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Back to basics:
Light in the atmosphere: Part 1 – Why the sky is blue

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When we look into the sky we see different colours all around us: the blue of the sky, white clouds, black clouds, red sunsets and dawns, rainbows. Even the night sky is not wholly black. Stars and planets, some of which can be seen by the naked eye to be coloured, twinkle, and the moon shows shades of grey, and sometimes can be orange, red or even blue. Our visual perception of these phenomena arises from a number of different physical effects – scattering, reflection, refraction. In this article we will consider those due to interaction of light with the basic molecules and particles of the air while Part 2 will examine the impact of water and ice particles on light transmission.

Table 1 Relative sizes of molecules, particles, water droplets, and wavelengths of light

Particle	Typical dimensions (m)
Oxygen molecule	10^{-10}
Sulphate particle	10^{-7}
Salt aerosol	10^{-6}
Cloud droplet	10^{-5}
Raindrop	10^{-3}
Blue-light wavelength	4.5×10^{-7}
Red-light wavelength	6.5×10^{-7}

Light and air

The radiant energy from the sun consists of waves that are spread across a wide part of the electromagnetic spectrum; the peak energy flux is in the so-called visible part of the spectrum – that part which our eyes detect (wavelengths between 4.3×10^{-7} and 6.9×10^{-7} m) and which, in combination, gives the colour white. These waves must travel through more than 100 km of increasingly denser atmosphere before reaching the ground. If the light did not interact with the atmosphere in its path we would see a black sky except when looking directly at the sun (not to be recommended!). However, just as waves on a river surface are scattered by boulders and reeds in their path, so the light waves are scattered by the molecules and particles that make up the atmosphere.

Table 1 shows the relative sizes of molecules, particles and water/cloud droplets that make up the atmosphere in comparison to typical wavelengths of two of the most commonly seen colours in the sky – blue and red. From analogy with the relative scattering of water waves by a reed (small) compared to a boulder (large) we would expect molecular scattering to be a lesser effect than that from (larger) particles; this is called Mie scattering. This is indeed so – direct light in a hazy sky, containing lots of particles, is less bright than in a clear sky, for example following rain that washes particulates out of the atmosphere.

The colour of the sky is due to a subset of this scattering. The spread of the wavelength within the spectrum of light from the sun is sufficient for different wavelengths, λ, to be scattered noticeably differently, proportional to λ^{-4}, just by a typical oxygen or nitrogen molecule. Thus blue light, being of shorter wavelength, is scattered more than red light, and, as there is significantly more energy from the sun in the blue wavelength band than in the even shorter wavelength violet, when we look away from the direct sun we see predominantly blue. A good deal of the other, longer, wavelengths may also be scattered but significantly less of the shorter blue/violet part of the spectrum gets through unscattered. This scattering by small molecules and particles much smaller than the wavelength of the wave is known as Rayleigh scattering, after the nineteenth-century physicist who first developed the theory. A detailed account of its mathematics can be found in Tricker (1970).

Rayleigh scattering predicts that a typical air molecule should scatter light predominantly forwards, or backwards, along the path of the incident light wave, but only by a factor of about 2 (Greenler 1980) relative to sideways scattering. Thus, in the very rare instances when the air is very clean, with few particulate pollutants or natural aerosols, the sky will appear to have much the same brightness whether you look close to the sun or towards the opposite side of the sky's dome. Generally, however, the sky's brightness varies substantially with direction. This is because the atmosphere is never devoid of microscopic particles, whose dimensions are comparable to, or larger than, the wavelengths of visible light (Table 1). In the relatively clean marine atmosphere the concentration of aerosols is of the order of $5 \times 10^6 m^{-3}$while in polluted city air it can be 1000 times this. The closer a particle's diameter is to the wavelength of the incident light, the stronger, and the more forward-directed, the scattering becomes (Fig. 1). Thus in a relatively clean atmosphere the moderate number of particles will tend to accentuate the brightness of the sky near the solar beam by producing more forward scattering, and not scattering as much light towards the surface away from the solar beam. In a very smoky urban environment the amount of scattering will be even greater, leading to a hazy, dull, atmosphere away from the solar beam.

The amount of scattering also depends on the length of the path between the source of light and the observer. This is most clearly seen by comparing the brightness and colour of, for example, a tree near you with a similar tree in the distance. The light reflected from the tree provides its colour, as seen by our eyes – the

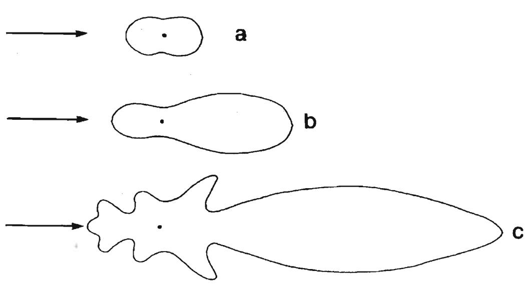

Fig. 1 Schematic representation of the angular variation in the Rayleigh scattering intensity from very small molecules or particles: (a) particle 2.5 per cent the size of the wavelength of the incident light, (b) particle 25 per cent the size of the wavelength, and (c) particle larger than the wavelength (after Greenler 1980)

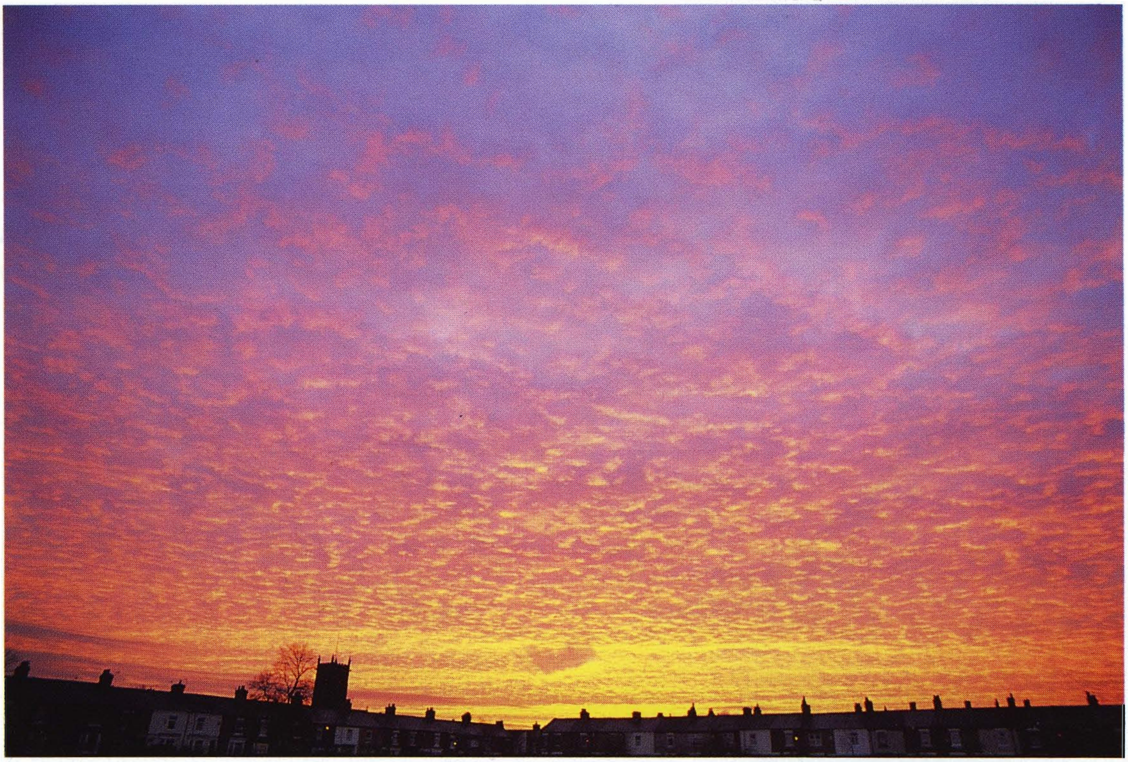

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Fig. 2 Underlit altocumulus at sunset, Thornaby-on-Tees, December 1994 (see article on p. 72)

CP © Ronald Saunders

Fig. 3 Crepuscular rays penetrating a layer of heavy stratocumulus, Grimsby, 12 February 1993 (see article on p. 72) more distant the object the bluer and paler it appears because of the greater length of atmosphere the light has travelled through, and so the greater the number of scattering events with air molecules and particles the light beam has undergone. At sunset and sunrise the path length of the solar beam through the atmosphere is at its maximum and so the greatest scattering occurs. This can be so extreme, particularly if the particulate concentration in the atmosphere is high, that the sky about the sun appears yellow or red since so much scattering has occurred that very little blue light penetrates to the ground from near the solar beam (see front cover and Fig. 2, p. 82).

This colouring of the sky is associated with a well known piece of weather lore: "Red sky at night, shepherd's delight; red sky in the morning, shepherd's warning". There is a practical element to this advice stemming from the fact that the east–west separation between weather fronts in the mid-latitudes is typically somewhat more than a day. A red sky in the morning would mean that the air was rich in particulates and, while clear in the east, clouds to the west would accentuate the scattering. Clouds to the west, and a particulate-rich atmosphere, suggest the possible presence of an airstream in advance of a warm front, and a clear sky to the east suggests that it is some time since the last weather front passed by. In contrast, a red sunset means that the western sky is clearing so rain is less likely, at least until the next day! It is worth cautioning, however, that this lore can break down under polluted anticyclonic conditions when very red skies can occur both morning and evening.

Reddening of the dusk and dawn sky can be very spectacular after volcanic eruptions. Eruptions (for example, Pinatubo in 1991 (Bigg 1992) or Krakatoa in 1883) raise aloft millions of tonnes of particulates and sulphur dioxide gas, which produces sulphate cloud condensation nuclei, into the stratosphere. This leads to spectacular sunsets around the globe during the succeeding years before the dust begins to settle out.

Coloured moons are also a product of significant scattering of the reflected solar beam by a high particulate concentration in the atmosphere. A particularly good example of a coloured moon was seen in September 1950 when a combination of strong westerly winds in the upper troposphere and a huge forest fire over the Rocky Mountains led to a lot of particulate matter in the atmosphere over western Europe. This produced such strong scattering that a blue–green moon was observed over much of the UK and the nearby Continent.

One of the most fascinating, and spectacular, atmospheric effects due to scattering is the phenomenon known as crepuscular rays (Fig. 3, p. 82). Crepuscular rays occur when beams of sunlight passing through gaps in distant obstacles illuminate aerosols nearer the observer. We see the beam of light only because of contrasts in forward or backward scattering. To see this most strongly you need to be looking towards, or away from, the sun (see Fig. 1). There is less scattering from the atmosphere in the shadow of the cloud, as there is less light penetrating into this region, than in the illuminated atmosphere around the cloud. Thus our eyes receive more scattered light from the unshaded volume, creating a contrast between the shaded and unshaded regions. The beams appear to be radiating from a point but this is an effect of perspective. In reality the sun is so far from the earth that all light beams are essentially parallel. However, if you look at a pair of parallel lines, such as a railway track, you will see them converge in the distance – perspective creating an illusion. Similarly, in certain circumstances you will see crepuscular rays converging on the opposite side of the sky dome to the sun; these are known as anti-crepuscular rays.

Twilight is also a scattering phenomenon. Direct light from the sun is no longer able to reach the earth's surface after sunset but for a while directly following this the direct solar beam is still illuminating the atmosphere overhead and we see this through the scattered light from the beam. Even further into twilight the atmosphere overhead is no longer directly illuminated but only indirectly by light scattered from the atmosphere further towards the sun.

Illusion and delusion

So far the atmosphere has been a quiescent participant in our study; molecules and particles have just happened to get in the way of the

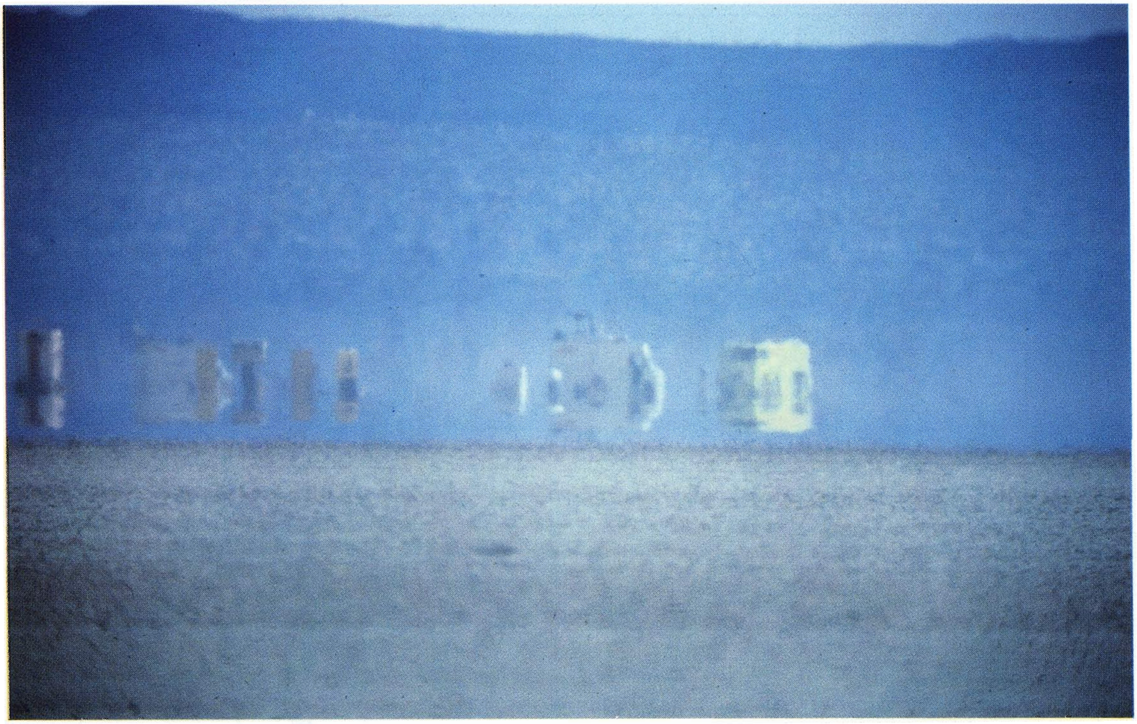

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Fig. 7 Superior mirage of space shuttle reception vehicles over Edwards Dry Lake, Edwards Air Force Base, California, 1981 (see article on p. 72)

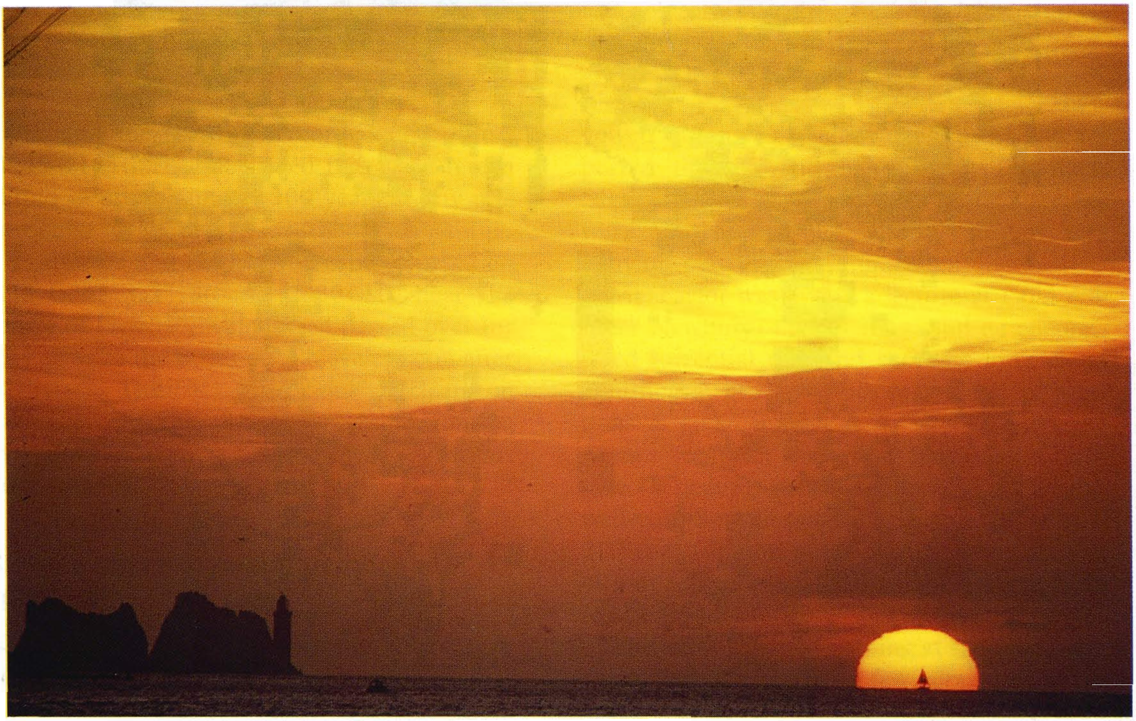

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Fig. 8 Sunset beyond the Needles, Isle of Wight, on a cold December evening. The small bump on the upper right of the sun's disc grew slightly and turned pure green as it set (see article on p. 72).

solar beam and scattering occurs. However, there is a class of atmospheric phenomena involving light (but not involving water droplets, the latter being discussed in Part 2) in which the atmosphere's temperature, or more precisely its density structure, plays an important rôle. These optical effects rely on the variation of the speed of light with the density of the medium through which the light is travelling, and the refraction of the beam as it passes from one medium to another.

You will have seen the refraction of light as it travels from air into glass or water. The denser media result in a slowing of the speed, which deflects the path of a beam according to Snell's law (Fig. 4):

$$\frac{\sin\alpha_i}{\sin\alpha_t} = \frac{n_t}{n_i}$$

where α_i is the incident angle of the beam in air of refractive index n_i, and α_t is the transmission angle of the beam in the receiving medium of refractive index n_t. The refractive index is the ratio of the speed of light ($3 \times 10^8 \mathrm{m\,s^{-1}}$) in a vacuum to that in the medium. Typical values are 1.00029 for air near the ground, 1.33 for water and 1.52 for glass. The net effect of refraction is to bend the light into the denser medium.

Warm air is less dense than cold air (see Brugge 1996) at the same pressure. Also, the atmosphere becomes less dense with height. Both of these effects can bend the path of a beam of light passing through the atmosphere. One of the most obvious manifestations of this distortion is the apparent flattening of the sun near sunrise or sunset. Light from the sun's disc is travelling through the maximum extent of atmosphere at this time (spending more time in the thicker, near-ground atmosphere), so it undergoes maximum refraction towards the ground (*i.e.* into the denser air). This will tend to raise the perceived upper edge of the sun, but it will raise the apparent lower edge even more, as the light from the lower edge has to travel through even more, and slightly denser (as lower), atmosphere. Thus the sun's disc will appear to be flattened as it approaches the horizon at sunset. The net effect of this refraction is to make sunset approximately a few minutes later, and sunrise a few minutes earlier, than it would be in the absence of the atmosphere; the refraction is enabling us to see over the real horizon. The precise time by which a day is lengthened depends on the latitude and the time of year.

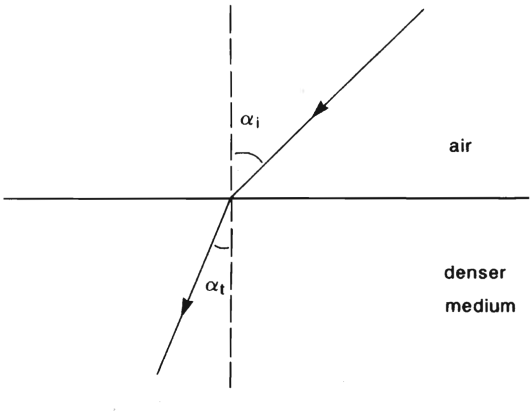

Fig. 4 Schematic of Snell's law – light travelling from air into a denser medium

Seeing objects on the surface of the earth over the horizon is also possible. If there is a temperature inversion in the lower atmosphere then light travelling upwards from the surface will be deflected, in the inversion layer, back down towards the cooler, denser air closer to the ground. The greater the temperature contrast over the path of the light, the stronger the refraction; thus the image is inverted. This is called a superior mirage (Fig. 5). Objects that are actually over the horizon can thus be observed to be suspended upside down. The same thing happens to sound waves – if you can sometimes hear a train whistle at your home that is usually not audible it may be because of an inversion between you and the railway deflecting sound waves back towards the ground.

Strongly heated ground can also lead to mirages. A road or desert surface will warm strongly during a summer day, heating the air above it perhaps 10–20 degC in excess of the surrounding surface air. This very warm air refracts light upwards. Thus, you can often see what looks like a pool of water on the surface between yourself and another object as light from the sky is being refracted into your line of vision (Fig. 6 and Fig. 7, p. 83). This is known as an inferior mirage. The same effect can also lead to an inverted image of a tall object

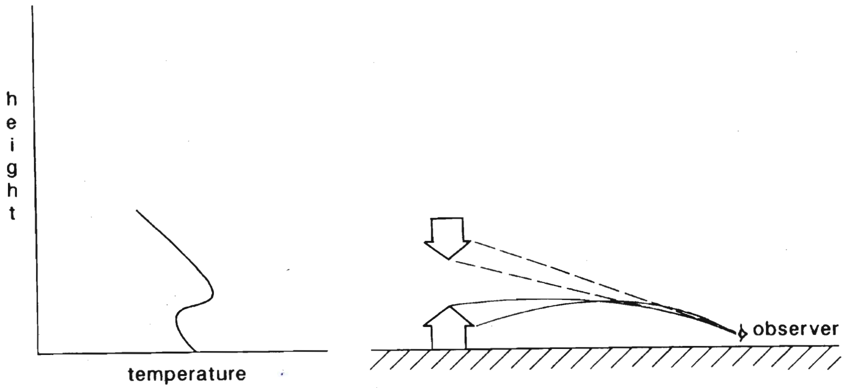

Fig. 5 Light ray paths for a superior mirage, with the atmospheric temperature profile shown on the left. Note the refraction downwards in the inversion.

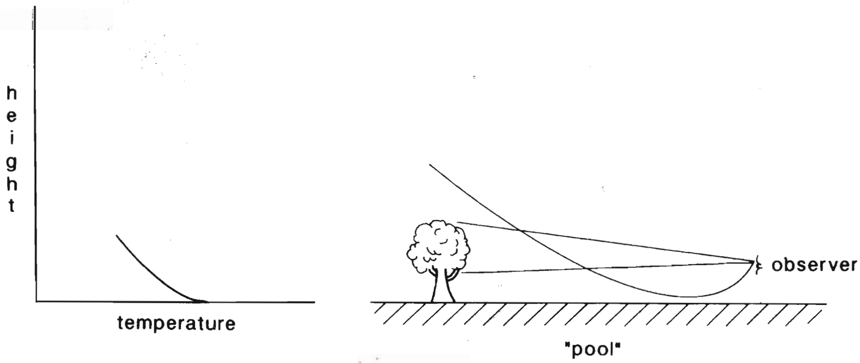

Fig. 6 Light ray path for an inferior mirage, with the atmospheric temperature profile on the left. Note the upwards refraction near the surface.

being seen in the 'pool', with the foot of the distant object becoming invisible because the light from it is refracted above the observer.

The temperature structure of the lower atmosphere can be quite complicated. This can lead to extreme forms of mirages, where the image is broken into fragments (the fata morgana, see Greenler (1980); Meteorological Office (1982)), or ducted images where light is trapped in a cool zone between two warmer layers above and below, and potentially transmitted over large distances (Greenler 1980).

The atmosphere is rarely still. Small-scale movement of air with different temperatures – turbulence – is occurring all the time. The movement of air parcels with different temperatures, and hence densities, across your line of vision will cause minor refraction of beams of light. This leads to, for example, the twinkling of stars and the shimmering observed through the convection currents just above a heated radiator. Twinkling involves not just the rapid slight movement of the apparent position of the star, but also rapid changes in colour as different wavelengths of a star's spectrum are refracted more or less by the atmospheric fluctuations, or changes in brightness as the light is focused or broadened by the parcels acting as lenses.

The green flash

One last phenomenon worth mentioning here combines both atmospheric refraction and scattering. This is the green flash. Occasionally, if there is clear air, no cloud in the western sky, and a very sharp horizon, as the sun sets there will be a few seconds (Minnaert 1959) when the red light around the sun will turn green (see Fig. 8, p. 83, and Candy, this issue). This phenomenon arises predominantly because of refraction, but the green colour is due to scattering. Recall that as the sun's disc sets, its image will be more and more refracted down towards the earth's surface. As the top of the rim disappears, the difference in refraction of different wavelengths means that the wavelengths most refracted will be the last to be seen. From passing a beam of light through a prism you should have observed that the most refraction occurs at the shorter wavelength, or blue/violet, end of the spectrum. You would, therefore, expect the last light from the setting sun to be blue, but this is the wavelength most subject to scattering in the very long path this last light must travel through the atmosphere. Thus what is observed is green – the combined effect of refraction and scattering.

One of the clearest examples of the wavelength dependence of refraction is in the rainbow, an atmospheric phenomenon caused by water droplets and one of the topics discussed in Part 2 of this series.

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The green flash

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The green flash, an atmospheric optical phenomenon that may be observed at sunset, was once considered to be an astonishing phenomenon, to the extent of being associated with legends. Old texts (prior to Greenler 1980) tend to refer to the hard-to-see big naked-eye green flashes/rays (that occur when the upper part of the solar disc is on the point of disappearing below the horizon – its upper strip being observed to turn an emerald shade of green for less than a second). Nowadays, with the use of a telescope, it is possible to see a 'green flash' in the sense of a tiny telescopic flash or green rim, both of these being related to superior mirages. These latter phenomena do not only occur as the sun vanishes from view; indeed often one can observe several consecutive small flashes detaching from the sun's upper edge as the sun slowly sinks towards the horizon.

History

Questions about the probable cause of the green flash first appeared in the scientific literature towards the end of the nineteenth century (see, for example, Winstanley 1873; Verne 1882). Seamen were the first to recognise its existence, and this is the reason why everybody immediately thought that sunshine, when filtered through the ocean waves, let only the green part of the visible spectrum through to the observer (Omond 1886).

Later, however, the green flash was observed during sunset over land and in the desert, so that this simple assumption crumpled at once.