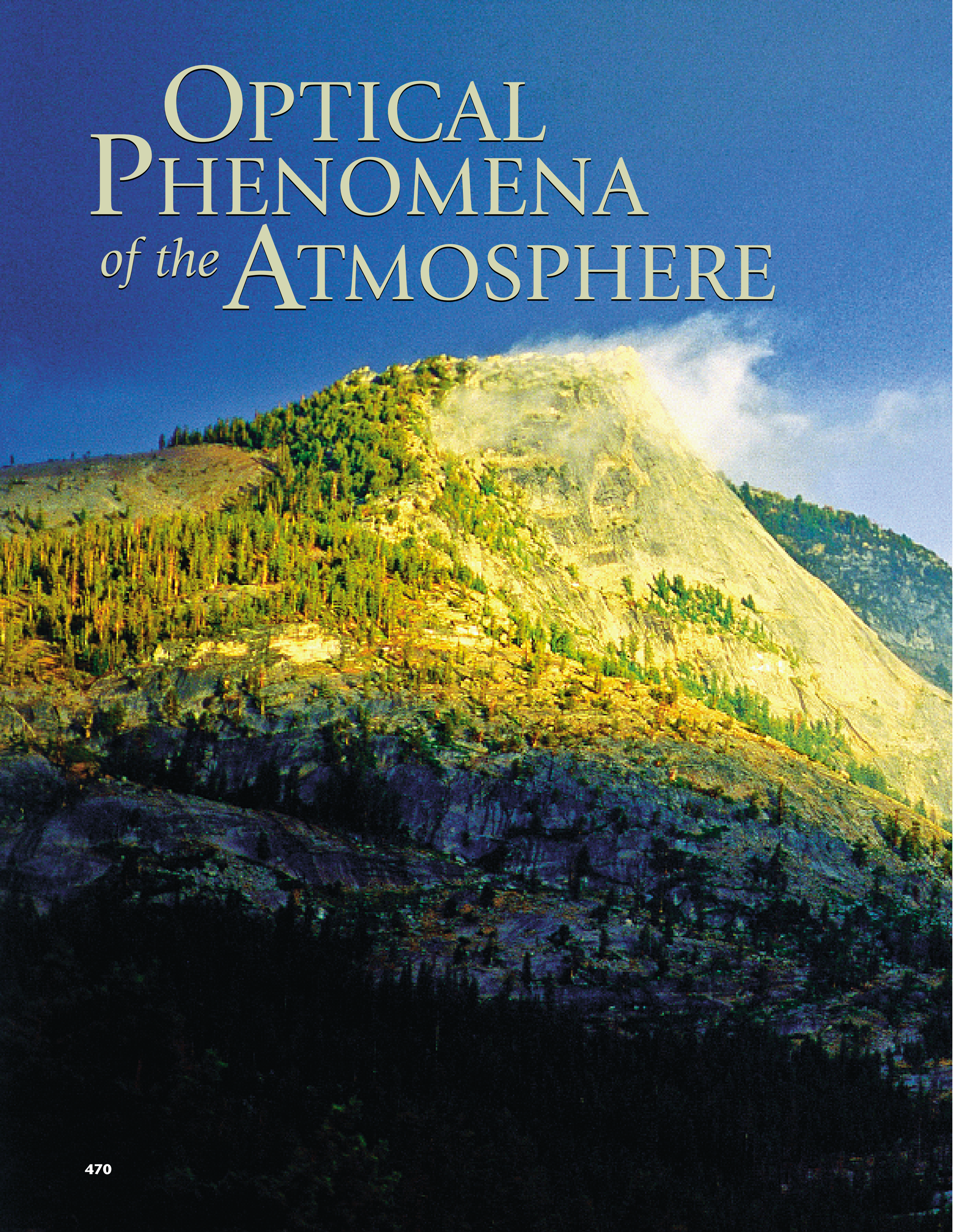
Optical Phenomena of the Atmosphere



Rainbow in California's Yosemite National Park. *(Photo by Marc Muench)*

One of the most spectacular and intriguing of natural phenomena must surely be the rainbow. Its splash of colors has been the focus of poets and artists alike, not to mention every amateur photographer within reach of a camera. In addition to rainbows, many other optical phenomena, such as halos, coronas, and mirages, are common in our atmosphere. In this chapter, we consider how the most familiar of these displays occur. By learning about these spectacles, and by knowing when and where to look for them, you should become better able to identify each type. It is hoped that these fascinating displays will be witnessed more frequently as a result of this study.

Nature of Light

The light that forms the array of colors that constitute the rainbow, or the deep blue color of the sky, originates as white (visible) light from the Sun. It is the interaction of white sunlight with our atmosphere that creates the numerous optical phenomena that take place in the sky.

In Chapter 2 we considered some properties of light and how they contribute to occurrences like the blue sky and the red color of sunset. Here we examine other properties of light and describe how light interacts with the gases of the atmosphere, as well as with ice crystals and water droplets, to generate still other optical phenomena. We consider four basic properties of light: reflection, refraction, diffraction, and interference. The sections that follow consider reflection and refraction; diffraction and interference are considered later, in the section on coronas.

Reflection

Light traveling through the emptiness of outer space travels at a uniform speed and in a straight line. When light rays encounter a transparent material, such as a piece of glass, however, some rays bounce off the surface of the glass, whereas others are transmitted at a slower velocity through the glass. The rays that bounce back from the surface of the glass are said to be *reflected.* It is reflected light that allows you to see yourself in a mirror. The image that you see in a mirror originates as light that first reflected off you toward the mirror and then was bounced from the silvered surface of the mirror back to your eyes. When light rays are reflected, they always bounce off the reflecting surface at the same angle at which they meet that surface (Figure 16–1). This principle is called the **law of reflection.** It states that the angle of incidence (incoming ray) is equal to the angle of reflection (outgoing ray).

Although the angle of incidence always equals the angle of reflection, not all objects are perfectly smooth. Consequently, when light encounters a rough surface, the rays will strike the surface at different angles, which tends to scatter the light rays (Figure 16–2). When light is reflected

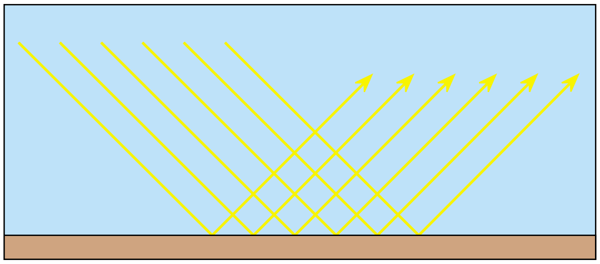


FIGURE 16-1 Reflection of light by a smooth surface.

from a rough surface, the image that you see is generally distorted or in some cases appears as multiple images. For example, the reflected image of the Sun when viewed on a rough ocean surface is not a circular disk, but rather a long narrow band, as shown in Figure 16–3. This bright band of light is formed because some of the sunlight that strikes each wave is reflected toward the viewer's eyes. What we are really seeing is not one image of the sun, but multiple, distorted images of a single light source. Even something that appears as smooth as a page in this book is sufficiently rough to disperse the light in all directions, making it possible to see the print from any direction. In contrast, if this page were perfectly smooth and all the light was approaching from a specific direction, you would have to move your head to a position exactly opposite the light in order to read the print.

A type of reflection that is important to our discussion is **internal reflection.** Internal reflection occurs when light that is traveling through a transparent material, such as water, reaches the opposite surface and is reflected back into the transparent material. You can easily demonstrate this phenomenon by using a glass of water. Hold the glass of water directly overhead and look up through the water. You should be able to see clearly through the water, for very little internal reflection results when light strikes perpendicular to a surface. Keeping the glass overhead, move it sideways so that you look up at it at an angle. Notice how the underside of the surface of the water takes on the appearance of a silvered mirror. What you are observing is the total internal reflection that occurs when the light strikes the surface at an angle greater than 48° from the vertical. Internal reflection is an important factor in the formation of optical phenomena, such as rainbows. In this instance, sunlight

FIGURE 16-2 Incident light striking a rough surface is diffused.

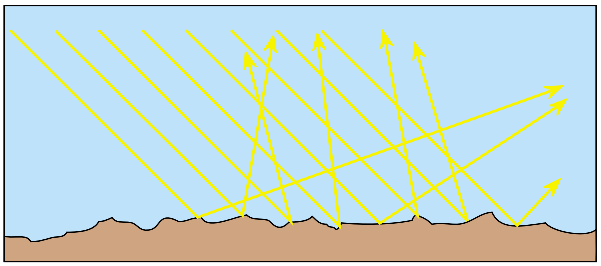


FIGURE 16-3 This long, narrow band of sunlight is really multiple, distorted images of the Sun reflected from the ocean surface. Deception Pass Bridge, Washington. *(Photo by Peter Skinner/ Photo Researchers, Inc.)*

entering the raindrops strikes the opposite surface and is reflected back toward an observer.

Refraction

When light strikes a transparent material such as water, the rays that are not reflected are transmitted through the water and are subjected to another well-known effect, called *refraction.*

Refraction is the bending of light as it passes obliquely from one transparent medium to another. You have undoubtedly noticed this phenomenon as you have stood in a swimming pool and observed your apparently bent limbs. Obviously, it had to be the light that played such a trick on your eyes.

Refraction is caused because the velocity of light varies, depending on the material that transmits it. In a vacuum, radiation travels at 3.0×10^{10} centimeters per second; and when it travels through air, its speed is slowed only slightly. However, in such substances as water, ice, or glass, its speed is slowed considerably.*

When light enters a transparent material perpendicular to its surface, only the velocity is affected. However, when light encounters a transparent medium at some angle other than 90°, the light rays are bent, as shown in Figure 16–4. Why light is refracted (bent) can best be demonstrated by an analogy. Imagine how an automobile responds should the driver fall asleep as the car nears a curve to the left. As the auto leaves the highway, the right front wheel will encounter the dirt shoulder before the left wheel does. Because of the soft nature of the dirt shoulder, the right wheel will slow while the left wheel, which is still on the pavement, will continue at the same rate of speed. The result will be a sudden turn of the auto toward the right, which will, it is hoped, waken the driver. Now if we can imagine that the path of the auto represents the path of light rays, and the pavement and softer shoulder represent air and water, respectively, we can see how light bends as it goes from air to water. As the light enters the water and is slowed, its path is diverted toward a line extending perpendicularly from the water's surface (Figure 16–4). Should the light pass from water into air, the bending will be in the opposite direction, that is, away from the perpendicular.

Recall that light bends because of a change in velocity. Thus, it follows that the greater the difference in the velocity at which the light travels through the materials involved, the greater the bending. Because light travels only slightly slower in air than in a vacuum, the amount of refraction in air is small; hence, air is said to have a small index of refraction. Water, in contrast, has a much larger refractive index; light will bend quite noticeably as it passes from air to water. The angle at which the light intersects the surface also affects the angle of refraction.

The bending of light caused by refraction is responsible for a number of common optical illusions. These optical happenings result because our brain perceives bent light as if it has traveled to our eyes along a straight path. Try to imagine "looking down" a bent light ray to view an object located around a corner. If you could see the object, your brain would place that object out from the corner in "plain sight." On occasion, you do see things that are "around the corner." One example is our view of the setting Sun. Several minutes after the Sun has actually slipped below the horizon, it still appears to us as a full disk. We will soon provide an explanation for this occurrence.

An illustration of how refraction causes optical illusions is found in Figure 16–5. Here we see how the refraction of light produces the apparent bending of a pencil that is immersed in water. The solid lines in this figure show the actual path taken by the light, whereas the dashed lines indicate how we perceive those same light rays. As we look down at the

*The speed of light is a constant; however, as it passes through various substances, this energy is delayed because of interaction with the electrons. The speed of light as it travels between these intervening electrons is the same as in a vacuum.

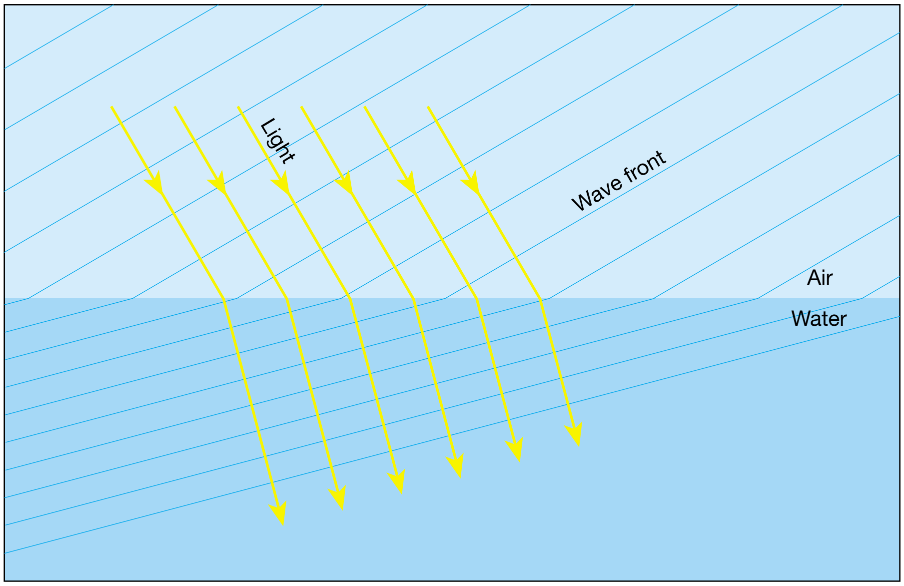


FIGURE 16-4 Refraction (bending) occurs as light waves pass from one material to another. The light will change direction because one part of the wave front slows before the other part.

pencil, the point appears closer to the surface than it actually is. Again, this situation occurs because our brain perceives that light as coming along the straight path indicated by the dashed line rather than along the actual bent path. Because all the light coming from the submerged portion of the pencil is bent similarly, this portion of the pencil appears nearer the surface. Therefore, where the pencil enters the water, it appears to be bent upward toward the surface of the water.

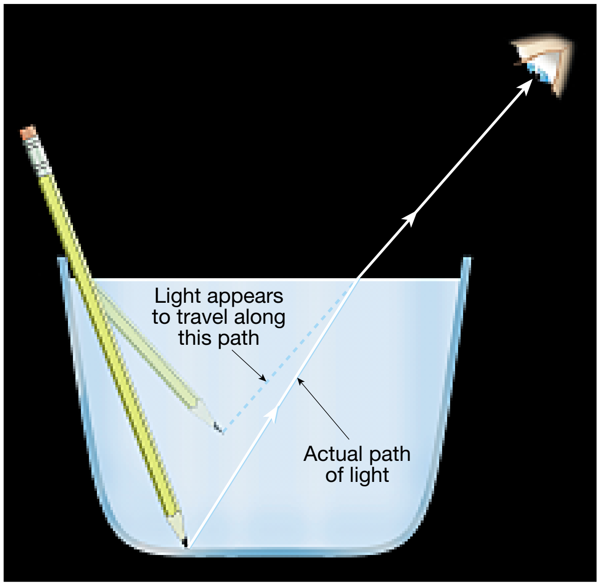
In addition to the abrupt bending of light as it passes obliquely from one transparent substance to another, light will also gradually bend as it traverses a material of varying density. As the density of a material changes, so does the velocity of light. Within Earth's atmosphere, for example, the density of air usually increases Earthward. The results of this gradual density change are an equally gradual slowing and bending of light rays. These rays acquire a direction of curvature that has the same orientation as Earth's curvature. This bending is responsible for the apparent displacement of the position of the stars, Moon, and Sun. When the Sun (or other celestial bodies) is near the horizon, this effect is particularly great, which explains why we can see the Sun for a few minutes after it has set below the horizon.* Figure 16–6 illustrates this situation. Recall that it is our inability to perceive light as bending that places the apparent position of the Sun above the horizon.

Mirages

One of the most interesting optical events common to our atmosphere is the **mirage.** Although this phenomenon is most often associated with desert regions, it can actually be experienced anywhere (see Box 16–1). One type of mirage occurs on very hot days when the air near the ground is much less dense than the air aloft. As noted, a change in the density of air is accompanied by a gradual bending of the light rays. When light is traveling through air that is less dense near the surface, the rays will develop a curvature in a direction opposite to Earth's curvature. As we can see in Figure 16–7, this direction of bending will cause the light reflected from a distant object to approach the observer from below eye level. Consequently, because the brain perceives the light as following a straight path, the object appears below its original position and is often inverted, as is the palm tree in Figure 16–7. The palm tree will appear inverted when the rays that originate near the top of the tree are bent more than those that originate near the base of the tree.

*Because it takes over eight minutes for solar radiation to reach Earth, we see the Sun in the position it was located about eight minutes earlier. This situation does not affect the apparent displacement of the Sun caused by atmospheric bending of solar radiation.

FIGURE 16-5 The pencil appears bent because the eye perceives light as if it were traveling along the dashed line rather than along the solid line, which represents the path of the refracted light.



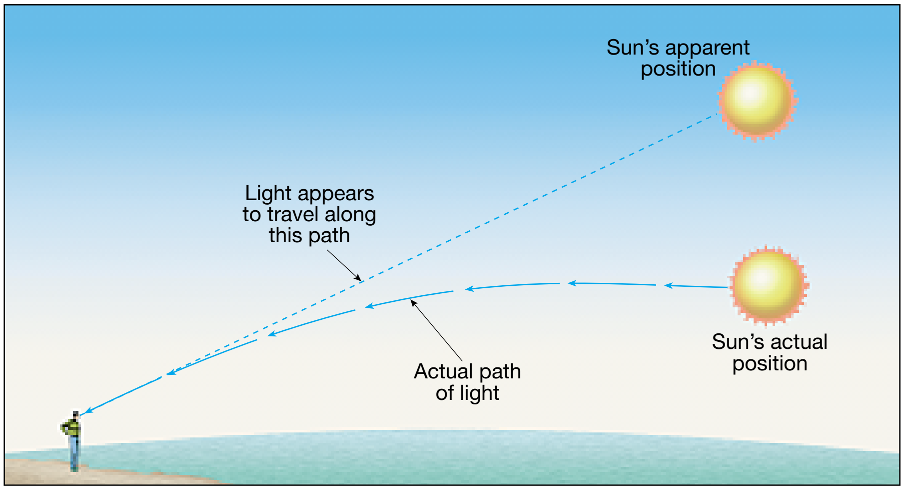


FIGURE 16-6 Light is refracted as it passes through the atmosphere, resulting in an apparent displacement of the position of the Sun.

In the classic desert mirage, a lost and thirsty wanderer encounters a mirage consisting of an oasis of palm trees and a shimmering water surface on which he can see a reflection of the palms. The palm trees are real, but the water and the reflected palms are part of the mirage. Light traveling to the observer through the cooler air above produces the image of the actual tree. The reflected image of the palms is produced, as stated earlier, from the light that traveled downward from the trees and was gradually bent upward as it traveled through the hot (less dense) air near the ground. The image of water is produced in the same manner as the reflection of the palms. Light that traveled downward from the sky is bent upward to generate the mirage of water. Such desert mirages are called **inferior mirages** because the images appear *below* the true location of the observed object.

In addition to the "desert mirage," another common type of mirage occurs when the air near the ground is much cooler than the air aloft. Consequently, this effect is observed most frequently in polar regions or over cool ocean surfaces. When the air near the ground is substantially colder than the air aloft, the light rays bend with a curvature having the same direction as Earth's curvature. As shown in Figure 16–8, this effect allows ships to be seen where ordinarily Earth's curvature would block them from view. This phenomenon is often referred to as **looming** because sometimes the refraction of light is so great that the object appears suspended above the horizon. In contrast to a desert mirage, looming is considered a **superior mirage** because the image is seen *above* its true position.

In addition to the rather easily explained inferior and superior mirages, a number of much more complex variations have been observed. They occur when the atmosphere develops a temperature profile in which rapid temperature changes are observed with height. Under these conditions, each thermal layer acts like a glass lens. Because each layer will bend the light rays somewhat differently, the size and shape of the objects observed through these thermal layers are greatly distorted. You may have observed an analogous sight if you have ever entered a "House of Mirrors" at the county fair. Here one of the mirrors makes you look taller, whereas others stretch the

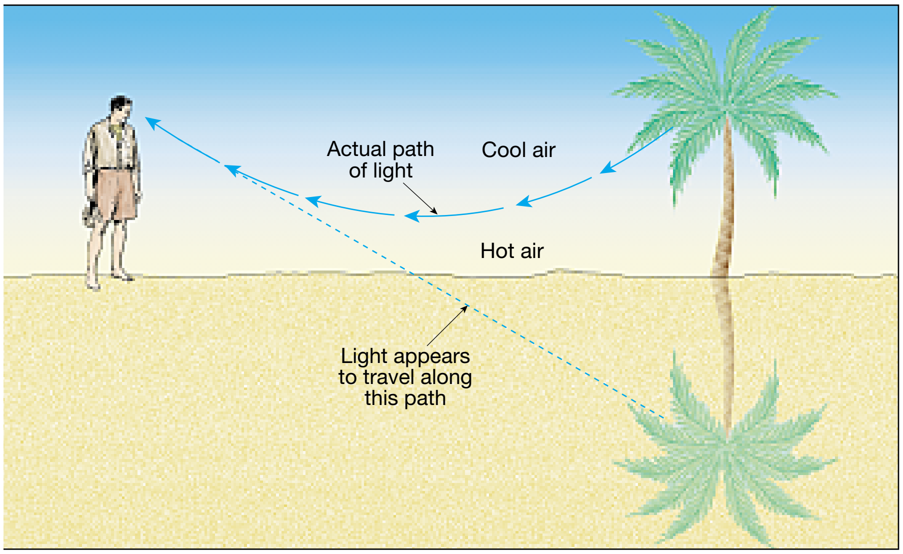


FIGURE 16-7 Light travels more rapidly in the hot air near the surface. Thus, as downward-directed rays enter this warm zone, they are bent upward so that they reach the observer from below eye level.

BOX 16-1 Are Highway Mirages Real?

You have undoubtedly seen a mirage while traveling along a highway on a hot summer afternoon. The most common highway mirages are in the form of "wet areas" that appear on the pavement ahead only to disappear as you approach (Figure 16–A). Because these "wet areas" always disappear as a person gets closer, many people believe they are optical illusions. This is not the case. Highway mirages, as well as all other types of mirages, are as real as the images observed in a mirror. As can be seen in Figure 16–A, highway mirages can be photographed. They are not "tricks played by the mind."

What causes the "wet areas" that appear on dry pavement? On hot summer days, the layer of air near Earth's surface is much warmer than the air aloft. Sunlight traveling from a region of colder (more dense) air into the warmer (less dense) air near the surface bends in a direction opposite to Earth's curvature (see Figure 16–7). As a consequence, light rays that began traveling downward from the sky are refracted upward and appear to the observer to have originated on the pavement ahead. What appears to the traveler as water is really just an inverted image of the sky. This can be verified by careful observation. The next time you view a highway mirage, look closely at any vehicle ahead of you at about the same distance as the "wet" area. Below the vehicle you should be able to see an inverted image of it. Such an image is produced in the same manner as the inverted image of the sky.

It is interesting to note that when the Sun and Moon are low on the horizon, they seem to be much larger than when they are overhead. This phenomenon is a true optical illusion that has nothing to do with the refraction of light. As meteorologist Craig Bohren stated: "The Moon illusion results from refraction by the mind, mirages from refraction by the atmosphere."

FIGURE 16-A Classic highway mirage on a South Dakota highway. *(Photo by Tom Bean, DRK Photo)*

image of part of your body and compress other portions. Mirages are capable of similarly distorting objects and occasionally will even form a mountainlike image over a barren ice cap or over an open ocean.

One mirage that changes the apparent size of an object is called **towering.** As the name implies, towering results in a much larger object. An interesting type of towering is called the **Fata Morgana.** It is named for the legendary sister of King Arthur, who was credited with the magical power of being able to create towering castles out of thin air. This optical phenomenon is most frequently observed in coastal areas, where sharp temperature contrasts are common. In addition to generating magical castles, the Fata Morgana probably explains the towering mountains that were observed by early explorers of the north polar region but that never materialized.

Rainbows

Probably the most spectacular and best known of all optical phenomena that occur in our atmosphere is the **rainbow** (Figure 16–9). An observer on the ground sees the rainbow

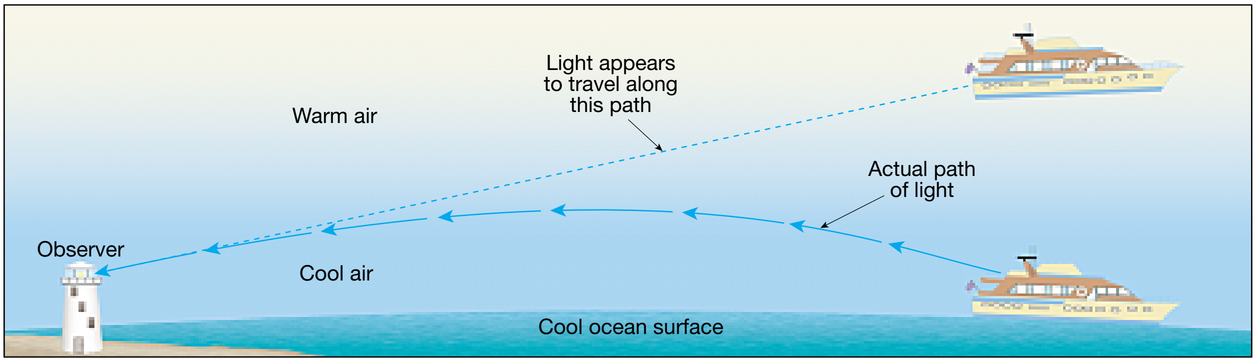


FIGURE 16-8 As light enters a cool layer of air, it will slow and bend downward. This results in objects that appear to loom above their true position.

as an arch-shaped array of colors that trail across a large segment of the sky. Although the clarity of the colors varies with each rainbow, the observer can usually discern six rather distinct bands of color. The outermost band of the bow is always red and blends gradually to orange, yellow, green, blue, and eventually ends with an innermost band of violet. Typically, these spectacular splashes of color are seen when the observer is situated with the Sun on one side and a rain shower occurring in the opposite part of the sky. However, a fine mist of water droplets generated by a waterfall or lawn sprinkler can also generate a miniature rainbow.

Like other optical phenomena, rainbows have been used by people as a means of predicting the weather. A well-known weather proverb illustrates this point:

> Rainbow in the morning, sailors take warning.
>
> Rainbow at night, sailors delight.

This bit of weather lore relies on the fact that weather systems in the mid-latitudes usually move from west to east. Remember that an observer must be positioned with his back to the Sun and facing the rain in order to see the rainbow. When a rainbow is seen in the morning, the Sun is

FIGURE 16-9 Rainbow over spruce trees in the taiga north of the Alaska Range. *(Photo by Michael Giannechini/Photo Researchers, Inc.)*

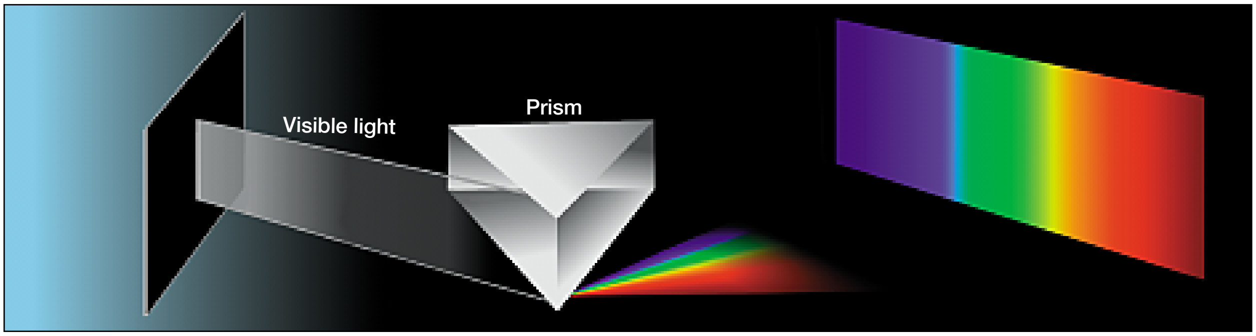


FIGURE 16-10 The spectrum of colors is produced when sunlight is passed through a prism and each wavelength of light is bent differently.

located to the east of the observer and the raindrops that are responsible for its formation must therefore be located to the west. In the early evening, the opposite situation exists—the rain clouds are located to the east of the observer. Thus, we predict the advance of foul weather when the rainbow is seen in the morning because the rain is located to the west of the observer and is traveling toward him. Conversely, when the rainbow is seen late in the day, the rain has already passed. Although this famous proverb does have a scientific basis, a small break in the clouds, which lets the sunshine through, can generate a late-afternoon rainbow. In this situation, a rainbow may certainly be followed shortly by more rainfall.

On those occasions when a rather spectacular rainbow is visible, an observer will occasionally be treated to a view of a dimmer secondary rainbow. The secondary bow will be visible about 8° above the primary bow and will suspend a larger arc across the sky (see Figure 16–13).* The secondary bow also has a slightly narrower band of colors than the primary rainbow, and the colors are in reverse order. Red makes up the innermost band of the secondary rainbow, and violet the outermost.

Although primary and secondary rainbows are produced in an almost identical manner, for clarity we consider first the formation of the primary bow. It should be apparent that sunlight and water droplets are needed for the generation of a rainbow. Also, let us not forget the observer, who must be located between the Sun and the rain.

To understand how raindrops disperse sunlight to generate the primary rainbow, recall our discussion of refraction. Remember that as light passes obliquely from the atmosphere to water, its speed is slowed, which causes it to be refracted (bent). In addition, each color of light travels at a different velocity in water; consequently, each color will be bent at a slightly different angle. Violet-colored light, which interacts most with the intervening material, travels at the slowest rate and is therefore refracted the most, whereas red light travels most rapidly and is therefore bent the least. Thus, when sunlight, which consists of all colors, enters water, the effect of refraction is to separate it into colors according to their velocity. Sir Isaac Newton is credited with demonstrating the concept of color separation, using a prism.

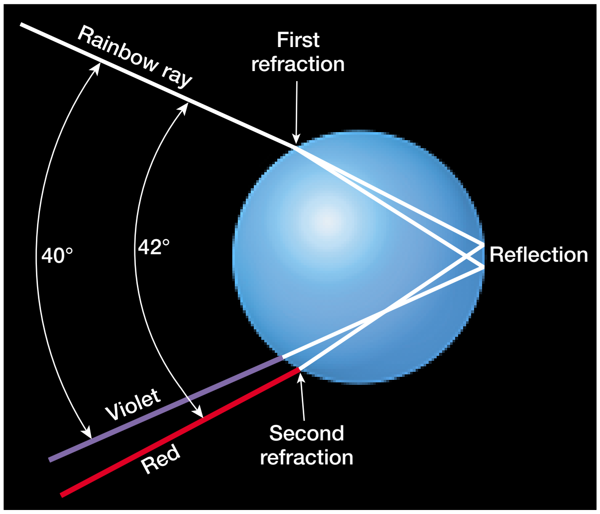
Light that is transmitted through a prism is refracted twice, once as it passes from the air into the glass and again as it leaves the prism and reenters the air. Newton noted that when light is refracted twice, as by a prism, the separation of sunlight into its component colors is quite noticeable (Figure 16–10). We refer to this separation of colors by refraction as **dispersion.**

When a rainbow forms, water drops act as a prism, dispersing sunlight into the spectrum of colors we see (Figure 16–11). On impacting with the droplet, the sunlight is refracted, with violet light bent the most and red the least. On reaching the opposite side of the droplet, the rays are reflected and exit the droplet on the same side they entered. After leaving the droplet, further refraction increases the dispersion already produced and accounts for the complete color separation.

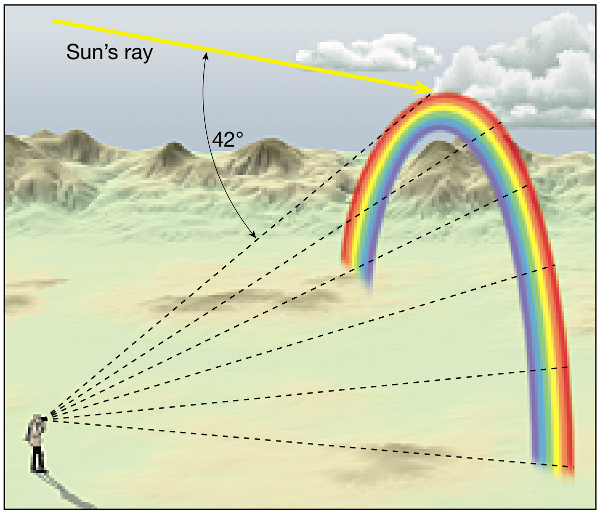
The angle between the incident sunlight and the dispersed colors that constitute the rainbow is 42° for red and 40° for violet. The other colors—orange, yellow, green, and blue—are dispersed at intermediate angles. Although each droplet disperses the full spectrum of colors, an observer will see only one color from any single raindrop. For example, if green light from a particular droplet reaches an observer's eye, the violet light from the droplet will pass over his head and the red light will fall toward the ground in front of him. Consequently, each observer sees his or her "own" rainbow generated by a different set of droplets and different sunlight from that which produces another person's rainbow.

The curved shape of the rainbow results because the rainbow rays always travel toward the observer at an angle between 40° and 42° from the path of the sunlight. Consequently, when an observer looks upward at 42° from the path of the sunlight, he or she will see the color red. When the observer looks to either side at an angle of 42° the color red will also be visible. In any direction at an angle of 42° from the path of the Sun's rays, droplets will be directing red light toward the observer. Thus, we experience a 42° semicircle of color across the sky that we identify as the arch shape of the rainbow. Because an observer in an airplane can also look downward at an angle of 42°, under ideal

*For reference, the diameter of the Sun is equal to about 0.5° of arc.



(a)



(b)

FIGURE 16-11 The formation of the primary rainbow. (a) Color separation results when sunlight is refracted and reflected by a raindrop to produce rainbow rays. (b) The curved shape of the rainbow results because the rainbow rays always travel toward the observer at an angle of 42° from the path of the sunlight.

conditions, he or she can see the rainbow as a full circle. In contrast, if the Sun is higher than 42° above the horizon, an Earthbound observer will not see a rainbow. So if you live in the midlatitudes, do not look for a rainbow during a summer rain shower occurring at midday.

As stated earlier, the secondary rainbow is generated in much the same way as the primary bow. The main difference is that the dispersed light that constitutes the secondary bow is reflected twice within a raindrop before it exits, as shown in Figure 16–12. The extra reflection results in a 50° angle for the dispersion of the color red (about 8° higher than the primary rainbow) and a reverse order of the colors.

In addition, the extra reflection accounts for a dimmer and therefore less frequently observed secondary bow (Figure 16–13). Each time light strikes the inner surface of the droplet, some of the light is reflected and the remainder is transmitted through the reflecting surface. The light that is transmitted through the back surface of the droplet does not contribute to the rainbow. Because the rays that form the secondary rainbow experience an additional reflection, they are not as bright as those that form the primary rainbow. Ideally, the secondary rainbow always forms; it is just not often discernible by the observer. In addition, other rainbows result because of three or even more internal reflections. These higher-order rainbows are too dim to be seen.

Halos, Sun Dogs, and Solar Pillars

Although a fairly common occurrence, halos are rarely seen by the casual observer. When noticed, the **halo** appears as a narrow whitish ring having a large diameter centered on the Sun (Figure 16–14). Look for halos on days when the sky is covered with a thin layer of cirrus clouds. In addition, this optical phenomenon is generally more often viewed in the

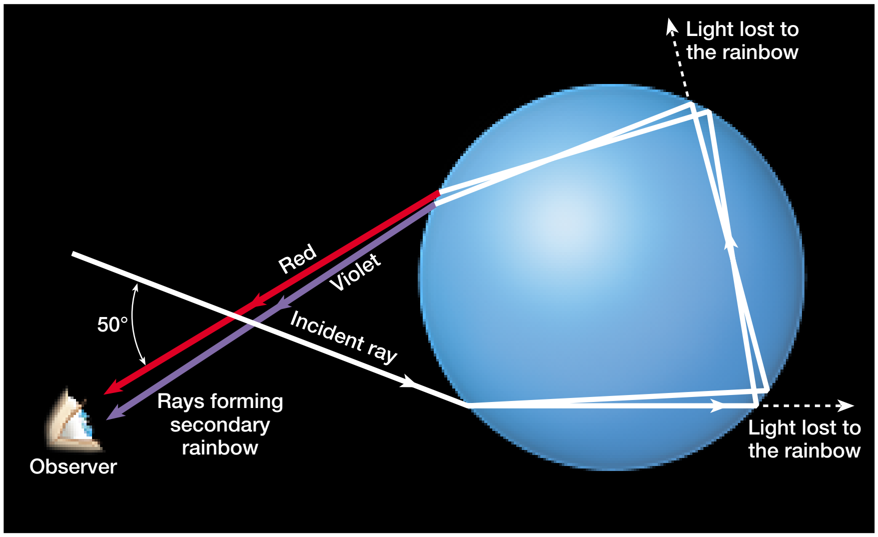


FIGURE 16-12 Idealized geometry of the rays that contribute to the secondary rainbow. By comparing this figure with Figure 16–11, you will see that the positions of the red and violet rays are reversed, which accounts for the order of the colors observed.

FIGURE 16-13 Double rainbow over Stonehenge, England. *(Photo by M. Dillon/CORBIS)*

morning or late afternoon, when the Sun is near the horizon. Occupants of polar regions, where a low Sun and cirrus clouds are common, are frequently treated to views of halos and associated phenomena. Occasionally, halos may also be seen around the Moon.

The most common halo is the *22° halo,* so named because its radius subtends an angle of 22° from the observer. Less frequently observed is the larger *46° halo.* Like the rainbow, the halo is produced by dispersion of sunlight. In the case of the halo, however, it is ice crystals rather than raindrops that refract light. Thus, as stated earlier, the clouds most often associated with halo formation are cirrus clouds. Because cirrus clouds often form as a result of frontal lifting, which in turn is associated with cyclonic storms, halos have been accurately described as harbingers of foul weather, as the following weather proverb attests:

FIGURE 16-14 A 22° halo produced by the dispersion of sunlight by cirrostratus clouds. *(Photo by Kevin Schafer/Peter Arnold, Inc.)*

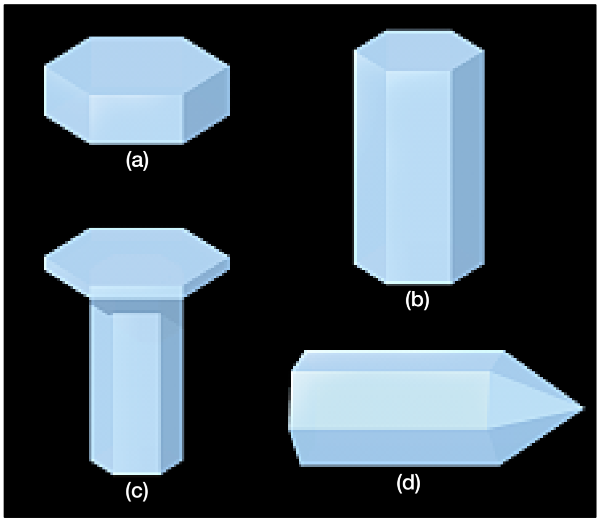


FIGURE 16-15 Common ice-crystal configurations that contribute to the formation of certain optical phenomena: (a) plate, (b) column, (c) capped column, and (d) bullet.

The moon with a circle brings water in her beak.

Four basic types of ice crystals are believed to contribute to the formation of halos: plates, columns, bullets, and capped columns (Figure 16–15). All these crystals are hexagonal (six sided), as is also the case for snowflakes.

Halos form when the ice crystals that compose cirrus clouds have random orientation. Because sunlight will strike the faces of these crystals at every possible angle, we might expect the scattered light to be dispersed equally in all directions. Yet just as we noted in the formation of the rainbow, as the angle at which the rays strike the surface changes so does the amount of dispersion, but only up to a point. After this point, a change in the angle of incidence does not appreciably change the direction of scattering. Consequently, a larger portion of the light will be scattered in one direction than in any other. For a six-sided ice crystal, this angle of maximum scattering is 22°; thus, we have the 22° halo.

The primary difference between 22° and 46° halos is the path that the light takes through the ice crystals. The scattering sunlight that is responsible for the 22° halo strikes one of the sides of the ice crystal and exits from an alternating side, as shown in Figure 16–16a. The angle of separation between the alternating faces of an ice crystal is 60°, which is the same as a common glass prism. Consequently, an ice crystal disperses light in a manner similar to a prism in order to produce the 22° halo. The 46° halo, by contrast, is formed from light that passes through one side of the crystal and exits at the base or top (Figure 16–16b). The angle separating these two surfaces is 90°. Light that passes through two ice faces separated by 90° is concentrated at an angle of 46°, which accounts for the latter halo.

Although ice crystals disperse light in the same manner as a raindrop (or prism), halos are generally whitish in color, partly because of the rather imperfect shape and size of ice crystals compared to rain droplets. The colors produced by this dispersion overlap and wash out each other. Occasionally, however, halos will be colored. Most commonly, a reddish band will be seen in the inner portion of the ring. Because red is refracted the least of all colors, we would expect to find it located on the inner edge of the halo, which is nearest the Sun. The other colors, which are refracted more than red, will tend to wash out each other, leaving the red surrounded by a whitish ring.

One of the most spectacular effects associated with a halo is called **sun dogs** or **parhelia.** These two bright regions, or "mock suns" as they are often called, can be seen adjacent to the 22° halo and usually slightly below the elevation of the Sun (Figure 16–17). Sun dogs form under the same conditions as, and in conjunction with, the halo, except that their existence depends on numerous ice crystals oriented vertically (see Figure 16–16). This particular orientation results when ice crystals are allowed to descend slowly. Then a large portion of the striking rays will be concentrated in two areas at a distance usually slightly greater than 22° from the Sun. When the Sun is near the horizon, so that the impact angle is perpendicular to the vertical crystal faces, the mock suns will appear directly on the 22° halo, with the sun positioned between them.

Another optical phenomenon that is related to the halo is the **sun pillar.** These vertical shafts of light are most often

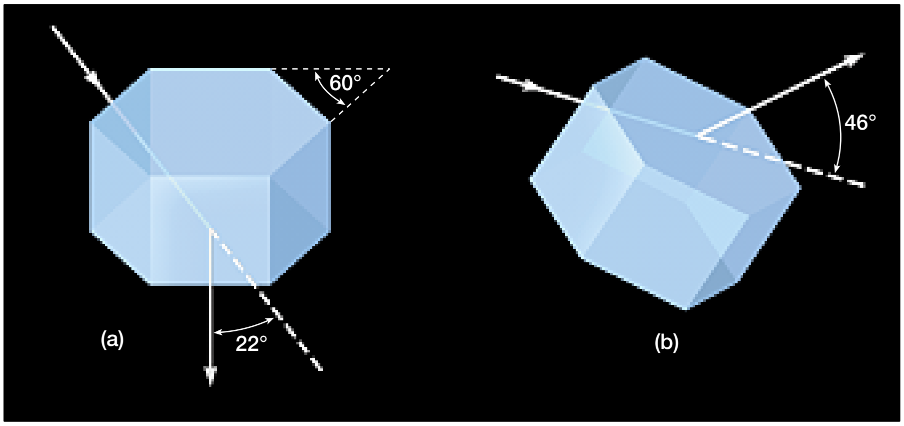


FIGURE 16-16 The paths that are taken by light to generate (a) the 22° halo and (b) the 46° halo.

FIGURE 16-17 Sun dogs, or parhelia, produced by the dispersion of sunlight by the ice crystals of cirrus clouds. *(Photo by E. J. Tarbuck)*

viewed near sunset or sunrise, when they appear to extend upward from the Sun (Figure 16–18). These bright pillars of light are created when sunlight is reflected from the lower sides of descending plates and capped columns, which are oriented like slowly falling leaves. Because direct sunlight is often reddish when the Sun is low in the sky, pillars will appear similarly colored as well. Occasionally, pillars that extend below the Sun can also be viewed.

The Glory

To the Earthbound observer, the **glory** is a spectacle that is rarely witnessed. The next time you are in an airplane and fortunate enough to have a window seat, however, look for the shadow of the aircraft projected on the clouds below (Figure 16–19). The airplane shadow will often be surrounded by one or more colored rings that constitute the glory. Each ring will be colored in a manner similar to the rainbow, with red being the outermost band and violet the innermost. Generally, however, the colors are not as discernible as those of the primary rainbow. When two or more sets of rings are seen, the inner one will be the brightest and thinnest.

Although the glory is most commonly seen by pilots, its name comes from its appearance when viewed by an observer located on the ground. The glory can be seen if an observer is located so that he or she is above a layer of fog with the Sun at his or her back. Should the observer's shadow be cast on the fogbank, the glory will enshroud the observer's

FIGURE 16-18 A Sun pillar is a shaft of sunlight reflected by ice crystals in high clouds. *(Photo by Warren Faidley/WeatherStock)*

FIGURE 16-19 The colored rings of a glory surround the shadow of an aircraft that is projected on the clouds below. *(Photo by Galen Rowell/CORBIS)*

head. When two people witness such a sight simultaneously, only the observer's own head will appear within the glory. Consequently, this type of "halo" has been represented in many ancient artistic works to glorify the wearer.

The glory is formed in a manner not unlike that of the rainbow. But the cloud droplets that are responsible for the glory are much smaller and more uniform in size than the raindrops that scatter the rainbow rays. The light that becomes the glory strikes the very edge of the droplets. These rays then travel to the opposite side of the droplet, partly by one internal reflection, and the remaining distance along the surface of the droplet. This path causes the rays to be backscattered directly toward the Sun. Because the glory always forms opposite the Sun's position, the observer's shadow will always be found within the glory.

The Corona

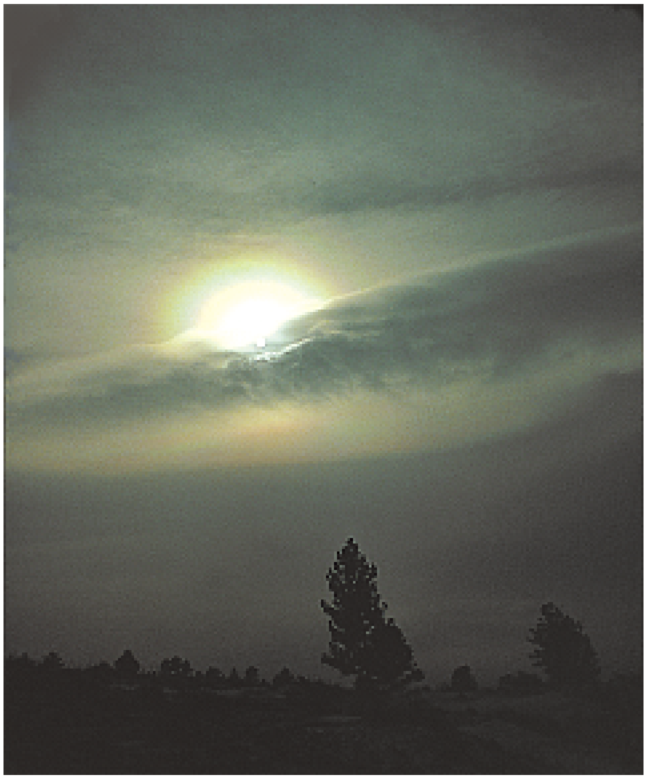
The only optical phenomenon more commonly witnessed in association with the Moon than the Sun is the corona. Typically, the **corona** appears as a bright whitish disk centered on the Moon or Sun. Whenever colors are discernible, the corona appears as several concentric rings, each with a red outer band and a bluish inner region (Figure 16–20).

The corona is produced when a thin layer of water-laden clouds, usually altostratus, veil the illuminating body. Although water droplets are responsible for scattering the light that produces the corona, the colors are not the result of reflection and refraction, as were the colors of the rainbow. Instead, the corona forms because of a slight bending of light that occurs as light passes near the edges of cloud droplets. Although we described light as traveling in a straight line, which it generally does, light will bend very slightly around sharp edges, a process referred to as **diffraction.** It is because of diffraction that even the sharpest shadow appears blurred at the edges when examined carefully.

Because of their small size, cloud droplets are particularly effective at bending light. From all sides of a cloud droplet, diffracted light will be directed into the "shadow" of the droplet. Here light rays will meet and interfere with each other. It is the **interference** of the various components of white light that generates the colors that make up the corona.

To help understand how interference produces color, we will need to recall our discussion of radiation in Chapter 2. Remember that light exhibits wave motion, much like ocean swells. White light consists of an array of colors, each

FIGURE 16-20 The corona. Typically, the corona appears as a bright whitish disk centered on the Moon or Sun. Those like the one shown above that display the colors of the rainbow are rare. *(Photo by Henry Lansford)*



with a different wavelength (distance from one crest to the next). That portion of visible light with the shortest wavelength appears violet, whereas the portion with the longest wavelength appears red (see Box 16–2).

When a light wave of any type becomes superimposed on another, interference results in a new wave having characteristics different from either of the interacting waves. In the generation of the corona, interference occurs as light waves, which are diffracted around the edge of cloud droplets, converge out of phase. Two waves are out of phase when the crest of one is aligned with the trough of the other. When two similar but out-of-phase waves become superimposed, the result is the cancellation of both waves. When white light is diffracted, such that one color is out of phase whereas the other colors are in phase, the out-of-phase color will be subtracted from the light. When yellow light, for example, is subtracted from white light, the remaining light will appear blue. Because each color is bent a different amount, each color will experience destructive interference at a different angle. The result of the diffraction and interference caused by cloud droplets is an array of colors, each produced by the cancellation and subtraction of a different color.

BOX 16-2 Iridescent Clouds

Iridescent clouds are among the more spectacular and elusive of optical phenomena (Figure 16–B). These dramatic clouds contain areas of bright colors, generally violet, pink, and green (Figure 16–B). Like the corona shown in Figure 16–18, the display of colors associated with iridescent clouds is produced by the diffraction of sunlight or moonlight by small cloud droplets or ice crystals. Special conditions must exist before iridescent colors can be observed. It is important that the diffracting particles be sufficiently small and uniform in size. In addition, the cloud must be in the same part of the sky as the Sun or Moon. Most of the time when these conditions occur, the Sun's rays are so intense that the colors go unnoticed.

Furthermore, when clouds of vertical development are present, they generally contain cloud droplets that are too large or too varied in size to generate this play of colors. Such factors contribute to the relatively rare occurrence of these spectacular clouds. The best time to view iridescent clouds is when the Sun is behind a cloud or just after the Sun has set behind a building or topographic barrier.

FIGURE 16-B Iridescent cloud. *(Photo by Tom Schlatter, National Oceanic and Atmospheric Administration/Seattle)*

Chapter Summary

- The four basic properties of light are *reflection, refraction, diffraction*, and *interference.* The *law of reflection* states that when light rays are reflected, they always bounce off the reflecting surface at the same angle (the angle of reflection) at which they meet that surface (the angle of incidence). *Internal reflection* occurs when light that is traveling through a transparent material, such as water, reaches the opposite surface and reflects back into the transparent material. Internal reflection is an important factor in the formation of optical phenomena, such as rainbows. Refraction is the bending of light due to a change in velocity as it passes obliquely from one transparent medium to another. Furthermore, light will also gradually bend as it traverses a material of varying density. The bending of light by refraction is responsible for such common optical illusions as the apparent displacement of the position of the stars, Moon, and Sun.
- A *mirage* is an optical effect of the atmosphere caused by refraction when light passes from air with one density into air with a different density and the object appears displaced from its true position. An *inferior mirage* occurs when the image appears below the true location of the observed object. During a phenomenon called *looming*, objects sometimes appear to be suspended above the horizon. Looming is considered a *superior mirage* because the image is seen above its true position. A mirage that changes the apparent size of an object is called *towering.* A type of towering, called *Fata Morgana,* is frequently observed in coastal areas as towering castles that appear out of thin air.
- Perhaps the most spectacular and best known atmospheric optical phenomenon is the *rainbow.* Sunlight and water droplets are necessary for the formation of a rainbow. Furthermore, the observer must be between the Sun and rain. When a rainbow forms, the water droplets act as prisms and refraction disperses the sunlight into the spectrum of colors, a process called *dispersion.* The curved shape of the rainbow results because the rainbow rays always travel toward the observer at an angle between 40° and 42° from the path of the sunlight. In any direction (upward, sideward, etc.) at an angle of 42° from the path of the Sun's rays, droplets will be directing the color red toward the observer, thus forming a semicircle of color across the sky. In a *primary rainbow,* sunlight is reflected once within a raindrop. However, in a dimmer, less frequently observed, *secondary rainbow,* light is reflected twice within a raindrop before it exits.
- A *halo* is a narrow whitish ring with a large diameter centered on the Sun. They occur most often when the sky is covered with a thin layer of cirrus clouds. The most common halo is the 22° halo, so named because its radius subtends an angle of 22° from the observer. Less frequently observed is the larger 46° halo. Halos are produced by dispersion of sunlight from atmospheric ice crystals that refract light. The primary difference between 22° and 46° halos is the path that light takes through the ice crystals. One of the most spectacular effects associated with a halo is called *sun dogs* or *parhelia.* These two bright regions, or mock suns as they are often called, can be seen adjacent to the 22° halo. A *sun pillar,* most often viewed near sunset or sunrise, is a vertical shaft of light that appears to extend upward from the Sun.
- The *glory,* most commonly seen by pilots, consists of one or more colored rings that surround the observer's (airplane's) shadow projected on the clouds below. It forms in a manner not unlike that of a rainbow. The phenomenon can also be viewed by an observer on the ground when he or she is above a layer of fog with the Sun at his or her back. Here, the glory can appear as a "halo" surrounding the shadow of the observer's head cast on the fog.
- The only optical phenomenon more commonly witnessed in association with the Moon than the Sun is the *corona,* a bright whitish disk centered on the Moon or Sun. A corona is produced when water droplets in a thin layer of water-laden clouds, usually altostratus, scatter light from the illuminating body. The colors of the corona are the result of a process called *diffraction,* the slight bending of light as it passes near the edges of cloud droplets. From all sides of a cloud droplet, diffracted light will be directed into the "shadow" of the droplet. Here light rays will meet and interfere with each other. It is the *interference* (interaction of some light frequencies, or colors, which can cause them to be canceled) of the various components of white light that generates the colors that make the corona.

Vocabulary Review

corona (p. 483)
diffraction (p. 483)
dispersion (p. 478)
Fata Morgana (p. 476)
glory (p. 482)
halo (p. 479)
inferior mirage (p. 475)
interference (p. 483)
internal reflection (p. 475)
law of reflection (p. 472)
looming (p. 475)
mirage (p. 474)
rainbow (p. 476)
refraction (p. 473)
sun dogs or parhelia (p. 481)
sun pillar (p. 481)
superior mirage (p. 475)
towering (p. 476)

Review Questions

1. Which of the six colors of the rainbow is refracted at the greatest angle? Why?
2. State the law of reflection.
3. If you have ever been close to a large movie screen, you might have noticed that the screen is made of a number of small glassy particles oriented at slightly different angles rather than one very smooth surface. Why do you think this is so?
4. When light travels from warm air into a region of colder air, its path will curve. Will it curve away from the cold and toward the warm, or vice versa?
5. Why does a mirage always disappear when the observer gets near?
6. What is meant by an inferior mirage? A superior mirage?
7. If you were looking for a rainbow in the morning, which direction would you look? Why that direction?
8. Explain why the secondary rainbow is dimmer than the primary rainbow.
9. How are halos and rainbows similar? How are they different?
10. What is the orientation of the ice crystals that produce a halo? Sun dogs?
11. What gives the glory its name?
12. How are the colors of a corona produced?
13. Describe the relative positions of the observer, the optical phenomenon, and the illuminating body for each of the following:
    a. rainbow
    b. halo
    c. glory
    d. corona
    e. sun dogs
14. At what time of day, if any, can each of the optical phenomena listed in question 13 be best observed?
15. What types of particles (water droplets or ice crystals) are found in the clouds (or fog) that generate each of the optical phenomena listed in question 13?

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
- **Critical thinking exercises**
- **Links to chapter-specific web resources**
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