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The phenomena of conical refraction

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The newly developed techniques for growing large transparent crystals by slow solidification from melts are of great value for those interested in optical investigations with such crystals. In two recent communications,[1,2] attention was drawn to the very striking demonstrations of conical refraction possible with crystals of aromatic organic compounds. A transparent block of naphthalene, a centimetre square and half a centimetre thick, prepared by Mr T M K Nedungadi and mounted between parallel glass plates has enabled me to pursue the subject further and make some observations which appear well worthy of being placed on record.

As mentioned in the earlier communications, the angles of internal and external conical refraction are both large in naphthalene; so much so that conical refraction can be shown in the same way as ordinary birefringence, viz., by viewing a line of print through the crystal block. Figures 1(a) and (b) illustrate the effects observed in this way. It will be seen that a dot in print appears as a circle, and a circle as two concentric rings, when seen through the crystal at the correct orientation.

Several years ago, I noticed and described a very remarkable optical effect[3] associated with conical refraction which is observed when a small luminous object faces a parallel plate of aragonite suitably orientated and held at some little distance from it. A bright erect image of the luminous object superposed on a field of general illumination may then be seen anywhere on a line behind the crystal which is a prolongation of its join with the object. The same effect is shown in a much more striking way by a naphthalene block. Not only is the image seen much more intense than with aragonite, but it can also be traced to much greater distances, indeed up to about a metre, and is visible even when the luminous object is similarly far removed from the crystal. The effect is illustrated by figure 2(a) which is a human profile scratched with a needle on a glass plate covered by black varnish and placed in front of the naphthalene plate, while figure 2(b) reproduces the image of the same received on a photographic plate placed behind the crystal. It will be noticed that the features of the profile are recognizable in the

[1] *Nature* (*London*), 1941, **147**, 268.
[2] *Proc. Indian Acad. Sci.*, 1941, **A14**, 221.
[3] *Nature* (*London*), 1921, **107**, 747.

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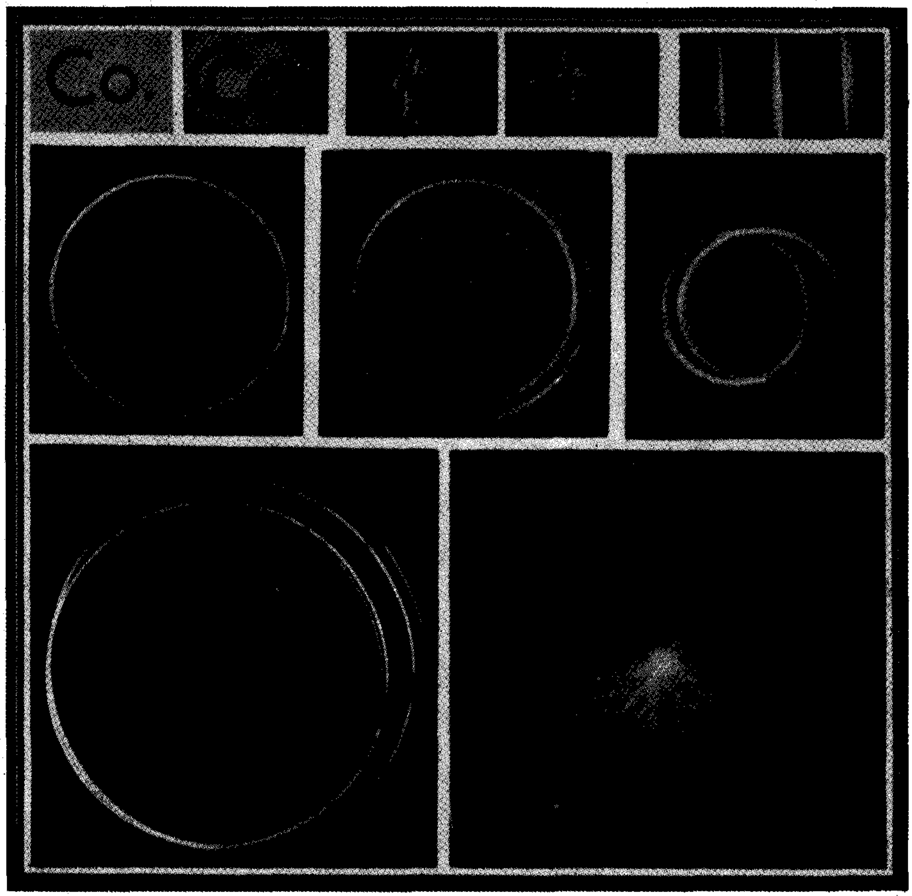
(4) (5 & (

(7) (8)



Figures 1–8. Illustrating conical refraction in biaxial crystals.

image, though slightly distorted owing to the optical imperfections of the crystal. The images formed in this way by the crystal plate show a strong chromatic dispersion, and it is therefore necessary to use monochromatic light (the green rays of the mercury lamp) in photographing the effect.

An explanation of this remarkable property of biaxial crystals was given by me in 1922.[4] This is completely confirmed by the present experiments which show that the phenomenon is of fundamental significance in relation to the physical theory of conical refraction. The image-formation in the rear of the crystal arises from the intense concentration of luminosity which occurs at the singular or

[4] *Philos. Mag.*, 1922, **43**, 510.

conical point on the wave-surface within the crystal. This is shown by the fact that the image is most intense at the rear surface of the crystal where the waves emerge from the crystal at the terminus of the axis of single ray velocity (figure 8). Using a point source of light and covering up the illumination in the field behind the crystal except for a small aperture at the position of the image, the light is found to diverge from the bright spot in the form of a hollow cone. When both the source and the aperture are situated on the faces of the crystal, this is identical with the Hamilton-Lloyd experiment demonstrating external conical refraction.

In the usual discussions of conical refraction, the geometric aspects of the problem receive attention, while the closely related physical aspects are practically ignored, though the latter are as interesting and important as the former. Corresponding to the two geometric properties of the ray-surface discovered by Hamilton, we have two physical properties, namely the intense concentration of intensity at the singular or conical point and the vanishing of the intensity along the circle of contact of the tangent plane with the ray-surface. Both the bright spot and the dark circle surrounding it may be traced to a considerable distance behind the crystal using a point-source of light and a low-power magnifier.

The phenomena exhibited by a naphthalene crystal in certain respects present an exceptional simplicity. The image of a fine pin-hole illuminated by monochromatic light and viewed in perfect focus through the crystal appears as a single sharply defined circle (figure 4), the so-called Poggendorff dark circle being then non-existent. Figure 5 shows the ultra-focal image where the two circles are just separated, and figure 8 the case when the microscope is focussed on the second surface of the crystal, the bright spot at the centre being then conspicuous. Figure 6 is the appearance of a fine illuminated pin-hole seen through a fairly thick plate of aragonite at as near a perfect focus as possible. It will be seen that we have now not a single circle, but two *intersecting* curves, one of which notably departs in shape from circularity. This feature is a general one shown by all biaxial crystals of which the angles of internal and external conical refraction differ sensibly, the coincidence of the two curves in naphthalene being a special feature due to the identity of the two angles.

Figures 3 and 7 illustrate the dispersion of conical refraction as observed with a naphthalene crystal in two different ways. In the former, a straight slit illuminated by the total light of a mercury lamp is employed as the source, and the crystal itself forms the spectral images of the source as already explained. In figure 7, on the other hand, a fine pin-hole is employed as the source (as in figure 4 but with a thicker plate) and is viewed in exact focus. Four distinct circles are then seen corresponding to the four brightest rays of the mercury lamp.

The photographs illustrating this article were obtained for me by Mr V S Rajagopalan.