it glows dull red, but as it heats up, the *glow becomes a bright orange and eventually yellow.* This effect is the consequence of Wien's law and shows that as a body gets hotter, it emits more light at shorter and hence yellower colors.

We can see this effect illustrated in figure 3.6. In the diagram, we see the amount of energy radiated at each wavelength (color) by three bodies of different temperatures. Notice that the hotter body has its most intense emission (highest point) at a shorter wavelength than the cooler body. This is what gives it a different color.

*If $E$ is measured in joules and $\lambda$ in meters, $\mathrm{h} = 6.63 \times 10^{-34}$ joule-second (known as Planck's constant) and $\mathrm{hc} = 1.99 \times 10^{-25}$ joule-meters.

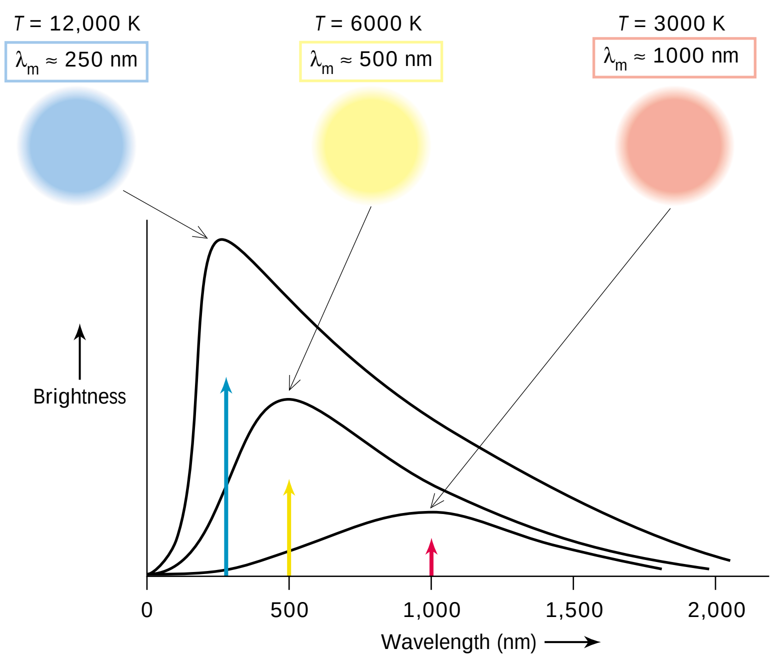



**FIGURE 3.6**
As a body is heated, the wavelength at which it radiates most strongly, $\lambda_m$, shifts to shorter wavelengths, a relation known as "Wien's Law." Thus, the color of an electric stove burner changes from red to yellow as it heats up. Note also that as the object's temperature rises, the amount of energy radiated increases at *all* wavelengths.

You might note that the wavelength at which the Sun radiates most strongly corresponds to a blue-green color, yet the Sun looks yellow-white to us. The reason we see it as whitish is related to how our eyes perceive color. Physiologists have found that the human eye interprets sunlight (and light from all extremely hot bodies) as whitish, with only tints of color. The light from such hot bodies obeys Wien's law but not with pure colors. Thus, cool stars look white tinged with red, while very hot stars look white tinged with blue.

Wien's law, named for the German physicist who discovered it near the turn of the century, is extremely important because we can use it to measure how hot something is simply from the color of light it radiates most strongly. The law has a few very important exceptions, which we will discuss later, but it works accurately for most stars and planets.

## EXTENDING OUR REACH

### TAKING THE TEMPERATURE OF THE SUN

To measure a distant body's temperature using Wien's law, we proceed as follows. First we measure the body's brightness at many different wavelengths to find at which particular wavelength it is brightest (that is, its wavelength of maximum emission). Then we use the law to calculate the body's temperature. To see how this is done, however, we need a mathematical expression for the law.

If we let $T$ be the body's temperature, measured in Kelvin* and $\lambda_m$ be the wavelength in nanometers at which it radiates most strongly (fig. 3.6), Wien's law can be written in the form

$$T = \frac{3 \times 10^{6\dagger}}{\lambda_m}$$

The subscript m on $\lambda$ is to remind us that it is the wavelength of maximum emission.

As an example, let's measure the Sun's temperature. The Sun turns out to radiate most strongly at a wavelength of about 500 nanometers. Then, substituting $\lambda_m =$ 500 nanometers, we find

$$T = \frac{3 \times 10^6}{500} = \frac{3 \times 10^6}{5 \times 10^2}$$
$$= 0.6 \times 10^4 = 6000 \text{ Kelvin}$$

This is within a few hundred degrees of the actual value.

*See p. 55 for discussion of the Kelvin temperature scale.

†The constant $3 \times 10^6$ K-nm is more accurately $2.898 \times 10^6$. We round it off here to make calculations easier. The error this creates is small.

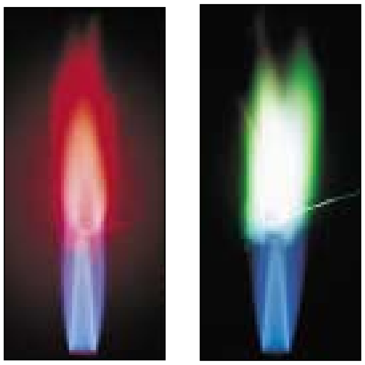
We must be careful in applying Wien's law when we look at the light that objects *reflect,* as opposed to light that they emit. For example, the red color of an apple and the green color of a lime come from the light they reflect and have nothing to do with temperature. The apple does emit some radiation, but if it is at normal room temperature, its radiation will be mostly in the infrared.

Wien's law makes good sense if you think about the relation between energy and temperature. Hotter things carry more energy (other quantities being equal) than cooler things. Also, bluer light carries more energy than red. Thus, it is reasonable to expect that hotter bodies emit bluer light.

Our discussion above has been qualified several times by terms such as *usually* and *most.* The reason for these qualifications is that Wien's law applies only to a class of objects known as blackbodies.

### Blackbodies and Wien's Law

A **blackbody** is an object that absorbs all the radiation falling upon it. Because such a body reflects no light, it looks black to us when it is cold; hence its name. Experiments show that when blackbodies are heated, they radiate more efficiently than other kinds of objects. Thus, they are both excellent absorbers and excellent emitters. Moreover, the intensity of their radiation changes smoothly from one wavelength to the next with no gaps or narrow peaks of brightness. Very few objects are perfect blackbodies, but many of the objects we will study are near enough to being blackbodies that we can use Wien's law with little fear of its being in error. For example, the electric stove burner, the Sun, and the Earth all obey Wien's law quite satisfactorily.



Bunsen invented the Bunsen burner for just this purpose: the study of the colors created by chemicals in a flame. His work was instrumental in the development of the basic ideas of spectra as probes of chemical composition.

The photographs above show the effect of strontium (red) and copper (green) on the burner's flame.

(Courtesy of Stephen Frisch.)

On the other hand, gases (unless compressed to a very high density) are generally not blackbodies and do not obey Wien's law. Interstellar clouds, for example, can radiate strongly only in narrow wavelength ranges, such as the red part of the visible spectrum or the millimeter wavelength part of the radio spectrum. The clouds' color is determined by composition more than temperature. You can easily demonstrate the importance of composition in determining color with a gas flame on a stove or Bunsen burner. Normally the flame has a blue part and a yellow part. The yellow part is blackbody radiation from very hot specks of carbon soot. However, the blue part is caused by nonblackbody emission from carbon atoms. If you add chemicals to the flame, the flame's color may change dramatically. For example, if you hold some copper sulfate crystals with a pair of pliers in the flame, the flame will take on a greenish-blue color caused by the emission wavelengths of copper.

So far we have described some of the general properties of electromagnetic radiation, such as its wave nature and the existence of different wavelength regions, but we have not explained the origin of the radiation. Radiation originates in matter, and we must thus look more closely at the structure of matter if we are to understand radiation's origin. That is our next goal, and, as we will see, it will lead us not only to an understanding of the nature of atoms but also to an explanation of how we can detect those atoms in remote astronomical bodies.

## 3.3 ATOMS

The structure of atoms determines both their chemical properties and their light-emitting and light-absorbing properties. For example, iron and hydrogen not only have very different atomic structures but also emit very different wavelengths of light. From those differences astronomers can deduce whether an astronomical body—a star or a planet—contains iron, hydrogen, or whatever chemicals happen to be present. Therefore, an understanding of the structure of atoms ultimately leads us to an understanding of the nature of stars.

## Structure of Atoms

We described in the introduction to this text how an atom has a dense core called a *nucleus* around which smaller particles called *electrons* orbit (fig. 3.7). The nucleus is in turn composed of particles called *protons* and *neutrons;* the protons have a positive charge, the neutrons have no charge, and the electrons have a negative charge. Moreover, it is the positive electrical charge of the protons that attracts and hold the negatively charged electrons in their orbits.

Those orbits are generally extremely small. For example, the diameter of the smallest electron orbit in a hydrogen atom is only about $10^{-10}$ (1 ten-billionth) meter. This infinitesimal size leads to effects that operate at an atomic level that have no counterpart in larger systems. The most important of these effects is that the electron orbits may have only certain prescribed sizes. Although a planet may orbit the Sun at any distance, an electron may orbit an atomic nucleus at only certain distances, as when you climb a set of stairs, you can be only at certain discrete heights. For example, in a hydrogen atom the electron can have an orbital radius of 0.0529 $n^2$ nanometers where $n$ is 1, 2, 3, etc., but *it cannot have intermediate values;* that is, the orbits are said to be **quantized.**

The above restriction on orbital sizes results from the electron's acting not just as a particle but also as a wave. That is, just as light itself has a wave-particle duality, so too does an electron. The electron's wave nature forces the electron to move only in orbits whose circumference is a whole number of wavelengths. If it were to move in other orbits, the electron's wave nature would "cancel" it out.*

Electrons in orbit have another property totally unlike those of planets in orbit: they routinely shift from one orbit to another. This shifting changes their energy, as can be understood by a simple analogy.

The electrical attraction between the nucleus and the electron creates a force between them like a spring. If the electron increases its distance from the nucleus, the spring must stretch. This requires giving energy to the atom. Likewise, if the electron moves closer to the nucleus, the spring contracts and the atom must give up, or emit, energy. We perceive that emitted energy as light or, more generally, electromagnetic radiation. The wavelength of that radiation is not the same for all atoms. But to understand why, we need to say a bit more about atomic structure. In particular, we need to describe what makes one kind of atom different from another. For example, what makes iron different from hydrogen.

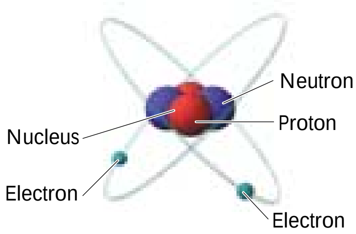
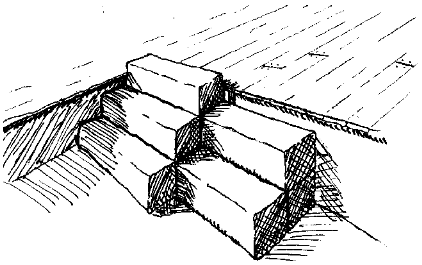



FIGURE 3.7
Sketch of an atom's structure, showing electrons orbiting the nucleus. The electrons are held in orbit by the electrical attraction between their negative charge and the positive charge of the protons in the nucleus. "Orbits" are in reality more like clouds.

You can see the effect of electrical charges in action when you take clothes out of a dryer. As the clothes tumble in the machine, electrical charges rub off some articles and accumulate on others. These charges remain for a while on the clothes even after the machine is turned off, causing, for example, socks to stick to shirts and lingerie. When you pull them apart, you can feel the attraction of the electricity that makes them stick to each other.



## The Chemical Elements

Iron and hydrogen are examples of what are called chemical **elements.** A chemical element is a substance composed only of atoms that all have the same number of protons. For example, hydrogen consists exclusively of atoms that contain 1 proton; helium, of atoms that contain 2 protons; carbon 6; oxygen 8; and so forth. Although the identity of an element is determined by the number of protons in its nucleus, the chemical properties of each element are determined by the number of electrons orbiting its nucleus. However, the number of electrons must equal the number of protons. This means that each atom has an equal number of positive and negative electrical charges and is therefore electrically neutral.

Table 3.3 lists some of the more important elements we will discuss during our exploration of the Universe and the number of protons each contains.

*The wave nature of the electron has another important effect. It "smears" the electrons. As a result, although we have described the electrons as orbiting like tiny spheres around the nucleus, most scientists prefer to think of them as moving within an electron cloud.

TABLE 3.3
Astronomically Important Elements

| Element | Number of Protons | Number of Neutrons* |
|---|---|---|
| Hydrogen | 1 | 0 |
| Helium | 2 | 2 |
| Carbon | 6 | 6 |
| Nitrogen | 7 | 7 |
| Oxygen | 8 | 8 |
| Silicon | 14 | 14 |
| Iron | 26 | 30 |

*The number of neutrons listed here is the number found in the most abundant form of the element. Different neutron numbers can occur and lead to what are called *isotopes* of the element.

In summary then, atoms consist of a nucleus containing protons and neutrons around which electrons orbit. The electrons are bound to the nucleus by the electric attraction between the protons and electrons. Electrons may shift from one orbit to another accompanied by a change in the atom's energy. The identity of the atom—the element—is determined by the number of protons in its nucleus. With this picture of the atom in mind, we can now turn to how light is generated within atoms.

## 3.4 THE ORIGIN OF LIGHT

We saw above that when an electron moves from one orbit to another, the energy of the atom changes. If the atom's energy is increased, the electron moves outward from an inner orbit. Such an atom is said to be **excited.** On the other hand, if the electron moves inward toward the nucleus, the atom's energy is decreased.

Although the energy of an atom may change, the energy cannot just disappear. One of the fundamental laws of nature is the **conservation of energy.** This law states that energy can never be created or destroyed, it can only be changed in form. According to this principle, if an atom loses energy, that energy *must reappear in some other form*. One important form in which the energy reappears is light, or, more generally, electromagnetic radiation.

How is the electromagnetic radiation created? When the electron drops from one orbit to another, it alters the electric energy of the atom. As we described earlier, such an electrical disturbance generates a magnetic disturbance, which in turn generates a new electrical disturbance. Thus, the energy released when an electron drops from a higher to a lower orbit becomes an electromagnetic wave, a process called **emission** (fig. 3.8).

Emission plays an important role in many astronomical phenomena. The aurora (northern lights) is an example of emission by atoms in the Earth's upper atmosphere, and sunlight and starlight are examples of emission in those bodies.

The reverse process, in which light is stored in an atom as energy, is called **absorption** (fig. 3.9). Absorption lifts an electron from a lower to a higher orbit and excites the atom by increasing the electron's energy. Absorption is important in understanding such diverse phenomena as the temperature of a planet and the identification of star types, as we will discover in later chapters.

Emission and absorption are particularly easy to understand if we use the photon model of light. According to this model, an atom emits a photon when one of its

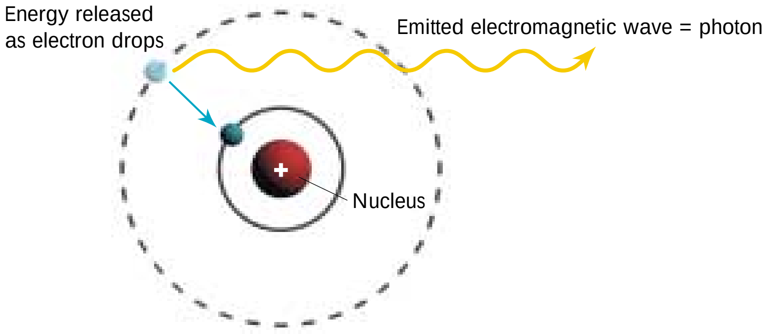



FIGURE 3.8
Energy is released when an electron drops from an upper to a lower orbit, causing the atom to emit electromagnetic radiation.

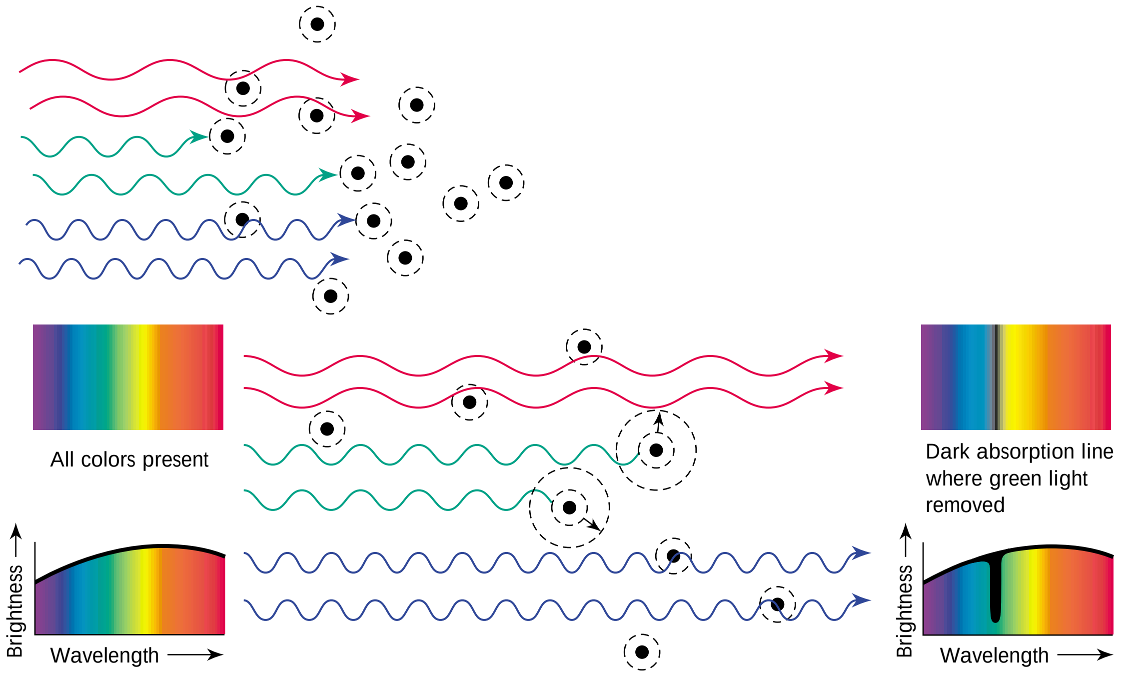



FIGURE 3.9
An atom can absorb light, using the light's energy to lift an electron from a lower to a higher orbit. To be absorbed, the energy of the light's photons must equal the energy difference between the atom's electron orbits. In this example, the green light's energy matches the energy difference, but the red and blue light's energy does not. Therefore, only the green is absorbed. The upper two spectra show what you would see when looking at the dispersed light. The bottom two spectra show a plot of the light's brightness.

electrons drops from an upper to a lower orbit. Similarly, an atom absorbs light when a photon collides with it and "knocks" one of its electrons into an upper level.

You may find it helpful in understanding emission and absorption if you think of an analogy. Absorption is a bit like drawing an arrow back preparatory to shooting it from a bow. Emission is like the arrow being shot. In one case, energy of your muscles is transferred to and stored in the flexed bow. In the other, it is released as the arrow takes flight.

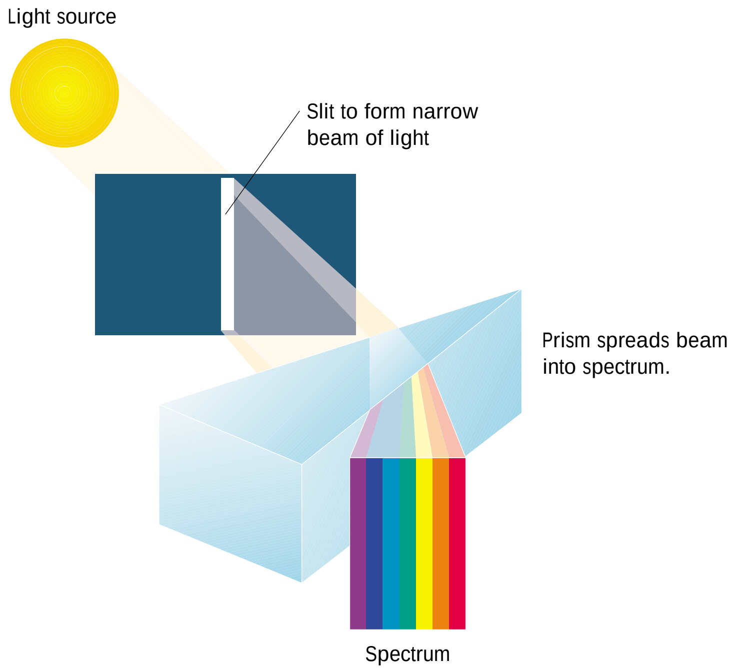



**FIGURE 3.10**
Sketch of a spectroscope and how it forms a spectrum. Either a prism or grating may be used to spread the light into its component colors.

## 3.5 FORMATION OF A SPECTRUM

The key to determining the composition and conditions of an astronomical body is its spectrum. The technique used to capture and analyze such a spectrum is called **spectroscopy.** In spectroscopy, the light (or more generally the electromagnetic radiation) emitted or reflected by the object being studied is collected with a telescope and spread into its component colors to form a spectrum by passing it through a prism or a grating consisting of numerous, tiny, parallel lines (fig. 3.10). Since light is emitted from atoms as electrons shift between orbits, we might expect that the light will bear some imprint of the kind of atom that creates it. That is usually the case, and astronomers can search for the atom's "signature" by measuring how much light is present at each wavelength.

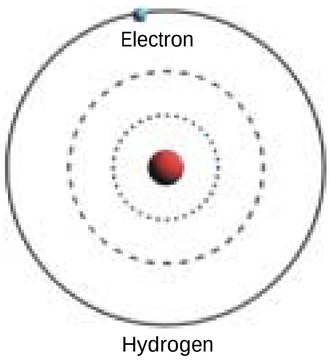
Spectroscopy is such an important tool for astronomers that we should look in greater detail at how it works. Specifically, why does an atom produce a unique spectral signature? To understand that, we need to recall how light is produced.

### How a Spectrum Is Formed

We saw earlier that each kind of atom has a different number of electrons. This means that each kind of atom has a different set of electron orbits. Figure 3.11 shows schematically some of the possible orbits of the electron of a hydrogen atom and a few of the orbits of the two electrons in a helium atom. Because the atom's energy determines what orbit its electrons move in, orbits are sometimes referred to as **energy levels.**

When an electron moves from one energy level (orbit) to another, the atom's energy changes by an amount equal to the difference in the energy between the two levels. As an example, suppose we look at light from heated hydrogen. Heating speeds up the atoms, causing more forceful and frequent collisions, knocking each excited atom's electron to outer orbits. However, the electrical attraction between the nucleus and the electron draws the electron back almost at once. Suppose we look at an electron shifting from orbit 3 to orbit 2, as shown in figure 3.12. As the electron shifts downward, the atom's energy decreases, and the energy lost appears as light.

The wavelength of the emitted light can be calculated from the energy difference of the levels and the relation we mentioned earlier between energy and wavelength



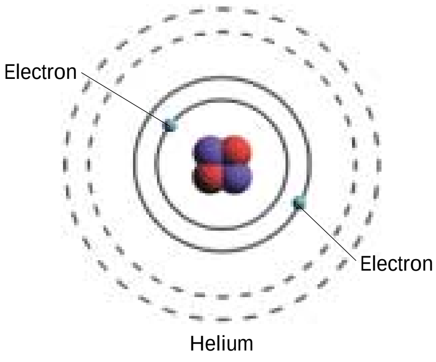




**FIGURE 3.11**
Sketch of electron orbits in hydrogen and helium. The orbits are drawn only schematically and are not to scale.

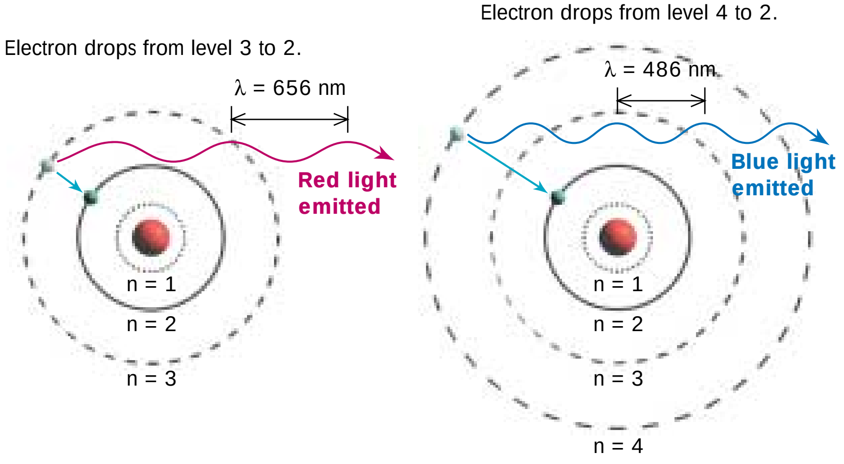



FIGURE 3.12
Emission of light from a hydrogen atom. The energy of an electron dropping from an upper to lower orbit is converted to light.

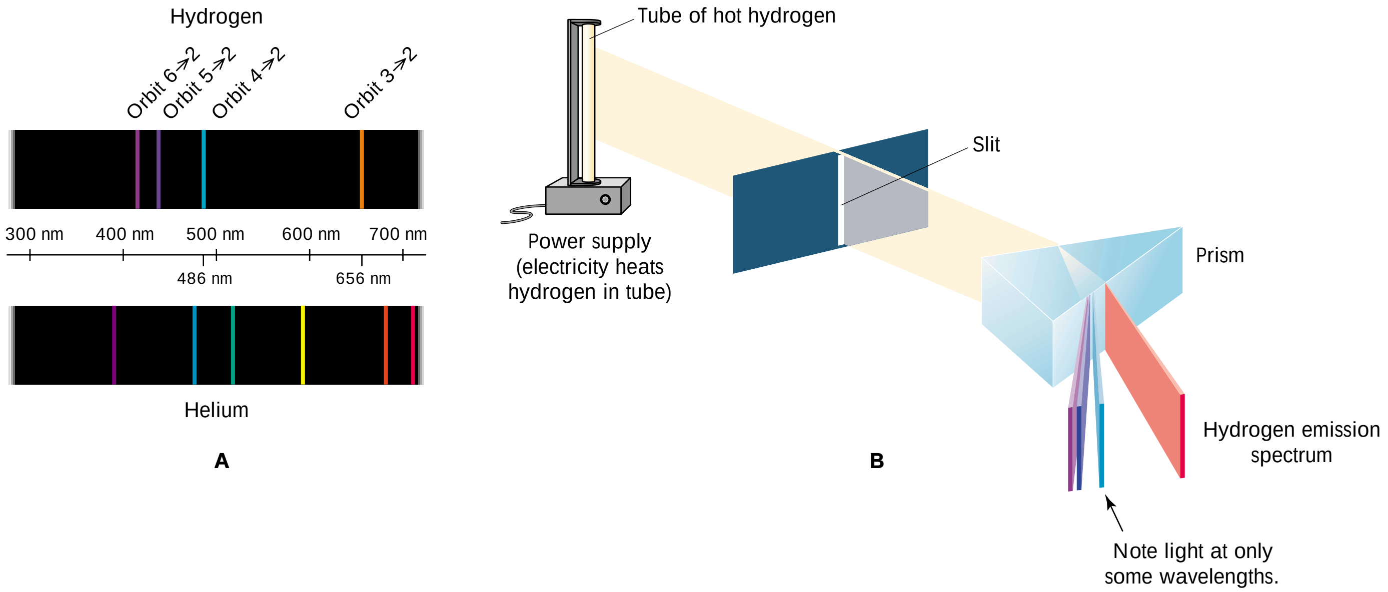



FIGURE 3.13
(A) The emission spectra of hydrogen and helium. (B) A hot, low-density gas creates an emission spectrum.

($E = hc/\lambda$). If we evaluate the wavelength of this light, we find that it is 656 nanometers, a bright red color. An electron dropping from orbit 3 to orbit 2 in a hydrogen atom will always produce light of this wavelength.

If, instead, the electron moves between orbit 4 and orbit 2, there will be a different change in energy because orbit 4 has a different energy from that of orbit 3. That different energy will have a wavelength different from 656 nanometers. A calculation of its energy change leads in this case to a wavelength of 486 nanometers, a turquoise blue color. If we made a similar calculation for a different kind of atom, we would discover that its wavelengths in general differ from those of hydrogen (see fig. 3.13A). Thus, a signature of hydrogen is its red 656-nanometer and blue 486-nanometer lines, and that signature offers astronomers a way to determine what astronomical objects are made of.

## Identifying Atoms by Their Light

If we spread the light from a hot gas into a spectrum, we will see that in general the spectrum contains light at only certain wavelengths. For example, if the gas is hydrogen, we will see in the spectrum the red and turquoise blue colors described earlier as well as violet light corresponding to electrons dropping from orbit 5 to 2 (fig. 3.13A). We will see no light at most other colors because hydrogen has no electron orbits corresponding to those energies. Therefore, the spectrum shows a set of brightly colored lines separated by wide, dark gaps. This is how an emission-line spectrum is formed.

Other kinds of atoms have other electron orbits and therefore other energy levels. This makes them emit light at different wavelengths. For example, if we were to look at a gas of heated helium atoms, we would again see a bright line spectrum, but because the orbits in helium atoms differ from those in hydrogen atoms, the helium spectrum is different from the hydrogen spectrum, as you can see in figure 3.13A. The spectrum thus becomes a means of identifying what atoms are present in a gas.

It is also possible to identify atoms in a gas from the way they absorb light. Light is absorbed if the energy of its wavelength corresponds to an energy that matches the difference between two energy levels in the atom. If the wavelength *does not* match, the light will not be absorbed, and it will simply move past the atom, leaving itself and the atom unaffected.

For example, suppose we shine a beam of light that initially contains all the colors of the visible spectrum through a box full of hydrogen atoms. If we examine the spectrum of the light after it has passed through the box, we will find that certain wavelengths of the light have been removed and are missing from the spectrum (fig. 3.14). In particular, the spectrum will contain gaps that appear as dark lines at 656 nanometers

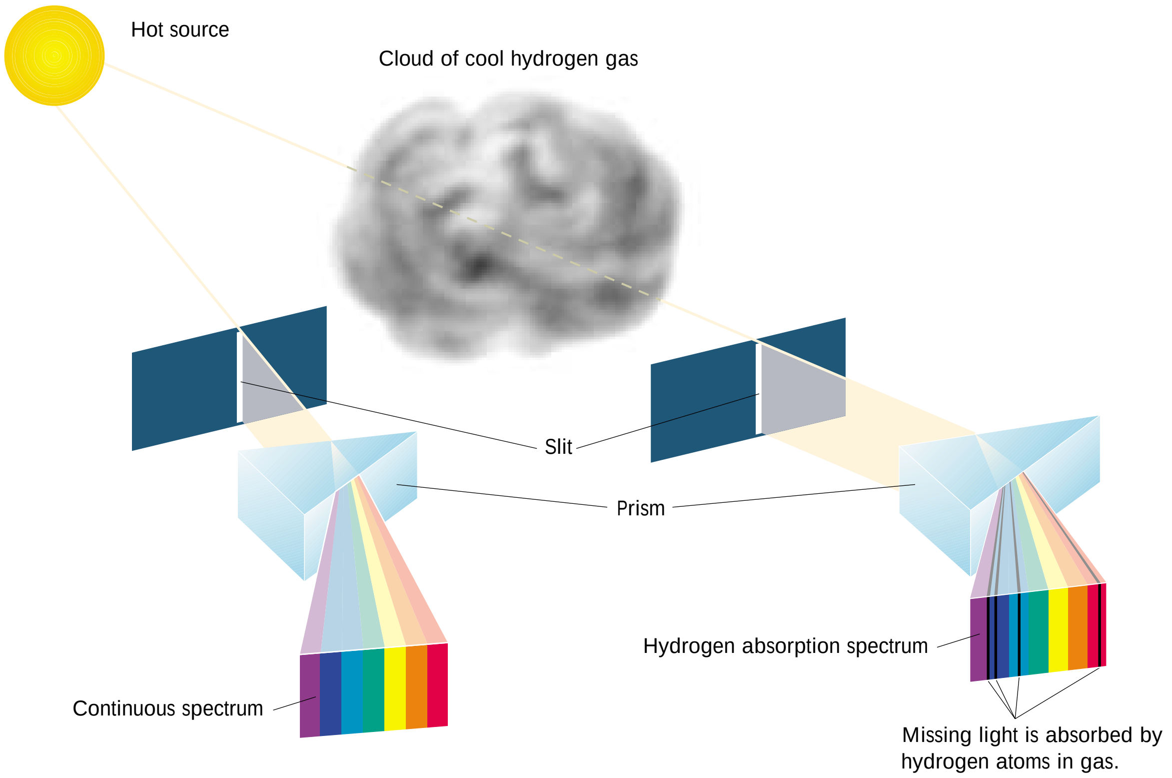



**FIGURE 3.14**

Gas between an observer and a source of light that is hotter than the gas creates an absorption-line spectrum. Atoms in the gas absorb only those wavelengths whose energy equals the energy difference between their electron orbits. The absorbed energy lifts the electrons to upper orbits. The lost light makes the spectrum darker at the wavelengths where it is absorbed.

and 486 nanometers, precisely the wavelengths at which the hydrogen atoms emit. The absorption spectrum is, in effect, the opposite of the emission spectrum.

These gaps are created by the light at 656 nanometers and 486 nanometers interacting with the hydrogen and lifting electrons from orbit 2 to 3 and orbit 2 to 4, respectively. Light at other wavelengths in this range has no effect on the atom.

Thus, we can tell that hydrogen is present from either its emission or its absorption spectral lines. In our discussion above, we have considered light emitted and absorbed by individual atoms in a gas. If the atoms are linked to one another to form molecules, such as water or carbon dioxide, they too produce emission and absorption lines. In fact, even solid objects may imprint spectral lines on light that reflects off them.

In the above examples, we have considered light emitted from or absorbed by the body we wish to identify. But even reflected light generally bears some imprint of the surface from which it came. For example, when light from the Sun reflects from an asteroid, spectral features appear that were not present in the original sunlight. This gives astronomers information about the surface composition of bodies too cool to emit significant light of their own.

We conclude that in general we can identify the kind of atoms or molecules that are present by examining either the bright or dark spectrum lines. Gaps in the spectrum at 656 nanometers and 486 nanometers imply that hydrogen is present. Similar gaps at other wavelengths would show that other elements are present. By matching the observed gaps to a directory of absorption lines, we can identify the atoms that are present. *This is the fundamental way astronomers determine the chemical composition of astronomical bodies.*

## Types of Spectra

Although a spectrum may bear the imprint of the matter that emitted the light, it may also have certain general properties. For example, the spectrum of a hot, tenuous gas is generally different from that of a hot dense solid, regardless of the composition of either the gas or the solid. Therefore, it will be helpful to learn to recognize such gross properties of spectra as well.

Spectra have the three basic forms listed below:

1. For some sources, the light is emitted in such a way that the intensity changes smoothly with wavelength and all colors are present. We say such a light has a **continuous spectrum** (fig. 3.15A). For a source to emit a continuous spectrum, its atoms must in general be packed so closely that the electron orbits of one atom are distorted by the presence of neighboring atoms. Such conditions are typical of solid or dense objects such as the heated filament of an incandescent lightbulb or a nail heated by a blowtorch.
2. Some heated objects have a spectrum in which light is emitted at only a few particular wavelengths while most of the other wavelengths remain dark (fig. 3.15B). This type of spectrum is called an **emission-line spectrum.** Emission-line spectra are usually produced by hot, tenuous gas, such as that in a fluorescent tube, the aurora, and many interstellar gas clouds.
3. A still different type of spectrum arises when light from a hot, dense body passes through cooler gas between it and the observer. In this case, nearly all the colors are present, but light is either missing or much dimmer at some wavelengths (fig. 3.15C). This causes the bright background to be crossed with narrow dark lines where the light of some colors is fainter or absent altogether. The resulting spectrum is therefore called a **dark-line** or **absorption-line spectrum.**

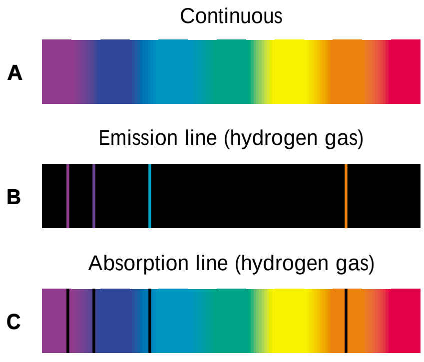



**FIGURE 3.15**
Types of spectra: (A) continuous, (B) emission-line, and (C) absorption-line.

Absorption lines were first detected astronomically in 1802, when the English scientist William H. Wollaston viewed sunlight through a prism and a narrow slit. Interested in learning whether each color blended smoothly into its neighbor (red into orange, orange into yellow, and so forth), he noticed dark lines between some of the colors but paid little attention to them. These dark lines in the Sun's spectrum were independently

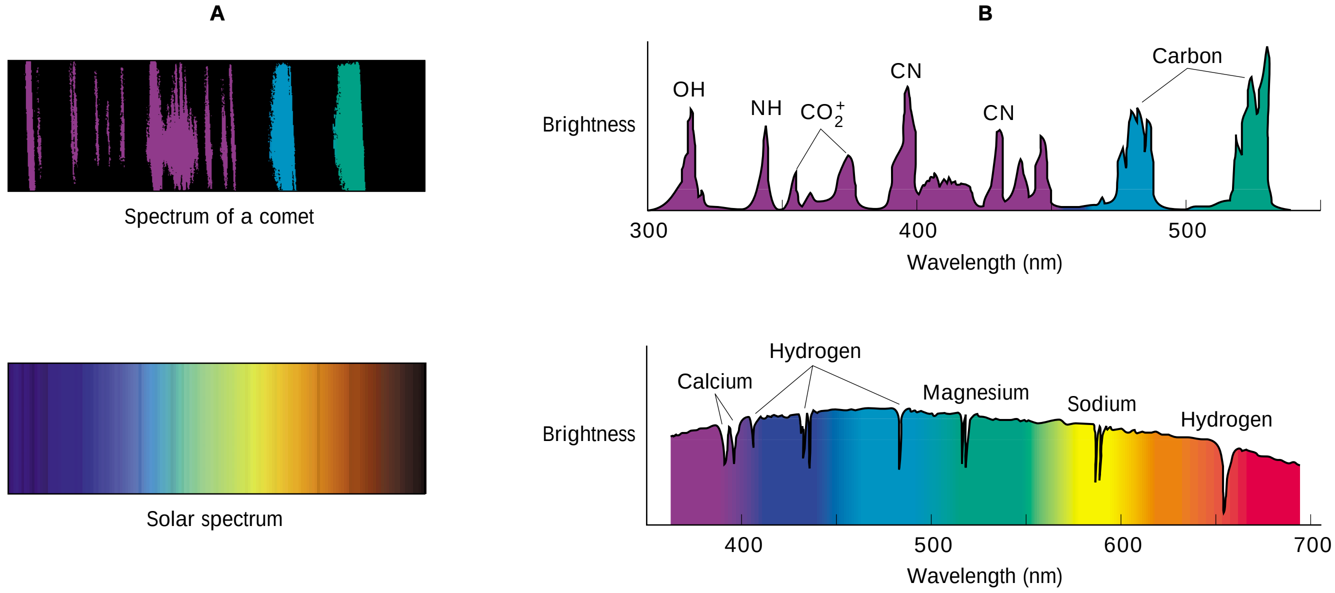



**FIGURE 3.16**
(A) The spectrum of a comet
(Courtesy of Stephen M. Larson, University of Arizona)
and the Sun.
(Courtesy of Mees Solar Observatory, University of Hawaii.)
(B) Graphical representation of their spectra.

discovered a few years later by the German scientist Joseph Fraunhofer, who catalogued them and discovered similar lines in other stars. In fact, because nearly all stars have absorption-line spectra, this spectrum type is especially important in astronomy. However, if we consider the physical process of spectrum formation, such absorption-line spectra are really just a special case of continuous spectra with light missing at some wavelengths.

## Depicting Spectra

Spectra can be displayed in several ways. One method is simply to take a photograph of the light after it has been spread out by a prism or grating. Figure 3.16A shows two spectra, one an emission-line spectrum from a comet and the other an absorption-line spectrum from the Sun. Notice that in the former there are bright regions separated by large regions where there is no light, but in the latter there are certain very narrow regions (the dark absorption lines) where there is little or no light.

Another extremely useful way to depict a spectrum is to plot the brightness of the light at each wavelength. Figure 3.16B shows the spectra of the comet and the Sun illustrated above depicted in this latter fashion.

## Analyzing the Spectrum

Regardless of how the spectrum is depicted, the first step facing an astronomer is to identify the spectral features. This is done by measurement of the wavelengths and then consultation of a directory of spectral lines. By matching the wavelength of the line of interest to a line in the table, astronomers can determine what kind of atom or molecule created the line. A look at a typical spectrum will show you that some lines are hard to see, being faint and weak. On the other hand, some lines may be very obvious and strong. The strength or weakness of a given line turns out to depend on the number of atoms or molecules absorbing (or emitting, if we are looking at an emission line) at that wavelength. Unfortunately, the number of atoms or molecules that can absorb or emit depends not just on how many of them are present but also on their temperature, as we will discuss more fully in chapter 12. Nevertheless, astronomers can deduce from the strength of emission and absorption lines the relative quantity of each atom producing a line and thereby deduce the composition of the material in the light source. Table 3.4 shows the result of such an analysis for our Sun, a typical star.

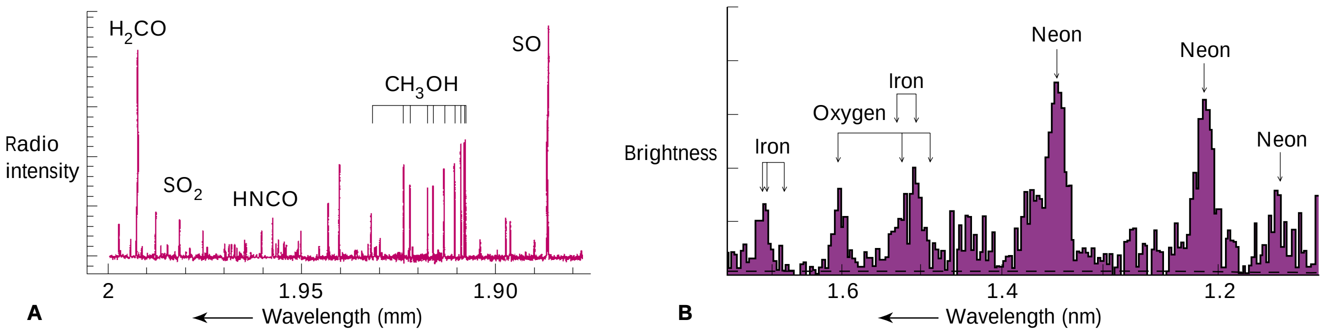



**FIGURE 3.17**

(A) A radio spectrum of a cold interstellar cloud.

(Courtesy of Doug McGonagle, FCRAO.)

(B) An X-ray spectrum of hot gas from an exploding star.

(Courtesy of P. F. Winkler, Middlebury College.)

TABLE 3.4

Composition of a Typical Star, Our Sun*

| Element | Relative Number of Atoms | Percent by Mass |
|---|---|---|
| Hydrogen | $10^{12}$ | 70.6% |
| Helium | $9.77 \times 10^{10}$ | 27.4% |
| Carbon | $3.63 \times 10^{8}$ | 0.31% |
| Nitrogen | $1.12 \times 10^{8}$ | 0.11% |
| Oxygen | $8.51 \times 10^{8}$ | 0.96% |
| Neon | $1.23 \times 10^{8}$ | 0.18% |
| Silicon | $3.55 \times 10^{7}$ | 0.07% |
| Iron | $4.68 \times 10^{7}$ | 0.18% |
| Gold | 10.0 | $1.4 \times 10^{-7}$% |
| Uranium | less than 0.3 | less than $5.7 \times 10^{-9}$% |

*The table lists some of the most common elements. Gold and uranium are included only to illustrate how extremely rare they are. Notice that they are a million or more times rarer than iron, which is itself thousands of times rarer than hydrogen. (From Anders and Grevesse, *Geochim Cosmochim Acta* 53 [1989]:197.)

## Astronomical Spectra

Let us now apply what we know about spectra to astronomical bodies. We begin by using a telescope to obtain a spectrum of the object of interest. Next we measure the wavelengths and identify the lines. As an example, consider the spectrum of the Sun in figure 3.16A.

We can see from the spectral lines that the Sun contains hydrogen. In fact, when a detailed calculation is made of the strength of the lines, it turns out that the Sun is about 71% hydrogen.* Similar observations show that the spectrum of a comet consists mainly of emission lines from such substances as the molecules carbon dioxide and CN. Thus, we know that comets contain these substances. Moreover, recalling our earlier discussion of types of spectra (continuous, emission-line, or absorption-line), we can tell that the CN and carbon dioxide must be gaseous because the spectrum consists of emission lines. There may be other gases present too, but without seeing their spectral features, we cannot tell for sure.

Although the examples we have used above involve spectra of visible light, one of the most useful features of spectroscopy is that it may be used in *any* wavelength region. For example, figure 3.17 shows a radio spectrum and an X-ray spectrum.

Regardless of the wavelength region we use, the spectrum allows us to determine what kind of material is present. In addition, it can sometimes reveal to us in what direction and how fast that material is moving.

*Expressed in a slightly different way, this means that roughly 9 out of 10 atoms in the Sun are hydrogen. Hydrogen contributes only about 71% of the mass because it is the lightest element.

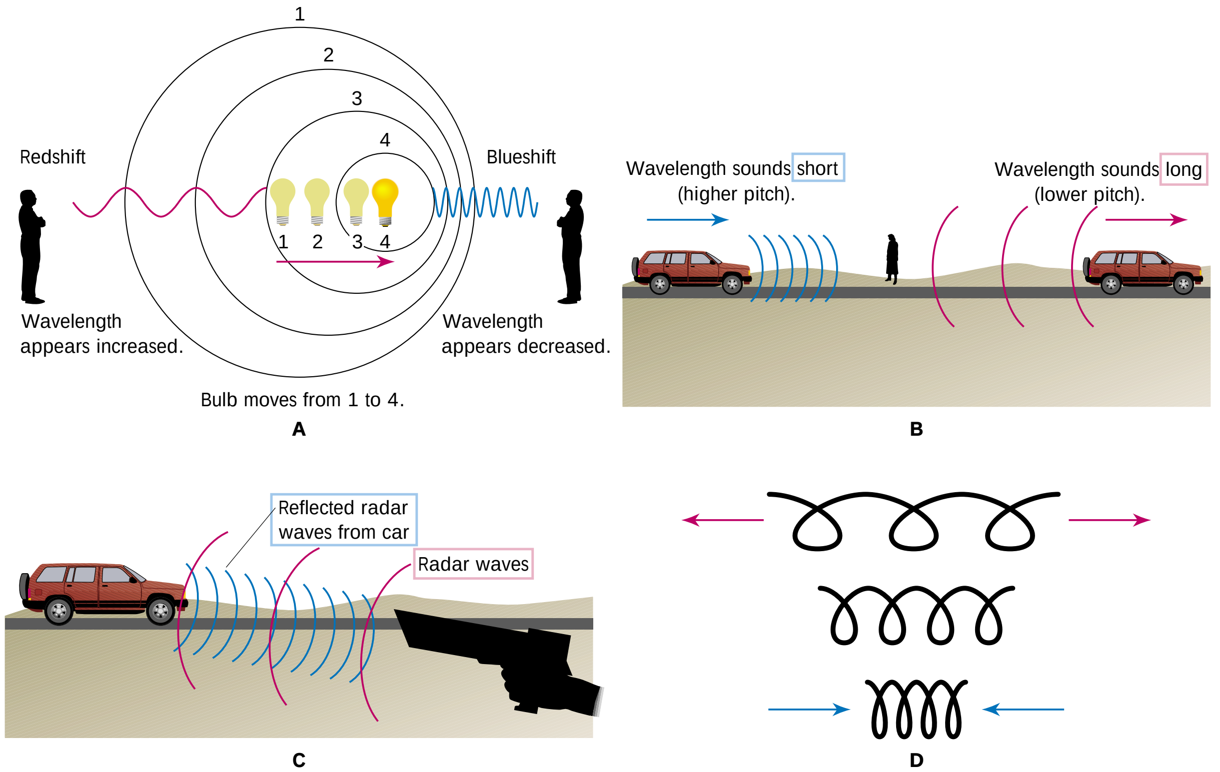



**FIGURE 3.18**

(A) The Doppler shift: waves appear to shorten as a source approaches and lengthen as it recedes. (B) Doppler shift of sound waves from a passing car. (C) Doppler shift of radar waves in a speed trap. (D) A Slinky illustrates the shortening of the space between its coils as its ends move toward each other and a lengthening of the space as the ends move apart.

## 3.6 THE DOPPLER SHIFT


Animation 3.18
*The Doppler effect.*

If a source of light is set in motion, its spectral lines shift to new wavelengths in a phenomenon known as the **Doppler shift.** If the light source moves away from us, we observe its wavelengths as longer, while if the source approaches, we observe that the wavelengths decrease, as illustrated in figure 3.18A. The amount of shift we observe depends on the source's speed, so by measuring the shift, we can determine how fast the source is moving toward or away from us. Astronomers refer to the speed of such motion toward or away from an observer as radial velocity.

The Doppler shift occurs for any relative motion along the line between source and observer* and for *any* kind of wave. For example, you have probably heard the Doppler shift of sound waves as the horn of a passing car changes pitch (fig. 3.18B). Likewise, you may have been caught speeding when a police officer bounced radar waves off your car and from their observed shift determined that you were driving too fast (fig. 3.18C). But why does motion create a shift in wavelength?

A simple way to think of how the Doppler shift occurs is to imagine that when a light source moves away from you, it "stretches" the waves—think of a toy Slinky being stretched—and that when the source moves toward you, it "compresses" them, as

*Motion perpendicular to the line of sight creates no observable Doppler shift unless the velocity is nearly the speed of light.

shown in figure 3.18D. Notice that the stretching or compression occurs if either you or the source moves.

Mathematically, the wavelength shift occurs because the wavelength we observe, $\lambda$, is a combination of the true wavelength, $\lambda_0$, plus the distance the source moves during the time a single wave is emitted. With this interpretation and a little algebra, we can derive a formula for the radial velocity of the source, $v$, given its wavelength shift, $\lambda - \lambda_0$. The result of such a calculation is that the wavelength shift, often written $\Delta\lambda$,* is

$$\Delta\lambda = (\lambda - \lambda_0) = \frac{\lambda_0 v}{c}$$

$\Delta\lambda$ = Wavelength shift
$\lambda$ = Measured wavelength (what we observe)
$\lambda_0$ = Emitted wavelength
c = Speed of light
$v$ = Velocity of source along the line of sight (radial velocity)

*Note: A negative v means the distance between the source and observer is decreasing. A positive v means that distance is increasing. That is, the source and observer are moving apart.*

Therefore, if we can measure the wavelength shift, we can solve for the source's radial velocity (that is, its velocity along the line of sight to the object).

Astronomers often refer to Doppler shifts that increase the measured wavelength as redshifts and those that decrease the measured wavelength as blueshifts, regardless of whether the waves are of visible light. Thus, even though we may be describing radio waves, we will say that an approaching source is blueshifted and a receding one is redshifted. We will save for later chapters how to measure the shift and calculate $v$.

The previous sections show how important a source of information electromagnetic radiation is. It provides information about the temperature, composition, and motion of astronomical objects. However, we often observe that radiation after it has passed through our atmosphere. Thus, we must ask how the atmosphere affects the radiation passing through it.

## 3.7 ABSORPTION IN THE ATMOSPHERE

Gases in the Earth's atmosphere absorb electromagnetic radiation, affecting the flow of heat and light through it. The amount of this absorption depends strongly on wavelength. For example, the gases affect visible light hardly at all and so our atmosphere is nearly completely transparent at the wavelengths we see with our eyes. On the other hand, some of the gases strongly absorb infrared radiation while others strongly block ultraviolet radiation.

Molecules in general are excellent absorbers (and emitters) because they can store energy in more ways than atoms can. As we have described earlier, atoms store energy by lifting electrons to upper orbits. Molecules can store energy not only by lifting electrons but also by the spinning and vibrating motions of the molecule as a whole. These added ways to store energy are what make molecules such powerful blockers of radiation at many wavelengths.

This nearly total blockage of infrared and ultraviolet radiation results from the ability of molecules such as carbon dioxide, water, and ozone to absorb at a wide range of wavelengths. For example, carbon dioxide and water molecules strongly absorb infrared wavelengths. Likewise, ozone ($O_3$) and ordinary oxygen ($O_2$) strongly absorb ultraviolet radiation, while oxygen and nitrogen absorb X-rays and gamma radiation. As a result of this absorption by molecules, virtually no infrared, ultraviolet, X-ray, or gamma ray radiation can pass through our atmosphere.

Animation 3.19
*Absorption by atmosphere.*

The transparency of the atmosphere to visible light compared to its opacity (non-transparency) to infrared and ultraviolet radiation creates what is called an **atmospheric window.** An atmospheric window is a wavelength region in which energy comes through easily compared to other wavelengths (fig. 3.19).

Without atmospheric windows, it would be impossible for us to study astronomical objects from the ground. As it is, the visible window allows us to study stars and galaxies (which radiate lots of visible energy), but the lack of ultraviolet and the rarity of infrared windows makes it very difficult to observe objects that radiate strongly in those spectral regions. This is one of several reasons why astronomers so badly need telescopes in space, where there is no absorption by our atmosphere.

*The Greek letter $\Delta$, or delta, is widely used to stand for "the change in quantity."

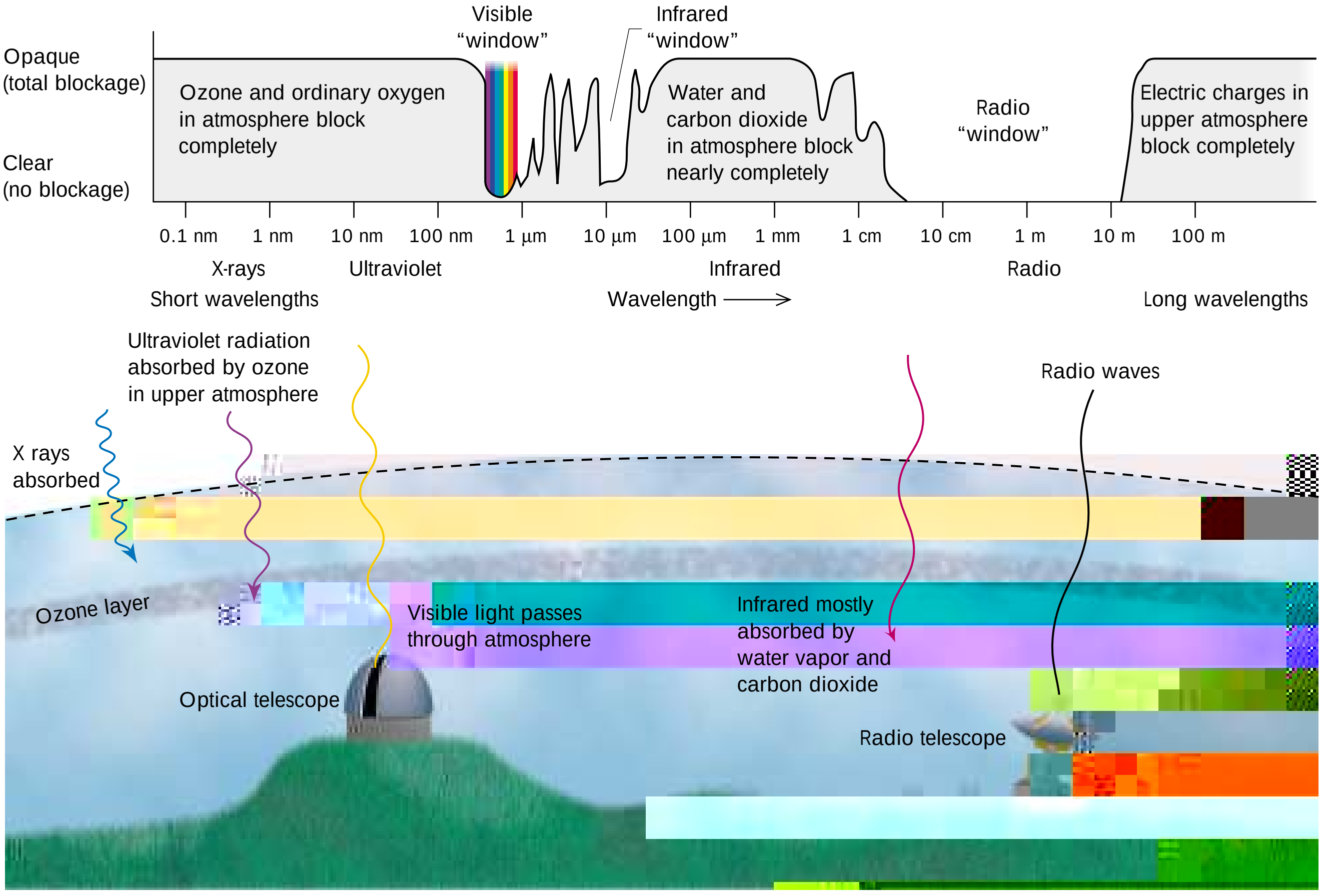



**FIGURE 3.19**
Atmospheric absorption. Wavelength regions where the atmosphere is essentially transparent, such as the visible spectrum, are called “atmospheric windows.” Wavelengths and atmosphere are not drawn to scale.

# *Summary*

4. A star's radiation is brightest at a wavelength of 400 nanometers. Its temperature is about
   (a) 4000 K.
   b) 12,000 K.
   (c) 1500 K.
   (d) 750 K.
   (e) 7500 K.

5. If an object's spectral lines are shifted to longer wavelengths, the object is
   (a) moving away from us.
   (b) moving toward us.
   (c) very hot.
   (d) very cold.
   (e) emitting X rays.

# *Further Explorations*

Steffy, Philip C. "The Truth about Star Colors." *Sky and Telescope* 84 (September 1992): 266.

Zajonc, Arthur. *Catching the Light: The Entwined History of Light and Mind.* New York: Bantam Books, 1993.

### Web Site

Please visit the *Explorations* web site at **http://www.mhhe.com/arny** for additional on-line resources on these topics.

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