Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 64 (1984)

Heft: 3

Artikel: The physics of asterism in sapphire

Autor: Moon, A.R. / Phillips, M.R.

DOI: https://doi.org/10.5169/seals-49548

Schweiz. mineral. petrogr. Mitt. 64, 329–334, 1984

The Physics of Asterism in Sapphire

by *A. R. Moon** and *M. R. Phillips**

Abstract

The star image observed in silky sapphire (the optical phenomenon of asterism) is shown to result from the incoherent superposition of reflected Fraunhofer diffraction patterns which arise when light is scattered from precipitates strictly orientated within the sapphire host. The theory explains why long, thin precipitates produce sharper stars than their shorter and wider counterparts and why a cabochon is normally required to observe the star image.

Keywords: Asterism, Precipitates, Sapphire

INTRODUCTION

When so called «silky» sapphire is cut «en cabochon» (i.e. semi-ellipsoidal) with its base perpendicular to the c-axis and is illuminated with parallel light, a six-rayed star appears over its surface. This is the optical phenomenon of asterism. The star axes are perpendicular to precipitate phases which lie in the basal plane of the sapphire orientated along the first or second prism faces of the sapphire host.

A theory recently put forth to explain this phenomenon involves the scattering of light from needle-like precipitates which have a circular cross-section (Weibel et al., 1980; Wüthrich and Weibel, 1982 and Wüthrich et al., 1983). In this theory the light impinging on such a precipitate is scattered into a conical surface, the precipitate being the cone axis. The star image is formed by three bands of light, each band being a rim of a conic section from a scattered cone of light at normal incidence. This explanation of asterism leads to the con-

* Department of Physics, The New South Wales Institute of Technology, P.O. Box 123, Sydney 2007, Australia.

clusion that the star image is independent of the precipitate dimensions. However, it is well known that long, thin precipitates give a sharper star than do their shorter and wider counterparts (FRONDEL, 1954; EPPLER, 1958 and NASSAU, 1981) and that a more desirable star image can be obtained by altering the precipitates dimensions by using an appropriate heat treatment on a cut cabochon (NASSAU, 1981). In view of this and the fact that a cabochon is normally needed to observe the star image an alternate theory of asterism in sapphire to the above is needed.

DISCUSSION

Studies of exsolved phases in both natural (TAIT, 1957; NASSAU, 1968; MOON, 1982; SHARMA, 1982 and MOON and PHILLIPS, 1984) and artifical (PHILLIPS, 1981) star sapphire have all observed needle precipitates having definite rectangular cross-sections (Fig. 1.) ranging from near square to rectangular strips (the shorter dimension being parallel to the c-axis). The needles have lengths ranging up to hundreds of micrometers, cross-sectional dimensions of the order of the wavelength of light and have all been identified as minerals other than the sapphire host.

A scattering theory which can suitably explain the optical phenomenon of asterism in sapphire is Fraunhofer diffraction. By applying Babinet's Principle of Complementary Apertures to a precipitate face lying in the basal plane of the

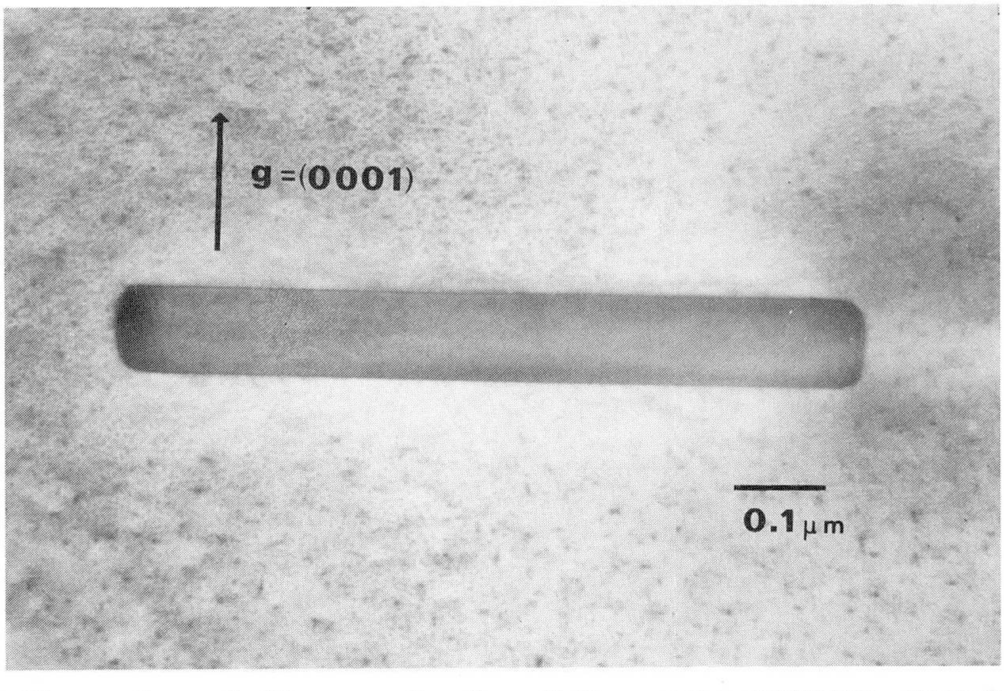

Fig. 1 Electron micrograph of the cross-section of a needle-like precipitate of 0.5 $FeTiO_3 \cdot 0.5 Fe_2O_3$ examined in Australian black star sapphire.

sapphire (allowable due to the difference in refractive index between precipitate and matrix), the precipitate is then equivalent to a rectangular aperture having the dimensions of the precipitate. The distribution of intensity for light Fraunhofer diffracted from a rectangular aperture having width b and length l is given by the formula

$$I \sim b^2 \cdot l^2 \cdot \frac{\sin^2 \alpha}{\alpha^2} \cdot \frac{\sin^2 \beta}{\beta^2}$$

where $\alpha = \frac{\pi \cdot b \cdot \sin\theta}{\lambda}$, $\beta = \frac{\pi \cdot l \cdot \sin\omega}{\lambda}$, λ the wavelength of incident light and θ and ω angles measured from the normal through the centre of the aperture in planes parallel to the width and length of the aperture respectively. For light incident normal to a precipitate having a length much greater than its width, its width being of the order of the wavelength of light, the resulting diffraction pattern is perceived as a narrow continuous band of light perpendicular to the precipitate axis. Each star arm is formed by the incoherent superposition of diffraction patterns reflected from similarly orientated precipitates and thus a narrow band of light is formed. However, as the precipitate length becomes comparable to its width, light is also diffracted in a direction parallel to the precipitate axis. The amount of light diffracted in this direction increases as the precipitate length decreases and the Fraunhofer diffraction pattern resembles a cross (Fig. 2.). When these diffraction patterns are incoherently superposed a wider band of light is formed. Since there are three sets of precipitates which follow

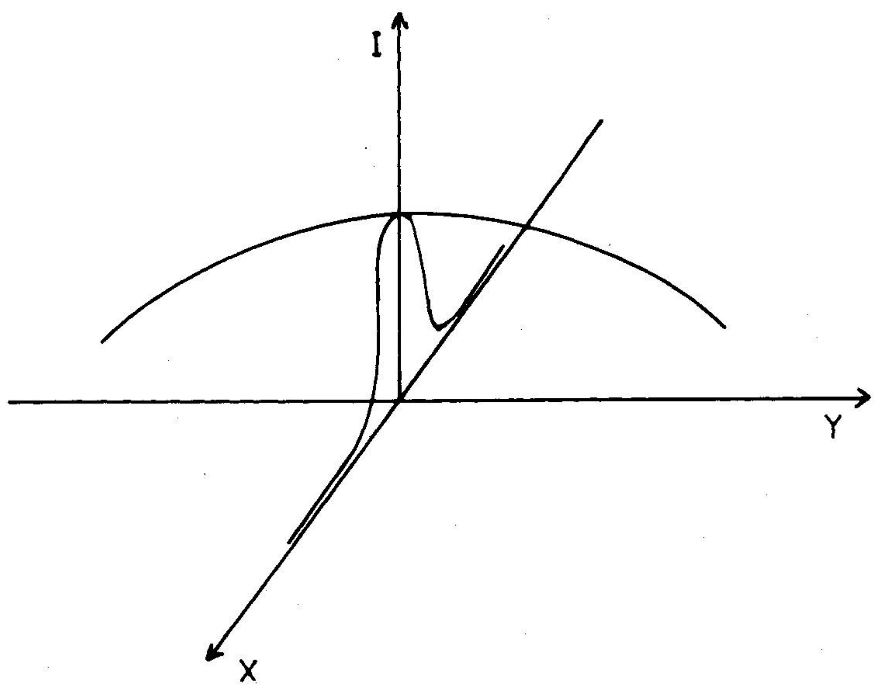

Fig. 2 The Fraunhofer light intensity distribution from a rectangular aperture which has long dimension parallel to X and short to Y. As the length decreases the distribution along X broadens.

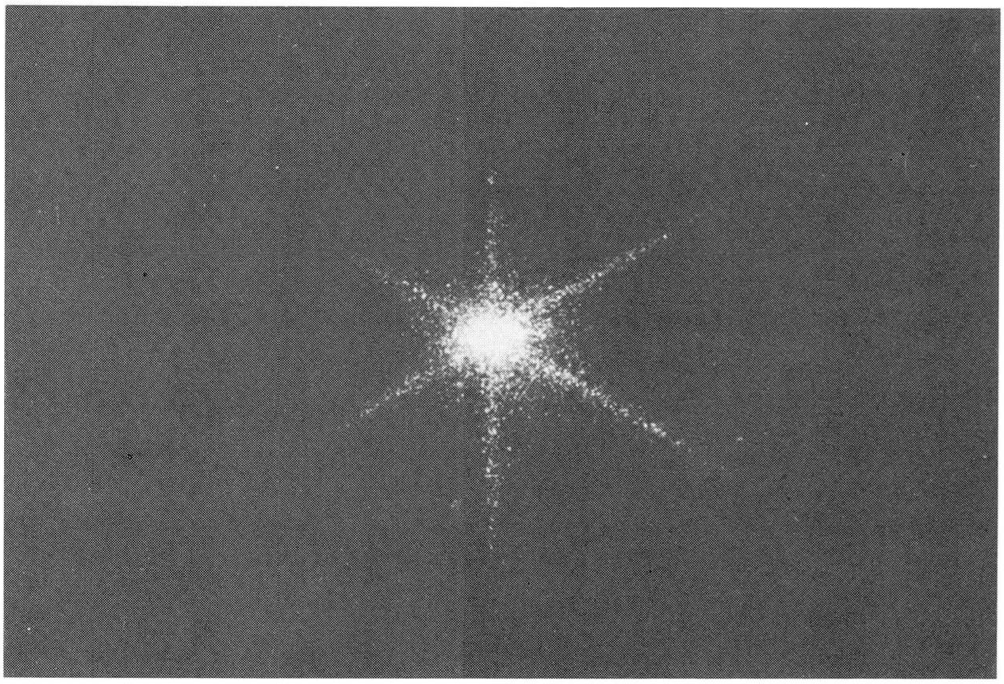

Fig. 3 A six-rayed star formed by illuminating a polished basal section with He-Ne laser light. Note that a focusing lens is not required in this case since the laser light is coherent and has very little divergence.

the trigonal symmetry of the sapphire host (i.e. aligned at sixty degrees to one another) a regular six-rayed star is produced (Fig. 3.). Therefore long, thin precipitates will produce a sharp (narrow) star whereas shorter precipitates will give a wider star with the star image becoming less well defined (wider) as the precipitate length decreases. Even in the case where light is incident normal to a precipitate having a circular cross-section, if such were observed, the Fraunhofer diffraction equation still gives the most accurate representation of the observed distribution of light intensity (LUNBERG, 1968 and BIRKOFF, 1971).

For a Fraunhofer diffraction pattern to be observed two conditions must be satisfied (i) the incident light be parallel and (ii) the plane of observation be at infinity. The first condition is satisfied by having the source illuminating the stone a reasonable distance from it's surface (e.g. direct sunlight). The cabochon does not render the incident light parallel (i.e. collimate the light). Thus, if the light source is too close to the gem's surface a star image is not observed. The cabochon in facts as a biconvex lens which focuses the star image and hence satisfies the second requirement for Fraunhofer diffraction.

For an opaque hemi-spherical cabochon the star image will be focused above the gem at a distance $f = R/2(n-1)$ (Fig. 4.), where R is the radius of curvature and n is the refractive index of sapphire (WÜTHRICH and WEIBEL, 1982 and WÜTHRICH et al., 1983). The location of the star image above the gem is verified by it's parallactic motion, since the apparent displacement of the star is in a direction opposite to an actual shift in observer position. The distance above

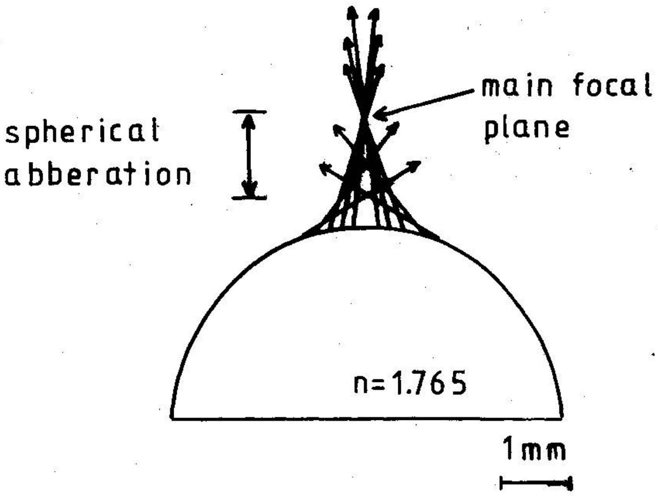

Fig. 4 The star image appears a distance 2 mm above an opaque stone's surface when a cabochon with radius 3 mm is used to focus the scattered light. Note the spherical abberation inherent in the lens.

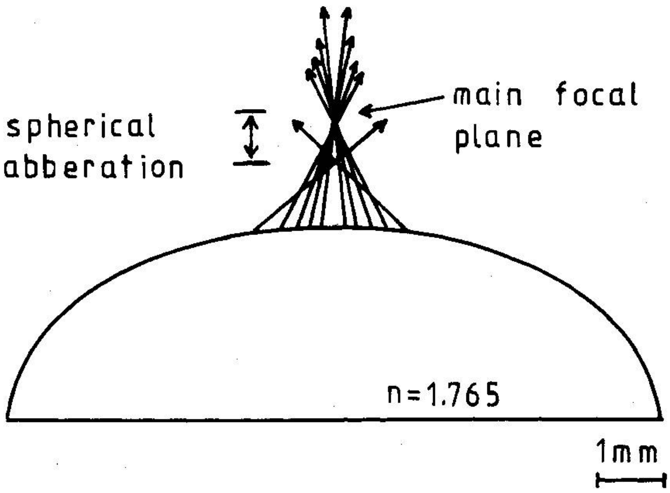

Fig. 5 By aspherising the lens in Fig. 4 (for example the elliptical lens above) a sharper star image is produced since the amount of spherical abberation in the lens is reduced without effecting the focal length.

the cabochon at which the star is focused is also dependent on the opacity of the gem, with the focal length decreasing with it. Opaque stones will give a sharper star image than translucent ones since they focus less incident light which is non paraxial (i.e. they produce less spherical abberation). The perculiar elliptical shape of some cabochons results from firstly an attempt to improve the sharpness of the star image by reducing the spherical abberation (inherent in all spherical lenses) by aspherising the cabochon (Fig. 5.) and secondly from having a star arm parallel to the longer cabochon axis to enhance the aesthetic appeal of the gem.

CONCLUSION

The type of scattering described here is by no means the only type possible. For example, the bluish and reddish borders on the star arms observed by FRONDEL (1954) are certainly the result of Rayleigh scattering. However, the incoherent superposition of Fraunhofer diffraction patterns giving rise to a star image is by far the most commonly observed optical phenomenon in sapphire.

References

BIRKOFF, R. D. (1976): «Light Scattering from Micron-size Fibers», J. Opt. Soc. Am., 67: 564–569.

EPPLER, W. F. (1958): «Notes on Asterism», J. Gemm., 6: 195–212.

FRONDEL, C. (1954): «Commercial Synthesis of Star Sapphires and Star Rubies», Min. Eng. Trans., Jan.: 78–80.

LUNDBERG, J. L. (1968): «Light Scattering from Large Fibers at Normal Incidence», J. Coll. Inter. Sc., 29: 365–585.

MOON, A. R. (1982): «Asterism in Australian Sapphire», Micron, 13: 265–266.

MOON, A. R., and PHILLIPS, M. R. (1984): «An Electron Microscopy Study of the Exsolved Phases in Natural Black Australian Sapphire», Micron, 15, 143–146.

NASSAU, K. (1968): «On the Cause of Asterism in Star Corundum», Amer. Min., 53: 300–305.

NASSAU, K. (1981): «Heat Treating Ruby and Sapphire», Gems and Gemmology, 17: 121–131.

PHILLIPS, D. S. (1980): «Precipitation in Star Sapphire I. Identification of the precipitate», Phil. Mag., A42: 385–404.

SHARMA, TH. G. (1982): «Asterism in Sri-Lankian Corundum», Schweiz. mineral. petrogr. Mitt., 62: 15–20.

TAIT, A. S. (1955): «Asterism in Corundum», J. Gemm., 5: 65–72.

WEIBEL, M., WESSICKEN, R., WOENSDREGT, C. and WÜTHRICH, A. (1980): «Sternsaphir und Sternquarz», Schweiz. mineral. petrogr. Mitt., 60: 133–136.

WÜTHRICH, A. and WEIBEL, M. (1981): «Optical Theory of Asterism», Phys. Chem. Min., 7: 53–54.

WÜTHRICH, A., WEIBEL, A. and GUBELIN, E. (1983): «Elucidating on the Optical Theory of Chatoyancy and Asterism», Aust. Gemm., Feb.: 3–5.

Manuscript received 20 June, 1984.