Fig. 2-1. Twilight sky 55 minutes before sunrise over Cheyenne, WY, 29 Jun 2019. Jan Curtis.

Fig. 2-2. The other side of Twilight: Earth's Shadow with rising full Moon in the Belt of Venus over Cheyenne, WY, 21 Nov 2018. Jan Curtis.

Wonders of the Atmosphere
Chapter 2: The Clear Atmosphere: Sky Colors and Mirages

2.1 The Colorful Canopy of Atmosphere

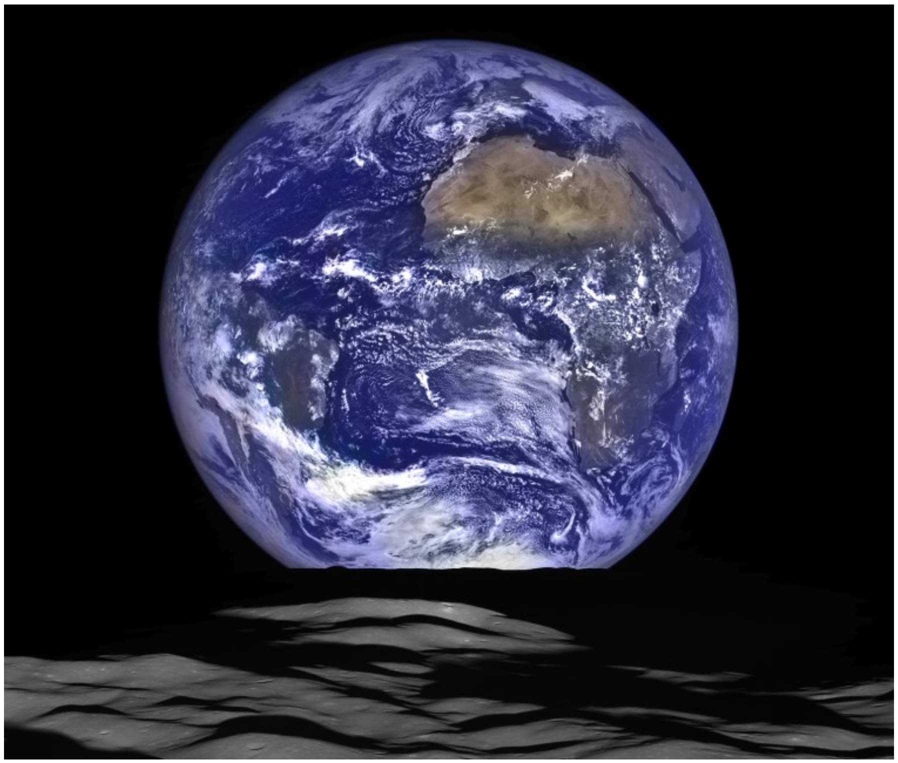

Fig. 2-3. View of Earth in the black sky over the Moon on Oct 12, 2015. NASA/GSFC/Arizona State University.

"Why is the sky blue?"

At the 2nd International Conference on Light and Color (1984) Bob Greenler presented a demonstration that suggested how the colors of the sky and the Sun arise. In a darkened room, he shone a circular light beam from a projector through a tank of clear water and onto a screen. The beam made a bright white circle on the screen. Then, drop-by-drop he added skim milk to the water. As the milky water brightened, the circle of light on the screen dimmed. Soon though, colors emerged. The milky water turned pale blue (somewhat like the sky) and as it did the circle of light on the screen turned orange (somewhat like the Sun at sunset).

"I've just made a sunset," said Bob, "and if you're not quite convinced…" At that precise moment, Bob simultaneously turned off the projector with the beam and turned on a second projector, with a photograph of the setting Sun on the screen that coincided with and matched the orange circle perfectly.

This experiment provokes a question. How can adding white skim milk to pure water produce both blue and orange without a chemical reaction simply by shining a white light through it?

Let's go back in time. The first serious attempt to explain why the sky is blue was given by none other than Leonardo da Vinci, who noted

> "**that the blueness we see in the atmosphere is not intrinsic colour**…. as an illustration of the colour of the atmosphere I will mention the smoke of old and dry wood, which, as it comes out of a chimney, appears to turn very blue, when seen between the eye and the dark distance. But as it rises, and comes between the eye and the bright atmosphere, it at once shows of an ashy grey colour" ***Theory of Colours***.

Leonardo wrote this at least 150 years before Newton discovered that white light is a mixture of all the colors of the spectrum. One hundred fifty years after Newton's discovery John Tyndall in 1869 made a similar observation with fuller understanding of the nature of light and color.

Fig. 2-4. As the blue atmospheric canopy thins to the vacuum of space, it tints only the bottom of the Moon blue, 08 Aug, 2001. NASA ISS002.

> "On windless days [in Killarney] the columns of smoke rose above the roofs of the cottages. The lower part of each column was shown up by a dark background of pines, the top part by the light background of clouds. The former was blue because it was mainly seen through dispersed light the latter was reddish because it was seen through transmitted light.

Tyndall stood on the doorstep of explaining why the sky is blue. He correctly distinguished between light that is transmitted and light that is scattered (he called it dispersed). Thus, the sky is blue because of a form of color segregation in the atmosphere. Blue light tends to be scattered in all directions in the atmosphere while red light tends to be transmitted through the atmosphere. Then Tyndall, a great experimental scientist, prequelled Greenler's demonstration. He shone a light through a glass tube, which he slowly filled with smoke and noted that the smoke turned blue and the light that penetrated dimmed and turned red. But Tyndall drew the wrong conclusion. He thought that aerosols were the atmosphere's scattering particles. Also, he couldn't explain why blue was scattered and red transmitted.

Two years later, beginning in 1871, Lord Rayleigh finally proved that the sky is blue due to preferential scattering of short light waves by air molecules by deriving the law for what we now call Rayleigh scattering in his honor (see §2.3). He also proved that aerosols and other larger particles reduce the blue (see §2. 6).

Fig. 2-5. Left: The sky over the Grand Canyon on a clear day. Right: Same photo except with a vertical strip of sky inverted. SDG.

Using Rayleigh scattering, we can also explain the varied colors of the twilight skies of Fig. 2-1 and Fig. 2-2 and why the sky on the Moon is black except for stars (Fig 2-3).

The sky on the Moon is always black because there is nothing, no air, no clouds, no dust to scatter the sunlight. As a result, sunlight blazes right to the Moon's surface with a brilliance and intensity and stark contrast with the black sky that shocked the Astronauts who landed there even though they knew what to expect before landing.

The great canopy of atmosphere that the Earth drags along as it whirls through the vacuum of Space (Fig. 2-4) is responsible for the all the optical phenomena we see in the sky, starting with the multicolored sky itself. Cloud cover turns it gray, smoke from forest fires turns it red, and twilight gives birth to a whole range of sky colors. At every single moment, color varies over the entire sky.

Even on the clearest day the deep blue sky overhead grades to almost white at the horizon, as in Fig. 2-5, where a vertical strip of sky over the Grand Canyon has been has been turned up-side down in the twin photo on the right to emphasize how pronounced the normal vertical gradation of sky color is, and how we normally don't even notice it.

2.2 Molecular Atmosphere: Rayleigh Scattering

Rayleigh scattering applies to particles that are tiny compared to the length of light waves, such as air molecules. The diameters of Nitrogen (N_2), Oxygen (O_2), Argon (Ar), and Water Vapor (H_2O), which constitute 99.96% of all air molecules, are, respectively 0.346, 0.364, 0.196, and 0.265 nm (nanometers or billionths of a meter). All are less than one thousandth the shortest wave of visible light (400 nm = 0.4 μm).

The law of Rayleigh scattering states that a tiny particle of a given size scatters light with efficiency *inversely* proportional to the 4^{th} power of the wavelength. For example, when wavelength doubles tiny particles scatter only $(½)^4 = {}^1/_{16}{}^{th}$ as efficiently.

Therefore, air molecules scatter violet light with up to $(7/4)^4 \approx 9.4$ times the efficiency they scatter red light. As a result, whereas sunlight peaks in the middle of the visible light spectrum, skylight is a highly selective mixture that decreases with increasing wavelength, hence decreasing amounts of violet, blue, green, yellow, orange, and red (Fig. 2-6). Combining this mixture with the sensitivity of the human eye, which is greatest in the middle of the visible light spectrum, and the daytime sky we see is blue.

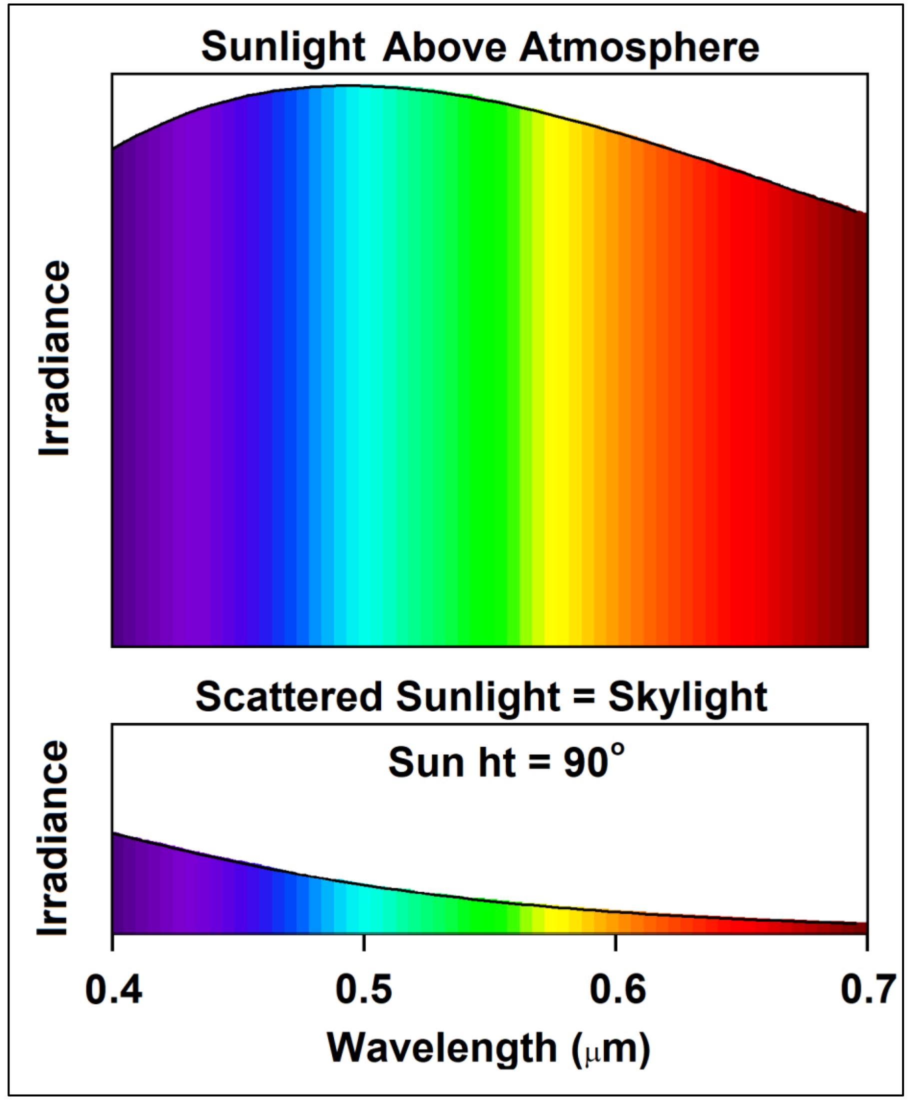

Fig. 2-6. Top: Black Body Irradiance at 5750 K approximates sunlight atop the atmosphere. Bottom: Skylight scattered from a sunbeam reaching sea level when the Sun is at the zenith. SDG.

Rayleigh scattering doesn't quit at night. It also works by the light of the silvery Moon, turning the night sky as blue as the daytime sky, though only ≈ 1/400,000th as bright, which is why we can't see it. But with a long enough exposure, photographs reveal its color (Fig. 2-7).

Fig. 2-7. The sky at night with a full Moon over Cheyenne, WY, 3:30 MDT 27 June 2021. Jan Curtis.

So, now when someone asks,

"Why is the sky blue?"

The simple answer is,

"Rayleigh scattering!"

But what if someone asks the next logical questions,

"Why do the Sun and Moon turn orange or red at the horizon (as in Fig. 2-8) and what causes all the sky colors around sunrise, sunset and twilight (as in Fig. 2-1 and Fig. 2-2)?"

Then the simple answer is,

"*More* Rayleigh scattering!"

Fig. 2-8. Moonrise sequence 13 Oct 2019 at 2½ minute intervals. The closer the Moon to the horizon the redder, and darker it appears. Jan Curtis.

That is because Rayleigh scattering both giveth and taketh.

Imagine a single photon of light trying to get through the atmosphere but forced to run a gauntlet of molecules armed with paddles. Each time a paddle hits the photon it scatters it in some other direction. In a tenuous atmosphere, like that of Mars, almost all the photons will get to the ground without being hit. A few might be hit once. In a thick atmosphere, like that of Venus, even if it were clear and not cloud-covered, most photons would be scattered several times before they finally strike the ground, or escape back to space.

Earth's atmosphere is thin, but thick enough so that a fair fraction of photons will be hit and scattered. This is where it gets interesting, because the red photons can more easily avoid the paddles, but they

Fig. 2-9. Earth's wafer thin atmosphere at sunrise, 25 Nov 2009. The sky fades to black above about 50 km. NASA.

too get scattered. And, if the photons take a longer path through the atmosphere, as at sunrise or sunset, the scattered photons (i. e., the skylight) more likely to make it to the ground from low viewing angles, may not be blue, but yellow, or orange, or red.

Thus, skylight in a thick atmosphere such as that of Venus is always the result of *multiple scattering*. In Earth's thin atmosphere, multiple scattering plays a varied role, which makes for the most wondrous sky colors though it always impairs rainbows, halos, and the like.

2.3 The Thin Atmosphere and its Layers

When the Sun is high in the sky, the sky is blue not only because of Rayleigh scattering but also because the atmosphere is both geometrically and optically thin. On Venus, a furnace with a surface temperature of 465°C and a surface pressure 90 times that at sea level on Earth, multiple Rayleigh scattering turns the sky yellow-orange.

Fig. 2-9 indicates how thin Earth's atmosphere is relative to its radius, thinner than the glaze on a donut. The height at which the sky grades to the blackness of space is only about 50 km (not including the aurora). That is less than 1% Earth's radius (6370 km).

How fast does the air thin? At 5.5 km air pressure is half that at sea level. That is less than 1/1000th Earth's radius. Air is too thin for any human to long live at 5.5 km, and as height increases pressure continues decreasing, halving every 5.5 km when temperature is 0°C ($\boldsymbol{T}$ = 273 K), and more rapidly when the air is colder and denser.

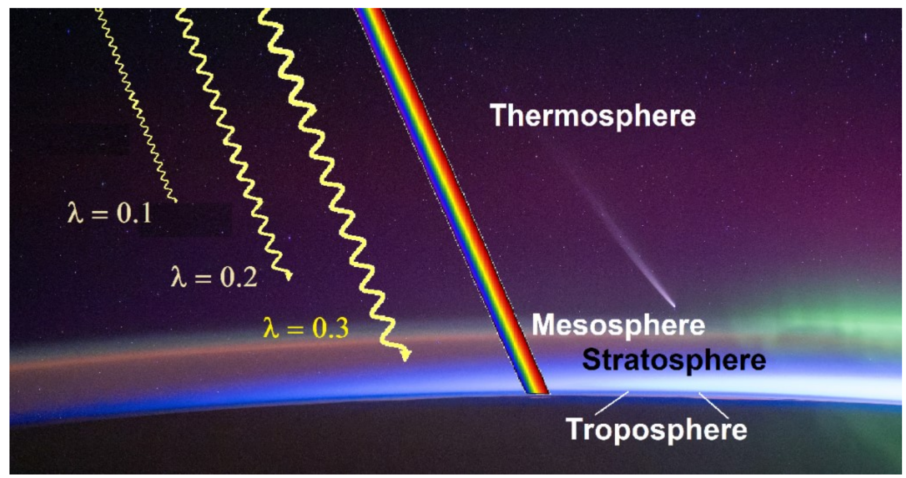

Fig. 2-10. Penetration of solar radiation and layers of the atmosphere with a comet and an aurora. Diagram, SDG. Photo, NASA/Matthew Dominick.

Fig. 2-10 illustrates the fate of solar radiation beaming down through the atmosphere. Starting around 700 km, the shortest wave lethal ultraviolet radiation (λ < 0.2 μm) strikes and is absorbed by the widely separated molecules, splitting them into atoms of O, N, and H, and ionizing some. This raises $\boldsymbol{T}$ to 1000°C at quiet times, and perhaps 2000°C when the Sun is active. Virtually all of this lethal radiation, which would easily destroy life's huge, far less stable DNA and RNA molecules, is absorbed and extinguished above 100 km.

Longer, but still lethal UV radiation ($\lambda < 0.32$ µm) penetrates deeper into the atmosphere, where it is absorbed by ozone (O_3 is produced when O atoms drift down and combine with O_2 molecules) mainly from 60 to 30 km. That raises temperature to a maximum of about 0°C at about 50 km. Much longer UV and visible light passes through the clear atmosphere (though some is scattered as skylight), producing sunburn and heating the ground.

Thus, there are three heights where the atmosphere is heated and tends to be warm – 1: above 100 km, 2: around 50 km and, 3: at the ground. Between these are two levels where it is cold because there is little heating – 1: around 85 km, and 2: between about 8 and 18 km. The result is four distinct layers in the atmosphere.

1. **The Troposphere** is the lowest layer of the atmosphere, the layer where all life, all weather and almost all clouds occur. The hot ground heats the air, which then rises, cooling as it rises, to make clouds and weather. The turbulent rising and cooling cease at the **tropopause**, about 8 km near the Poles and 18 km near the Equator, where temperatures typically range between -50°C and -80°C. The tropopause forms a cap that only thunderstorms briefly puncture.

2: **The Stratosphere** lies directly above the tropopause. Except in the dead of winter at high latitudes, temperature increases with height to about 0°C at 50 km. The stratosphere is a clear region of no storms or clouds, except in the dead of winter at high latitudes, where it gets so cold that thin, iridescent, nacreous Polar Stratospheric clouds sometimes form (see Chapter 14).

3. **The Mesosphere** lies directly above the stratosphere and extends to about 85 km. The top of the mesosphere is the coldest place in the atmosphere, occasionally getting so cold at higher latitudes (mainly in summer!) that extremely tenuous noctilucent clouds form.

4. **The Thermosphere** extends from 85 km up to about 700 km. This is where Auroras form (see Chapter 3) when protons and electrons expelled from the Sun collide with the atmosphere's gases. Ions formed by these collisions and by the Sun's UV radiation occupy the thermosphere and mesosphere in a layer called the **Ionosphere**.

2.4 Sky Color and Optical Thickness

When the Sun is high in the sky, air molecules scatter only a modest fraction of sunlight, so most reaches the ground directly when it is clear. In other words, the atmosphere is optically thin for visible light, i. e., it has a small *optical thickness*, $\boldsymbol{\tau}$, or *optical depth* (usually defined as the optical thickness for vertical light beams).

Optical thickness, $\boldsymbol{\tau}$, is the standard measure of the fraction of photons in a light beam that penetrate a medium without being disturbed. The greater the optical thickness of a medium, the smaller is the fraction of light that passes through it without being scattered or absorbed.

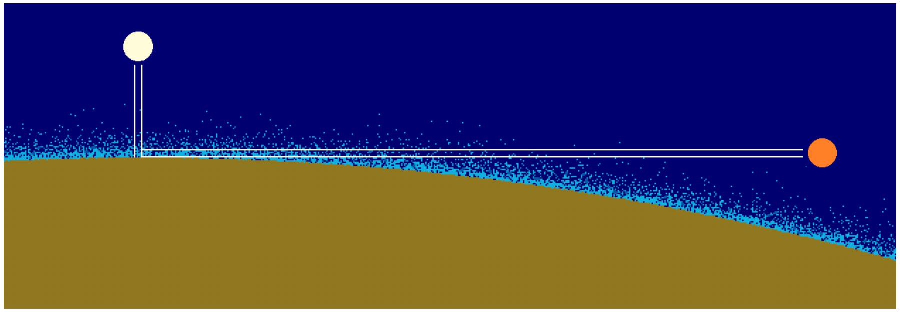

Fig. 2-11. Path length through the atmosphere for Sun at the zenith and at the horizon. The longer the atmospheric path the redder lights appear. SDG.

Optical thickness is expressed in exponential terms using the Euler number, $\boldsymbol{e} \approx 2.71828$. The fraction of photons in a light beam that pass undisturbed through a medium is $e^{-\tau}$ and the fraction scattered or absorbed is $(1 - e^{-\tau})$ When optical thickness is 1, $e^{-1} \approx 36.8\%$ of the light passes undisturbed and 63.2% has been scattered or absorbed. When optical thickness is 3, $e^{-3} \approx 5\%$ passes through and 95% has been scattered or absorbed.

Fig. 2-12. Windows of Manhattan's skyscrapers reflect the orange light of the setting Sun. SDG.

In the pure, molecular atmosphere the optical thickness for a vertical light beam reaching sea level is $\tau = 0.360$ for violet light of $\lambda = 0.4$ µm, meaning 30% is scattered and 70% penetrates. For red light of $\lambda = 0.7$ µm, $\tau = 0.0364$ so that only 3.6% is scattered and 96.4% penetrates. The mean optical depth of the pure molecular atmosphere averaged over the visible spectrum, is $\tau \approx 0.09$, so that only ≈ 9% is scattered or absorbed and ≈ 91% gets to sea level undisturbed. Of course, aerosols and clouds increase the atmosphere's optical thickness, sometimes by orders of magnitude.

Because the atmosphere is a geometrically thin veneer enveloping the Earth, the lower the Sun or Moon in the sky the longer the light path through the atmosphere (Fig. 2-11), the greater the optical thickness, the more light is scattered (perhaps multiple times) and the less penetrates. A light beam at the horizon must penetrate about 38 times as much air to reach sea level as a light beam at the zenith, so that the optical thickness is about 38 times greater. That means that $e^{-(0.0364\times38)} \approx 25\%$ of red light with $\lambda = 0.7$ µm remains in the direct sunbeam but only $e^{-(0.36\times38)} \approx 1.15\times10^{-6}$ or little more a millionth of the violet light of $\lambda = 0.4$ µm remains in the direct sunbeam.

Fig. 2-13. The Alpenglow on Mt. Denali. Jan Curtis.

Thus, the Sun and Moon (Fig. 2-8) turn red at the horizon because the optical thickness of the light path through the atmosphere is so large that most of the short waves – virtually all of the violet and most of the blue light – are scattered out of the beam before it reaches sea level. The Sun may still *appear* white at the horizon on clear days because it is still so blinding bright it oversaturates our eyes and most camera settings. One way to tell the true color of the horizon Sun is by its reflection on sunlit objects including clouds and windows of skyscrapers (Fig. 2-12), though they too can be blinding bright.

The reddened light of the rising or setting Sun also turns sunlit snow pink. This effect is nowhere more pronounced than when in the twilight moments just before sunrise or after sunset in the lowlands a high snow-covered mountain towers into the sunlight to take on the Alpenglow (Fig. 2-13). The alpenglow's rosy color is due to a mixture of reddened sunlight and blue skylight.

Fig. 2-14. Sunlit clouds appear white if near, pink if distant. SDG.

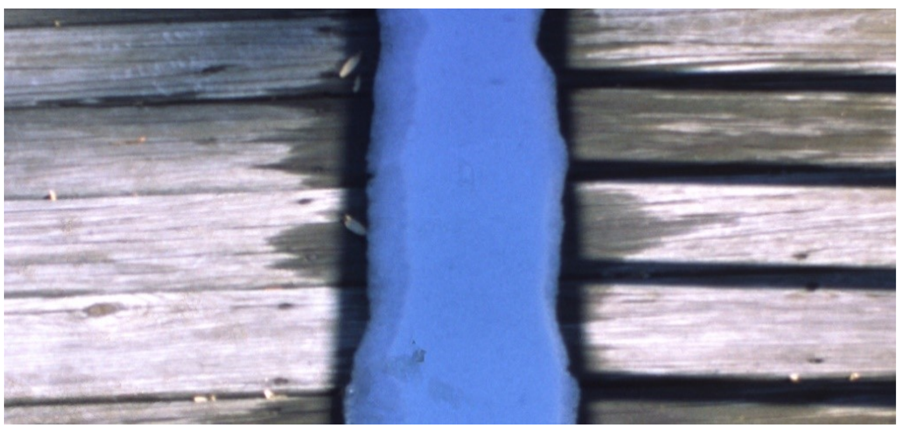

Fig. 2-15. A strip of blue snow in the shade of a deck's railing. SDG.

Bright, sunlit objects, such as clouds, which appear white when close, appear reddened when seen through a great optical thickness of atmosphere (Fig. 2-15) because Rayleigh scattering removed a substantial fraction of the shorter waves. That, of course, goes for skylight as well. Thus, we have the general rule

All bright lights including skylight, seen through a great thickness of atmosphere are reddened.

Shaded objects also change color in the atmosphere. On clear days, shaded white snow appears blue as in Fig. 2-15, because it is illuminated by blue skylight. In this scene snow had melted everywhere on the deck except in a strip where the shade of the railing remained almost still for several hours around noon. The Impressionists especially loved playing with the colors of sunlit and shaded snow.

2.5 Reddened Skies

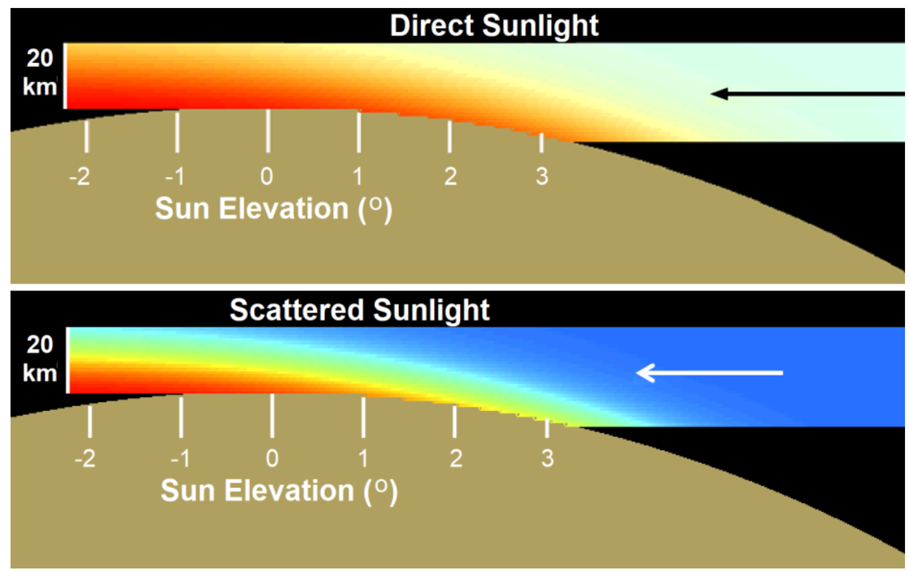

Fig. 2-16. The color of direct sunlight (top) and sunlight scattered (bottom) at any point in the atmosphere when the Sun is near the horizon. SDG.

Just as sunlight reddens as it passes through the atmosphere so does skylight, and the greater the optical thickness each must penetrate the redder each gets. If the optical thickness is great enough, eventually there will be almost no violet and blue light remaining in the sunbeam to be scattered, so even the scattered light will redden.

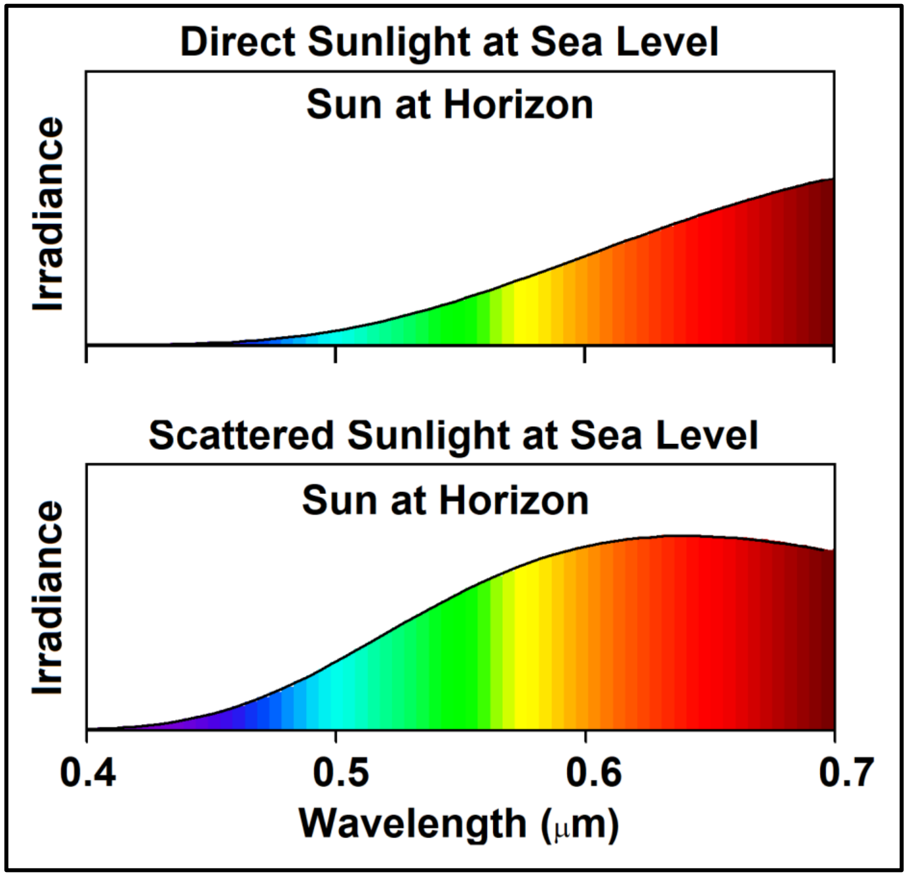

Fig. 2-17. Spectrum of direct and scattered sunlight at sea level in a pure molecular atmosphere when the Sun is at the horizon. SDG.

This is illustrated in Fig. 2-16 where near white sunlight (top panel) from the right reddens as it moves to the left through the atmosphere. The scattered sunlight (bottom panel) is initially deep blue, but it too reddens noticeably after it has penetrated a distance through the lower atmosphere, and eventually it too turns red, especially on the twilight side of the Earth if it has passed close enough to Earth's surface. Fig. 2-17 shows that the spectrum of *sunlight* reaching sea level when the Sun is at the horizon (top panel) has so little violet and blue after passing through the equivalent of 38 atmospheres that the scattered light (bottom panel) still consists mainly of longer waves and thus is orange.

Even at high noon on the clearest days skylight grades to almost white (i. e., reddens) at the horizon (Fig. 2-5). The beam of skylight at the horizon is a mixture of nearby blue scattered sunlight and optically distant scattered sunlight that was initially blue but was in turn depleted and reddened by a second Rayleigh scattering event on its way through the atmosphere to the observer. Skylight thus is an example of multiple Rayleigh scattering both giving and taking!

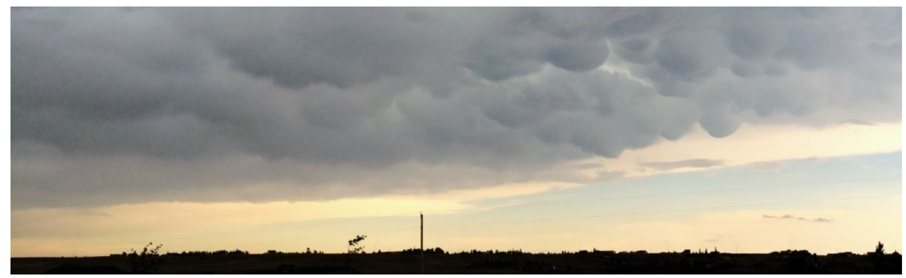

Fig. 2-18. As a dark cloud cover extends further toward the left on 29 Jul 2016 at Cheyenne, WY, the near horizon sky reddens to the left. Jan Curtis.

The horizon sky of a molecular atmosphere can turn orange during the day if a dark thunderstorm comes overhead, covering all but the distant horizon and blotting out all nearby blue skylight (see Fig. 7-4). In Fig. 2-17 the horizon sky reddens toward the left as the overcast extends further into the distance. Conversely, distant thunderstorms that only block distant (reddened) skylight turn the horizon sky bluer!

The reddening of the daytime horizon sky can be even more pronounced during a total solar eclipse. Fig. 2-19 was taken from an Alaska Air flight diverted into the umbra of the 09 March 2016 eclipse at an altitude of 12 km. For an observer in the center of the umbra the closest point of the atmosphere that receives direct sunlight is as much as 125 km away, and that sunlight comes from only the thinnest crescent of the Sun. That reddens the horizon sky further because light coming from crescent edge of the Sun is redder than light coming from the center of the Sun's disk (Fig. 1-2).

Fig. 2-19. Sky color near the horizon during the total solar eclipse, 09 March 2016 seen from 12 km. ©Rachael C. & Sofia S., flight attendants.

Of course, reddened horizon skies occur far more frequently – twice a day – at sunrise, sunset, and twilight. Around sunrise and sunset the optical thickness sunbeams must penetrate to reach the surface is large enough to turn the horizon sky of a molecular atmosphere yellow or orange, as in Fig. 2-20 and Fig. 2-21, *but not red*. Only deep in twilight is the optical thickness large enough in a molecular atmosphere to turn the horizon sky red. Fig. 2-22 illustrates the change of sky color near the horizon, over Brooklyn, NY from the deep red of twilight to the orange of dawn to daytime blue.

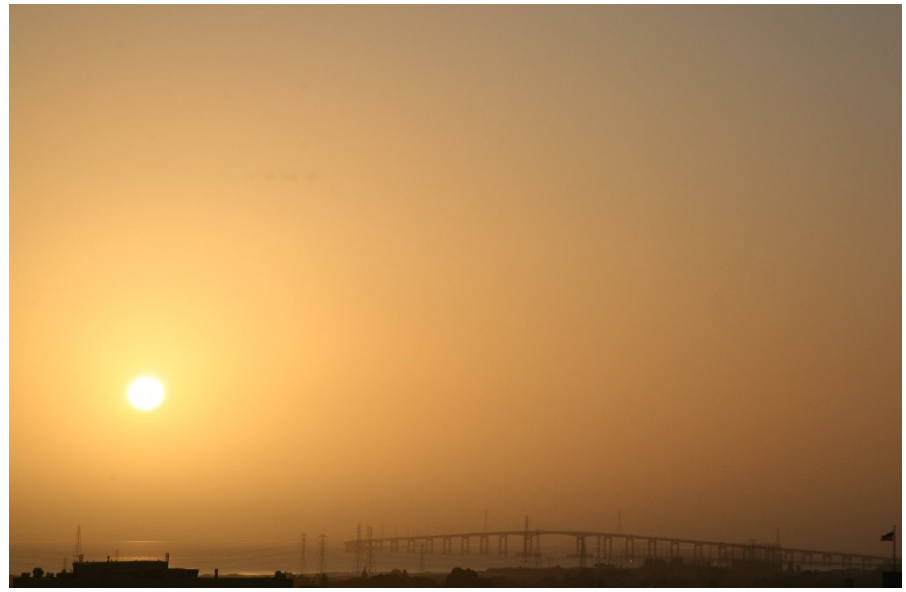

Fig. 2-20. An orange sky soon after sunrise over San Mateo 01 Jul 2016. SDG.

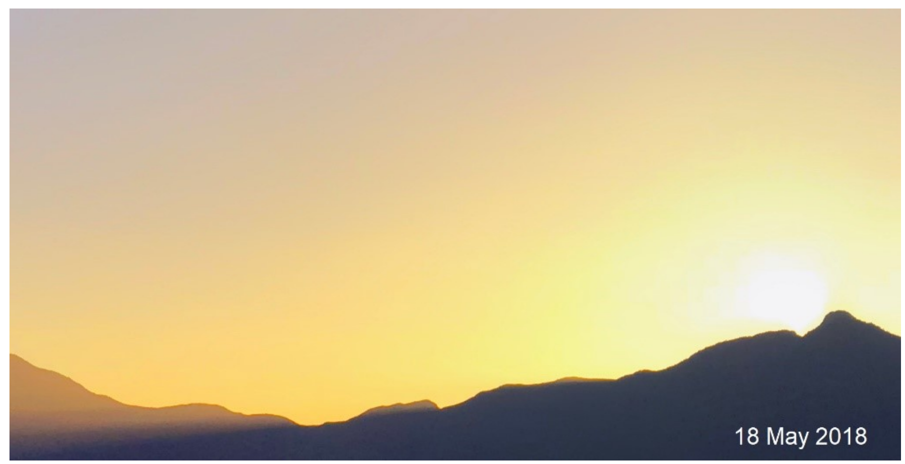

Fig. 2-21. Yellow sunrise sky over Rincon Mountain, AZ 18 May 2018. Jan Curtis.

In clear air, the reddened twilight colors are largely restricted to the sky just above the horizon and grade rapidly to blue as the optical thickness decreases toward the zenith, as in Fig. 2-1.

Fig. 2-22. Sky color from twilight red to orange dawn to blue day over NYC. SDG.

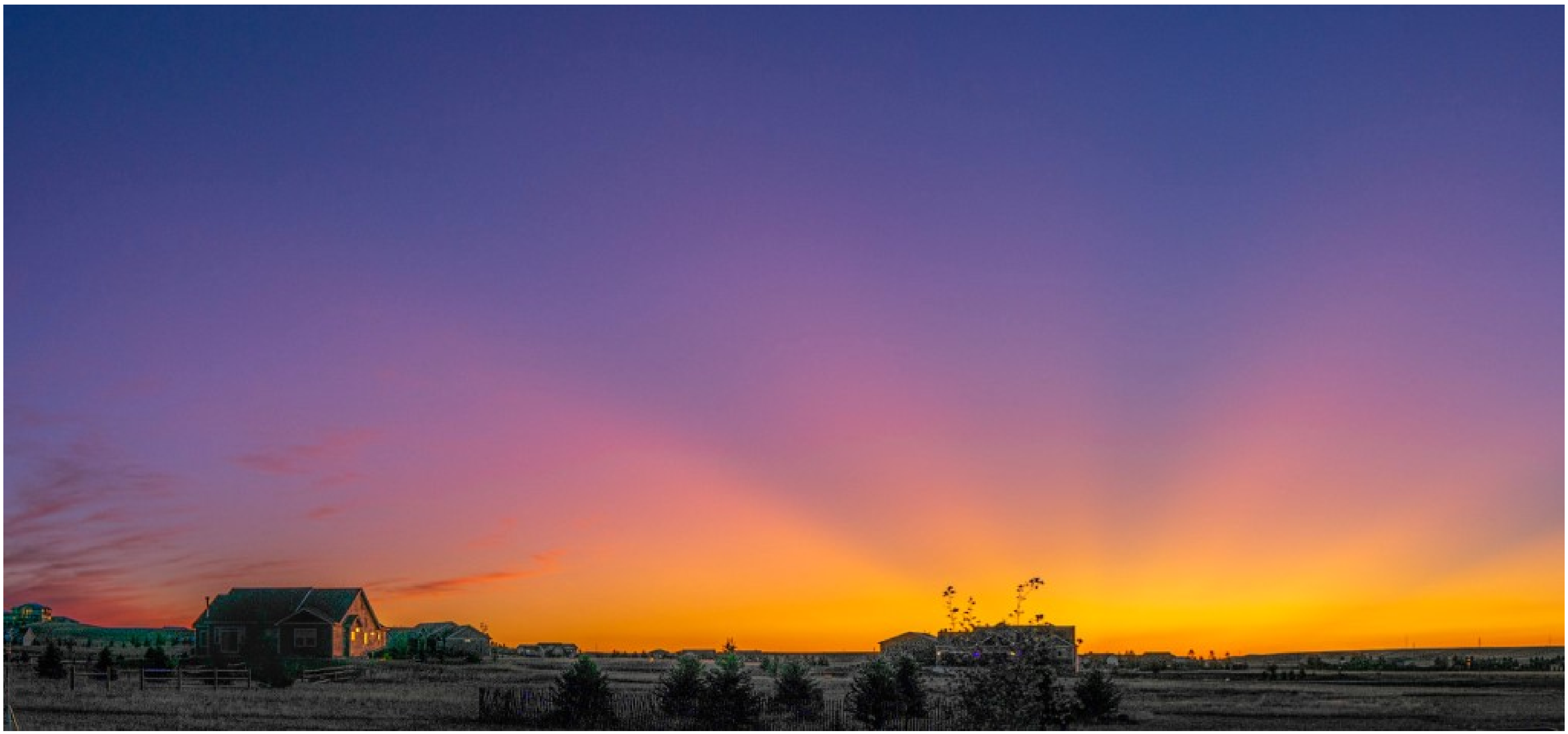

Fig. 2-23. A twilight sky with pink and purple tones and crepuscular rays 18 minutes before sunrise on 24 Sep 2019 following the eruption of Raikoke. Jan Curtis.

Clouds that do not cover the entire sky can embellish the near horizon twilight colors and spread them over the sky. Examples are spotted through the book but are the focus of §4.2 and §12.2. Aerosols can also enrich the colors of the twilight sky.

2.6 Aerosols, Skylight and Color: Mie Scattering

There are features of sky color, such as the pink and purple of volcanic twilights (Fig. 2-23) and blue-tinted Blue Ridge Mountains (Fig. 2-24) that involve more than a pure molecular atmosphere.

Leonardo da Vinci reasoned that the blue tint of distant dark mountains occurs because,

> "The medium lying between the eye and the object seen, tinges that object with its colour, as the blueness of the atmosphere makes the distant mountains appear blue…"

Intervening skylight gradually brightens dark, often shaded, landscape features and turns them bluer as the optical thickness to them increases, although with enough distance, they turn almost as white as the horizon sky and may ultimately disappear in haze.

The blue of the distant Blue Ridge Mountains is most pronounced on days when the sky is hazy and the humidity is high. The haze is due to aerosol particles, some of which grow from organic molecules called isoprenes exhaled by the thick forests that cover the Blue Ridge Mountains.

Aerosol particles can alter the lighting of the sky immensely. They vary widely in chemistry, size, shape, and concentration. Salt particles fizz up from the ocean when waves break or bubbles burst. Dust or soil particles are swept up from the ground by brisk winds. Plants spew pollen into the air (which can produce pollen coronas – Chapter 14). Smoke is lofted into the air by forest and brush fires. Major volcanic eruptions blast ash and noxious gases high into the stratosphere. The Earth and biosphere exchange innumerable gases with the atmosphere. Meteors provide a constant influx of materials from space that burn up upon entering the atmosphere. And now, human activity provides more than half the aerosols injected into the atmosphere.

Fig. 2-24. Blue Ridge Mountains facing SW at Wolf Mountain Overlook, height, 1650 m on the Blue Ridge Parkway, 11 June 2024 at the time of the light green spring flush. SDG.

Hydrometeors – cloud droplets, raindrops, ice crystals and other ice particles – also greatly affect the light and color of the sky.

Hydrometeors in fog and clouds can block the Sun completely if they are numerous enough or, when conditions are just right, may produce optical wonders including rainbows (Chapter 9), halos (Chapter 11), and coronas, iridescence, and glories (Chapter 14).

Aerosols and hydrometeors span a wide range of sizes. Particle size is important in atmospheric optics because it affects the efficiency of scattering and how long the particles remain in the atmosphere. For reference, recall that air molecules are ≈ 0.0003 µm in diameter, or less than 1/1000th the wavelength of violet light, which places them in the Rayleigh scattering regime. Most long-lived aerosols range in size between 0.1 and 2.0 µm in diameter, which places them in the Mie scattering regime. Smaller aerosols quickly coagulate while larger ones start to fall out of the atmosphere.

The fall speed of particles less than about 100 µm in diameter is proportional to the square of the diameter. An aerosol 1 µm in diameter requires 1 year to fall 1 km while an aerosol 100 µm in diameter takes only about 1 hour to fall 1 km. Because smoke particles from forest and brush fires tend to be about 0.3 µm in diameter they fall so slowly they can travel around the world many times if rain or snow does not wash them out of the air. Aerosols in dust storms and especially sandstorms fall out much faster because they tend to be 10 µm or larger. Pollen grains range from 5 to over 100 µm in diameter and rarely remain airborne for more than a few hours though ragweed pollen, the source of hay fever can remain airborne long enough to reach human nostrils because it is only about 30 µm in diameter.

Hydrometeors are larger on average than aerosols. Most cloud and fog droplets range from about 10-20 µm in diameter and fall between 0.3 and 1,2 cm/s, which is why clouds float by and do not fall out of the sky. Ice crystals are larger on average – 50 to 1000 µm long and fall up to about 1 m/s, producing long trails. Raindrops range from 200 to over 2000 µm in diameter, fall up to 10 m/s and leave visible rain swaths. Hailstones have reached 20 cm in diameter, and these lethal monsters whiz out of the sky at up to 50 m/s or 100 mph.

Size not only affects how long particles remain in the atmosphere, it determines how far they can get into our lungs when we inhale them, and how they interact with light. Particles less than 2.5 µm in diameter (PM 2.5) pose the greatest threat to health because their tiny terminal velocity means that they tend to be swept along with the airflow and hence penetrate deepest into the lungs.

The size of particles critically affects their *scattering efficiency*, the area of the light that is scattered divided by the cross-section area of the particle. Scattering efficiency increases rapidly with particle size up to about 1 µm. Tiny particles such as molecules are extremely inefficient scatterers of light. If you hold a dinner plate horizontally a few feet over the ground when the Sun is overhead, the shadow of the plate will have almost the exact same area as the plate itself. Thus, its scattering efficiency is 1. But if you could do this with an air molecule, its 'shadow' would have less than one trillionth the area of the molecule! In other words, the scattering efficiency of an air molecule is less than one trillionth! An analogy to the molecule's low scattering efficiency is that when you swim in the ocean beyond the surf, the waves pass by you on their way to the shore as if you scarcely existed because they are much longer than you.

Despite the miniscule scattering efficiency of molecules, the sky is bright because there are so many air molecules. At sea level, every cubic centimeter contains about 27 billion-billion (2.7×10^{19}) molecules. Even with this enormous number, Rayleigh scattering by molecules reduces the irradiance of sun beams by only about 10% after passing through 10 km of air at sea level.

If molecules scattered light with 100% efficiency (like the plate), about 90% of a sunbeam would be scattered before it passed through a single centimeter of air at sea level. Air molecules would have a high scattering efficiency if light behaved like tiny meteors instead of waves. Then, molecules would 'burn up' sunbeams much as they burn up meteors that streak through the atmosphere, which collide with every air molecule in their path. But unlike corpuscles or meteors, waves have the remarkable ability to skirt tiny particles.

The scattering efficiency of tiny particles increases with their size. Rayleigh scattering of a fixed wavelength increases as $\boldsymbol{r}^4$, while area increases with $\boldsymbol{r}^2$ so when radius doubles, scattering efficiency increases by a factor of $2^4 / 2^2 = 4$. As particles approach the size of the wavelength their efficiency increases more gradually, then oscillates, and their color behavior becomes more complex.

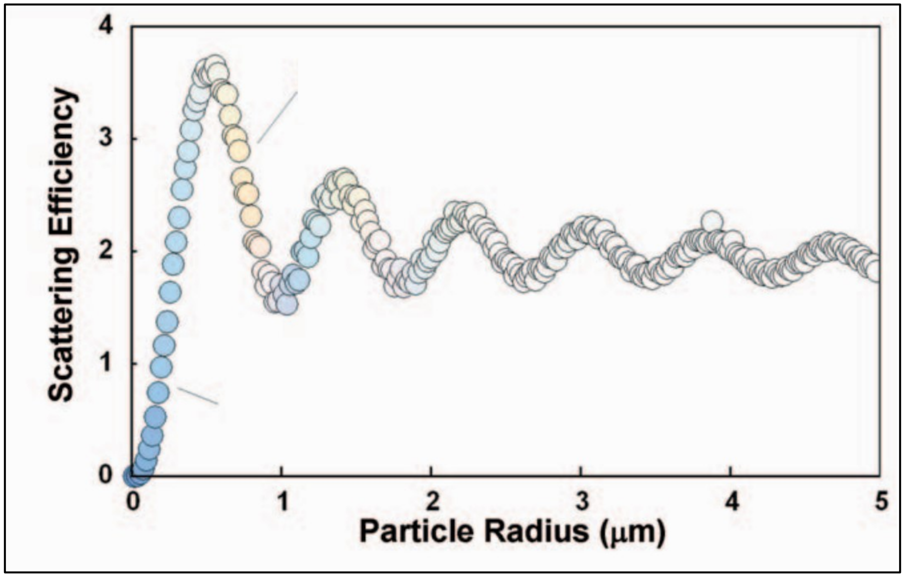

Fig. 2-25. Color of Mie scattered light and light scattering efficiency as a function of particle size. SDG.

One important consequence of the rapid increase of scattering efficiency with small particle size is that hazy air may not contain *more* aerosols it may just contain *larger* aerosols. When relative humidity rises above about 70% hygroscopic aerosols get wet, just as salt crystals do, and begin to swell (*deliquesce*), scattering light more efficiently. Thus, hazy days may just be more humid than clear days.

When particle diameter approaches about one tenth the wavelength of light Mie scattering takes over. Scattering efficiency reaches a peak when particle diameter is about three times the wavelength of light. As particle size continues to increase, scattering efficiency begins to oscillate, and eventually levels off for particles much larger than the wavelength of light (Fig. 2-25). Scattering efficiency greater than 1 occurs as waves bend into the particle's shadow.

H_2O molecules are the only molecules in Earth's atmosphere that cluster and condense to droplets or ice crystals to form fog and clouds. O_2 and N_2 have much lower boiling points and remain gases.

Fig. 2-26. A plane takes off into a crimson red predawn twilight over NYC in October, 1991 due to Pinatubo's stratospheric cloud of droplets ≈ 1.5 µm in diameter, which scatter long waves more efficiently than short waves. SDG.

So long as water remains a vapor (a gas) light waves from the Sun bypass H_2O molecules even more easily than other air molecules because H_2O molecules are smaller. And since water vapor is a minor constituent of the atmosphere, averaging only 0.33% of all air molecules, its total optical thickness is quite small. But if all that water vapor condensed into typical fog-size droplets with diameters about 15 μm, its optical thickness would increase to 300 and so little light would get through the fog or cloud to the ground that the sky would be almost pitch black!

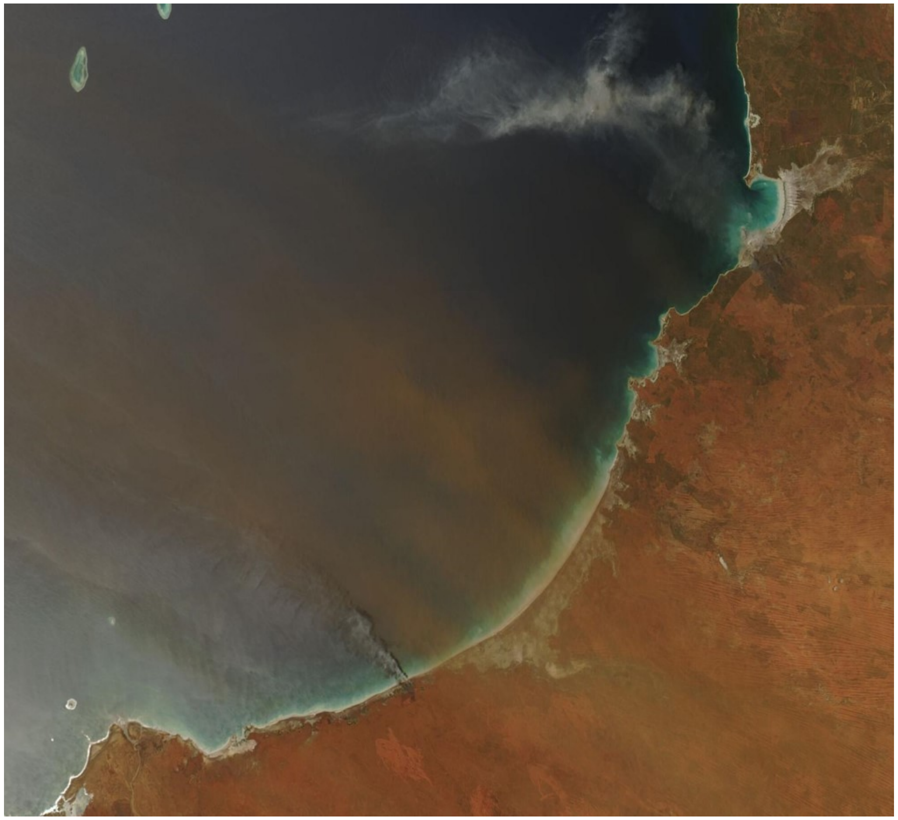

Fig. 2-27. Plume from the dust storm of 10 Dec 2023 over western Australia consisted of brick-red aerosols swept aloft from the brick-red surface. Two gray plumes from fires are also seen. NASA MODIS image.

When Mount Pinatubo had its great explosive eruption on 15 June 1991 it shot tons of sulfur dioxide and ash up to 35 km into the normally clear stratosphere. Large particles quickly fell out of the stratosphere, and were then washed out of the atmosphere by rain and snow, but tiny aerosols and the water vapor that combined with the sulfur dioxide to form tiny droplets of dilute sulfuric acid remained aloft for up to several years. The scattering caused by these particles reduced the sunlight reaching the ground by 10% and cooled the global climate by about 0.4°C for more than a year.

Pinatubo's cloud of droplets also produced wondrous red twilight skies (Fig 2-26) similar to those seen after other major eruptions such as Tambora in 1815 (which inspired the artist, J. M. W Turner), and Krakatau in 1883. Pinatubo's cloud reached New York City by October 1991, and one cloudless morning, almost an hour before sunrise over New York City, when the ground still lay in the shadow of night, sunlight illuminated the stratosphere and was scattered. Because the droplets were about 1.5 μm in diameter, they were just the right size to scatter red light more efficiently than blue, as Fig 2-25 shows, so the sky turned a brilliant crimson red.

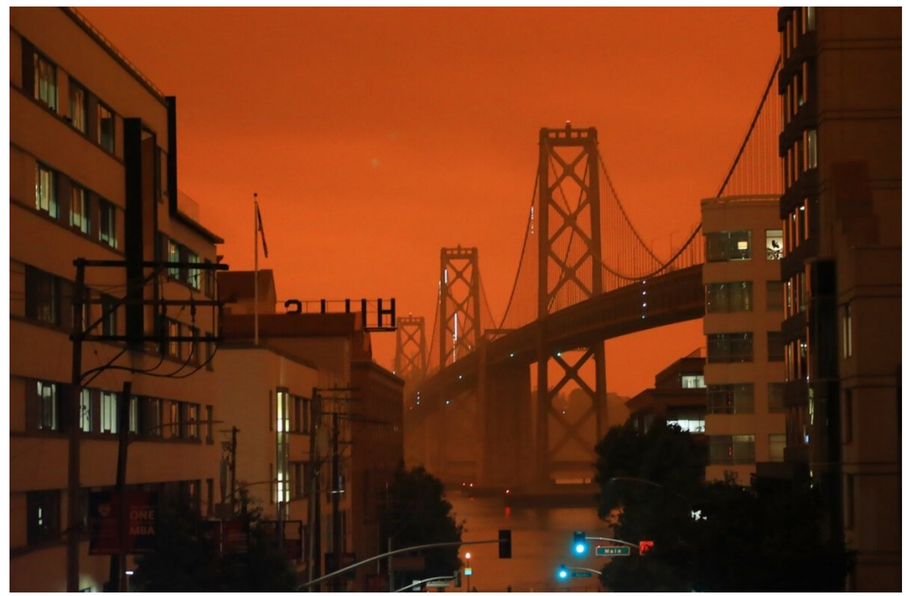

Fig. 2-28. Wind carried smoke from extensive forest fires in North California over San Francisco and turned the sky blazing red on 9 Sept 2020. NYT.

Closer to dawn, the Sun reaches the Jet stream level where blue scattered skylight adds to the red stratospheric light This somewhat unusual combination, which leads to the occasional volcanic purple twilight, peaks when the Sun is about 5° below the horizon, as in Fig 2-23. Volcanic purple is only seen near the Sun because aerosols scatter light mainly by small angles. Further from the Sun the twilight sky aloft is blue. Purple or pink twilight skies do occur routinely in the Belt of Venus (Fig. 2-2), a strip above Earth's shadow, where reddened sunlight mixes with blue scattered light.

Red volcanic twilights may in extreme cases last a couple of years. Less than a year after Pinatubo erupted only the tiniest aerosol particles and droplets remained in the stratosphere. Too small to produce red twilights, these aerosols scattered all colors of light with comparable efficiency. Thus they produced a near white haze that muted the blue of pristine skies for at least two years until they fell out of the stratosphere and were quickly washed out by rain.

Smoke from dust and sand storms and from forest fires also turn the sky red, but each for a different reason. The red of dust storms and sandstorms is largely due to sunlight reflected by large grains of sand and soil colored red by iron oxide abundant in the parent rocks of the desert. An exemplary case was the dust storm of 10 Dec 2023 in Western Australia, where the dust in the large brick-red plume was soil lifted from the deep, brick red ground. (Fig 2-27).

Fig. 2-29. A hazy day in Hong Kong seen from Sky Terrace 428. Water bloated aerosols bleach the sky and reduce visibility. SDG.

Fig. 2-27 also shows gray smoke plumes from fires north of Broome (near the top-right) and further southwest (just left of center near the bottom) extending from Eighty Mile Beach. From satellite most smoke plumes from fires look bluish gray where they are optically thin and have a reddish cast where they are optically thick.

Fig. 2-30. Aerosols make the sky whiter and brighter, especially near the Sun. The scene is in Madrid 12 Jan 2008, a day that was only slightly hazy. SDG.

On the ground, smoke from forest and brush fires always has a reddish cast. If the smoke is optically thick it can turn a cloudless sky deep red even at noon, as on 10 Dec 2020 in San Francisco (Fig. 2-28), or make it as dark as night. Aerosols from forest fires are generally less than 0.5 μm in diameter, so they scatter short waves with somewhat higher efficiency than long waves, but to the first or second power of wavelength as opposed to the 4^{th} power of Rayleigh scattering. Hence the washed out, gray-blue color. Look at a thin smoke, as Leonardo da Vinci did, and you will see that it is a blue-gray. But, just as in the case of pure, molecular air, if smoke is optically thick enough, almost all the blue light has been scattered and the light that is able to penetrate is primarily red.

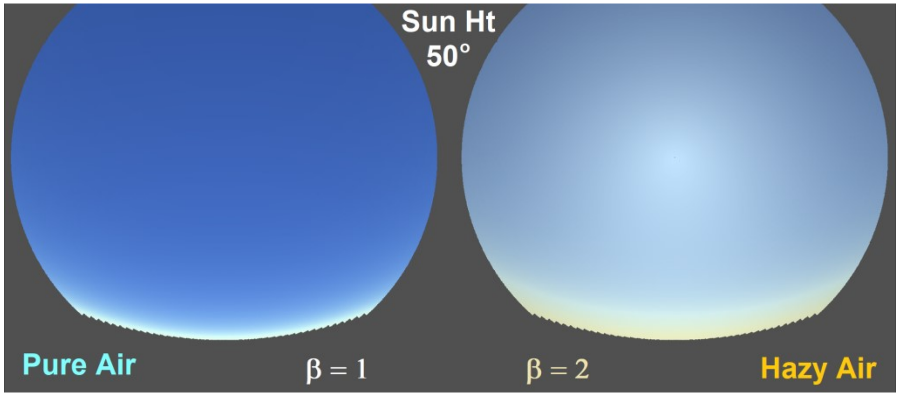

Fig. 2-31. Simulated deep blue sky light in pure air (left) gives no hint of sun's location, In hazy air (right) the sky is whiter and brighter, especially around the Sun, and redder near the horizon. SDG.

Aerosols seldom produce the dramatic skies of dust storms and forest fires, which result from such extremely large injections of aerosols that they increase the atmosphere's optical thickness by a factor of 10 to 100, or even more. The normal impact of aerosols is to reduce visibility, give everything a hazy appearance, and bleach the sky's pristine blue, and, so long as they do not increase optical thickness too much, brighten the sky (Fig. 2-29), especially right around the Sun (Fig 2-30). One aesthetically pleasing feature is that aerosols often enrich sunset colors. On very hazy days, the Sun will turn deep red and may even disappear when still above the horizon.

Fig. 2-31 show two simulations that compare sky light and color for a pure, molecular atmosphere (left panel) and for an atmosphere where aerosols double optical thickness (*turbidity*, β = 2) (right panel). With pure air, the sky is deep blue aloft and grades to a thin white strip near the horizon. Sky color and light give no hint of where the Sun is because Rayleigh scattering spreads almost evenly in all directions. When aerosols double the optical thickness the sky is notably brighter and whiter, especially around the Sun, and the sky just above the horizon has already turned orange even though the Sun in these simulations is 50° above the horizon.

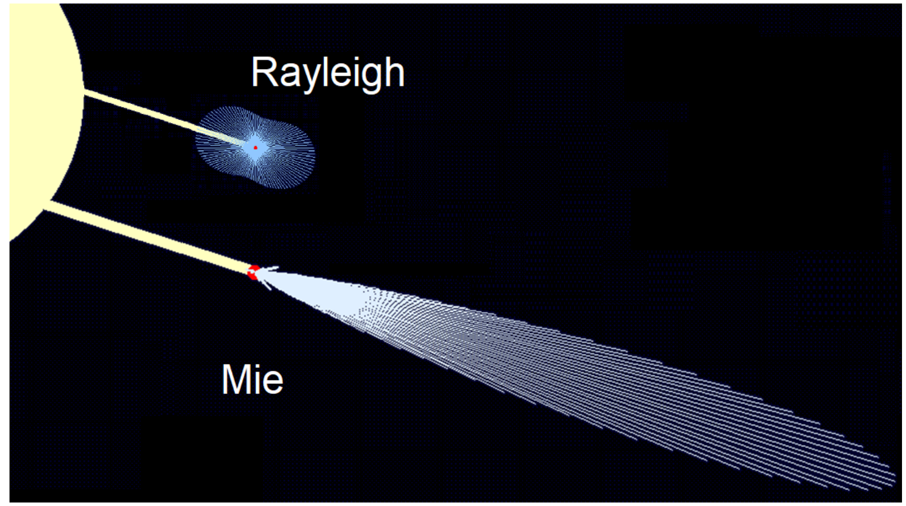

Fig. 2-32. Tiny particles scatter mainly blue light in all directions. Large particles scatter all colors more equally but mostly by small angles. SDG.

The differences in clear sky appearance are largely due to differences between Rayleigh scattering by the tiny molecules, and Mie scattering by the much larger aerosols. Mie scattering is much more efficient and much more uniform across the visible light spectrum than Rayleigh scattering, but deflects light by much smaller angles on average (Fig. 2-32). Hence it is Mie scattering that makes the sky near the Sun appear brighter and whiter. Similarly, the glare from a dirty window can be blinding when facing the Sun.

2.7 Polarization

In the molecular atmosphere, skylight is almost completely polarized 90° away from the Sun. Light waves are transverse by nature. That means the electric field always points at right angles to the direction of light beams. If the light beam is vertical, the electric field points horizontally. When a molecule scatters light from a vertical light beam to the East, the electric field of the scattered light will point NS and still be horizontal.

Thus, in general. scattering at right angles to the initial light reduces the electric field from two dimensions to one dimension. In other words, scattering at right angles to the Sun polarizes skylight.

Fig. 2-33. Near identical photographs of the sky, except a polarizing lens has been used to maximum effect on the left. SDG.

Because the molecular atmosphere is almost completely polarized about 90° from the Sun the sky on pristine days free of pollution is noticeably darker and deeper blue than near or opposite the Sun. If you aim a camera equipped with a polarizing lens at the polarized part of the sky, you can turn the lens until light with the one remaining direction is almost completely extinguished, so that the sky turns quite dark and deep blue. All other objects darken, but if they are not polarized they will darken by less than 50% and stand out against the darker sky As a result, clouds stand out in polarized photographs of the sky about 90°from the Sun (Fig 2-33).

As we will see, the primary rainbow is also highly polarized.

2.8 Mirages: Refraction Gone Awry

Mirages are visual distortions and displacements of objects caused by refraction of light in the atmosphere. In that sense these optical illusions are much like the distorted images seen in curved mirrors at amusement parks. But mirages are much subtler. Light waves traversing the atmosphere never bend by much more than 1° because even in the densest air the speed of light is only about 0.04% slower than in a vacuum. Bending by an angle of 1° may seem tiny, but since our eyes can distinguish angles as small as 0.01° we can easily detect mirages.

Fig. 2-34. An inferior mirage. What appears as a pond on the road is actually the shimmering air, and the upside down car is an image of the real car.

The most well-known and perhaps most common mirage is the desert mirage or *inferior mirage* (inferior because the image appears below the object), which also occurs over level, superheated roads. When you look down the road at a glancing angle (Fig. 2-34) the image you see seems like a pool of water in the road. The real 'object' you see is the sky. And since the superheated, light air is buoyant, it swirls up turbulently, imparting a shimmering appearance of wavy water. Any object, such as a car, that appears on the road above the 'water' will be accompanied by an upside-down image of the car just below.

Inferior mirages have one additional property. Since the waves curve upward, there is a distance beyond which objects on the ground disappear from sight. (That is also why distant thunder cannot be heard.) Cars crossing beyond this line will simply vanish. Such vanishing may explain why the Israelites in the desert thought Pharaoh's army was swallowed up by the Sea.

Fig. 2-35. A superior mirage over Finland's cold waters. Images of sand bars appear as forested hills in the air. ©Pekka Parviainen.

In the case of the inferior mirage, the air touching the road is so much hotter than the air only a few feet above that it is less dense. That represents the anomalous situation in which air density increases with height, which only occurs for a short height above superheated ground. Everywhere else in the atmosphere density decreases with height, so light waves curve downward.

Superior mirages occur when the ground or water is much colder than the air above so that air density decreases at an unusually rapid rate with height. For the *superior mirage* (Fig. 2-35) the image appears *above* the object and may be magnified to resemble castles or mountains in the sky. Superior mirages are most dramatic when there is an elevated inversion, a zone above the observer's eyes where temperature increases with height. An elevated inversion acts like a mirror on the ceiling to produce an upside down image of an object you can also see straight ahead (Fig. 2-36). Superior mirages have tricked Arctic explorers into reporting nonexistent islands such

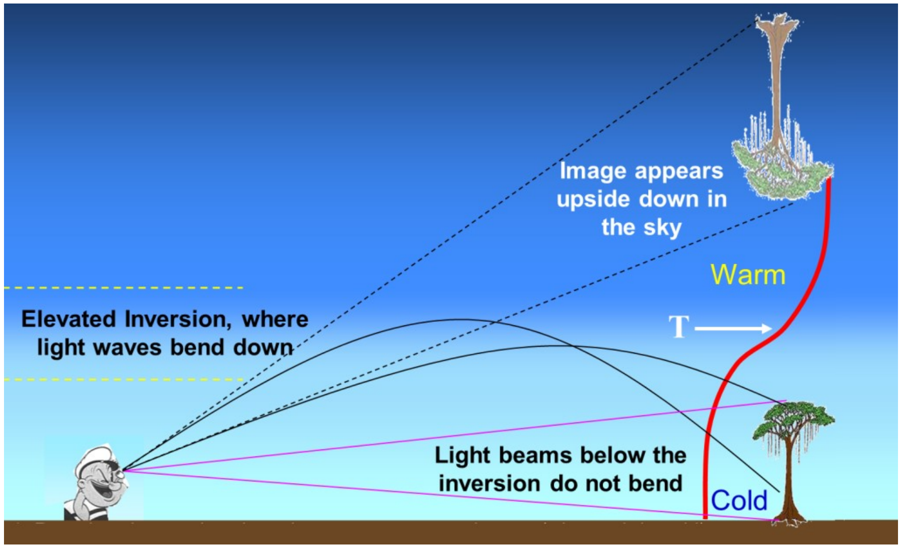

Fig. 2-36. Path of light beams and elevated, inverted superior mirage of a Palm tree with an elevated inversion. Curvature is exaggerated. SDG.

as Crocker land, named to extract funds from a wealthy banker.

One superior mirage occurs without fanfare twice or more each day. When the Sun and the Moon appear to rest atop the horizon, 1: their true (astronomical) positions are just *below* the horizon and, 2: they look flattened. Refraction of light beams passing almost horizontally through the atmosphere, curve much as in Fig. 2-36 and make the Sun and Moon appear higher in the sky than its astronomical position. The bending increases rapidly toward the horizon as the beams pass through a rapidly increasing optical thickness of atmosphere to reach ground level the lower the Sun or Moon in the sky The increase is so rapid that when the Sun or Moon rests on the horizon refraction lifts the bottom by 0.6° but only lifts the top by 0.48°. This makes the horizon Sun and Moon appear squashed by about 20% on average.

Fig. 2-37. Flattened moonset from the International Space Station, 16 Apr 2003. Don Pettit, NASA.

From space or from a jet plane, the bending of the Sun or Moon seen at the horizon is double that seen from sea level and the flattening is exaggerated to the absurd. This is shown in the photo montage of Fig. 2-37, taken by Don Pettit from the International Space Station. Note also that the setting Moon first turns bluer and then redder as it is progressively squashed approaching the invisible horizon.

The superior mirage of the Sun near the horizon makes the Sun rise earlier and set later than the astronomical times of sunrise and sunset. Since the Sun moves across the sky at the rate of 15° per hour (360° per day) or 0.5° per 2 minutes, daylight is increased by 4 minutes each day at the equator, where the Sun path is vertical and by more at higher latitudes, where the Sun rises and sets more obliquely.

2.9 The Green Flash and the Blue Flash

Elevated inversions at sunrise or sunset produce extra bending that can prolong day even more but also distort the image of the Sun in strange ways, so that it may break in pieces or resemble a Chinese lantern, as in Fig. 2-38. The extra bending can also make the atmosphere behave like a prism, separating the colors at sunrise and sunset. Since shorter waves are refracted more, they will appear elevated above the main body of the setting Sun.

Fig. 2-38. The green flash with the Chinese lantern effect of a refraction-squashed and distorted Sun. ©Pekka Parviainen.

Fig. 2-39. Blue Flash and Green Flash fragments atop the setting Sun 2000 m above sea level near Cheyenne, WY 30 Jan 2024. Jan Curtis.

This is the origin of the Green Flash, linked to the legend that those who have seen the Green Flash can never err in matters of love. (That does not hold for seeing a *photograph* of the Green Flash.).

Fig. 2-40. The Moon exiting Earth's shadow, 21 Jan 2019. At far right the Moon has emerged from Earth's shadow. Immediately to the left the Moon is tinted blue while further left and deeper into the shadow the Moon is red. Jan Curtis.

Shouldn't there be a Blue Flash above the Green Flash, and a Violet Flash above the Blue? Indeed, the Blue Flash exists, but virtually never at sea level, because virtually all the blue light has been scattered out of the direct sunbeam at the horizon before it reaches sea level (top panel of Fig. 2-17). The Blue Flash is reported on rare occasion on land at least about 2000 m above sea level, where the optical thickness of the setting (or rising) sunbeam is small enough for some blue light to be transmitted (Fig 2-39). We don't know of any report of a Violet Flash.

2.10 Light of the Eclipsed Moon and Ozone

The refraction of sunbeams at sunrise or sunset into Earth's shadow has another beautiful optical effect. During Lunar Eclipses the Moon lies in the Earth's geometric shadow and should be invisible except for any starlight it blocks. But during most Lunar Eclipses the Moon is quite visible, as in Fig 2-40 because it doesn't lie in the shadow of Earth's atmosphere (Fig. 2-41). The Moon is lit by sunlight that penetrates the atmosphere, skirting above the Earth's surface, and bends by up to about 1.2° into the Earth's shadow. That is almost twice the bending of sunlight at sunrise or sunset because the path through the atmosphere to reach the Moon is almost twice what an observer at sea level sees at sunrise or sunset. The optical thickness the sunlight must pass through is also doubled, with the result that the red of the Moon during a Lunar eclipse is much deeper than the red of the Moon at sunrise or sunset.

There are times the Moon does disappear during a Lunar Eclipse. Following the eruption of Pinatubo, the atmosphere's optical thickness increased so much that the eclipsed Moon was blotted out for up to two years. The Moon's color and brightness during a Lunar eclipse provides a measure of stratospheric pollution.

As the eclipsed Moon enters or exits Earth's shadow a fringe of blue light often appears on the part of the Moon at the shadow's edge. The blue color results from a competition in which absorption dominates scattering. As this light beam grazes by the Earth, its closest approach is 12 or more km above sea level, (Fig. 2-41). The result is less scattering in the thin air of the stratosphere and more absorption by Ozone (O_3), which is concentrated in the stratosphere.

Ozone is the only naturally occurring atmospheric gas that absorbs visible light appreciably, and it absorbs with a great preference for orange light. The amount of ozone in the atmosphere is tiny—about 1 part per 2 million—so that if it were all brought to sea level, it would form a layer only about 3 mm deep (300 Dobson units), on average and up to 6 mm over the Arctic. The 3 mm of ozone absorbs about 1.5% of the orange light but only 0.3% of the blue or violet light when the Sun is at the zenith, but more than 25% of the orange light when it is at the horizon, and more than 50% of the light that passes back out of the atmosphere on the way to the Moon.

The blue fringe is sensitive to the amount of ozone. If the sunbeam grazes the Arctic during a time of high ozone content, the blue is deep, but if it passed over the ozone hole of Antarctica the fringe would not turn blue.

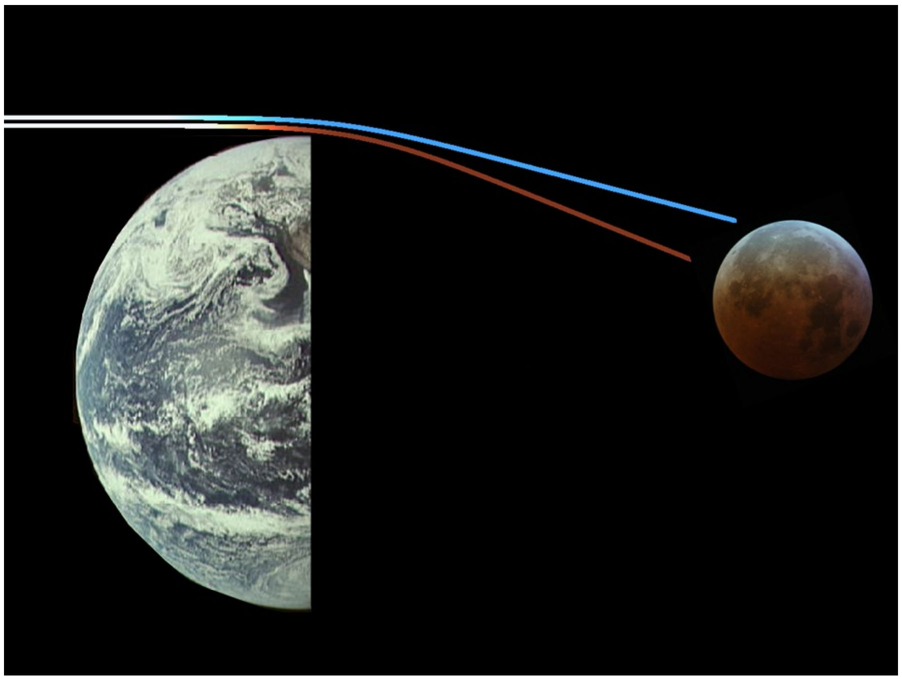

Fig. 2-41. Sunbeams changing color as they pass through the atmosphere and refract into the umbra. The higher beam turns blue as orange light is absorbed by ozone in the stratosphere. The lower beam refracts more and turns red as short waves are scattered more in the troposphere. SDG.

By absorbing orange light, ozone is also what keeps the sky around the zenith sky blue when the Sun is near the horizon. Computer models of sky color show that without ozone, the zenith sky at sunrise and sunset would be almost white! And it deepens the blue of the sky of deep twilight (see §12.2). Never did a blue sky owe so much to so little.

2.11 Sky Color Gallery

Fig. 2-42. A trick photo. A view down into deep blue Crater Lake, not the sky, which always grades whiter near the horizon. SDG.

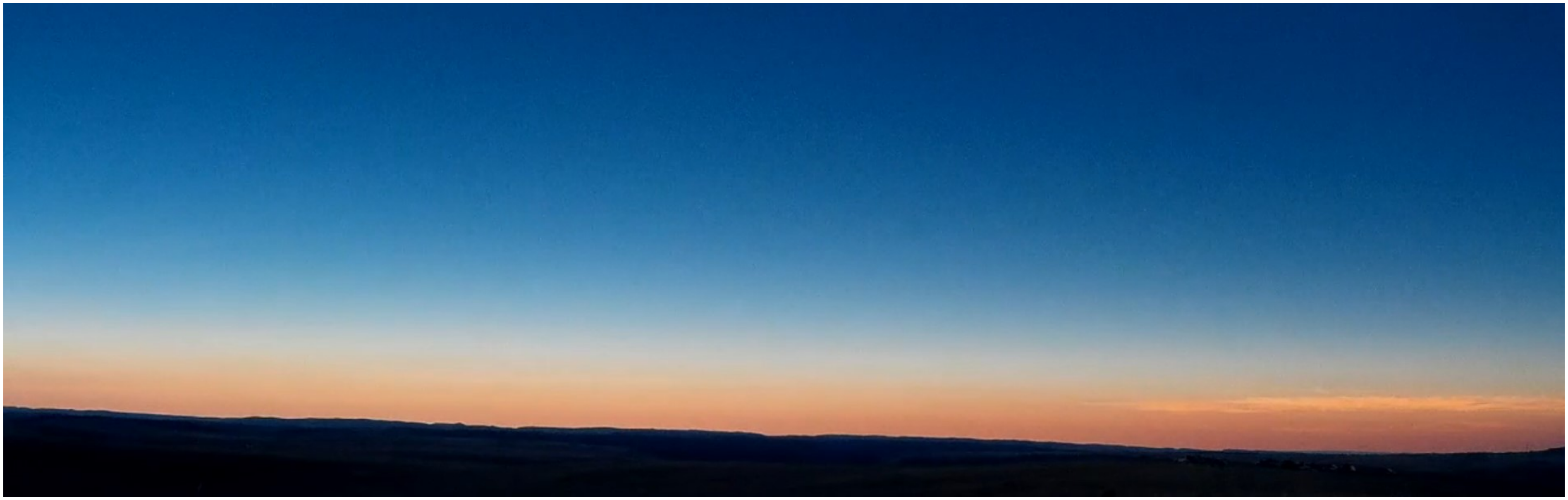

Fig. 2-43. Sky at the depth of the total solar eclipse 11:46:33, 21 Aug 2017, east of Glendo State Park, WY. Jan Curtis Video at https://vimeo.com/236354795

Fig. 2-44. A purple twilight sky over Cliffside Park, NJ (?). SDG

Fig. 2-45. World Trade Center Towers emerge from haze layer. ©Aaron Wasserman.

Fig. 2-46. Twilight sky after El Chichon, Siesta Key, FL. SDG.

Fig. 2-47. Blue Ridge haze. SDG.

Fig. 2-48. Noon sky downwind from Mullen Fire at Cheyenne, WY 26 Sep 2020. Jan Curtis.

Fig. 2-49. Being overtaken by Earth’s shadow of night 20 Mar 2015. SDG.