Optical phenomena for mountaineers

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This article is intended as a guide for the mountaineer to various optical phenomena which may be seen in the Earth's atmosphere. My intention is to indicate how and why these phenomena occur, but without delving too deeply into the theory. It is my belief that a simple, basic understanding of the processes involved in all natural phenomena is sufficient to lead one to an increased awareness and appreciation of the beauty of the natural world. I certainly hope that this article may help the reader to this end.

When visible radiation (light) passes through a vacuum (such as space) it travels at a constant speed, and in a straight line (relativistic and gravitational effects are not considered here). When passing through matter, any combination of the following five processes may occur: reflection, refraction, diffraction (including interference), scattering and absorption. A proper understanding of these processes would be a very long task, so we will give nothing more than a superficial explanation of each. Reflection occurs at the boundary between any two media: for instance, at the boundary between air and a mirror, or that between air and the sea surface. The simple geometric laws of reflection are well known.[1] Refraction is caused by the dependence of the speed of light on the density of a medium: when the density of matter varies along the path of a light ray, that path is diverted from a straight line. It is a reasonable fact (on the face of it) that light travels more slowly in a more dense medium, and below we will see that this explains refraction phenomena involving ice-crystals, and hot layers of air near to the Earth's surface. Diffraction is a much more difficult phenomenon to explain, and owes its origin to the fact that light is a wave phenomenon. As a particular example, imagine that a small, circular obstacle is placed so as to intercept a beam of light (e.g. sunlight), and the shadow of the obstacle is cast on to a screen. A close inspection—possibly requiring a magnifying glass—of the edges of the shadow on the screen will reveal that concentric lines of light and dark 'fringes' may be seen. These are the result of light waves of different wavelengths arriving in phase and out of phase at a given point on the screen, from the edge of the obstacle.[1] Scattering is just what it says, i.e. the scattering of light, from small particles and molecules. For various reasons, to do with the fact that the wavelengths of the light are about the same size as the dimensions of the 'scatterers' (particles, etc.), this scattering may be more intense in some directions than in others (in contrast to simple reflection), and is also strongly dependent on the wavelength (i.e. the colour) of the light. Violet light is more strongly scattered than red light. The fifth effect, absorption, mainly occurs when molecules of the gases composing the atmosphere take in radiation and are so raised to an excited energy state. The physical processes which account for this absorption are extremely complex, and for the present purpose it is sufficient simply to know that the atmosphere is capable of absorbing radiation. The absorption is different for different gases, and is colour (wavelength) dependent: it is normally very weak though (in the visible region), and absorption is usually only important over very large distances.

Simple reflection phenomena are the easiest of all to understand, since our everyday experience confirms their existence, and it is with these we will begin. In the atmosphere one of the most famous (and most alarming!) of phenomena is the Brocken spectre, which is entirely a reflection process. As many mountaineers will know, the Brocken spectre may be seen most clearly at sunrise or sunset, when a fog or mist is present. In mountainous regions this often occurs when an evening mist is driving up from the valleys. In such cases, looking away from the sun a huge shadowy figure may be seen to appear in front of the observer, at an indeterminate distance into the fog. The mechanism is as follows: the shadow of the observer is cast onto the fog and the light round it is reflected. The apparent size is an illusion; the observer in fact sees a life-size shadow (because the rays of light from the sun are parallel) quite near, but often mistakes it for a much larger figure at greater distance. I have seen what may be described as an 'artificial Brocken spectre' while working in the open on a foggy night (in fact preparing for a scientific balloon flight the following morning). I stood in front of a powerful arc lamp which was being used and my shadow was eerily thrown onto the fog and towered above me. In this case, of course, the sense of size was real, since the rays of light from the lamp were not parallel, as in the case of the sun, and my shadow was expanded.

14 *The Spectre of the Brocken* (reproduced from *The Beauties and Wonders of Nature,* circa 1840)

An early sighting of the Brocken spectre proper was mentioned by Omond[2] in 1892, who explains: 'The shadow is formed on the surface of the mist near the spectator, but he regards it as being at the furthest limit that he can see through the mist'.

One other, rather uncommon, reflection phenomenon I have observed is sometimes called the 'sub-sun'. I observed this from the observatory at the Jungfraujoch,[3] early one morning in winter. As the sun was rising in the south-east behind me, I saw in the north-western horizon a reflection of the sun, presumably on a cloud layer, at about 100 km distance (judged from the known topography). The mountain peaks at either side of the Jungfraujoch (the Jungfrau and the Mönch) cast shadows which met at the sub-sun. This was also observed by a colleague. The scale of this most impressive phenomenon is, of course, enormous, but it is basically a very simple reflection effect.

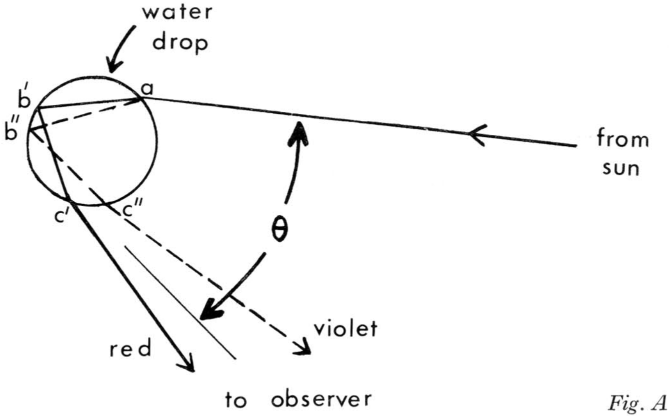


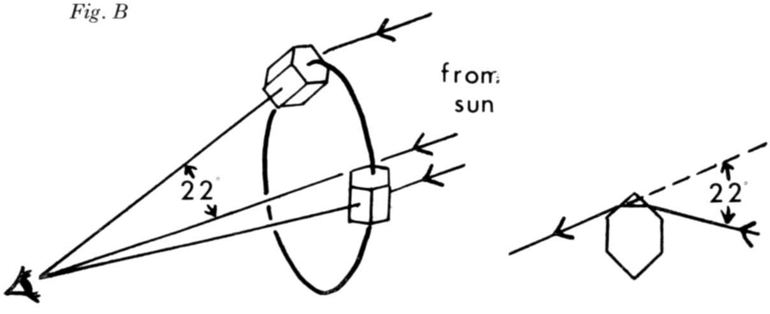
Fig. A

Although more complicated, refraction phenomena are perhaps the most common. The best-known, of course, is the rainbow, though to my knowledge no pot of gold has yet been found. In a sense this follows on well from the effects we have just mentioned, because reflection is involved. Fig. A shows a water drop in the atmosphere, and its effect on a single ray of light that happens to impinge on it. As the ray enters the (more dense) drop, refraction occurs at point *a*. Refraction, or the bending of a light ray, is more extreme for violet light than for red light (i.e. it is dependent on wavelength) and so the violet rays (broken line) are more affected than the red rays (continuous line). Refraction at *a* is followed by internal reflection[1,6] at b', b'' and a final refraction on exit from the drop at c', c''. The figure shows just the extreme red and violet rays, but the other colours are, of course, distributed between them. The observer sees the colours of the rainbow in the raindrop, or rather in the many raindrops in a given volume of air. A more detailed consideration shows that the angle θ between the directions of incident and exident rays is 42° (the angular separation between the red and violet rays is greatly exaggerated in the figure). Because of this the curve joining all the points in the sky such that $\theta = 42°$ (for a fixed position of the observer's eye) forms the characteristic bow shape. On occasions, a fainter secondary rainbow can be seen at an angle of

$\theta = 51°$; this is caused by two reflections (like b', b'') inside the water drop, and in this case the colours are in reverse order (i.e. the red is on the inside). The requirement of many water droplets and clear sunlight explains why rainbows are seen most often following rain, as clouds are breaking up. If the drops are very small, as in a mist for example, the clear distinction of the colours is lost, and the 'fog-bow' may be seen. This occurs when the diameter, d, of the droplets becomes as small as the wavelength of the light, λ, i.e. about 0·5 micron, and is due not to refraction, but to scattering. It is known that backward scattering is particularly intense for certain values of the ratio λ/d^4 at angles of θ (see Fig. A) of between 0 and 15°, and this is the case in a fog-bow; it should be noted, however, that the angle θ involved is much less than 42° as in the case of a rainbow, so the fog-bow has a smaller diameter. A similar phenomenon has been observed in the droplets of water constituting dew on a grass surface, and even, as Minnaert points out,[5] on such unusual surfaces as a weed-covered pond!

These bows arise from refraction, reflection and scattering (in the case of the fog-bow) in and by liquid water drops. Ice crystals also produce very beautiful refraction and reflection effects, and these—since they require a low air temperature for the formation of the ice—are more pertinent to mountain regions. These phenomena are generally termed 'haloes' and may appear as circles, bows, crosses and points of light in the sky.

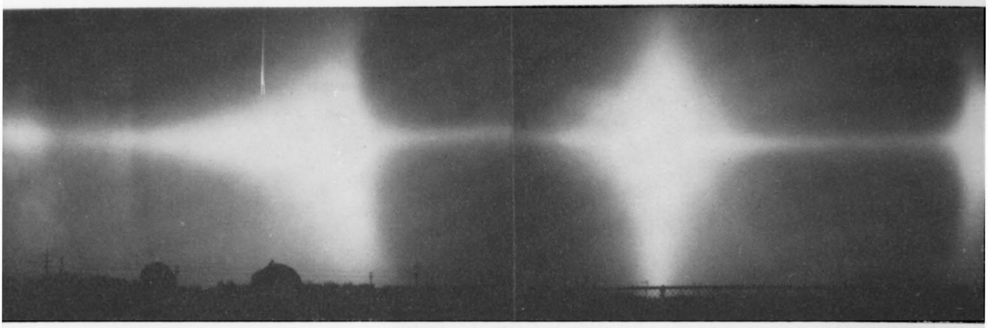
Fig. B



(a)

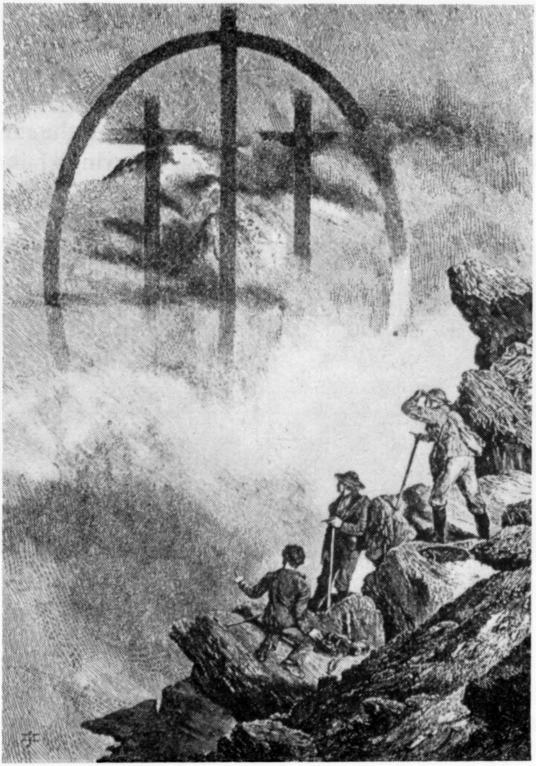
(b)

The most common, the 22° ring halo, is often seen around the sun (or occasionally the moon) when high cirro-stratus clouds occur (these being composed of ice-crystals), and is coloured, from red on the inside to blue on the outside. The angle between the sun and the ring is 22° as a result of the refraction process within the tiny ice 'prisms', as shown in Fig. B. The ice-crystals usually grow so as to produce hexagonal cylinders and, as shown in Fig. B(*a*), refraction causes a ray of light to be deviated by 22° from its incident direction. The crystals are, of course, distributed randomly in orientation, but enough are present at the necessary orientation (Fig. B(a)) at any one time to produce this beautiful effect. Because the refraction is wavelength-dependent (cf. the similar case for a water droplet in Fig. A) so the colours of the spectrum are produced. Only once, and then very briefly, have I observed a ring halo, from the Kleine Scheidegg plateau, when the sun was going down behind the Mönch: a rock peak blocked out the sun's disc from view and, with the glare removed, one could clearly see the halo. This point is well worth remembering when trying to observe all halo phenomena, of course; if the bright dazzling disc of the sun can be blocked off from the eye, one stands far more chance of observing a faint halo than otherwise.



15 *Halo and Mock Suns.* Photo: E. A. Ripley

There are a large number of other, more esoteric, halo phenomena, often dependent on the shape and orientation of ice crystals. Since we only have space here to refer to a few, the reader is referred elsewhere for further reading.[5,6] The 'mock suns' appear on either side of the ring halo at the same height as the sun: these mock suns are in fact local 'concentrations' of light arising from a large number of ice-crystals having their axes vertical (Fig. B(*b*)). When significant numbers of *plate-like* crystals exist, however, simple reflection effects give rise to light 'pillars' and light 'crosses'. These phenomena are simple to understand: when plate-like crystals are arranged so that a significant number float nearly horizontally, then when the sun is low, a vertical pillar of diffuse light may appear by reflection from the faces of the crystals. A similar effect can occur in the horizontal plane. Ice-crystals often assume preferred orientations in the atmosphere as a result of the fact that they are spinning like tops in the Earth's gravity field. When the vertical and horizontal pillars occur together one sees a 'cross' centred on the sun, or sometimes centred on the mock suns. The story of the 1865 Matterhorn expedition is famous.[7] This was the first successful attempt on the peak, but tragedy struck on the descent when four of the party fell to their deaths. Later in the day, Whymper reports having seen '. . . a mighty arch, rising above the Lyskamm, high into the sky. Pale, colourless and noiseless, but perfectly sharp and defined, except where it was lost in the clouds, this unearthly apparition seemed like a vision from another world; and, almost appalled, we watched the development of two vast crosses, one on either side'. Whymper gives further information as to this sighting in a footnote: 'The sun was directly at our backs—that is to say the fog-bow was opposite to the sun. The time was 6.30pm. The forms were at once tender and sharp; neutral in tone; were developed gradually, and disappeared suddenly. The mists were light—that is, not dense—and were dissipated in the course of the evening. It has been suggested that the crosses were probably formed by the intersection of other circles or ellipses'.



16 *Crosses on the Matterhorn* (reproduced from *Scrambles Amongst the Alps*, 1871)

The effect of these significant 'signs' so soon after the tragic loss of their colleagues had an obviously traumatic effect on Whymper and his remaining companions.

Here, however, we come upon a strange fact, which does not appear to have been noticed by Minnaert[5] in his account of the Whymper sighting—that is, that the phenomenon was seen, *not* around the sun, but opposite in the sky to the sun. As we have seen, in general halo phenomena and associated mock suns, crosses and so on appear *around* the sun. It therefore seems difficult to explain the sighting: Whymper had a reputation of being a reliable and trustworthy observer, and also the 'vision' was seen by his companions,[7] so the validity of the phenomenon must be assumed. Perhaps a particular geometry of ice-crystal can be involved to explain it: yet again, perhaps it *was* a supernatural event, and we should not try to discover a cause!*

Finally in the section on refraction we should mention the mirage—although mountaineers are very unlikely to experience this if they stick to mountains! The mirage arises because strong temperature gradients in air can act just like

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* We have no room for much further discussion on this interesting point but it is pointed out by Tricker[6] that a faint mock sun can appear at 180° from the sun, at the anthelion. Lowitz reported in 1794[6] seeing 'the oblique antihelic arcs' passing through this point. Even so, this does not explain Whymper's double cross phenomenon, although the appearance of mock suns at 120° from the sun may be involved. For further reading we refer to Tricker's recent book.[6]

a prism of ice or a water drop: they can bend light as a result of the variations of the speed of light with temperature[2] (light travels faster in hot air than in cold). The well-known case of the oasis in the desert is one example; a similar one may be seen over a tarmacadam road on a hot day. Looking into the distance bright 'puddles' may be seen on the road. This is, in fact, light from the sky which is bent up away from the road and towards the observer's eye by refraction in the very hot layer of air immediately above the road surface; the shimmering effect is caused by the variations in the temperature (and so the density) of the air. An interesting, though rare, phenomenon is the inverted (or superior) mirage, in which a distant object appears higher than its true position because the air near the ground is markedly *colder* than that higher up, a situation which can arise, for example, in the cool evening after a very hot day.

When it comes to diffraction, we will limit ourselves to a consideration of one effect only, the corona. This has the appearance of diffuse rings of light, slightly coloured, round the sun (or moon) when seen through thin water (as opposed to ice) clouds. The angular radius of the rings can vary from less than 1° to about 10°—much less than the radius of the halo caused by ice-crystals. The latter also has a much sharper appearance and so should not be confused with the corona. The corona is caused by the diffraction of the sun's rays around the spherical drops of water in the cloud. The radius and colours of the rings depend on the size distribution of droplets in the cloud, and very clear coronae only develop in clouds in which the droplets are uniform: when the sizes of droplets vary a great deal, a large number of coronae occur simultaneously, and contrast is lost.

The fourth class of phenomenon which was mentioned at the beginning was scattering. Light rays are scattered, or are deviated from a straight line path, by particles and by molecules in the atmosphere. The 'amount' of scattering into any given angle depends on the size (diameter) of the scatterer (be it a molecule or a speck of dust) and the wavelength of the light. We have already seen how scattering can account for the fog-bow since (for quantum—or in other words microscopic scale—reasons) light can be scattered backwards into certain angles more than others. The best known scattering effect is the red sky sometimes seen at sunset. In this phenomenon the spectrum of colours (red to violet) is separated by scattering. Since red is the *least* deviated from a straight line, the sun's image is predominantly red—the shorter wavelength colours are scattered away preferentially.

As in all things natural, however, the complexity of nature makes impossible any rigorous classification, and we are obliged to create a further class of phenomena, which includes those involving several of the five basic processes simultaneously. The first of these is the 'glory' which may sometimes be seen surrounding the head of a Brocken spectre. The glory is a series of concentric coloured rings (with red on the outside) seen on a cloud or fog, similar to a corona (the latter, however, is seen around the sun, in contrast to the glory, which is seen around the anti-solar point). The relation between the glory and corona lies in the type and size of water droplets which cause them both. A detailed explanation of a glory is not easy: it seems likely that light is scattered backwards by the small droplets of the cloud or fog and that this back-scattered light then forms a corona by diffraction around the drops in the path to the observer.

The glory may frequently be seen from aircraft and mountains, although I have only seen it from the former. This sighting occurred while flying in an experimental aircraft involved in some high-altitude stratospheric measurements. Extensive strato-cumulus cloud was present with a fairly stable and flat top at about 10,000 ft. After our measurements, our aircraft was descending and as we approached within about 1000 ft of the cloud top, I saw a faint glory. As we descended further the colours grew stronger, and the shadow of the aircraft became visible across the centre of the coloured rings, until, just before entering the cloud, a beautiful brightly coloured glory could be seen with a sharp shadow of the aircraft lying across it. The aircraft's shadow was slightly larger than the red-to-red diameter of the glory.

A case of a more conventional glory seen in connection with a Brocken spectre from a mountain was reported by Stott in 1891,[8] based on his experiences on Ben More in Scotland; '. . . at a short distance we saw a halo of pale light painted on the mist as on a canvas, and in the centre the shadow of the cairn and of ourselves upon it. Much as we had read of it, we had not believed that the appearance could be so very realistic when the substance on which it was produced was semi-transparent mist'.

The second 'complex' phenomenon, which is probably the most complicated of all those we have discussed, is the 'green flash'. This has been observed from both mountains and from sea-level, and occurs during sunrise and sunset, though somewhat infrequently. As the sun sets, for example, at the moment when perhaps less than a fifth of the sun's disc is visible above the horizon, a green or green/blue colour may become visible on the uppermost rim of the sun's disc. This may last for up to ten seconds, but is characteristically very short in duration. The colour of the sun is reported to change continuously from yellow through white to bright green. Occasionally, a ripple or flash of green may be seen (although one wonders how much of this may be caused by a movement of the observer's eye as he detects the green light). Parker reports an observation of this elusive but beautiful phenomenon during sunrise observed over the North Sea horizon: the weather conditions were clear though it had recently rained. He says[9] '. . . suddenly, a most vivid point of emerald green light appeared on the horizon. It came without any premonitory sign and its appearance was that of an intense green light suddenly appearing and waxing stronger and stronger, and then rapidly changing into a more brilliant rose-white, the upper limb of the sun's disc being seen just rising above the horizon. The duration of the green light was from one to one and a half seconds . . .'.

The explanation of this effect, the observation of which has so far eluded me, is intricate, and runs in this way: when the sun is very low, its light must travel a very large distance through the atmosphere in order to reach the observer, and in doing this most of its yellow and orange light is absorbed by weak atmospheric absorption bands. This leaves the red, green, blue and violet. Scattering accounts for the loss of the violet and some of the blue light (since short wavelengths are, as we have seen, scattered more than long wavelengths), leaving the red and the green/blue. The third effect that comes into play is then refraction in the lower layers of the atmosphere as the red light is refracted most to appear lower than the green/blue, which leaves, if only the upper rim of the sun is visible, a green rim. The three processes—absorption, scattering and refraction—do, of course, occur simultaneously. The correct combination of circumstances will not often occur, which means that the effect is uncommon, and also only lasts a brief time. If the explanation just given is correct, this implies that the *lower* limits of the sun should be tinged with red, and this has indeed been observed on occasions when the lower edge of the sun appears, for example, behind a cloud bank in the far horizon. In effect there are two images of the sun, one green, one red, the former slightly above the latter. The green flash has usually been seen over the sea, where the horizon is very flat and distant, but there is no reason why it should not be seen from a mountain over a distant horizon, except that since the air is thinner, each effect (absorption, scattering and refraction) will be less pronounced, and so the probability of seeing the green flash is very likely lower.

There our brief survey of optical phenomena in the atmosphere must end. It is hoped that the descriptions and explanations given above may encourage the reader, if he has not done so already, to observe carefully the atmosphere for the sudden appearance of any of these beautiful phenomena. The mountaineer is lucky to be able to climb and walk in regions where the conditions of clear air and low temperature permit the full range of these phenomena to be observed and enjoyed.

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