Sunlight bending through ice crystals in cirriform clouds produces bands of color called sundogs, or parhelia, on both sides of the sun on this cold winter day in Minnesota.
The sky is clear, the weather cold, and the year, 1818. Near Baffin Island in Canada, a ship with full sails enters unknown waters. On board are the English brothers James and John Ross, who are hoping to find the elusive “Northwest Passage,” the waterway linking the Atlantic and Pacific oceans. On this morning, however, their hopes would be dashed, for directly in front of the vessel, blocking their path, is a huge towering mountain range. Disappointed, they turn back and report that the Northwest Passage does not exist. About seventy-five years later Admiral Perry met the same barrier and called it “Crocker land.”

What type of treasures did this mountain conceal—gold, silver, precious gems? The curiosity of explorers from all over the world had been aroused. Speculation was the rule, until, in 1913, the American Museum of Natural History commissioned Donald MacMillan to lead an expedition to solve the mystery of Crocker land. At first, the journey was disappointing. Where Perry had seen mountains, MacMillan saw only vast stretches of open water. Finally, ahead of his ship was Crocker land, but it was more than two hundred miles farther west from where Perry had encountered it. MacMillan sailed on as far as possible. Then he dropped anchor and set out on foot with a small crew of men.

As the team moved toward the mountains, the mountains seemed to move away from them. If they stood still, the mountains stood still; if they started walking, the mountains receded again. Puzzled, they trekked onward over the glittering snow-fields until huge mountains surrounded them on three sides. At last the riches of Crocker land would be theirs. But in the next instant the sun disappeared below the horizon and, as if by magic, the mountains dissolved into the cold arctic twilight. Dumbfounded, the men looked around only to see ice in all directions—not a mountain was in sight. There they were, the victims of one of nature’s greatest practical jokes, for Crocker land was a mirage.
White and Colors

We know from Chapter 2 that nearly half of the solar radiation that reaches the atmosphere is in the form of visible light. As sunlight enters the atmosphere, it is either absorbed, reflected, scattered, or transmitted on through. How objects at the surface respond to this energy depends on their general nature (color, density, composition) and the wavelength of light that strikes them. How do we see? Why do we see various colors? What kinds of visual effects do we observe because of the interaction between light and matter? In particular, what can we see when light interacts with our atmosphere?

We perceive light because electromagnetic waves stimulate antenna-like nerve endings in the retina of the human eye. These antennae are of two types—rods and cones. The rods respond to all wavelengths of visible light and give us the ability to distinguish light from dark. If people possessed rod-type receptors only, then only black and white vision would be possible. The cones respond to specific wavelengths of visible light. Radiation with a wavelength between 0.4 and 0.7 micrometers (µm) strikes the cones, which immediately fire an impulse through the nervous system to the brain, and we perceive this impulse as the sensation of color. (Color blindness is caused by missing or malfunctioning cones.) Wavelengths of radiation shorter than 0.4 µm, or longer than 0.7 µm, do not stimulate color vision in humans.

White light is perceived when all visible wavelengths strike the cones of the eye with nearly equal intensity.* Because the sun radiates almost half of its energy as visible light, all visible wavelengths from the midday sun reach the cones, and the sun usually appears white. A star that is cooler than our sun radiates most of its energy at slightly longer wavelengths; therefore, it appears redder. On the other hand, a star much hotter than our sun radiates more energy at shorter wavelengths and thus appears bluer. A star whose temperature is about the same as the sun's appears white.

Objects that are not hot enough to emit radiation at visible wavelengths can still have color. Everyday objects we see as red are those that absorb all visible radiation except red. The red light is reflected from the object to our eyes. Blue objects have blue light returning from them, since they absorb all visible wavelengths except blue. Some surfaces absorb all visible wavelengths and reflect no light at all. Since no radiation strikes the rods or cones, these surfaces appear black. Therefore, when we see colors, we know that light must be reaching our eyes.

White Clouds and Scattered Light

One exciting feature of the atmosphere can be experienced when we watch the underside of a puffy, growing cumulus cloud change color from white to dark gray or black. When we see this change happen, our first thought is usually, “It's going to rain.” Why is the cloud initially white? Why does it change color? To answer these questions, let’s investigate the concept of scattering.

When sunlight bounces off a surface at the same angle at which it strikes the surface, we say that the light is reflected, and call this phenomenon reflection (see Fig. 19.1). There are various constituents of the atmosphere, however, that tend to deflect solar radiation from its path and send it out in all directions. We know from Chapter 2 that radiation reflected in this way is said to be scattered. (Scattered light is also called diffuse light.) During the scattering process, no energy is gained or lost and, therefore, no temperature changes occur. In the atmosphere, scattering is usually caused by small objects, such as air molecules, fine particles of dust, water molecules, and some pollutants. Just as the ball in a pinball machine bounces off the pins in many directions, so solar radiation is knocked about by small particles in the atmosphere.

Cloud droplets about 10 µm or so in diameter are large enough to effectively scatter all wavelengths of visible radiation more or less equally, a phenomenon we call geometric scattering. Clouds, even small ones, are optically thick, meaning that

*Recall from Chapter 2 that visible white light is a combination of waves with different wavelengths. The wavelengths of visible light in decreasing order are: red (longest), orange, yellow, green, blue, and violet (shortest).
they are able to scatter vast amounts of sunlight and there is very little chance sunlight will pass through unscattered. These same clouds are poor absorbers of sunlight. Hence, when we look at a cloud, it appears white because countless cloud droplets scatter all wavelengths of visible sunlight in all directions (see Fig. 19.2).

As a cloud grows larger and taller, more sunlight is reflected from it and less light can penetrate all the way through it (see Fig. 19.3). In fact, relatively little light penetrates a cloud whose thickness is 1000 m (3300 ft). Since little sunlight reaches the underside of the cloud, little light is scattered, and the cloud base appears dark. At the same time, if droplets near the cloud base grow larger, they become less effective scatterers and better absorbers. As a result, the meager amount of visible light that does reach this part of the cloud is absorbed rather than scattered, which makes the cloud appear even darker. These same cloud droplets may even grow large and heavy enough to fall to the earth as rain. From a casual observation of clouds, we know that dark, threatening ones frequently produce rain. Now, we know why they appear so dark.

**Blue Skies and Hazy Days**

The sky appears blue because light that stimulates the sensation of blue color is reaching the retina of the eye. How does this happen?

Individual air molecules are much smaller than cloud droplets—their diameters are small even when compared with the wavelength of visible light. Each air molecule of oxygen and nitrogen is a selective scatterer in that each scatters shorter waves of visible light much more effectively than longer waves. This selective scattering is also known as Rayleigh scattering (see Table 19.1).

As sunlight enters the atmosphere, the shorter visible wavelengths of violet, blue, and green are scattered more by atmospheric gases than are the longer wavelengths of yellow, orange,
and especially red. In fact, violet light is scattered about 16 times more than red light. Consequently, as we view the sky, the scattered waves of violet, blue, and green strike the eye from all directions. Because our eyes are more sensitive to blue light, these waves, viewed together, produce the sensation of blue coming from all around us (see Fig. 19.4). Therefore, when we look at the sky it appears blue (see Fig. 19.5). (Earth, by the way, is not the only planet with a colorful sky. On Mars, dust in the air turns the sky red at midday and purple at sunset.)

The selective scattering of blue light by air molecules and very small particles can make distant mountains appear blue.

*The reason for this fact is that the intensity of Rayleigh scattering varies as $\frac{1}{\lambda^4}$, where $\lambda$ is the wavelength of radiation.

Haze can scatter light from the rising or setting sun, so that we see bright lightbeams, or crepuscular rays, radiating across the sky. A similar effect occurs when the sun shines through a break in a layer of clouds (see Fig. 19.7). Dust, tiny water droplets, or haze in the air beneath the clouds scatter sunlight, making that region of the sky appear bright with rays. Because these rays seem to reach downward from clouds, some people will remark that the “sun is drawing up water.” In England, this same phenomenon is referred to as “Jacob’s ladder.” No matter what these sunbeams are called, it is the scattering of sunlight by particles in the atmosphere that makes them visible.
Red Suns and Blue Moons

At midday, the sun seems a brilliant white, while at sunset it usually appears to be yellow, orange, or red. At noon, when the sun is high in the sky, light from the sun is most intense—all wavelengths of visible light are able to reach the eye with about equal intensity, and the sun appears white. (Looking directly at the sun, especially during this time of day, can cause irreparable damage to the eye. Normally, we get only glimpses or impressions of the sun out of the corner of our eye.)

Near sunrise or sunset, however, the rays coming directly from the sun strike the atmosphere at a low angle. They must pass through much more atmosphere than at any other time during the day. (When the sun is 4° above the horizon, sunlight must pass through an atmosphere more than 12 times thicker than when the sun is directly overhead.) By the time sunlight has penetrated this large amount of air, most of the shorter waves of visible light have been scattered away by the air molecules. Just about the only waves from a setting sun that make it on through the atmosphere on a fairly direct path are the yellow, orange, and red. Upon reaching the eye, these waves produce a bright yellow-orange sunset (see Fig. 19.8).

Bright, yellow-orange sunsets only occur when the atmosphere is fairly clean, as it would be after a recent rain. If the atmosphere contains many fine particles whose diameters are a little larger than air molecules, slightly longer (yellow) waves also would be scattered away. Only orange and red waves
would penetrate through to the eye, and the sun would appear red-orange. When the atmosphere becomes loaded with particles, only the longest red wavelengths are able to penetrate the atmosphere, and we see a red sun.

Natural events may produce red sunrises and sunsets over the oceans. For example, the scattering characteristics of small suspended salt particles and water molecules are responsible for the brilliant red suns that can be observed from a beach (see Fig. 19.9). Volcanic eruptions rich in sulfur can produce red sunsets, too. Such red sunsets are actually produced by a highly reflective cloud of sulfuric acid droplets, formed from sulfur dioxide gas injected into the stratosphere during powerful eruptions, like that of the Mexican volcano El Chichón in 1982 and the Philippine volcano Mt. Pinatubo in 1991. These fine particles, moved by the winds aloft, circled the globe, producing beautiful sunrises and sunsets for months and even years after the eruptions. These same volcanic particles in the stratosphere can turn the sky red after sunset, as some of the red light from the setting sun bounces off the bottom of the particles back to the earth’s surface. Generally, these volcanic red sunsets occur about an hour after the actual sunset (see Fig. 19.10).

Occasionally, the atmosphere becomes so laden with dust, smoke, and pollutants that even red waves are unable to pierce the filthy air. An eerie effect then occurs. Because no visible waves enter the eye, the sun literally disappears before it reaches the horizon.

The scattering of light by large quantities of atmospheric particles can cause some rather unusual sights. If the dust, smoke, particles, or pollutants are roughly uniform in size, they can selectively scatter the sun’s rays. Even at noon, various colored suns have appeared: orange suns, green suns, and even blue suns. For blue suns to appear, the size of the suspended particles must be similar to the wavelength of visible light. (This situation produces a type of scattering called Mie scattering. Refer back to Table 19.1, p. 519.) When these particles are present they tend to scatter red light more than blue, which causes a bluing of the sun and a reddening of the sky. Although rare, the same phenomenon can happen to moonlight, making the moon appear blue; thus, the expression “once in a blue moon.”

In summary, the scattering of light by small particles in the atmosphere causes many familiar effects: white clouds, blue skies, hazy skies, crepuscular rays, and colorful sunsets. In the absence of any scattering, we would simply see a white sun against a black sky—not an attractive alternative.
Light that passes through a substance is said to be transmitted. Upon entering a denser substance, transmitted light slows in speed. If it enters the substance at an angle, the light’s path also bends. This bending is called refraction. The amount of refraction depends primarily on two factors: the density of the material and the angle at which the light enters the material.

Refraction can be demonstrated in a darkened room by shining a flashlight into a beaker of water (see Fig. 19.11). If the light is held directly above the water so that the beam strikes the surface of the water straight on, no bending occurs. But, if the light enters the water at some angle, it bends toward the normal, which is the dashed line in the diagram running perpendicular to the air-water boundary. (The normal is simply a line that intersects any surface at a right angle. We use it as a reference to see how much bending occurs as light enters and leaves various substances.) A small mirror on the bottom of the beaker reflects the light upward. This reflected light bends away from the normal as it re-enters the air. We can summarize these observations as follows: Light that travels from a less-dense to a more-dense medium loses speed and bends toward the normal, while light that enters a less-dense medium increases in speed and bends away from the normal.

The refraction of light within the atmosphere causes a variety of visual effects. At night, for example, the light from the stars that we see directly above us is not bent, but starlight that enters the earth’s atmosphere at an angle is bent. In fact, a star whose light enters the atmosphere just above the horizon has more atmosphere to penetrate and is thus refracted the most. As we can see in Fig. 19.12, the bending is toward the normal as the light enters the more-dense atmosphere. By the time this “bent” starlight reaches our eyes, the star appears to be higher than it actually is because our eyes cannot detect that the light path is bent. We see light coming from a particular direction and interpret the star to be in that direction. So, the next time you take a midnight stroll, point to any star near the horizon and remember: This is where the star appears to be. To point to the star’s true position,
you would have to lower your arm just a bit (about one-half a degree, according to Table 19.2).

As starlight enters the atmosphere, it often passes through regions of differing air density. Each of these regions deflects and bends the tiny beam of starlight, constantly changing the apparent position of the star. This causes the star to appear to twinkle or flicker, a condition known as scintillation. Planets, being much closer to us, appear larger, and usually do not twinkle because their size is greater than the angle at which their light deviates as it penetrates the atmosphere. Planets sometimes twinkle, however, when they are near the horizon, where the bending of their light is greatest.

The refraction of light by the atmosphere has some other interesting consequences. For example, the atmosphere gradually bends the rays from a rising or setting sun or moon. Because light rays from the lower part of the sun (or moon) are bent more than those from the upper part, the sun appears to flatten out on the horizon, taking on an elliptical shape. (The sun in Fig. 19.14, p. 525, shows this effect.) Also, since light is bent most on the horizon, the sun and moon both appear to be higher than they really are. Consequently, they both rise about two minutes earlier and set about two minutes later than they would if there were no atmosphere (see Fig. 19.13).

You may have noticed that on clear days the sky is often bright for some time after the sun sets. The atmosphere refracts and scatters sunlight to our eyes, even though the sun itself has disappeared from our view. Twilight is the name given to the time after sunset (and immediately before sunrise) when the sky remains illuminated and allows outdoor activities to continue without artificial lighting. (Civil twilight lasts from sunset until the sun is 6° below the horizon, while astronomical twilight lasts until the sky is completely dark and the astronomical observation of the faintest stars is possible.)

The length of twilight depends on season and latitude. During the summer in middle latitudes, twilight adds about 30 minutes of light to each morning and evening for outdoor activities. The duration of twilight increases with increasing latitude, especially in summer. At high latitudes during the summer, morning and evening twilight may converge, producing a white night—a nightlong twilight.

In general, without the atmosphere, there would be no refraction or scattering, and the sun would rise later and set earlier than it now does. Instead of twilight, darkness would arrive immediately when the sun disappears below the horizon. Imagine the number of sandlot baseball games that would be called because of instant darkness.

Occasionally, a flash of green light—called the green flash—may be seen near the upper rim of a rising or setting sun (see Fig. 19.14). Remember from our earlier discussion that, when the sun is near the horizon, its light must penetrate a thick section of atmosphere. This thick atmosphere refracts sunlight, with purple and blue light bending the most, and red light the least. Because of this bending, more blue light should appear along the top of the sun. But because the atmosphere selectively scatters blue light, very little reaches us, and we see green light instead.

Usually, the green light is too faint to see with the human eye. However, under certain atmospheric conditions, such as when the surface air is very hot or when an upper-level inversion exists, the green light is magnified by the atmosphere. When this happens, a momentary flash of green light appears, often just before the sun disappears from view.

The flash usually lasts about a second, although in polar regions it can last longer. Here, the sun slowly changes in elevation and the flash may exist for many minutes. Members of Admiral Byrd’s expedition in the south polar region reported seeing the green flash for 35 minutes in September as the sun slowly rose above the horizon, marking the end of the long winter.
Up to this point, we have examined how light can interact with our atmosphere. Before going on, here is a review of some of the important concepts and facts we have covered:

- When light is scattered, it is sent in all directions—forward, sideward, and backward.
- White clouds, blue skies, hazy skies, crepuscular rays, and colorful sunsets are the result of sunlight being scattered.
- The bending of light as it travels through regions of differing density is called refraction.
- As light travels from a less-dense substance (such as outer space) and enters a more-dense substance at an angle (such as our atmosphere), the light bends downward toward the normal. This effect causes stars, the moon, and the sun to appear just a tiny bit higher than they actually are.

**BRIEF REVIEW**

The Mirage: Seeing Is Not Believing

In the atmosphere, when an object appears to be displaced from its true position, we call this phenomenon a mirage. A mirage is not a figment of the imagination—our minds are not playing tricks on us, but the atmosphere is.

Atmospheric mirages are created by light passing through and being bent by air layers of different densities. Such changes in air density are usually caused by sharp changes in air temperature. The greater the rate of temperature change, the greater the light rays are bent. For example, on a warm, sunny day, black road surfaces absorb a great deal of solar energy and become very hot. Air in contact with these hot surfaces warms by conduction and, because air is a poor thermal conductor, we find much cooler air only a few meters higher. On hot days, these road surfaces often appear wet (see Fig. 19.15). Such “puddles” disappear as we approach them, and advancing cars seem to swim in them. Yet, we know the road is dry. The apparent wet pavement above a road is the result of blue skylight refracting up into our eyes as it travels through air of different densities. A similar type of mirage occurs in deserts during the hot summer. Many thirsty travelers have been disappointed to find that what appeared to be a water hole was in actuality hot desert sand.

Sometimes, these “watery” surfaces appear to shimmer. The shimmering results as rising and sinking air near the ground constantly change the air density. As light moves through these regions, its path also changes, causing the shimmering effect.

When the air near the ground is much warmer than the air above, objects may not only appear to be lower than they really are, but also (often) inverted. These mirages are called inferior (lower) mirages. The tree in Fig. 19.16 certainly doesn’t grow upside down. So why does it look that way? It appears to be inverted because light reflected from the top of the tree moves outward in all directions. Rays that enter the hot, less-dense air above the sand are refracted upward, entering the eye from below. The brain is fooled into thinking that these rays came from below the sky.
ground, which makes the tree appear upside down. Some light from the top of the tree travels directly toward the eye through air of nearly constant density and, therefore, bends very little. These rays reach the eye “straight-on,” and the tree appears upright. Hence, off in the distance, we see a tree and its upside-down image beneath it. (Some of the trees in Fig. 19.15 show this effect.)

The atmosphere can play optical jokes on us in extremely cold areas, too. In polar regions, air next to a snow surface can be much colder than the air many meters above. Because the air in this cold layer is very dense, light from distant objects entering it bends toward the normal in such a way that the objects can appear to be shifted upward. This phenomenon is called a superior (upward) mirage. Figure 19.17 shows the atmospheric conditions favorable for a superior mirage. (A special type of mirage, the Fata Morgana, is described in the Focus section on p. 527.)

On December 14, 1890, a mirage—lasting several hours—gave the residents of Saint Vincent, Minnesota, a clear view of cattle nearly 13 km (8 mi) away.
Halos, Sundogs, and Sun Pillars

A ring of light encircling and extending outward from the sun or moon is called a halo. Such a display is produced when sunlight or moonlight is refracted as it passes through ice crystals. Hence, the presence of a halo indicates that cirriform clouds are present.

The most common type of halo is the 22° halo—a ring of light 22° from the sun or moon.* Such a halo forms when tiny suspended column-type ice crystals (with diameters less than 20 µm) become randomly oriented as air molecules constantly bump against them. The refraction of light rays through these crystals forms a halo like the one shown in Fig. 19.18. Less common is the 46° halo, which forms in a similar fashion to the 22° halo (see Fig. 19.19). With the 46° halo, however, the light is refracted through column-type ice crystals that have diameters in a narrow range between about 15 and 25 µm.

Occasionally, a bright arc of light may be seen at the top of a 22° halo (see Fig. 19.20). Since the arc is tangent to the halo, it is called a tangent arc. Apparently, the arc forms as large six-sided (hexagonal), pencil-shaped ice crystals fall with their long axes horizontal to the ground. Refraction of sunlight through the ice crystals produces the bright arc of light. When the sun is on the horizon, the arc that forms at the top of the halo is called an upper tangent arc. When the sun is above the horizon, a lower tangent arc may form on the lower part of the halo beneath the sun. The shape of the arcs changes greatly with the position of the sun.

A halo is usually seen as a bright, white ring, but there are refraction effects that can cause it to have color. To understand this, we must first examine refraction more closely.

When white light passes through a glass prism, it is refracted and split into a spectrum of visible colors (see Fig. 19.21). Each wavelength of light is slowed by the glass, but each is slowed a litt-
Because longer wavelengths (red) slow the least and shorter wavelengths (violet) slow the most, red light bends the least, and violet light bends the most. The breaking up of white light by “selective” refraction is called **dispersion**. As light passes through ice crystals, dispersion causes red light to be on the inside of the halo and blue light on the outside.

When hexagonal platelike ice crystals with diameters larger than about 30 µm are present in the air, they tend to fall slowly and orient themselves horizontally (see Fig. 19.22). (The horizontal orientation of these ice crystals prevents a ring halo.) In this position, the ice crystals act as small prisms, refracting and dispersing sunlight that passes through them. If the sun is near the horizon in such a configuration that it, ice crystals, and observer are all in the same horizontal plane, the observer will see a pair of brightly colored spots, one on either side of the sun. These colored spots are called **sundogs**, **mock suns**, or **parhelia**—meaning “with the sun” (see Fig. 19.23, and the opening photo on p. 516). The colors usually grade from red (bent least) on the inside closest to the sun to blue (bent more) on the outside.

Whereas sundogs, tangent arcs, and halos are caused by refraction of sunlight through ice crystals, **sun pillars** are caused by reflection of sunlight off ice crystals. Sun pillars appear most often at sunrise or sunset as a vertical shaft of light extending upward or downward from the sun (see Fig. 19.24). Pillars may form as hexagonal platelike ice crystals fall with their flat bases oriented horizontally. As the tiny crystals fall in still air, they tilt from side
Platelike ice crystals falling with their flat surfaces parallel to the earth produce sundogs.

The bright areas on each side of the sun are sundogs.
to side like a falling leaf. This motion allows sunlight to reflect off the tipped surfaces of the crystals, producing a relatively bright area in the sky above or below the sun. Pillars may also form as sunlight reflects off hexagonal pencil-shaped ice crystals that fall with their long axes oriented horizontally. As these crystals fall, they can rotate about their horizontal axes, producing many orientations that reflect sunlight. So, look for sun pillars when the sun is low on the horizon and cirriform (ice crystal) clouds are present. Figure 19.25 is a summary of some of the optical phenomena that form when cirriform clouds are present.

Rainbows

Now we come to one of the most spectacular light shows observed on the earth—the rainbow. Rainbows occur when rain is falling in one part of the sky, and the sun is shining in another. (Rainbows also may form by the sprays from waterfalls and water sprinklers.) To see the rainbow, we must face the falling rain with the sun at our backs. Look at Fig. 19.26 closely and note that, when we see a rainbow in the evening, we are facing east toward the rainshower. Behind us—in the west—it is clear. Because clouds tend to move from west to east in middle latitudes, the clear skies in the west suggest that the showers will give way to clearing. However, when we see a rainbow in the morning, we are facing west, toward the rainshower. It is a good bet that the clouds and showers will move toward us and it will rain soon. These observations explain why the following weather rhyme became popular:

Rainbow in morning, sailors take warning,
Rainbow at night, a sailor’s delight.*

*This rhyme is often used with the words “red sky” in the place of rainbow. The red sky makes sense when we consider that it is the result of red light from a rising or setting sun being reflected from the underside of clouds above us. In the morning, a red sky indicates that it is clear to the east and cloudy to the west. A red sky in the evening suggests the opposite.
When we look at a rainbow we are looking at sunlight that has entered the falling drops, and, in effect, has been redirected back toward our eyes. Exactly how this process happens requires some discussion.

As sunlight enters a raindrop, it slows and bends, with violet light refracting the most and red light the least (see Fig. 19.27). Although most of this light passes right through the drop and is not seen by us, some of it strikes the backside of the drop at such an angle that it is reflected within the drop. The angle at which this occurs is called the critical angle. For water, this angle is $48^\circ$. Light that strikes the back of a raindrop at an angle exceeding the critical angle bounces off the back of the drop and is internally reflected toward our eyes. Because each light ray bends differently from the rest, each ray emerges from the drop at a slightly different angle. For red light, the angle is $42^\circ$ from the beam of sunlight; for violet light, it is $40^\circ$ (see Fig. 19.27b). The light leaving the drop is, therefore, dispersed into a spectrum of colors from red to violet. Since we see only a single color from each drop, it takes myriads of raindrops (each refracting and reflecting light back to our eyes at slightly different angles) to produce the brilliant colors of a primary rainbow.

**WEATHER WATCH**

During the summer, rainbows are occasionally seen after a thunderstorm. Because of this fact, the Shoshone Indians viewed the rainbow as a giant serpent that would sometimes rub its back on the icy sky and hurl pieces of ice (hail) to the ground.

Figure 19.27b might lead us erroneously to believe that red light should be at the bottom of the bow and violet at the top. A more careful observation of the behavior of light leaving two drops (see Fig. 19.28) shows us why the reverse is true. When violet light from the lower drop reaches an observer’s eye, red light from the same drop is incident elsewhere, toward the waist. Notice that red light reaches the observer’s eye from the higher drop. Because the color red comes from higher drops and the color violet from lower drops, the colors of a primary rainbow change from red on the outside (top) to violet on the inside (bottom).

Frequently, a larger second (secondary) rainbow with its colors reversed can be seen above the primary bow (see Fig. 19.29). Usually this secondary bow is much fainter than the primary one. The secondary bow is caused when sunlight

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*FIGURE 19.26*

When you observe a rainbow, the sun is always to your back. In middle latitudes, a rainbow in the evening indicates that clearing weather is ahead.
enters the raindrops at an angle that allows the light to make two internal reflections in each drop. Each reflection weakens the light intensity and makes the bow dimmer. Figure 19.30 shows that the color reversals—with red now at the bottom and violet on top—are due to the way the light emerges from each drop after going through two internal reflections.

As you look at a rainbow, keep in mind that only one ray of light is able to enter your eye from each drop. Every time you move, whether it be up, down, or sideways, the rainbow moves with you. The reason why this happens is that, with every movement, light from different raindrops enters your eye. The bow you see is not exactly the same rainbow that the person standing next to you sees. In effect, each of us has a personal rainbow to ponder and enjoy! (Can a rainbow actually form on a day when it is not raining? The answer to this question is given in the Focus section on p. 533.)

**FIGURE 19.27**
Sunlight internally reflected and dispersed by a raindrop. (a) The light ray is internally reflected only when it strikes the backside of the drop at an angle greater than the critical angle for water. (b) Refraction of the light as it enters the drop causes the point of reflection (on the back of the drop) to be different for each color. Hence, the colors are separated from each other when the light emerges from the raindrop.

**FIGURE 19.28**
The formation of a primary rainbow. The observer sees red light from the upper drop and violet light from the lower drop.

**FIGURE 19.29**
A primary and a secondary rainbow.

**FIGURE 19.30**
Two internal reflections are responsible for the weaker, secondary rainbow. Notice that the eye sees violet light from the upper drop and red light from the lower drop.
Coronas, Glories, and Heiligenschein

When the moon is seen through a thin veil of clouds composed of tiny spherical water droplets, a bright ring of light, called a corona (meaning crown), may appear to rest on the moon (see Fig. 19.31). The same effect can occur with the sun, but, due to the sun's brightness, it is usually difficult to see.

The corona is due to diffraction—the bending of light as it passes around objects. To understand the corona, imagine water waves moving around a small stone in a pond. As the waves spread around the stone, the trough of one wave may meet the crest of another wave. This situation results in the waves canceling each other, thus producing calm water. (This is known as destructive interference.) Where two crests come together (constructive interference), they produce a much larger wave. The same thing happens when light passes around tiny cloud droplets. Where light waves constructively interfere, we see bright light; where destructive interference occurs, we see darkness. Sometimes, the corona appears white, with alternating...
bands of light and dark. On other occasions, the rings have color (see Fig. 19.32).

The colors appear when the cloud droplets (or any kind of small particles, such as volcanic ash), are of uniform size. Because the amount of bending due to diffraction depends upon the wavelength of light, the shorter wavelength blue light appears on the inside of a ring, while the longer wavelength red light appears on the outside. These colors may repeat over and over, becoming fainter as each ring is farther from the moon or sun. Also, the smaller the cloud droplets, the larger the ring diameter. Therefore, clouds that have recently formed (such as thin altostratus and altocumulus) are the best corona producers.

When different size droplets exist within a cloud, the corona becomes distorted and irregular. Sometimes the cloud exhibits patches of color, often pastel shades of pink, blue, or green. These bright areas produced by diffraction are called iridescence (see Fig. 19.33). Cloud iridescence is most often seen within 20° of the sun, and is often associated with clouds such as cirrostratus and altocumulus.

Like the corona, the glory is also a diffraction phenomenon. When an aircraft flies above a cloud layer composed of water droplets less than 50 µm in diameter, a set of colored rings, called the glory, may appear around the shadow of the aircraft (see Fig. 19.34). The same effect can happen when you stand with your back to the sun and look into a cloud or fog bank, as a bright ring of light may be seen around the shadow of your head. In this case, the glory is called the brocken bow, after the Brocken Mountains in Germany, where it is particularly common.

For the glory and the brocken bow to occur, the sun must be to your back, so that sunlight can be returned to your eye from the water droplets. Sunlight that enters the small water droplet along its edge is refracted, then reflected off the backside of the droplet. The light then exits at the other side of the droplet, being refracted once again (see Fig. 19.35). However, in order for the light to be returned to your eyes, the light
actually clings ever so slightly to the edge of the droplet—the light actually skims along the surface of the droplet as a surface wave for a short distance. Diffraction of light coming from the edges of the droplets produces the ring of light we see as the glory and the broken bow. The colorful rings may be due to the various angles at which different colors leave the droplet.

On a clear morning with dew on the grass, stand facing the dew with your back to the sun and observe that, around the shadow of your head, is a bright area—the Heiligenschein (German for halo). The Heiligenschein forms when sunlight, which falls on nearly spherical dew drops, is focused and reflected back toward the sun along nearly the same path that it took originally. (Light reflected in this manner is said to be retroreflected.) The light, however, does not travel along the exact path; it actually spreads out just enough to be seen as bright white light around the shadow of your head on a dew-covered lawn (see Fig. 19.36).

### Summary

The scattering of sunlight in the atmosphere can produce a variety of atmospheric visuals, from hazy days and blue skies to crepuscular rays and blue moons. Refraction (bending) of light by the atmosphere causes stars near the horizon to appear higher than they really are. It also causes the sun and moon to rise earlier and set later than they otherwise would. Under certain atmospheric conditions, the amplification of green light near the upper rim of a rising or setting sun produces the illusive green flash.

Mirages form when refraction of light displaces objects from their true positions. Inferior mirages cause objects to
appear lower than they really are, while superior mirages displace objects upward.

Halos and sundogs form from the refraction of light through ice crystals. Sun pillars are the result of sunlight reflecting off gently falling ice crystals. The refraction, reflection, and dispersion of light in raindrops create a rainbow. To see a rainbow, the sun must be to your back, and rain must be falling in front of you. Diffraction of light produces coronas, glories, and cloud iridescence. We can see the Heiligenschein on a clear morning when sunlight falls on nearly spherical dew drops.

**Meteorology Now**—Assess your understanding of this chapter's topics with additional quizzing and tutorials at http://now.brookscole.com/ahrens8

**Key Terms**
The following terms are listed in the order they appear in the text. Define each. Doing so will aid you in reviewing the material covered in this chapter.

reflected light, 518
crepuscular rays, 520
reflection (of light), 523
twilight, 524
green flash, 524
mirage, 525
inferior mirage, 525
superior mirage, 526
Fata Morgana, 526
halo, 527
tangent arc, 527
dispersion (of light), 528
dog, parhelia, 528
sun pillars, 528
rainbow, 530
corona, 533
diffraction, 533
iridescence, 534
Heiligenschein, 535

**Questions for Review**

1. (a) Why are cumulus clouds normally white? (b) Why do the undersides of building cumulus clouds frequently change color from white to dark gray or even black?
2. Explain why the sky is blue during the day and black at night.
3. What can make a setting (or rising) sun appear red?
4. Why do stars "twinkle"?
5. Explain why the horizon sky appears white on a hazy day.
6. How does light bend as it enters a more-dense substance at an angle? How does it bend upon leaving the more-dense substance? Make a sketch to illustrate your answer.
7. Since twilight occurs without the sun being visible, how does it tend to lengthen the day?
8. On a clear, dry, warm day, why do dark road surfaces frequently appear wet?
9. What atmospheric conditions are necessary for an inferior mirage? A superior mirage?
10. What process (refraction or scattering) produces crepuscular rays?

11. (a) Describe how a halo forms. (b) How is the formation of a halo different from that of a sundog?
12. At what time of day would you expect to observe the green flash?
13. Explain how sun pillars form.
14. What process (refraction, scattering, diffraction) is responsible for lengthening the day?
15. Why can a rainbow only be observed if the sun is toward the observer’s back?
16. Why are secondary rainbows higher and much dimmer than primary rainbows? Explain your answer with the aid of a diagram.
17. Suppose you look at the moon and see a bright ring of light that appears to rest on its surface. (a) Is this ring of light a halo or a corona? (b) What type of clouds (water or ice) must be present for this type of optical phenomenon to occur? (c) Is this ring of light produced mainly by refraction or diffraction?
18. Would you expect to see the glory when flying in an aircraft on a perfectly clear day? Explain.
19. Explain how light is able to reach your eyes when you see (a) a corona (b) a glory (c) the Heiligenschein

**Questions for Thought**

1. Explain why on a cloudless day the sky will usually appear milky white before it rains and a deep blue after it rains.
2. How long does twilight last on the moon? (Hint: The moon has no atmosphere.)
3. Why is it often difficult to see the road while driving on a foggy night with your high beam lights on?
4. What would be the color of the sky if air molecules scattered the longest wavelengths of visible light and passed the shorter wavelengths straight through? (Use a diagram to help explain your answer.)
5. Explain why the colors of the planets are not related to the temperatures of the planets, while the colors of the stars are related to the temperatures of the stars.
6. If there were no atmosphere surrounding the earth, what color would the sky be at sunrise? At sunset? What color would the sun be at noon? At sunrise? At sunset?
7. Why are rainbows seldom observed at noon?
8. On a cool, clear summer day, a blue haze often appears over the Great Smoky Mountains of Tennessee. Explain why the blue haze usually changes to a white haze as the relative humidity of the air increases.
9. During a lunar eclipse, the earth, sun, and moon are aligned as shown in Fig. 19.37. The earth blocks sunlight from directly reaching the moon’s surface, yet the surface
of the moon will often appear a pale red color during a lunar eclipse. How can you account for this phenomenon?

10. Explain why smoke rising from a cigarette often appears blue, yet appears white when blown from the mouth.

11. During Ernest Shackleton’s last expedition to Antarctica, on May 8, 1915, seven days after the sun had set for the winter, he saw the sun reappear. Explain how this event—called the Novaya Zemlya effect—can occur.

12. Could a superior mirage form over land on a hot, sunny day? Explain.

13. Explain why it is easier to get sunburned on a high mountain than in the valley below. (The answer is not that you are closer to the sun on top of the mountain.)

14. Why are stars more visible on a clear night when there is no moon than on a clear night with a full moon?

15. During the day, clouds are white, and the sky is blue. Why then, during a full moon, do cumulus clouds appear faintly white, while the sky does not appear blue?

**Problems and Exercises**

1. Choose a 3-day period in which to observe the sky 5 times each day. Record in a notebook the number of times you see halos, crepuscular rays, coronas, cloud iridescence, sun dogs, rainbows, and other phenomena.

2. Make your own rainbow. On a sunny afternoon or morning, turn on the water sprinkler to create a spray of water drops. Stand close to the spray as possible (without getting soaked) and observe that, as you move up, down, and sideways, the bow moves with you.
   (a) Explain why this happens.
   (b) Also, explain with the use of a diagram why the sun must be at your back in order to see the bow.

3. Take a large beaker or bottle and fill it with water. Add a small amount of nonfat powdered milk and stir until the water turns a faint milky white. Shine white light into the beaker, and, on the opposite side, hold a white piece of paper.
   (a) Explain why the milk has a blue cast to it and why the light shining on the paper appears ruddy.
   (b) What do you know about the size of the milk particles?
   (c) Is this a form of Rayleigh scattering or geometric scattering? Explain.
   (d) How does this demonstration relate to the color of the sky and the color of the sun—at sunrise and sunset?

**Questions for Exploration**

1. At MeteorologyNow™, go to Meteorology Interactive, select Sky Identification and click on Atmospheric Optics. Explore the imagery of atmospheric optics. Define in your own words the physical process that leads to formation of
   (a) Sundogs
   (b) Rainbows
   (c) Halos.

2. At MeteorologyNow™, go to Meteorology Interactive, select Sky Identification and click on Atmospheric Optics; choose any two or three optical phenomena. Go to Weather Forecasting and click on Forecasting to examine a current surface weather map. Next, use a “weather cams” web site to try to locate a current picture of each of the optical phenomena selected. Some nice “weather cams” web sites to try: http://cirrus.sprl.umich.edu/wxnet/wxcam/html, and www.weatherimages.org/weathercams.html.

3. At MeteorologyNow™, go to Meteorology Interactive, select Sky Identification and click on Atmospheric Optics to explore the imagery of three optical phenomena. Describe the physical process that leads to the formation of each phenomenon.

4. The Green Flash (http://mintaka.sdsu.edu/GF/): Using your own words, explain the principle behind the green flash. Where and when are you most likely to see it? How might you photograph it? Is it always green?

5. Atmospheric Halos (http://www.sundog.clara.co.uk/halo/halosim.htm): Describe the relationship between the shape of ice crystals and the different types of halos. What types of halos have you seen? What were the atmospheric conditions at the time?