Light, Color, and Atmospheric Optics

There are four primary mechanisms through which light traveling through the atmosphere is modified: reflection, refraction, scattering, and diffraction. We will examine each of these mechanisms in detail.

White and Colors

About half of the electromagnetic radiation from the sun that strikes the upper atmosphere is visible light (400 – 700 nm), while most of the radiation from the sun that penetrates the atmosphere and reaches the earth's surface is in visible wavelengths. As sunlight penetrates the atmosphere it may be absorbed, scattered, reflected, or refracted before reaching the surface.

We perceive light with the help of antenna-like nerve endings located in our eyes (rods and cones). Our eyes detect different intensities (light and dark) and different colors depending on the wavelengths that of visible radiation. White light is a combination of all wavelengths from 400 – 700 nm in nearly equal intensities. The sun radiates almost half of its energy as visible light. The peak intensity of the sun's electromagnetic radiation corresponds with the color yellow. Because all visible wavelengths from the sun reach the cones in nearly equal intensities when the sun is close to directly overhead (with a slight peak at yellow) the sun appears yellowish-white during the middle of the day.

The Color of Objects

How are objects too cool to directly emit radiation (non-luminous) seen? What influences their color? For non-luminous objects, color is determined by the wavelengths of light that an object *reflects* or *scatters.* An object that appears blue *reflects or scatters* blue light and absorbs all other wavelengths. The color white may be produced by *reflection/scattering* of all visible wavelengths while the absorption of all these same wavelengths produces black. Reflection occurs when light is deflected from an object obeying a geometric "Law of Reflection." In general an object that reflects a significant portion of the light that falls on it acts like a mirror (like calm water). This type of reflection is known as *specular reflection*. Some materials reflect light from rough surfaces that produce *diffuse reflection* (like snow).

Scattered Light

Scattering results from the deflection of light as it "bounces" off of various materials. Scattered light may proceed in any direction. Small objects, such as air molecules, fine dust particles, water molecules, or pollutants may cause scattering in the atmosphere. Cloud droplets 20 μm or larger in diameter can scatter all visible light. Even very small clouds are said to be *optically thick*, i.e., very little sunlight penetrates without being scattered. Clouds are also very poor absorbers of visible light. Clouds appear white because they effectively scatter all wavelengths of visible radiation thus scattering white light in all directions.

As a cloud grows taller, more sunlight is reflected from it and less light penetrates from above through to the base of the cloud. Any cloud over 1000 m in height allows relatively little light penetrate it. Hence the bases of such clouds appear dark. This darkening is exaggerated if the cloud contains droplets bigger than 20 μm because bigger droplets are better absorbers than scatterers.

Blue Skies and Hazy Days

Skies are blue on clear days due to scattering. Air molecules of oxygen and nitrogen are selective scatterers that scatter shorter wavelengths (blue) of visible light more effectively than longer wavelengths. This is known as *Rayleigh scattering*. Rayleigh scattering, along with an increased sensitivity of our eyes to blue light, makes the sky appear blue in all directions on clear days.

Selective scattering of blue light can make distant mountains appear blue (the Blue Ridge Mountains of Virginia, for instance). A *blue haze* consisting of terpenes (hydrocarbon particles released by vegetation that combine chemically with small amounts of ozone) may also cover a landscape and create a similar effect.

When small particles of dust, salt and smoke are found in abundance in air the sky begins to turn from blue to white. These small particles scatter all wavelengths of visible light resulting in a white haze. Haze beneath a break in the clouds can scatter light from the sun, so that we see bright light beams, or *crepuscular rays*, radiating across the sky.

Red Suns and Blue Moons

At midday on when the sky is clear the sun appears to be yellowish-white. At sunrise and sunset on clear days the sun may appear to be deep yellow, orange, or red. These color variations result from the amount of atmosphere the sun’s rays must penetrate at various times of the day. At noon (when the sun is overhead) all wavelengths are received in the eye with nearly equal intensity. Recall that a combination of all wavelengths together in equal abundance is seen as white light. The sun, therefore, appears yellowish-white at midday. At sunrise or sunset the rays coming from the sun strike the surface of the earth at a low angle. These rays must pass through much more atmosphere than at any other time of the day. The atmospheric thickness that rays from the sun must travel through is about twelve times longer at sunrise/sunset than it is at midday. The thicker atmospheric path results in a greater scattering of shorter wavelengths by the air molecules (and other particles) present. If scattering occurs over a long enough distance the scattered wavelengths are gradually diminished as most scatter off in directions such that they are not captured by the eye. The remaining long waves are the only visible wavelengths that reach the eye. Redder sunsets occur when the atmosphere contains a higher concentration of particulates such as dust, smoke, etc.

Blue suns/blue moons are produced by extremely small particles suspended in the air (size wise on the same order of magnitude of the wavelengths of visible light). When these particles are present they tend to scatter red light more so than blue which causes a bluing of the sun or moon.

Atmospheric Optics

Refraction is the bending of light that occurs as a beam of light slows down upon entering a denser medium from a less dense medium (such as air into water). Refraction is responsible for a variety of optical phenomena in the atmosphere.

As starlight passes through the atmosphere at night it encounters regions of differing air density (mostly due to temperature changes). Each of these regions refracts the beams of light differently, constantly changing the apparent position of the stars. This causes stars 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 much greater than the angle at which their light deviates as it penetrates the atmosphere.

Twilight is the name given to the time just after sunset (and immediately before sunrise) when the sky is illuminated. The length of twilight depends on both season and latitude. Twilight is a result of both refraction and scattering of sunlight when the sun is below the horizon and results in a gradual transition from light to darkness (and vice versa). Without twilight, darkness would arrive immediately after the sun disappeared below the horizon.

A mirage is an optical illusion created in the atmosphere due to refractive effects. When the air near the ground is much warmer than the air above, objects may appear to be both lower than they really are and also (often) inverted. These mirages are called *inferior mirages*. In polar areas, the air is cold and dense. Light from distant objects bends in such a way that the objects can appear shifted upward. This phenomenon is known as *superior mirage*.

A *halo* is a ring of light around the sun or moon. Halos are caused by refraction of light through ice crystals in *cirriform clouds*. A very common type of halo is the 22^o halo, often observed in cirriform clouds. Halos are due to randomly oriented ice crystals less that 20 microns in diameter that are abundant in the atmosphere. Occasionally, a bright arc of light may be seen at the top of a 22^o halo. Since the arc is tangent to the halo, it is called a *tangent arc.* The arc forms due to large hexagonal pencil-shaped ice crystals that fall with their long axes horizontal to the ground. Refraction of sunlight through the ice crystal produces the bright arc of light.

Dispersion is the separation of white light into its component colors. Dispersion may be thought of as selective refraction, with different wavelengths being refracted or bent through different paths. Dispersion usually produces colorful optical phenomena.

When plate-like hexagonal ice crystals with diameters larger than about 30 μm are present in clouds they tend to fall slowly and orient themselves horizontally. In this position, the ice crystals act as small prisms, dispersing (separating white light into its component colors) sunlight that passes through them. If the sun is near the horizon, and it, the ice crystals, and the observer are all in the same horizontal plane, the observer may see a pair of brightly colored spots, on either side of the sun known as *sundogs*.

While halos, tangent arcs, and sundogs are caused by refraction, *sun pillars* are *reflective* phenomena. Pillars may form as ice crystals fall horizontally. As the crystals fall in still air, they tilt from side to side like a falling leaf. This allows sunlight to reflect off the tipped surfaces of the crystals, producing a relatively bright column in the sky above or below the sun.

Rainbows

Rainbows occur when rain is falling in one part of the sky, but the sun is shining in another. To see the rainbow, one must face the falling rain with the sun at one's back. When looking at a rainbow, we are actually looking at sunlight that has entered the falling drops and has been redirected (due to both reflection and refraction) to our eyes. Each color of sunlight has its own specific angle at which it is redirected and only a single ray from each raindrop enters the eye. The full rainbow is a result of millions of drops producing a single colored ray of light each.

Coronas (crown) are bright rings of light often found around the sun or moon. *Coronas* are due to *diffraction* (bending) of light around small, uniform particles in the atmosphere. Glories and Heiligenschein are also diffractive optical phenomena.