SUMMER SOLAR HALOS IN NEW ZEALAND

JOHN DUDLEY AND DAVID HIRST

Atmospheric optical phenomena are fascinating to observe, and provide a rich source of examples that can be used to enrich classroom and lecture treatments of introductory optics. Understandably, many physics textbooks and physics instructors make use of commonly observed atmospheric effects such as rainbows and mirages to supplement more formal instruction, and students generally appreciate this opportunity to apply their knowledge of physics to the world outside a lecture or laboratory environment.

New Zealand Halos

One of the most spectacular examples of atmospheric optical phenomena is the atmospheric halo which results from the refraction of light in ice crystals in the upper atmosphere [1-2]. The most commonly observed halo is probably the complete circular halo observed around the moon at night, but the widest variety of halos occur in broad daylight around the sun. Because halo effects involve ice crystals, it is commonly believed that daytime solar halos cannot readily be observed in countries such as Australia and New Zealand that have warmer climates.

Although it is certainly true that the most spectacular solar halo displays are observed at Arctic or Antarctic latitudes [3], it is nonetheless possible to see many different halo displays all year round at all latitudes. This is because the temperature in the upper troposphere 10 km above the earth's surface is typically -40°C or below, and even in high summer, ice crystals can be present in cirrus clouds formed at this altitude. Under these conditions, all that is required to see solar halos is some keen observation, and perhaps an awareness of the possible effects that can be seen if only one looks!

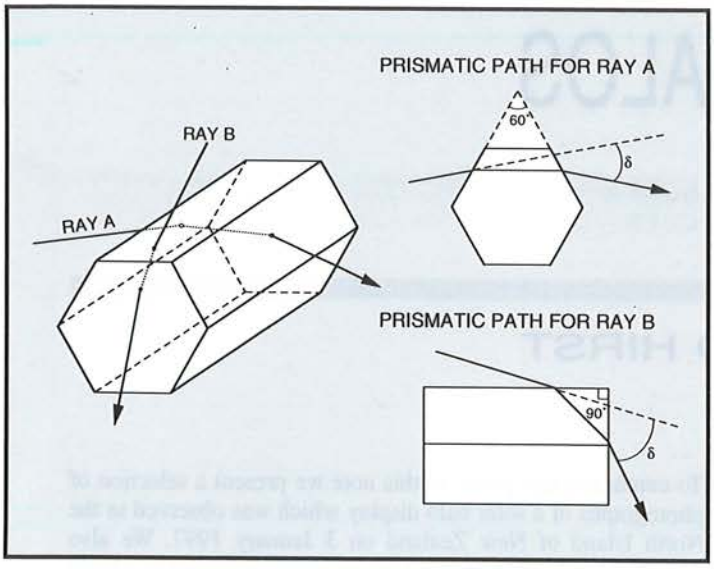
To emphasise this point, in this note we present a selection of photographs of a solar halo display which was observed in the North Island of New Zealand on 3 January 1997. We also include a brief explanation of the underlying physics at a level which we hope is suitable for inclusion in introductory lecture treatments of geometric optics. The distribution of high-altitude cloud is not always uniform, and consequently many halos do not form complete circles. **Figure 3** (see inside back cover) shows an incomplete halo observed during the display of January 3 1997. The halo is centred about the sun (blocked by the photographer's finger) and has an angular radius of 22°. The halo display lasted approximately half an hour, and evolved dramatically during this period as the cloud distribution changed with the prevailing wind. At one stage during the display, it was possible to observe not only a complete 22° halo, but also another much larger arc at an angle of 46° from the sun. Portions of both halos are shown in **Figure 4** (see inside back cover). The stronger upper arc is part of the 22° halo, while the lower weaker arc is part of the 46°halo.

The Optics of Halos

Halo formation can be understood using only elementary geometrical optics. Ice crystals are hexagonal in form, and the 22° and 46° halos can be explained simply by considering the refraction of light rays in columnar pencil-like ice crystals as shown in **Figure 1**. The figure shows two paths that a light ray can take through a hexagonal ice crystal. Ray A passes through alternate side faces of the crystal, and the figure shows how the ray is refracted exactly as if it had passed through a prism with an apex angle of 60°. Ray B passes through a side face and an end face of the crystal, and the figure shows how this ray is refracted exactly as if it had passed through a prism with an apex angle of 90°. A good understanding of the origin of the halos in the photographs can now be obtained simply by ▷

Dr John Dudley and Dr David Hurst are in Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand.

email j.dudley@auckland.ac.nz



1 *Important ray paths in columnar ice crystals.*

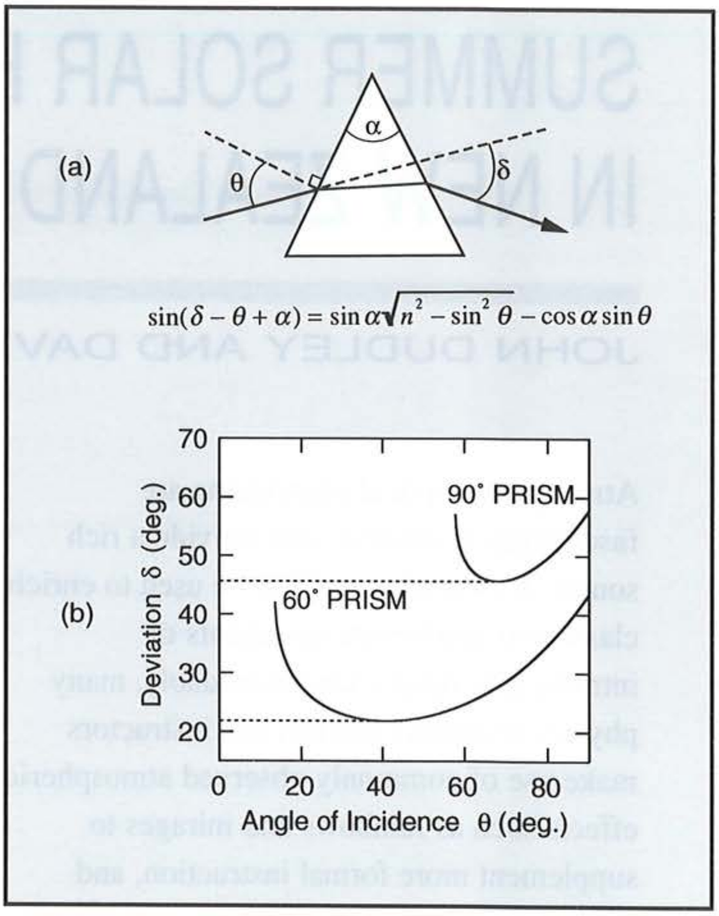
calculating how the incident light ray is deviated from its original direction for both of these cases.

Ray tracing through prisms is a standard problem in geometrical optics [**4**], and for a prism of refractive index n and apex angle U it is straightforward to derive a general result relating the incident angle to the deviation as shown in **Figure 2(a)**. The amount of deviation depends on the angle of incidence, and it is well known that the deviation takes on a minimum value when the incident ray passes symmetrically through the prism. This minimum deviation angle 8min is given by the relation:

$$\sin\left(\frac{\delta_{\min}+\alpha}{2}\right)=n\sin\frac{\alpha}{2} \qquad (1)$$

To relate this analysis to solar halo formation, **Figure 2(b)** shows explicitly how the deviation varies with incident angle for the 60° and 90° prisms associated with hexagonal ice crystals. Note here that we take the refractive index of ice as n-1.31. The deviation takes on a clear minimum value at some particular angle of incidence, and the dashed lines highlight the value of the minimum deviation for the 60° prism ($\delta_{\min} \approx 22°$) and for the 90° prism ($\delta_{\min} \approx 46°$). The significance of these points of minimum deviation can be appreciated if we consider light rays incident on a prism over a range of incident angles. Because the magnitude of the deviation is similar for a range of angles close to the minimum deviation orientation, there will be a strong clustering of rays close to the minimum deviation angle, and a strong intensity maximum at this point. A very convenient demonstration of this is to place a spinning glass prism in the beam of a slide projector.

It is the existence of this intensity concentration near minimum deviation which leads to the formation of solar halos. When sunlight is incident upon randomly oriented ice crystals, then rays which pass through a 60° prism concentrate near a deviation of 22°, and rays which pass through a 90° prism concentrate near a deviation of 46°. If we consider a sky uniformly filled with randomly oriented crystals, and we look away from the sun at an angle of 22° or 46°, then we will see this concentration of light as a circular halo. In other words, the angular radii of the 22° and 46° halos in the photographs are determined by the minimum deviation angles for light rays passing through 60° and 90° ice crystal prisms respectively.



2 *The general result for the deviation in a prism as a function of incident angle is shown in Figure 2(a), whilst calculations for a 60° prism and a 90° prism are shown in Figure 2 (b).*

Dispersion in Halos

Since the refractive index of ice depends on wavelength, one can also simply explain the dispersion observed in the photographs using equation (1). Taking the refractive index of ice for red light as n = 1.31 and for blue light as n = 1.32, the angular radius of the "22° halo" varies from 21.8° for red light to 22.6° for blue light. Similarly, the angular radius of the "46° halo" varies from 45.7° for red light to 47.9° for blue light. Note that because of this strong dispersion, casual observers often confuse incomplete halos with rainbows. However, there are important differences between halos and rainbows, and a comparison of halos and rainbows can stimulate much discussion in a lecture or tutorial situation. In particular, it is important to note that it is the light refracted and **transmitted** through ice crystals which cause a halo, whilst it is the light refracted and **reflected** in water droplets which causes a rainbow. As a result, one must look in the direction of the sun to see a halo, and away from it to see a rainbow. A related effect is the difference in colour ordering seen in rainbows and halos. In a halo, blue light is observed on the outside of the arc and red is observed on the inside, but this colour order is reversed in a primary rainbow which involves a reflection of light inside a raindrop. It is also interesting to note that both the 22° and 46° halo have identical colour ordering (see **Figure 4**) whereas the secondary rainbow (which involves two ▷

3 *This incomplete 22° halo was observed on the 3rd of January from the North Island of New Zealand. The photographer's finger obscurs the sun.*

4 *These portions of 22° and 46° halos were also observed on the 3rd of January from the North Island.*

reflections) has a colour ordering which is the reverse of the primary bow. There are many other features of atmospheric halos that can be used to illustrate lecture treatments of optics, and the discussion here has concentrated only on the most visible features. The references contain more discussion of the mechanisms involved in halo formation, and reference [3] in particular presents the results of Monte Carlo simulations which examine in detail the effects of crystal shape and orientation. It is important to realise, however, that a very good understanding of atmospheric halos can be obtained using only the laws of simple geometrical optics presented here.

Notes on the Photographs

Both authors saw similar halo displays in cirrus cloud on the 3 January, but all the photos were taken by David Hirst with a Nikon F-3 using 35 mm positive slide film. All observations of solar halos should be carried out with extreme caution to avoid eye damage, and halo photographs which include the solar disc should be attempted only if there is very thick cloud cover, or if the sun is completely blocked (using a lens cap, for example). The best approach to halo photography is to take one exposure as recommended by the built-in light meter, as well as exposures over and underexposed by one f-stop.

References

1 R Greenler, *Rainbows, Halos and Glories*, Cambridge University Press, New York (1980).

2 DK Lynch & W Livingston, *Color and Light in Nature*, Cambridge University Press, New York (1995).

3 W Tape, "Atmospheric Halos," *American Geophysical Union*, Washington DC (1994).

4 FL Pedrotti & LS Pedrotti, *Introduction to Optics*, Prentice Hall, New Jersey (1993). ANZP