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.

Acknowledgements

I would like to thank Storm Dunlop, Photographic Editor, for providing the photographs for this article. Comments from the referees helped to make this a clearer paper.

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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.

Someone else suggested that the green shade was produced by the counter-image (negative) impressed on the retina by a red sun disappearing at sunset (Swan 1883; Pickering 1901), but it was shown that this outcome was possible even at sunrise; the arrival of colour photography proved that the green flash was real and not fictitious (Danjon and Rougier 1926; O'Connell and Treusch 1958).

Physical explanation

The theory of normal atmospheric disperson and refraction, of Rayleigh scattering of light by air molecules and other small particles, gives a first quantitative explanation of the green appearance of the upper edge of a very low sun, resulting in a strip of about half a minute of arc (in the vertical) (Shaw 1973). Near the horizon, the trajectory of the solar rays appears to be deviated from a straight line by about half a degree, the deviation being greater in extent for blue light than for red. The result is the formation of several solar discs, each with its own characteristic wavelength. The red disc is the lowest one, with the orange, yellow, green, blue and violet discs successively higher up in the sky. The light corresponding to the blue and violet discs does not reach the eye of the observer, due to Rayleigh scattering. Consequently, as the various solar discs get close to the horizon, the red one vanishes first, followed by the orange, then the yellow and finally the green.

The green effect at the upper solar rim is so small that it is not visible to the human eye, which has a resolving power of typically one minute of arc. If the sun is completely hidden by the horizon, the only light that may be visible is from the green part of the spectrum; this is a special case, which has nothing to do with the resolving power of the eye (Fraser 1975). In other circumstances there may exist mirage-type conditions, which act to magnify the phenomenon. For example, the presence of gravity waves (billows) travelling along an inversion layer can distort the apparent shape of the sun, and consequently its green upper rim, to produce larger flashes. The green ray, the green rim and the green segment are variations

Cumulus mediocris and congestus

CP © Ronald F. Saunders

Field of cumulus mediocris and congestus seen over south-eastern Germany from 33 000ft, 20 September 1989

of the same effect and are nowadays all collectively also known as the green flash (Greenler 1980).

There are certain atmospheric and topographic conditions which may promote the observation of the green flash, namely an obstacle-free and flat horizon (*e.g.* over the sea or a desert), a clear sky, and the absence of atmospheric pollution.

The greatest green flashes (*i.e.* ones that are visible even with the naked eye – hence the probable origin of popular legends such as those of Scotland) are related to inferior mirages, which make the outline of the setting sun appear first like a Greek 'omega' (see Fig. 1, p. 81), then like an American football; finally, during very rare circumstances, they end in a much bigger green flash. The telescopic stripes of the superior mirage are much smaller.

Notable historical observations of the phenomenon include those of Lord Kelvin (1899), who saw a remarkable blue flash from Mont Blanc, and that seen by members of the Byrd Antarctic Expedition who, on 16 October 1929, saw a green flash lasting for 35 minutes (Haines 1931). According to Schaefer (1992) the green flash can occur in about 25 per cent of the clearest sunsets. However, here Schaefer is not referring only to the naked-eye green flashes in the restricted sense of the old literature. According to Greenler's (1980) terminology the phrase 'green flash' includes the commonplace telescopic green flashes; Schaefer seems to follow the new terminology – hence the (apparent) high frequency of occurrence.

Photography

Figure 2 (p. 81) illustrates the telescopic green flash. In order to photograph this phenomenon it is essential to calculate the correct time of exposure, since an underexposure would not show the deep green colour, while an overexposed film would contain images from non-green wavelengths as well. The actual timing of the photograph is also important. According to Greenler (1980) most photographs do not reproduce the vividness of the actual green flash.

Figures 1 and 2 were photographed with the aid of a telescope (focal length = 1600 mm, diameter = 254 mm), and were observed near the Cimini Mountains at a height of about 700 m. The atmospheric layers were easily observable; they had vivid colours, ranging from a bright red to gold and yellow. In the upper half of the solar circumference it was possible to see something which resembled green waves, which moved upwards and appeared like small 'flames'. As a smaller portion of the sun remained visible, the green waves showed a greater and greater intensity, being concentrated mostly on the top of the circular segments of the sun.

Conclusion

The green flash is, indeed, a wonderful and astonishing phenomenon, which all readers of *Weather* should try to see for themselves.

Acknowledgement

I am grateful to the reviewers whose comments have led to an improved article.

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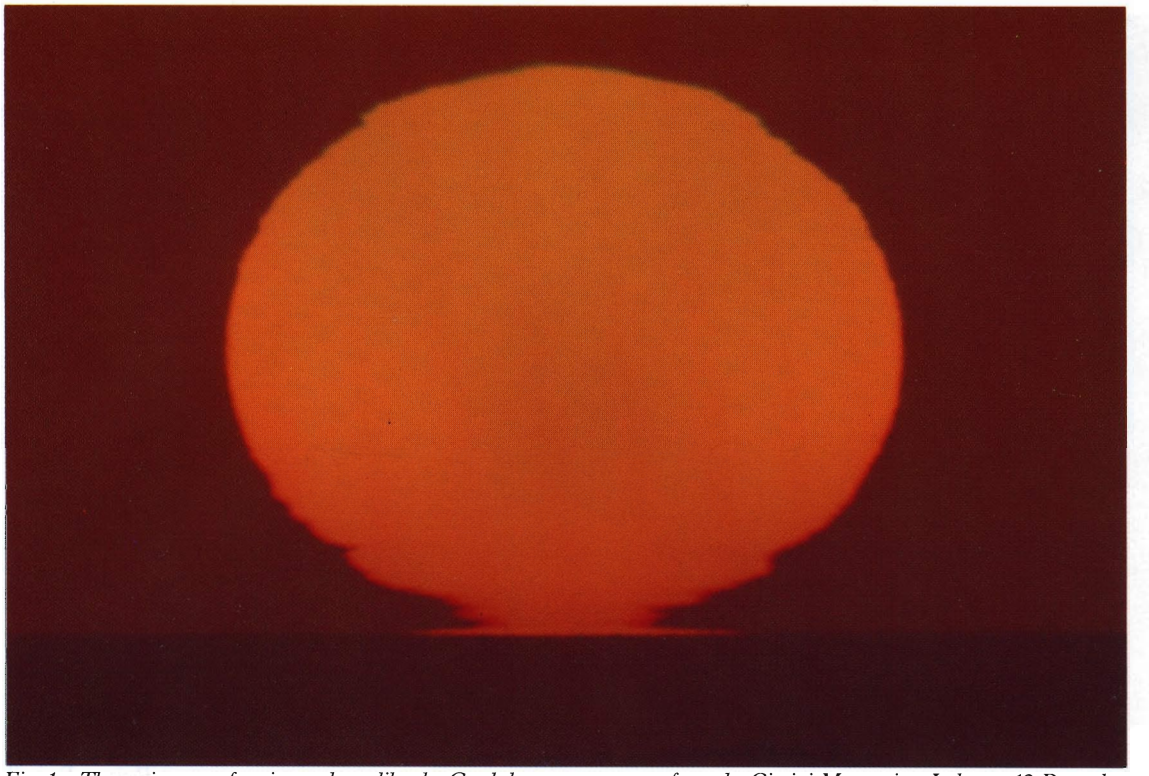

Fig. 1 The setting sun, forming a shape like the Greek letter omega, seen from the Cimini Mountains, Italy, on 12 December 1993 *(see article on p. 77)*

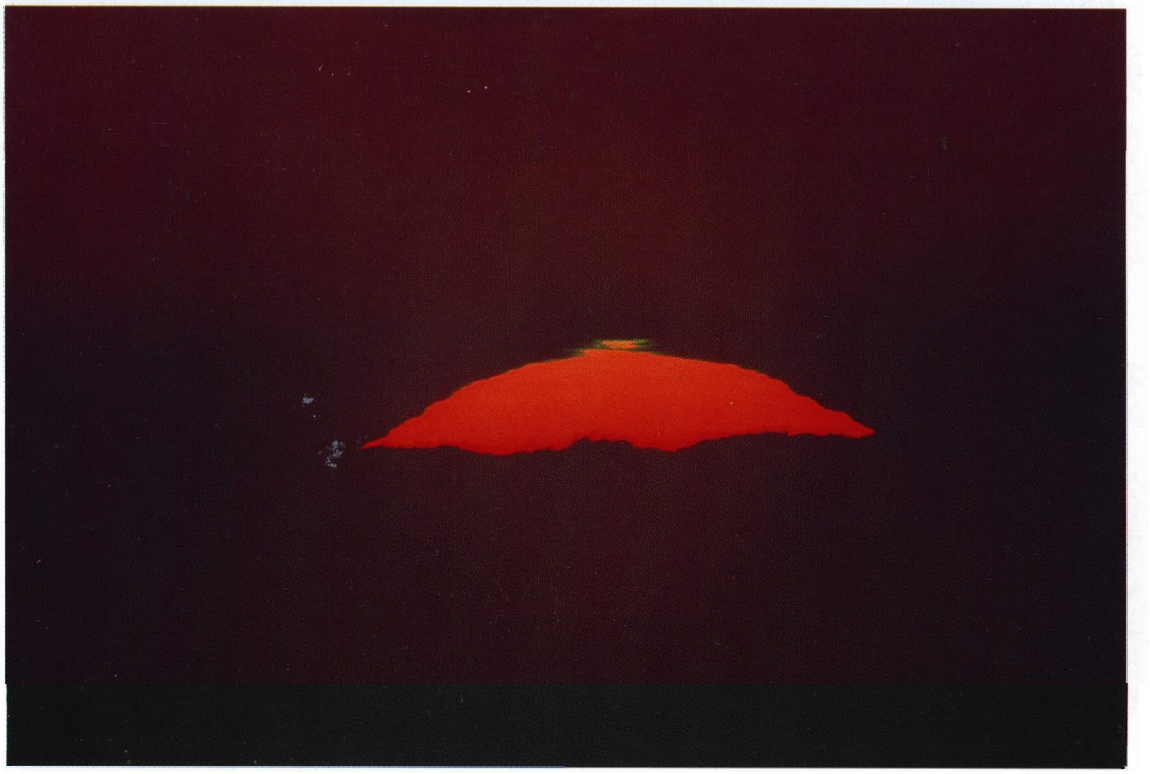

Fig. 2 The green flash at sunset on 7 November 1992 seen from Viterbo, Italy. Note the green coloration and the unusual golden colour on the top of the image. *(See article on p.77.)*