Fig. 1-1. The Sun seen through a smoke filled atmosphere from forest fires 20 minutes before sunset, 01 Aug 2021. Jan Curtis.

Wonders of the Atmosphere
Chapter 1: The Sun and Light

Started 02 June 2024

1.1 The Sun's Output

All the wonders of the atmosphere – its lights, colors, clouds, storms, rainbows, etc., etc., even the atmosphere itself, start, and will end, with the Sun (Fig. 1-1).

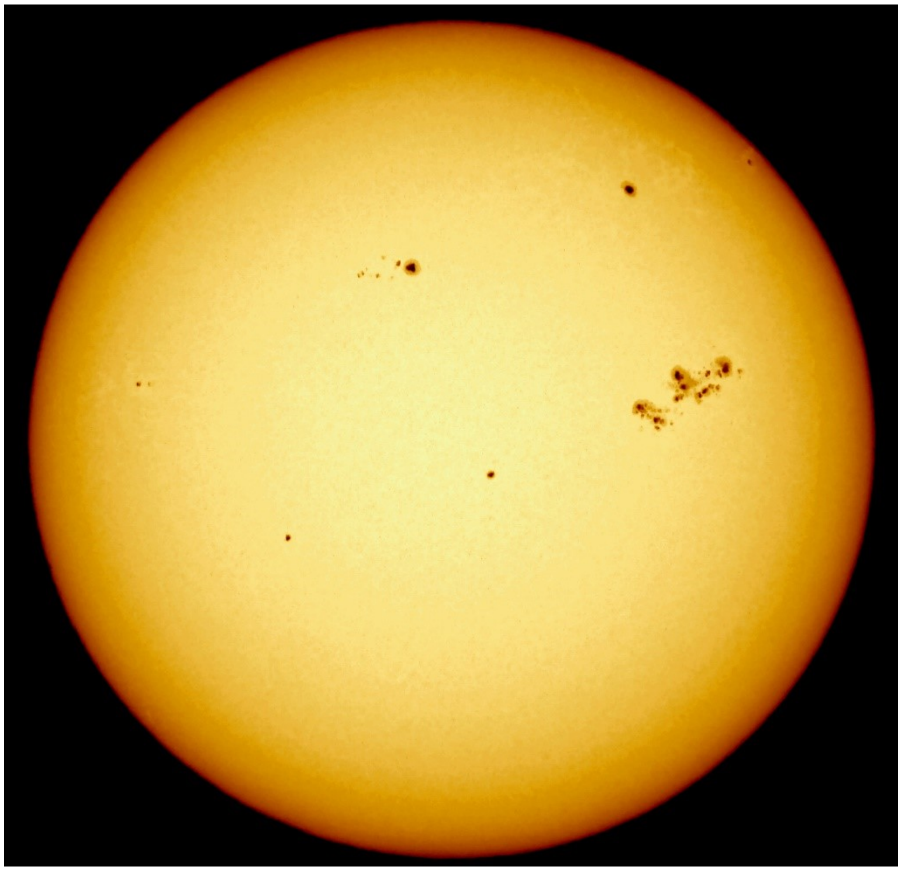

Fig. 1-2. The Sun showing sunspots and a red limb, 26 Mar 2024. Jan Curtis.

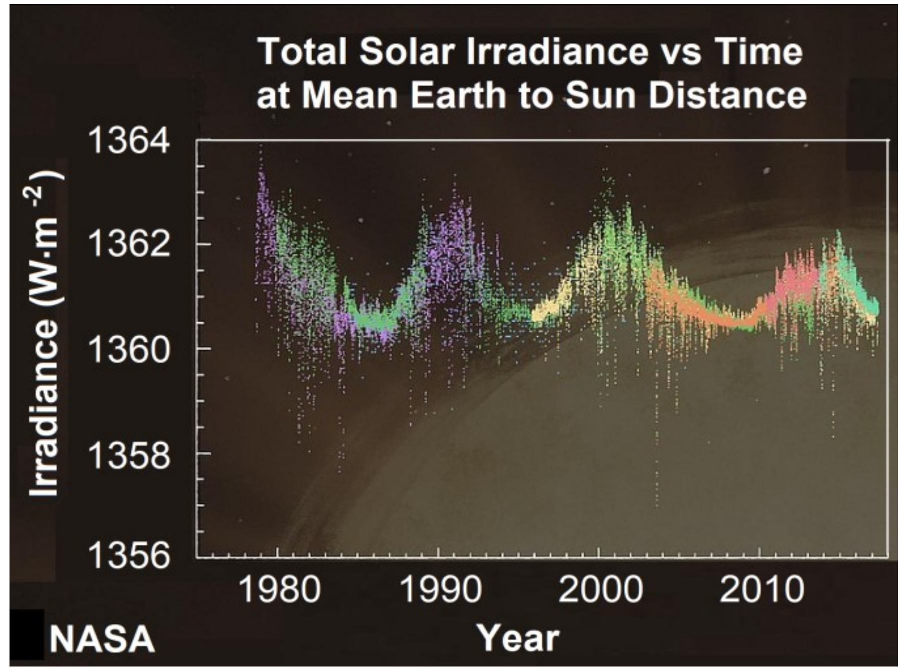

Fig. 1-3. Total Solar Irradiance vs time at mean Earth to Sun distance measured by seven NASA satellites.

Astronomers assure us that the Sun is a mediocre dwarf yellow star, blotched by sunspots ancient philosophers would have denied (Fig. 1-2). We owe our existence to the Sun's mediocrity and to its near constancy. A much hotter, blue Sun would have burned out long ago, far too soon to allow life to evolve. It would have made Earth so hot the oceans would have boiled away and its excessive UV radiation would have proven lethal to life. A much smaller, cooler red Sun would have left Earth a frozen planet and its inadequate UV radiation would not have had the energy to start and sustain life processes.

The Sun shines patiently with an average surface temperature of about 5750 K at an almost constant rate, as it has day after day (and night after night), and year after year, etc., etc., though it has slowly increased by 33% (and continues increasing) since settling down shortly after it and the rest of the Solar System formed some 4.6 billion years ago. That almost constant solar output is a requirement for us and for all life on Earth. Large variations in solar output would have alternately frozen and boiled away the atmosphere and oceans, and would have incinerated all life.

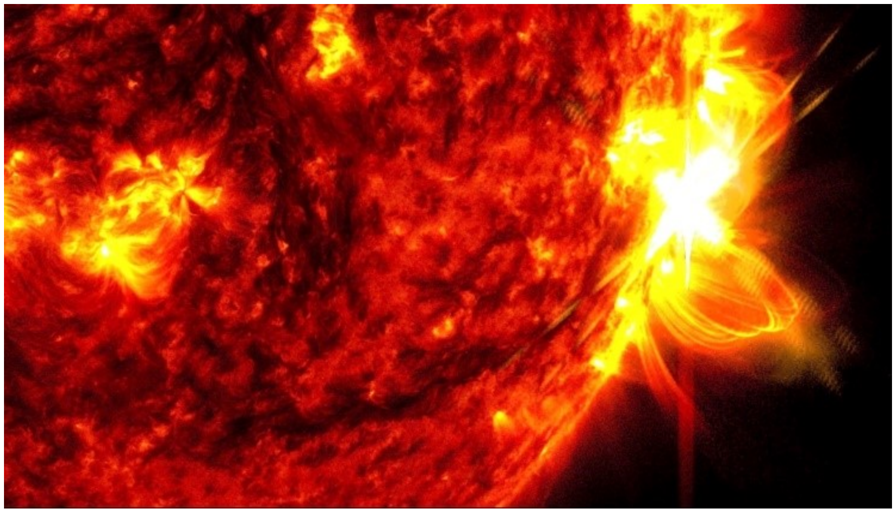

Fig. 1-4. Solar flare (white flash) of 14 May 2024 just above Coronal Loops, seen in extreme Ultraviolet. NASA/SDO (Solar Dynamics Observatory).

The Sun's output, or irradiance, averages 1361 Watts per square meter (W/m^2) just before entering the atmosphere when Earth is at its mean distance to the Sun (149.5 million km) (Fig. 1-3). That is more than enough to power an average American household (1215 W).

The Sun's main variation of irradiance, a mere 2 W/m^2 (0.15%) occurs over the roughly 11-year sunspot cycle. The Solar Wind, the relentless outflow of protons and electrons, is another story. This flow increases greatly when Solar Flares erupt from the Sun's Corona. When these Coronal Mass Ejections aim toward us, Earth's magnetic field redirects some to the night side sky. There, the protons and electrons, spiral down and smash into the atmosphere where they spark auroras (Chapter 3). But even the most powerful Solar Flares, which are so large they dwarf the Earth (Fig. 1-4), nudge solar irradiance by less than 0.2% and typically last less than an hour.

Auroras are an exception. All the atmosphere's other optical phenomena (except lightning) are produced when the Sun's light interacts with its molecules, aerosol particles, or hydrometeors (water or ice particles). Rainbows, halos, coronas, glories, and the light and colors of the sky and clouds result when the path of light is selectively absorbed (extinguished) or scattered (deflected). Scattering includes light not only spread like buckshot but highly directed by reflection, refraction, and diffraction. Let's consider these simpler processes, starting with reflection and refraction.

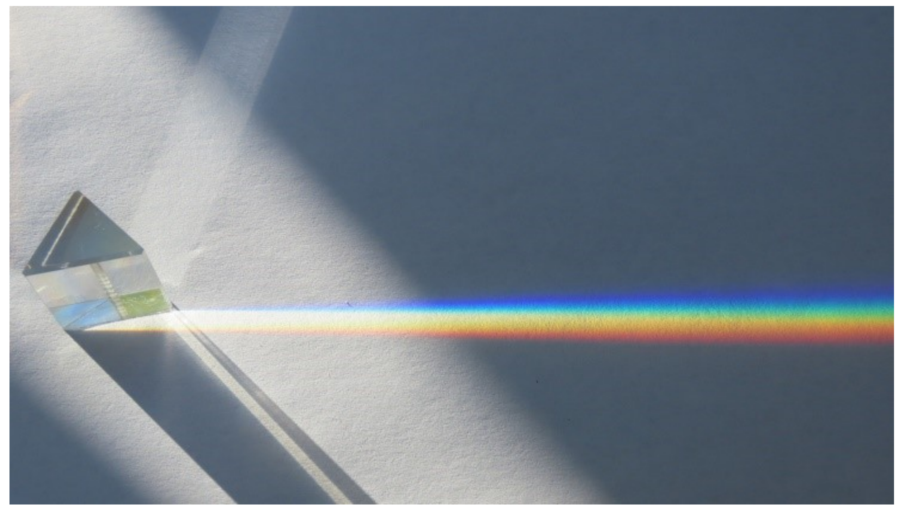

Fig. 1-5. A sunbeam striking a prism. Some light is reflected and some is refracted into a spectrum. SDG.

1.2 Reflection and Refraction

When sunlight strikes a glass prism, some reflects and some bends or refracts abruptly as it enters and exits. (The fractions of reflected vs. refracted light, so important for rainbows and halos, are given by

Fresnel's Law for water (see Fig. 9-16), and ice. Color hardly changes for light reflected from a prism but the refracted light splits into a beautiful rainbow-like spectrum of colors that range in order from the least to most refracted, red, orange, yellow, green, blue, and violet (Fig. 1-5).

Raindrops and ice crystals are the atmosphere's prisms. Rainbows (Chapter 9) are the spectra produced when a veil of raindrops refracts and reflects sunlight. Halos (Chapter 11) are the spectra produced when a veil of ice crystals refracts and/or reflects sunlight.

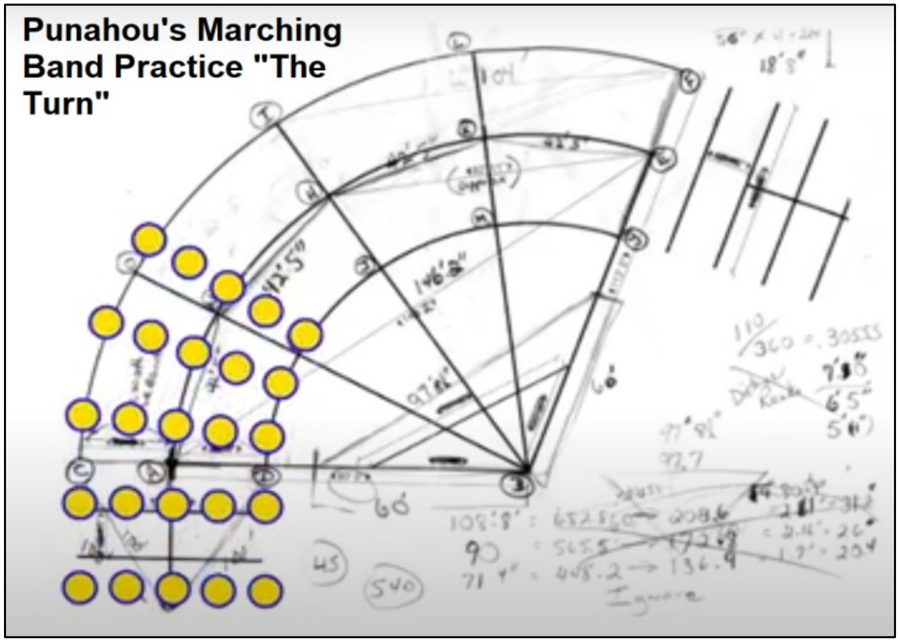

Fig. 1-6. Punahou's Marching Band practicing a turn illustrates refraction. Players on the outside of each line walk faster, making the line turn. https://www.youtube.com/watch?v=DGjfCVEg6qA

What causes refraction? In 1690, Christiaan Huygens showed that any wave refracts when one part of it moves more slowly than another. You can see this by videos of marching bands making a turn, or in Fig. 1-6, where each row of players or yellow circles represents a moving wave crest. The players on the outside of the turn must always move faster than those on the inside. Thus, ***Refracting waves always bend toward the region where they move more slowly***.

For example, water waves slow down as water gets shallower. When waves approach a shore obliquely, the parts of the waves nearest the shore in the shallowest water slow, so the waves refract more and more directly in towards shore. It was from observing ocean waves refracting as they approach the shore and comparing it to light refracting as it passed into and out of prisms that Huygens concluded that light consists of waves. Robert Hooke agreed, but Newton, his arch rival, didn't and this became the source of a great controversy. It would take more than a century to prove that light consists of waves.

In a vacuum, the speed of light is almost exactly 300 million meters per second (3×10^8 $m\cdot s^{-1}$), but it is slower in all substances, which is why light bends or refracts when it enters a substance obliquely. Even in air, the speed of light is slower than in a vacuum, but only by about 0.03% at sea level. Refraction of light that travels between air and water is therefore almost the same as between a vacuum and water. Even so, light sometimes refracts enough in the atmosphere to cause mirages (Chapter 2).

In water, the speed of light is about 2.25×10^8 $m\cdot s^{-1}$, or about ¾ of its value in a vacuum or in air. Therefore, when light passes obliquely from air to water it slows markedly and refracts by a noticeable angle. In ice, the speed of light is slightly faster than in water, or about 2.29×10^8 $m\cdot s^{-1}$, mostly because ice is less dense than water. In glass, the speed of light is only or about 2×10^8 $m\cdot s^{-1}$ or about ⅔ of its value in a vacuum. In diamond, the speed of light is about 1.24×10^8 $m\cdot s^{-1}$, or only about 41% of its value in a vacuum. That is just about the slowest that light travels in any natural substance,

Sometimes it is easier (math-wise) to turn things up-side down. This is the case with refraction. The *index of refraction*, ***n***, measures how much faster light moves in a vacuum than in a substance. For example, since light travels through water about ¾ the speed it does in a vacuum it travels about 4/3 as fast in a vacuum than in water, so the index of refraction of water, $\boldsymbol{n}(H_20) \approx 4/3 \approx 1.33$. *The larger the index of refraction of a substance the more light slows and therefore the more it bends on passing from a vacuum to the substance.*

The following inset contains just about the only equations in the book, the laws of reflection and refraction, illustrated in Fig. 1-7.

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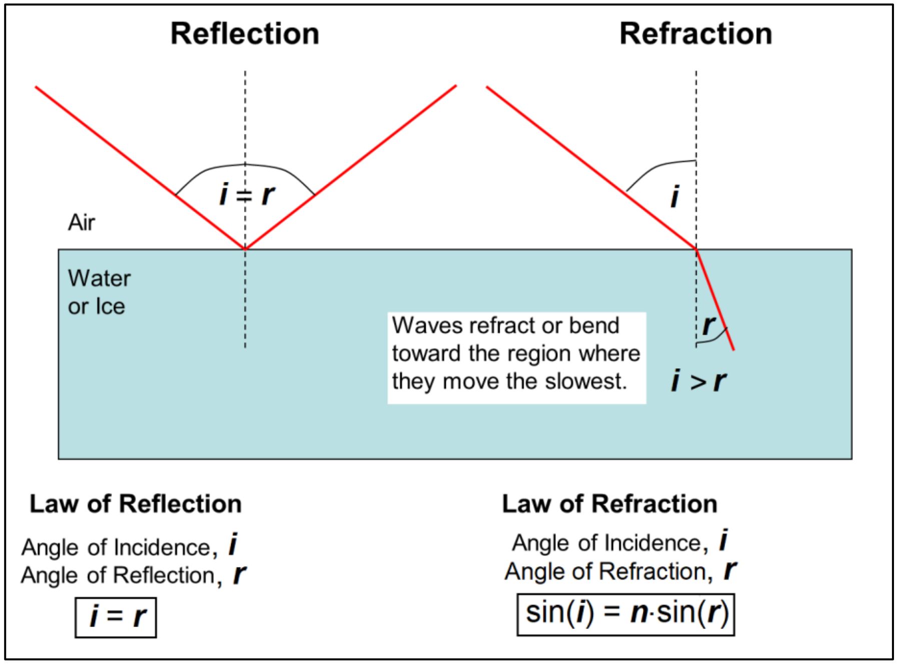

Fig. 1-7. Illustration of the Laws of Reflection and Refraction. SDG.

Law of Reflection, known even before Ancient times, is simply that the angle of reflection, ***r***, equals the angle of incidence, ***i***, or,

$$\boxed{i = r}$$

Snell's Law of Refraction, first discovered by Ibn Sahl in 984 CE, but rediscovered by Snell in 1621 is,

$$\boxed{\sin(i) = n \cdot \sin(r)}$$

Here, ***i*** is the angle of incidence in a vacuum, ***r*** is the angle of refraction in the substance, and ***n*** is the index of refraction of the substance.

Example 1: Light strikes water at ***i*** = 60°. Find ***r*** and the Deviation angle, ***D***.

For water, n ≈ 4/3 ≈ 1.333. To solve for angle ***r*** divide the Law of Refraction by ***n*** and then take the inverse sine.

$$\boxed{\sin(r) = \frac{\sin(i)}{n} \approx \frac{\sin(60°)}{4/3} \approx 0.65 \rightarrow r \approx 40.5°}$$

Light is deviated by the difference of the angles, ***D*** = ***i*** - ***r*** = 60° - 40.5° = 19.5°.

The deviation angle is important in locating optical phenomena such as rainbows, halos, and coronas (Chapters, 9, 11, and 13).

Example 2: If a light beam is aimed from water to air above the critical angle, $\boldsymbol{r}_{crit}$, it will be totally internally reflected and not be able to enter the air. Find the critical angle for water.

Approach: At the critical angle, the light in air just grazes parallel to the water surface so, ***i*** = 90º. Therefore, from the Law of Refraction

$$sin(r_{crit}) = \frac{3}{4} \times \sin(90°) \rightarrow r_{crit} \approx 48.6°$$

The critical angle limits the range of Sun elevation angles that can produce various ice crystal halos (see Chapter 11).

The speed of light also varies slightly with color in each substance, so that the angle of refraction varies with color. This variation, called *dispersion*, is the source of spectra. In most substances, including air, water, ice, glass, and diamond, the speed of light is slowest in violet light and fastest in red light. That is why violet light is refracted the most and red the least of the visible colors. In water, the speed of light decreases from a maximum of about 2.254×10^8 m·s^{-1} in red light to a minimum of 2.240×10^8 m·s^{-1} in violet light. In other words, the index of refraction of water increases from $\boldsymbol{n}_{\text{red}} = 1.331$ to $\boldsymbol{n}_{\text{violet}} = 1.339$. (The index of refraction for ice increases from $\boldsymbol{n}_{\text{red}} = 1.307$ to $\boldsymbol{n}_{\text{violet}} = 1.317$.)

When, for example, a narrow beam of sunlight strikes water at an angle of $\boldsymbol{i} = 60°$ from vertical, the red light bends by as little as 19.41° while the deepest violet bends by up to 19.70°, a difference of only 0.29°. Because refraction occurs when light both enters and exits a prism, the spectrum that results is about twice as wide, or about 0.58°. Incidentally, the beautifully colored glints that you see when you turn a faceted diamond ring in sunlight are tiny bits of spectra resulting from dispersion. No surprise that the facets of diamonds are cut at angles to maximize this glitter.

It was from the spectra produced by glass prisms that Isaac Newton first gave us some understanding of the nature of colors hidden in sunlight. Here is how he described his discovery.

> In the beginning of the Year 1666…I procured me a Triangular glass-Prisme, to try therewith the celebrated Phænomena of Colours…and made a small hole in my window-shuts, to let in a convenient quantity of the Suns light, I placed my Prisme at his entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby; but after a while…**I became surprised to see them in an oblong form**.[2]

The spectrum's elongated, oblong form was the key that led Newton to his discoveries about the nature of light and color. Using a second prism or a lens, Newton showed that the oblong spectrum of colors could be recombined into a circle of white light but the individual colors could never be further separated (though each color could be widened). So each color was connected to a particular range of refraction angles.

Newton, of course, realized that raindrops act like prisms and wrote, "Why the Colours of the Rainbow appear in falling drops of Rain, is also from hence evident." This was just one of the many properties of light that he described in the 1672 letter, along with the many experiments that he performed and urged others to perform to duplicate and hence validate his findings. Newton also realized that the *dispersion*, or different refraction of each color of light through glass, was the source of chromatic aberration, which limited the accuracy of refracting telescopes. To eliminate this problem, Newton invented a reflecting telescope using a mirror shaped like a parabola because all colors of light obey the law of reflection, namely, they are reflected at the same angle they struck the mirror ($\boldsymbol{i} = \boldsymbol{r}$).

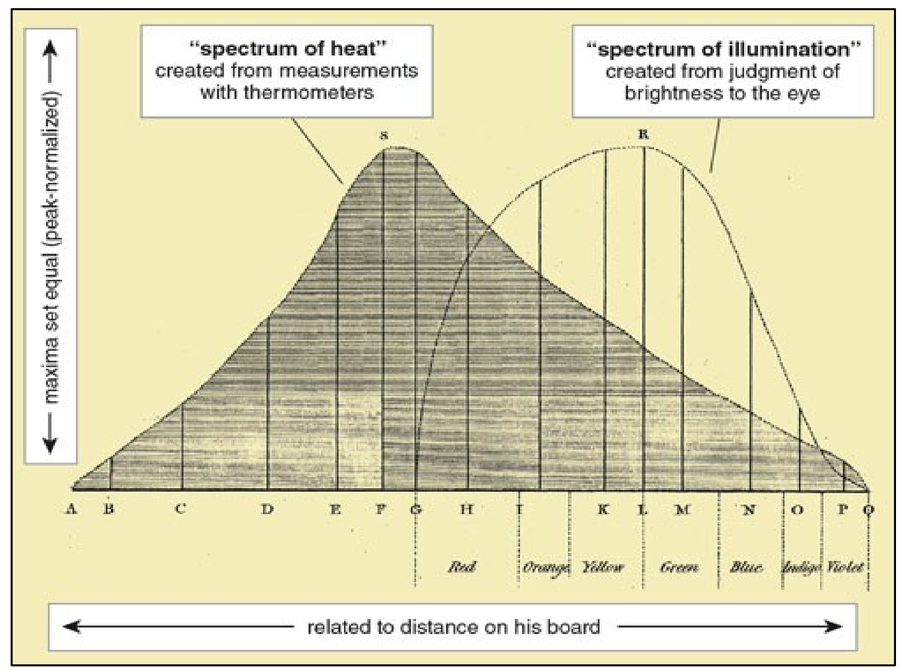

Fig. 1-8. Herschel's diagram illustrating the heating and the sensitivity of human vision as functions of the solar spectrum.

Incidentally, Newton's discovery of chromatic aberration led several people to design a compound lens made of two different kinds of glass to minimize chromatic aberration, naturally followed by a series of lawsuits over who was first.

Sir William Herschel made the next major advance on Newton's experiments with the refraction of sunlight. As an amateur astronomer (he was a professional musician and composer) whose many discoveries included double stars and the planet, Uranus, Herschel found the light blinding when he tried to examine sunspots. To mute the light he used filters of several different colors and noticed that while yellow *appeared* brighter red *felt* hotter.

That inspired Herschel in 1800, at the tender age of 61, to make the first attempt to measure the Sun's energy spectrum by measuring the temperature increase by placing one thermometer in the light of each color of the spectrum and noting how much warmer it was than a second thermometer in the dark part of the same room.

The warming increased through the visible spectrum from 1°C for violet light to almost 4°C for red light (Fig. 1-8). (Note: Because Herschel made his measurements when the Sun was only 29° above the horizon, the atmosphere had already scattered much of the violet and blue light out of the direct sunbeam and around the sky.) Current measurements of the irradiance of the solar spectrum both above the atmosphere and at sea level are shown in Fig. 1-9, and are compared to the theoretical curve (with spectral colors) derived by Max Planck in 1900 for a perfect radiator (black body) the same size as the Sun and at a temperature of 5750 K.

Because the warming increased continuously from violet to red, Herschel was inspired to move the thermometer to the dark region right next to the edge of the red light. Even though no light was visible, the warming peaked there at almost 8°F. He drew three original conclusions from these experiments, 1; The Sun emits what he jokingly called 'invisible light', and what we now call Infrared Radiation, 2: Light and Heat are both forms of radiant energy – just that our eyes are not designed to detect all forms of radiant energy and, 3: The human eye's sensitivity to color is greatest in the middle of the visible spectrum for yellow light and diminishes to zero at the violet and red ends of the spectrum.

Herschel also placed a thermometer just outside the violet region but didn't detect any warming. A year later, in February, 1801, Johann Ritter exposed sensitive photographic paper beyond the violet end of the spectrum, which then turned from silvery to black. He thereby discovered Ultraviolet Radiation. Thus, ***visible light is just one part of the much larger spectrum of electromagnetic radiation***, which includes from short to long waves, X-Rays, Ultraviolet Radiation, Visible Light, Infrared Radiation, Microwaves, and Radio Waves.

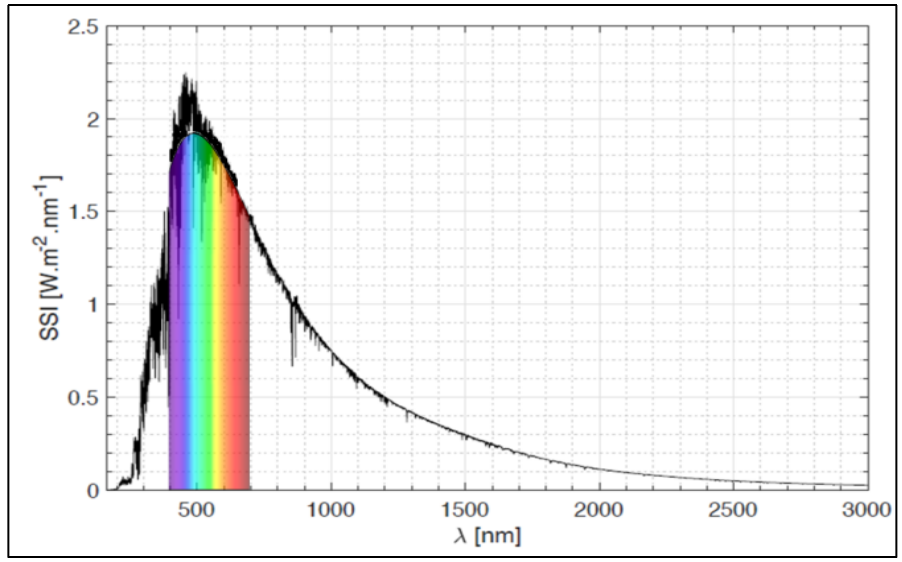

Fig. 1-9. Solar irradiance vs. wavelength above the atmosphere (black curve) vs. Black Body (Planck) irradiance for visible light (spectrum at 5750 K). European Space Agency.

1.3 Light Waves: Interference and Diffraction

When a rainbow appears in the sky a second bow often appears outside it. The outer or *secondary* bow is almost always fainter than

Fig. 1-10. Double rainbow with supernumerary bows (most pronounced on the left) inside the primary. Supernumerary bows result from interference of light waves striking raindrops and are more pronounced the smaller and more uniform in size the drops. 21 Sept 2023, Oracle, AZ. See Fig. 9-27. Jan Curtis.

the inner or *primary* bow, with colors in opposite order. In 1637, Descartes explained both the primary and secondary bows in terms of *geometric optics* – refraction, reflection and the circular cross section of raindrops. But inside some primary bows, as in Fig. 1-10, are extra, pastel color bands called *supernumerary rainbows* that could not be explained using geometric optics alone because they result from the interference of light waves emerging from small raindrops.

Coronas (Chapter 14), the rings of colored light that appear around the Sun or Moon in thin, often smooth-edged clouds, also can only be explained in terms of light waves. Indeed, it was the corona, or 'Crowns of Colours' that Newton acknowledged in the first page of his classic Treatise, ***Optics*** (1704) he was unable to explain.

> The Crowns of Colours, which sometimes appear about the Sun and Moon, I have endeavoured to give an Account of; but for want of sufficient Observations leave that Matter to be farther examined.

That's not all. In the next sentence Newton mentioned another phenomenon he could not explain.

> The Subject of the Third Book I have also left imperfect, not having tried all the Experiments which I intended when I was about these Matters, nor repeated some of those which I did try, until I had satisfied my self about all their Circumstances. To communicate what I have tried, and leave the rest to others for farther Enquiry is all my Design in publishing these Papers.

That subject, described by Francesco Grimaldi and published in 1665, two years after he died, was the widening of the shadow and the color bands that appear through a pinhole of sunlight.

> Grimaldo has inform'd us, that if a beam of the Sun's Light be let into a dark Room through a very small hole, the Shadows of things in this Light will be larger than they ought to be if the Rays went on by the Bodies in straight Lines, and that these Shadows have three parallel Fringes, Bands or Ranks of colour'd Light adjacent to them.

Both of these phenomena result from the wave nature of light, a conclusion that Newton did not accept. There are two main reasons it took scientists so long to prove that light consists of waves. First, whereas we can see water waves and watch their behavior, we cannot see light waves, we can only see light and color. Second, light waves are very short (too short to see anyway) and this made it difficult to devise experiments about light waves.

Since we can see water waves and observe their behavior, we use them to illustrate two wave phenomena – Interference and Diffraction. Interference is the adding or subtracting of waves from two or more sources. Diffraction is the curving of waves around a barrier.[4] Fig. 1-11 shows waves curving or diffracting into the lee of a floating dock for kayaks.

When bullets (particles) pass through a narrow opening they continue to travel in straight lines. That is not possible for waves. If waves did not spread when they passed through narrow openings impossible discontinuities of height for water waves, (Fig. 1-12), pressure for sound waves and electromagnetic field for light waves would result.

Fig. 1-11. Waves diffracting around a dock. SDG.

Interference is also easy to illustrate with water waves. In the top photo of Fig. 1-13 a single, continuous train waves was made in a calm lake by dipping one cup into and out of the water at the edge of a dock with a frequency of about twice a second. With only one wave train there was no interference.

In the bottom photo of Fig. 1-13 two intersecting wave trains were produced by dipping two cups about 3 feet apart with the same frequency. The two interfering wave trains produce a pattern of alternating wavy bands where the crests and troughs from each train coincide to reinforce each other (constructive interference) and flat bands where the crests of one train coincide with the troughs of the other to cancel each other (destructive interference).

Newton was well aware of these patterns in water waves but did not think they applied to light. In his 1672 letter, he stressed that although he had indeed found many *properties* of light, and though he thought that it consisted of some type of corpuscles and recognized it had undulatory properties, he acknowledged that he remained in the dark regarding the *nature* of light, and the wondrous process by which our eyes and brains transform light into the beauty of the colors.

But, to determine more absolutely, what Light is, after what manner refracted, and by what modes or actions it produceth in our minds the Phantasms of Colours, is not so easie. *And I shall not mingle conjectures with certainties.*

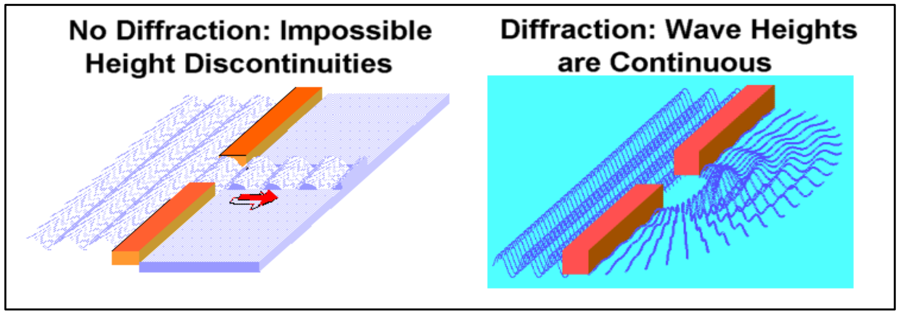

Fig. 1-12. Water waves passing through an opening. Waves that don't spread cause impossible height discontinuities (left). Therefore waves must spread or diffract (right). SDG.

But, in fact, Newton did conjecture that light consists of some form of corpuscles and for more than a century most scientists elevated Newton's conjecture to an almost inviolable doctrine.

Thomas Young therefore exhibited courage as well as insight when he went beyond conjecture to override doctrine.

Trained as a physician, Young was fascinated by how we perceive both light and sound, and was well aware of diffraction and interference of water waves, beats caused by two different frequencies of sound waves, and he was also aware of the problems attempting to explain supernumerary rainbows. Guessing that light consists of waves, he devised an experiment to prove it. In May, 1801 he demonstrated that each color of the spectrum consists of waves with a unique wavelength. The final form was the double slit experiment (Fig. 1-14) consisting of 1: a narrow beam of sunlight allowed into a dark room that, 2: passed through a prism then, 3: through a narrow slit allowing only one color from the spectrum through to, 4: two close parallel slits and through the slits, 5: onto a screen.

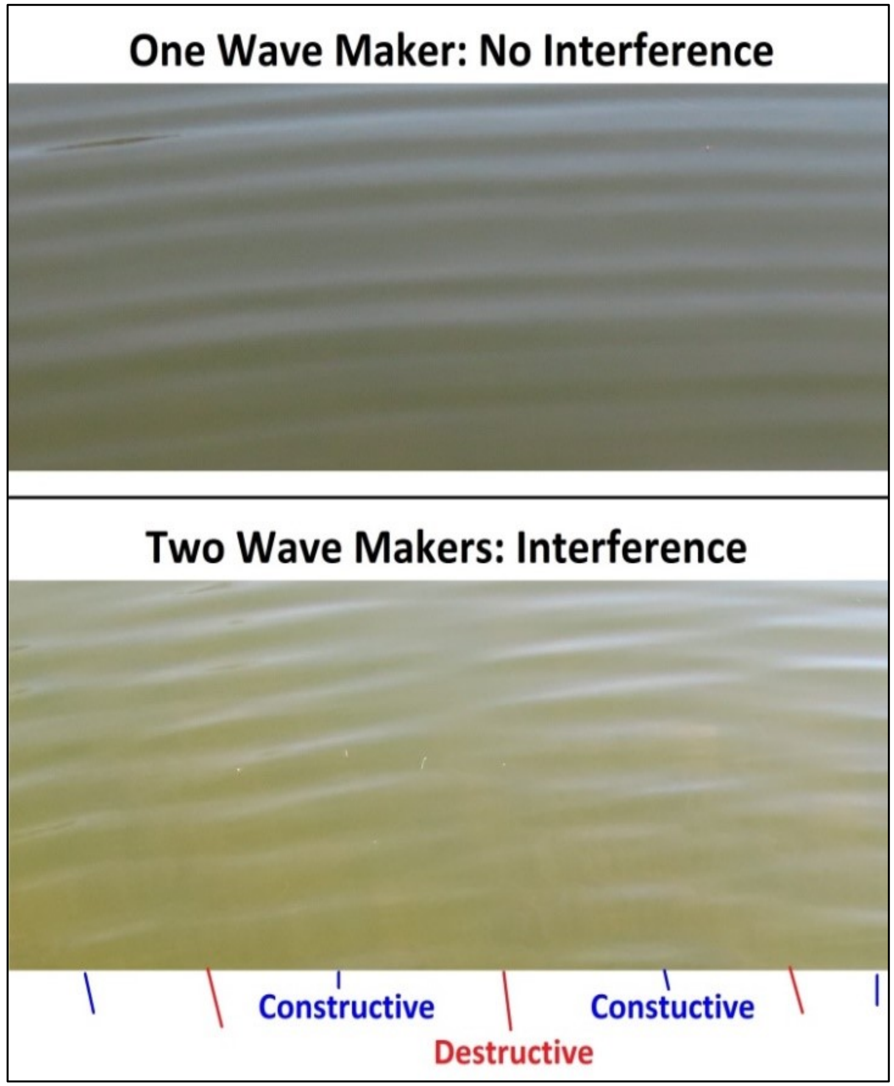

Fig. 1-13. Wave trains produced by repeatedly dipping one cup (top) and two cups (bottom) in a calm lake. In the bottom photo calm and wavy bands alternate as the result of interference. SDG.

If light consisted only of beams of particles the screen would have shown two narrow bright beams. But instead, it showed a wide, spreading pattern of alternating light and dark bands that could only have been caused by the diffraction (spreading) and interference of a wave train from each of the slits as they crossed paths, either adding or cancelling each other.

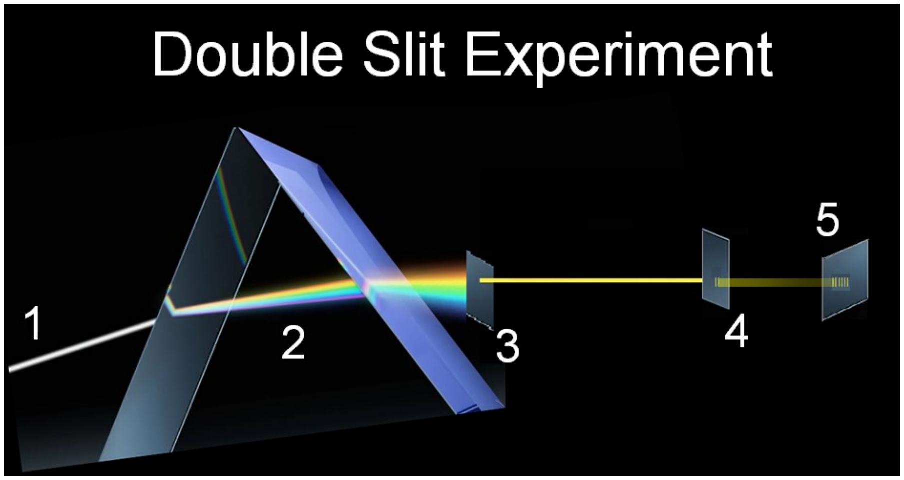

Fig. 1-14. Young's double slit experiment. When a narrow beam of one color of sunlight passes through two close parallel slits it produces a banded pattern of light, proving light consists of waves. SDG.

Because the diffraction pattern (the spacing of the bands) is a unique mathematical function of 1: the distance between the slits, 2: the distance from the slits to the screen, 3: the spacing of the bands, and, 4: the wavelength of the light (the only unknown in the equation), Young was able to calculate the wavelength of each color of light in the spectrum from violet, the shortest wavelength of any visible radiation (as short as 0.4 micrometers) to red, the longest (as long as 0.7 micrometers). Since a *micro*meter is one millionth of a meter that means that there are 2.5 million waves of short violet packed in every meter of a light beam.

Since the speed of light in a vacuum is almost exactly 300 million meters per second ($\approx 2.998\times10^{8}$ m/s) 7.5×10^{14} or 750 trillion violet light waves pass by every second, a frequency of 750 terahertz. The longer the wavelength of light, or properly electromagnetic radiation, the fewer waves pass by each second so the lower the frequency. Thus, FM and even longer AM radio waves, both much longer than light waves, have frequencies measured respectively in millions (megahertz) or thousands (kilohertz) of waves or cycles per second.

An extraordinary follow-up to Young's double slit experiment occurred some 125 years later, when a beam of electrons was aimed at a double slit and produced a diffraction pattern. That proved that not only are electrons particles, they are waves as well. Some twenty years earlier, in 1905, Einstein proved that the photoelectric effect showed that light has properties of particles (called *photons*) as well as waves. Together they comprise the so-called wave-particle duality that adds to the wondrous and sometimes exquisite nature of reality.

1.4 Light Waves: Scattering

Scattering is the general term for all the processes that occur when light strikes an object such as a raindrop or a medium such as air or water. These processes include transmission, reflection, refraction, diffraction, scattering in all directions, and absorption (extinction).

The word, scattering may create the mistaken impression that it is chaotic. No chaotic process could produce the coherent range of sky colors and precisely patterned rainbows, halos, and coronas.

Scattering is governed by Maxwell's Equations of Electrodynamics, whose mathematical solution depends on the nature, shape, and size of the particles. The math is complicated but, lo and behold, Ludvig Lorenz in 1890 and Gustav Mie in 1908 independently derived the all-encompassing solution for scattering of light by spheres. While Lorenz's work was overlooked, Mie's got instant recognition, so now we usually call the solution *Mie Scattering*.

Mie Scattering comes with bad news and good news. The bad news is that 1: even for spheres, the simplest geometric form, the math is extremely long and complicated, and, 2: it provides little physical insight. The good news is that, 1: air molecules, cloud droplets, and raindrops are close to spheres, 2: computer codes have been written to produce photorealistic images of sky color, coronas, rainbows, halos, etc. and, 3: simple scattering processes, such as reflection and refraction, dominate over large ranges of particle size (Fig 1-15).

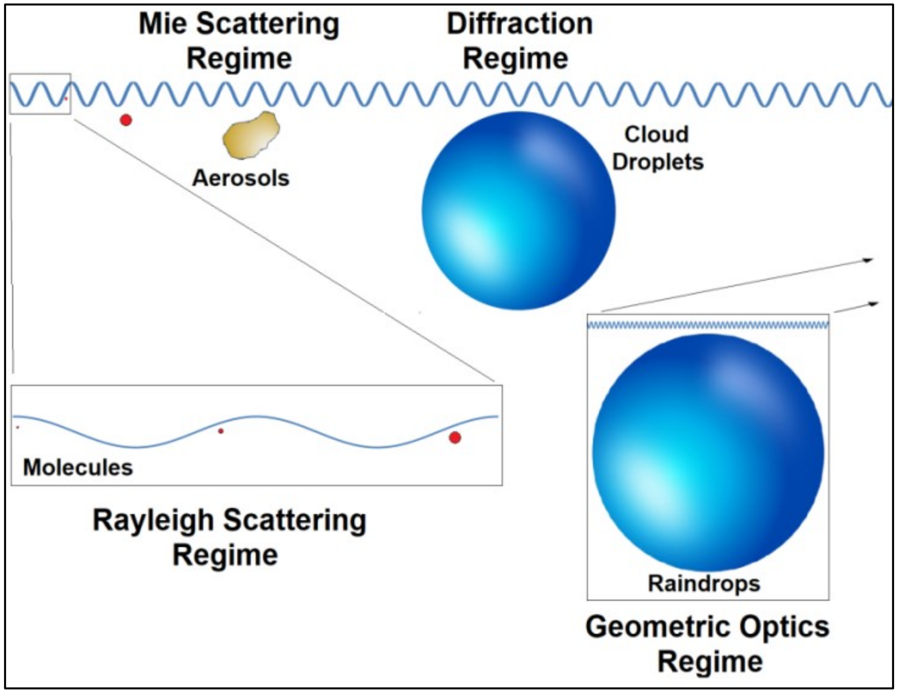

Fig. 1-15. Regimes of scattering processes as a function of the particle size relative to the wavelength of light. SDG.

Particles that are tiny compared to the wavelength of light, such as air molecules with diameters less than 1/1000th the wavelength of light, scatter light very inefficiently but obey a simplified law called Rayleigh scattering, by which scattering efficiency is *inversely* proportional to the 4th power of the wavelength. Many features of the light and color of the sky with a molecular atmosphere can be explained in terms of Rayleigh scattering (Chapter 2).

Scattering is most complicated when the particle size is comparable to the wavelength of light. This is the case for the smallest cloud droplets and ice crystals, which can produce cloud iridescence. It is also the case for small aerosol particles, which because of their varied shape and chemistry are near impossible to solve. In the atmosphere, the dominant impact of aerosols is to bleach the sky, increase haziness, and impact the global climate in complex ways that are a torment to climate scientists.

Scattering by particles from about 10 to 1000 times the length of light is accurately approximated by diffraction. Cloud droplets and small ice crystals fall in this size range. Diffraction phenomena include coronas and supernumerary rainbows.

For large particles (at least 500 or so times longer than light waves), such as raindrops and many ice crystals, scattering is accurately described by *geometric optics* (refraction and reflection) no matter their shape. Therefore, geometric optics explains many features of rainbows and ice crystal halos.

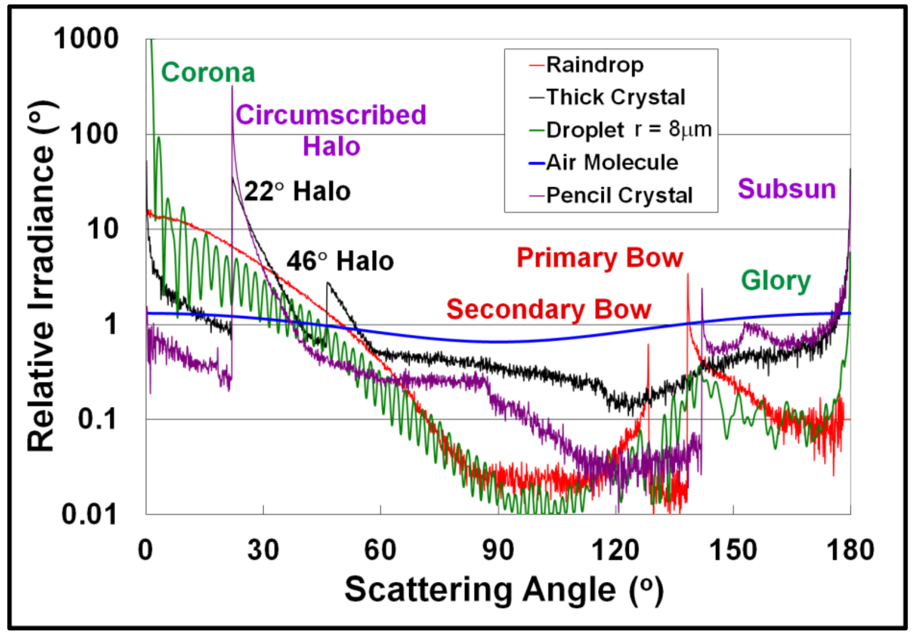

Fig. 1-16. Scattering intensity vs angle for air molecules (blue), cloud droplets (green), raindrops (red), tumbling thick ice crystal plates (black), and thin, horizontal ice crystals (purple). Peaks in intensity correspond to optical phenomena labelled in Figure and in text. SDG.

The brightness and colors of all the atmosphere's optical phenomena start with the visible light spectrum of the Sun and arise because scattering and absorption vary with the wavelength of light, the relative size of the scattering particle and the angle light is scattered.

The busy Fig. 1-16 serves as a master diagram of atmospheric optical phenomena. It shows the relative intensity of scattered light vs the deflection or scattering angle for air molecules (**blue**), raindrops (**red**), cloud droplets with radius, r_{DROP} = 8 µm (**green**), randomly oriented thick ice crystal plates (**black**), and horizontally oriented thin pencil ice crystals (**purple**).

Each of the pronounced peaks in the scattering curves of Fig. 1-16 corresponds to a specific optical phenomenon. Thus, for example, the two peaks in the red curve for (large) raindrops correspond to the primary and secondary rainbows.

Particles that are tiny compared to the wavelength of light, such as air molecules (**blue curve**), have no pronounced peaks. They scatter light with almost constant intensity in all directions to light and color the sky (Chapter 2).

Particles that are similar in size or somewhat larger than the wavelength of light, such as cloud droplets (**green curve**) or aerosol particles, scatter most light by small angles (forward scattering), which is why the sky is blinding bright around the Sun whenever it is hazy or when thin clouds are near the Sun.

The multitude of regular waves in the scattering curve of light with wavelength, λ = 0.55 µm by spherical cloud droplets of radius, r_{DROP} = 8 µm correspond to coronas and iridescence near the Sun and glories opposite the Sun (Chapter 14). Aerosol particles of the same size would have pronounced forward scattering peaks but due to their irregular shapes would not have the neatly organized waves. Thus, a sky laden with aerosol particles would not produce brilliant coronas or iridescence near the Sun but would simply glare with a blinding brightness (Chapter 2).

Raindrops (**red curve**) also have a pronounced forward scattering peak because much light passes through the drops with small deflection. That however is of much less interest to optics lovers than the two scattering peaks for raindrops at 138º and 129º, because they correspond to the primary and secondary rainbows (Chapter 9).

The two peaks for randomly oriented thick hexagonal plate-shaped ice crystals (**black curve**) correspond to circular halos, 22º and 46° from the Sun. Because ice crystals are basically hexagonal and not spherical, variations of their shape and orientation give rise to a multitude of halos (Chapter 11), some which have peaks of much greater irradiance in certain directions than for the randomly oriented crystals. Thus, for example, when the Sun is at the zenith, long pencil crystals (**purple curve**), that fall horizontally, produce a circumscribed halo that is as much as 8 times brighter than the 22° halo. And, when the Sun is low in the sky, horizontally falling thin plates produce a blinding bright subsun in the clouds below.

Skylight both taints and forms the background in which all these shining optical phenomena appear. So, next, let's see what happens to sunlight as it passes through clear air.

Fig. 1-17. A hawk flies across the Sun. 21 Aug 2020. Jan Curtis.