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Setting sun at Camperduin, The Netherlands on 3 September 1976

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To an observer who has a clear and unobstructed view of the distant horizon the setting of the sun is one of the most fascinating phenomena that can be seen in nature. The shapes and the colours of the disc of the setting sun are both beautiful and surprising, and they can be explained in terms of refraction, scattering and dispersion of light in the atmosphere. Teachers may therefore be able to explain and illustrate these topics of physics with the help of sunset phenomena. Linked classroom experiments on atmospheric refraction and scattering have been described elsewhere (e.g. Trowbridge 1973, Kruglak 1973, Johnston 1977).

Although my comments in this article relate to the setting sun, they apply equally well to the rising sun. I shall deal with normal sunset phenomena, sunsets over warm land or water and the characteristics of sunsets that occur when there is a layer in the atmosphere where temperature increases with height (an inversion). The phenomena to be described in connection with warm land or water and with an inversion are additional to those that occur under normal conditions. Therefore if there is an inversion at some height above a warm surface it might be possible to observe all the phenomena to be described during the course of one sunset.

Normal sunset phenomena

When the sun is low on the horizon the image of the sun's disc, as formed by the atmosphere, is seen to be oblate instead of circular (e.g. figure 3g, figures 5a, b). The height of the sun's disc is smaller than its width. This phenomenon is caused by the fact that the density of the air decreases with height above the earth's surface. Hence there is also a decrease in the refractive index μ. The difference between the value of μ at the top of the atmosphere ($\mu_t = 1.00000$) and its mean value at the earth's surface ($\mu_s = 1.00029$) is very small (Irwin 1977). Nevertheless it is this slight

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difference which causes the curvature of light rays known as atmospheric refraction.

Because of atmospheric refraction a celestial object appears to us to be slightly higher above the horizon than it really is (figure 1). The smaller the angle α between the direction of the incident light and the outer rim of the atmosphere, the greater will be the difference between the real and apparent height of the celestial object. The lower rim of the sun's disc is nearer the horizon than the upper rim, so α is smaller for light from the lower rim than it is for light from the upper rim. Therefore atmospheric refraction raises the lower rim more than the upper rim. When the lower rim of the sun's disc, for instance, is 35 minutes of arc below the horizon the observer actually sees it at the horizon (figure 2). At the same moment the upper rim appears to be 26.5′ above the horizon when it is in fact 3′ below it (the diameter of the sun's disc is 32′). It follows that the vertical diameter of the sun's disc will be only 26.5′ whereas one would expect it to be 32′; since atmospheric refraction does not affect the width of the sun's disc, the resulting flattening is $26.5/32 = 0.83$. One can easily observe this flattening with the naked eye on any day when visibility is good and the low sun is not obscured by clouds.

When sunlight passes through the atmosphere it is scattered by air molecules and by particles in the air. The blue part of the spectrum is scattered more than the red part. The closer the sun is to the horizon, the farther the sunlight has to travel through the atmosphere, and the more pronounced the effects of the scattering become. This is why the disc of the setting sun looks dimmer and redder than it is when higher in the sky. Since light from the bottom section of the disc has further to travel than light from the top section, the bottom section looks dimmer and redder than the top section.

Since the extent to which the sunlight is refracted by the atmosphere depends on the wavelength of the light, dispersion occurs. Again the effect is most pronounced at low solar elevation when the angle of incidence of the sunlight at the outer rim of the atmosphere is at its maximum. Because violet light is refracted more than other colours of the visible spectrum it appears to come from a point higher in the sky than does the red light (figure 1). Consequently in the image that the atmosphere forms of any point of the sun's disc the violet is above and separate from the red. These colours, together with the remaining colours of sunlight, make up a spectrum. The spectra of all the points overlap, except for those of the points on the upper and the lower rim of the sun's disc. Therefore the disc of the setting sun should have a violet upper rim and a red lower rim (figure 2) (Shaw 1973).

The latter can be observed quite often through low-power binoculars or a telescope. A violet or blue upper rim however is rarely seen; but when the air is 'clear' one usually finds (with the help of binoculars) that the upper rim of the sun's disc is green. This can be explained as follows. Owing to scattering, the violet or blue light of the upper rim is generally so dim that it cannot be seen. Green light has the shortest wavelength of the remaining colours, so the sun's upper rim looks green (figure 7a). However, the green rim cannot be seen with the naked eye, unless the remainder of the sun's disc is obscured by, for instance, the horizon, a dyke or a cloud.

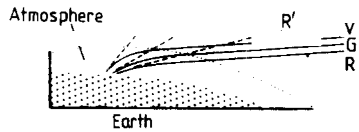

Figure 1 Because of atmospheric refraction celestial objects look as if they are slightly higher in the sky than they really are. An observer at the earth's surface, for instance, sees a star in the direction of V′, whereas the real direction of the star is indicated by V. The refraction of violet light (V) is greater than of green light (G) and red light (R). To an observer standing on the ground the violet, green and red light seem to come from the directions denoted by V′, G′ and R′ respectively. Notice that the violet light always seems to come from a point higher in the sky than the red light. The effect is exaggerated in the drawing

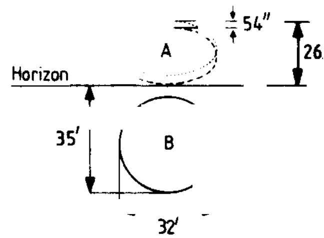

Figure 2 The observed position A and the real position B of the disc of the setting sun. Because of atmospheric refraction the sun seems to be entirely above the horizon whilst it is in fact below. The oblate shape of the sun is caused by the difference between the amount of refraction of the light coming from the upper rim and from the lower rim. The image of the sun, as formed by the atmosphere, in violet light (dotted oval; $\lambda = 0.4\mu m$) is higher in the sky than the image of the sun in red light (dashed oval; $\lambda = 0.7\mu m$), since violet light is refracted more than red light. The flattening of the sun's disc and the difference in the positions of the dotted oval and the dashed oval have been exaggerated in the drawing. Numbers refer to minutes and seconds of arc

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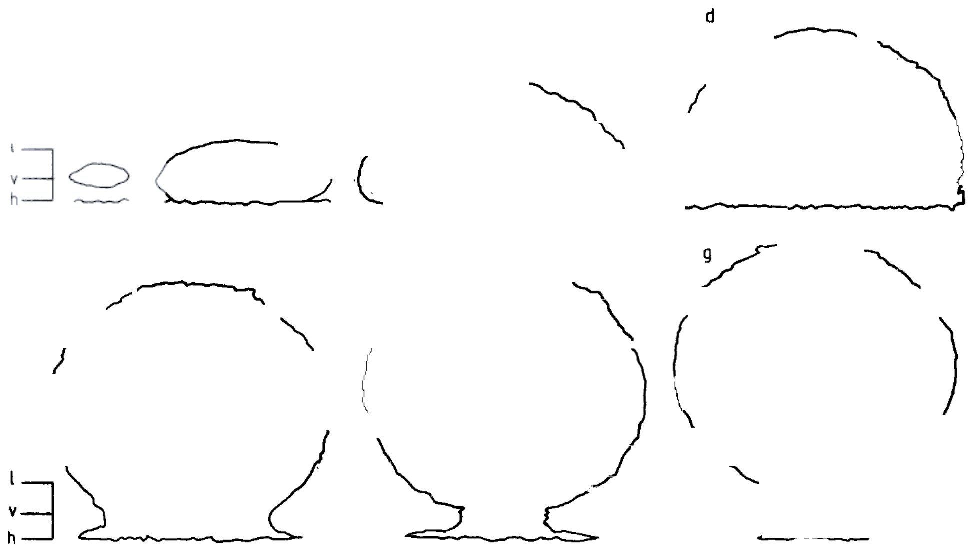


Figure 3 A sequence of shapes of the rising sun above a warm water surface. Between the horizon h and the vanishing line v one sees a reflection of the part of the sky (or sun) between the vanishing line and the limiting line l. In **a** the sun first appears at the vanishing line v. In **a, b** and **c** the broadest part of the first segment is seen to be above the horizon instead of on the horizon. When the sun is halfway above the horizon the sun's reflection can hardly be distinguished from the sun itself, **d**. The sun's disc is Ω shaped in **e** and **f**. In **g** the sun's reflection has become separated from the sun itself. (Schiermonnikoog, Dutch North Sea Islands, 22 May 1980). (Drawings of low-sun phenomena are taken from slides made by the author)

The green rim is one of the variants of the so called green flash phenomenon. More spectacular occurrences of this phenomenon are observed only under special atmospheric conditions which cause the brightness and the dimensions of the green image of the sun's upper rim to be intensified.

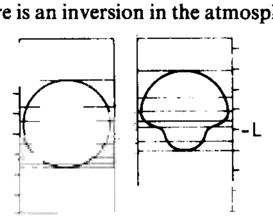
Sunsets over a warm surface

Sometimes the surface of land or water is warmer than the temperature of the air 2 m up. Then there will be a thin layer (a few centimetres thick) of warm air in contact with the surface. The index of refraction of the warm air in this lower layer is smaller than that of the cold air above. The curvature of the light rays will then be just the reverse of the normal curvature of the light rays in the atmosphere; light rays at grazing incidence are even 'reflected' in the warm layer of air. This is how the well known road mirage or desert mirage is formed (Fraser and Mach 1976).

When mirage conditions prevail an observer with an unobstructed view of the horizon sees a reflection of a small strip of the sky (or sun) on the horizon (figure 3). The upper boundary of the reflection is called the vanishing line (v); this line also indicates the lower boundary of the region of the sky (or sun) that is reflected in the warm layer of air above the earth's surface. An observer cannot see points of the sky (or sun) below the vanishing line—he or she sees the reflected sky (or sun) instead. The upper boundary of the region of the sky (or sun) that is reflected (the limiting line l) is usually a few minutes of arc above the horizon. This is why the setting sun is Ω shaped (figure 3e,f) and why the broadest part of the last segment of the sun's disc is seen to be above the horizon instead of on the horizon.

When mirage conditions prevail one can observe the green upper rim of the disc of the setting sun more easily. Just before the sun disappears at the vanishing line, the reflection of the green upper rim in the warm layer of air enlarges the green region near the horizon and increases the intensity of the green light (figure 7b). This phenomenon, which is called the green last segment, can be seen with the naked eye. This variant of the green flash is likely to be visible if the setting sun is observed through clear air over warm land or water.

Figure 4 The disc of the setting sun (left) and its distortion (right) when there is an inversion in the atmosphere



Inversion

Parallel to the earth's surface there are often layers in the atmosphere where the temperature of the air

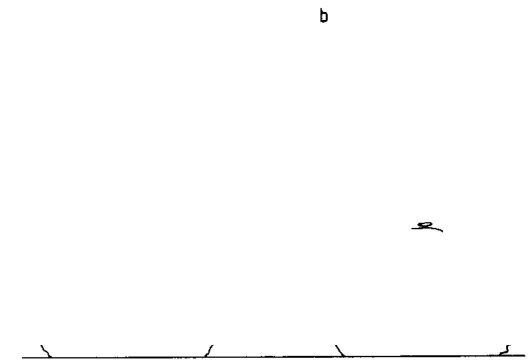


Figure 5 A sequence of shapes of the setting sun when there are inversions in the atmosphere. **a,** The droplet phenomenon of the setting sun. **b,** Flat top of the disc of the setting sun, caused by the same inversion that caused the phenomenon shown in **a**. Isolated segment below the disc of the setting sun. **c,** Protrusions at the top of the sun's disc. **d,** Green isolated segment above the setting sun. (Schiermonnikoog, Dutch North Sea Islands, 29 May 1978)

remains constant or increases with height. (Normally air temperature decreases with height.) Layers of this kind are called inversion layers. The index of refraction of the air in the inversion layer is usually smaller than the normal value at the same height; therefore the deviation of the light rays that pass through this layer will be greater than the normal deviation. This extra-large deviation is caused mainly by the lower boundary of the inversion layer; the deviation depends on the angle of incidence and hence on the height of the sun above the horizon. The total deviation of the light coming from the sun reaches a maximum value at a certain level near the horizon (Minnaert 1954), for instance the level indicated by L in figure 4. Consequently the images of points on the sun at that level are further removed from their real position than the images of points just above or below that level. Sections of the sky (or sun) above this level are compressed; sections below it are extended.

Figure 4 shows how the shape of the sun's disc is affected by the inversion. The images that the atmosphere forms of a number of horizontal lines on the disc of the sun are shown on the right, and their real positions on the left. In figure 5a an example is given of this phenomenon as observed by the author. There seems to be a droplet hanging on the sun. The flat top of the setting sun in figure 5b is caused by the same inversion that causes the droplet phenomenon in figure 5a. In figure 5b the upper section of the sun's disc is in the region that is compressed just above the L of figure 4.

An inversion can also be the cause of 'isolated segments' just above (figure 5d) or just below (figure 5b) the sun's disc and of related 'protrusions' that seem to grow out of the most inclined sides of the sun's disc (figure 5c). These phenomena occur when

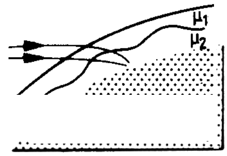


Figure 6 Light rays (arrows) emitted from one point on the sun's disc pass through the atmosphere and reach an observer on the earth's surface. The refraction of the light rays is affected by the waves that travel along the boundary of a layer of warm air (refractive index μ_1) and a layer of colder air (refractive index μ_2) below

waves travel along the boundary between the cold (dense) layer of air and the warmer (less dense) layer of air above (Fraser 1975). These waves are connected with differences in the wind speed or wind direction in the various layers. The waves originate in the same way as waves on a water surface: the latter occur when air moves over (denser) water.

The waves at the boundary of the warm and cold layers of air cause multiple images of a point on the sun's disc. This can be explained as follows. Light rays from the sun which fall on a portion of the wave that is tipped towards the observer are refracted very strongly, for the angle of incidence is large (upper light ray in figure 6). Light rays that fall on a portion of the wave that is tipped away from the observer are refracted only slightly, for the angle of incidence is small (lower light ray in figure 6). If the light rays shown in figure 6 come from the top of the sun's disc, then one will see two images of the top. In between the two images one often sees part of the sky above the sun, so the upper image appears to be isolated from the sun (see figure 5d).

The protrusions that appear to 'grow' out of the sides of the setting sun (figure 5c) and the isolated segment below the sun (figure 5b) are formed in the same way as the isolated segments above the sun. Other waves can cause similar effects; that is why one can sometimes observe several protrusions or isolated segments one above the other (figure 7d).

The boundaries of the isolated segments are always images of the rim of the sun's disc. The lower part of an isolated segment above the sun is an inverted image of the top segment of the disc of the setting sun; the upper part of the isolated segment is an erect image of the top segment of the sun's disc (Fraser 1975).

As we have seen, the rims of the isolated segments above the sun are images of the upper rim of the setting sun. If this upper rim is green (the green rim phenomenon described earlier) then the isolated segments above the sun enlarge the green area near the top of the sun and increase the intensity of the green light that is emitted from this region. When the

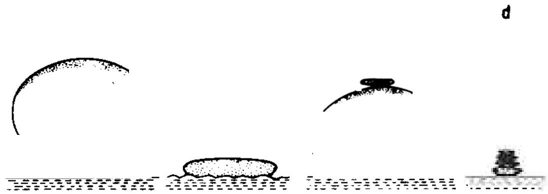


Figure 7 The different types of green flash that are observed (stippled areas are green): **a,** green rim; **b** green last segment; **c,** green isolated segment; **d,** green ray (made up of several green isolated segments)

isolated segments are relatively small they are entirely green and so form 'islands' of green light floating above the sun (figure 7c). If several green isolated segments occur at the very moment when only the green upper rim of the setting sun is above the horizon, then an observer without binoculars is likely to interpret these isolated segments one above the other as a 'green ray' which is shooting up out of the sun (figure 7d). If the air is clear and if one sees isolated segments below the sun or protrusions 'growing' out of the sides of the sun, then the green flash is likely to occur in the form of one or more green isolated segments above the sun; only very rarely does it occur in the form of the 'green ray'.

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A career in astronomy

D A Allen

Astronomy is ever before us. The media clamour for it. NASA's spectacular photographs adorn every magazine. The person in the street talks of quasars and black holes, and debates whether other civilisations are trying to contact us. Professional astronomy is painted in glamorous hues. As such, the subject excites the interest of many a youngster with a talent for science. Amateur astronomers are extraordinarily numerous, and are catered for by growing numbers of societies. Bookshops bulge with popular works on the subject.

So it should be. For astronomy is a pure science. Though they may rationalise with chronicles of such as NASA's contribution to the nonstick frying pan, in their hearts astronomers know that the direct benefit of studying something beyond the solar system is virtually nil. If we are to indulge in it at all, it must be with the blessing of a large slice of the taxpaying community. All we can offer in return for their support is information; the more who enjoy that information, the more astronomy can we indulge in.

And so astronomy is published and broadcast, and made accessible. With the result that the young, in large numbers, are asking 'How do I become an astronomer?'. Before attempting to answer that question, I want to debunk the popular view. Like so many subjects, beneath its glamorous veneer astronomy is routine, tedious and hard work. We do

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