A $\frac{1}{8}$ Å BIREFRINGENT FILTER FOR SOLAR RESEARCH

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Summary

A description is given of a wide-field birefringent filter having a bandwidth of $\frac{1}{8}$ Å at half-intensity, centred on Hα and tunable over ± 16 Å. Constructional details are included.

I. Introduction

Monochromatic photographs of the Sun are complementary to spectra, in that the latter provide detailed information about physical conditions and their depth variations at highly localized positions on the Sun, while the former provide information on variations across the surface. Birefringent filters of the type developed by Öhman (1938) and Lyot (1944) have been widely used in monochromatic photography of the chromosphere (e.g. flare patrols), prominences, and the corona, being preferred to spectroheliographs for many purposes on the counts of cost, compactness, speed, and convenience. In no case, however, has the spectral resolution approached that of the large spectrographs, the narrowest bandwidth used hitherto being $0 \cdot 5$ Å at half-intensity.

In view of the advantages of filters for studying extended regions on the Sun, we have designed and constructed (with the assistance of many colleagues) a birefringent filter having a bandwidth of $\frac{1}{8}$ Å at half-intensity. Operating at 40 °C, it is centred on Hα and is tunable over a total spectral range of ± 16 Å. It has a nominal total field angle of $2\frac{1}{4}°$ and a circular aperture of 35 mm. The particular bandwidth has been chosen so as to be small compared with that of the Sun's Hα line (rather more than 1 Å), and therefore suitable for a detailed study of chromospheric structure; but it is also comparable to the widths of normal Fraunhofer lines, one of which, the Fe line at $6569 \cdot 2$ Å with a central intensity of $0 \cdot 48$ (Allen 1934), falls conveniently within the tuning range. With the sizes of calcite crystal at present available, it seems unlikely that a much narrower bandwidth could be achieved in a birefringent filter of this type.

The design is described below, together with an account of the construction, which, we hope, will enable many of the difficulties to be avoided in other equivalent filters.

II. Design

The optical design is shown in Figure 1. It is a development from Lyot's original design and incorporates refinements due to Evans (1949). The detailed calculations of the filter characteristics have been computed by a method analogous to that of Jones (1941) and are described by Steel (1961).

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It may be recalled that, in its simplest form, the birefringent filter consists of a series of elements, each composed of a retardation plate of birefringent crystal (usually quartz or calcite) with axes parallel to the faces and lying between

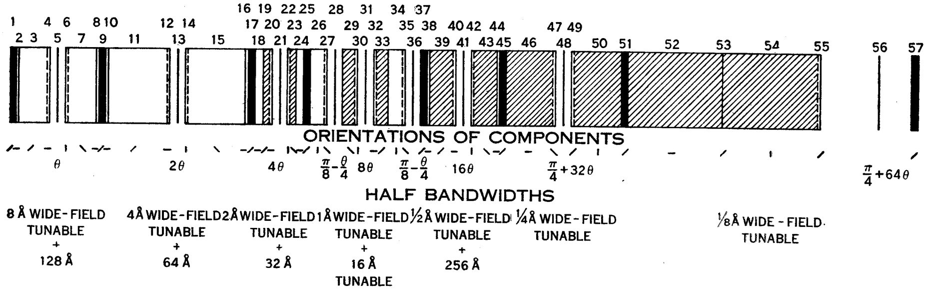


Fig. 1.—Optical design of $\frac{1}{8}$ Å filter. Scale drawing of the layout of the various optical components. For ready identification, calcite components are hatched and polarizers are drawn in black ; half- and quarter-wave plates are shown schematically, and windows before component 1 and after component 55 are omitted. Axis orientation in the surface is shown under each component, together with the relative orientations of the $\frac{1}{2}\lambda$ tuning plates. Details are as follows : 1, 9, 17, 25, 37, 45, 51, 57 : " Polaroid " polarizers, axes diagonal ; 4, 6, 12, 14, 20, 22, 30, 32, 40, 42 : compound quartz $\frac{1}{4}\lambda$ plates, axes parallel to edge ; 27, 35, 47, 49, 55 : compound quartz $\frac{1}{4}\lambda$ plates, axes diagonal ; 5, 13, 21, 28, 31, 36, 41, 48 : compound quartz $\frac{1}{2}\lambda$ plates, directions of axes immaterial ; 53 : compound quartz $\frac{1}{2}\lambda$ plate, axes diagonal ; 56 : mica $\frac{1}{2}\lambda$ plate, axis direction immaterial, mounted in cover glasses with 5′ angle between outer faces.

Tolerances on $\frac{1}{2}\lambda$ and $\frac{1}{4}\lambda$ plates : retardation $\pm 0\cdot 02\lambda$, axis direction $\pm 0\cdot 5°$.

Component	Material	Optic Axis* Orientation to Side	Axes to lie in Surface to within	Approx. Thickness (mm)	Retardation at Hα (λ)
2, 8	quartz	0°	1°	0·9	12¼
3, 7	quartz	45°	0·25°	14·0	192
10, 16	quartz	0°	0·5°	1·8	24½
11, 15	quartz	45°	0·1°	28·0	384
18, 24	quartz	0°	0·25°	3·5	48¼
26, 34	quartz	0°	0·05°	7·0	96
38, 44	quartz	0°	1°	0·45	6¼
19, 23	calcite	45°	0·05°	2·9	743
29	calcite	45°	0·025°	5·8	1 486¼
33	calcite	45°	0·025°	5·8	1 486
39, 43	calcite	45°	0·01°	11·6	2 972
46, 50	calcite	0°	0·005°	23·2	5 944
52, 54	calcite	0°	0·005°	46·4	11 888

* Tolerance on optic axis orientation : 0·5°.

polarizers whose axes bisect those of the retardation plate (Fig. 2 (*a*)). The transmittance of the element is a sinusoidal function of wavelength, i.e. a channel spectrum. In each successive element, the spacing between spectral maxima is halved, the filter as a whole transmitting a set of narrow lines (principal maxima) whose widths are determined by the thickest elements and spacings by the thinnest.

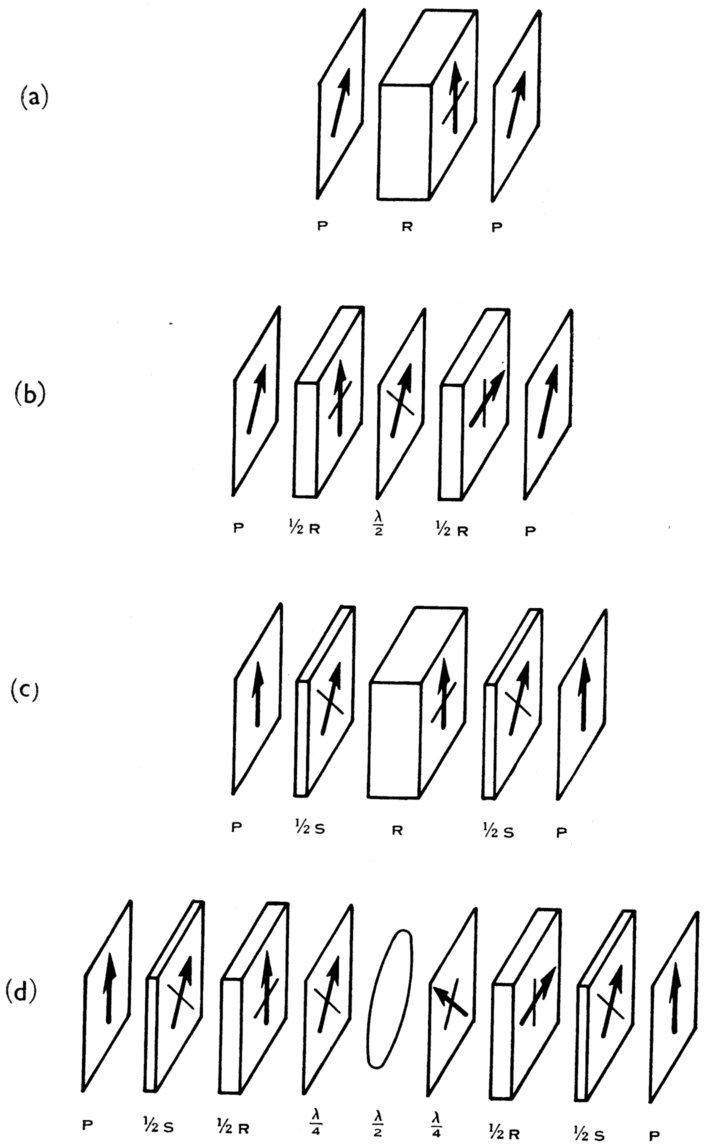


Fig. 2.—Basic types of birefringent filter element. (*a*) The simple element, with a retardation plate *R* between polarizers *P*. (*b*) Lyot's type I wide-field element. The retardation plate is split into halves, with axes crossed, and separated by a $\frac{1}{2}\lambda$ plate. (*c*) Evans's scheme of split elements. One retardation plate *R* lies between the halves of another retardation plate *S*. (*d*) Evans's scheme of split elements with tuning on the inner element. The inner retardation plate of (*c*) is split and separated by a pair of $\frac{1}{4}\lambda$ plates, between which lies a rotatable $\frac{1}{2}\lambda$ plate; retardation plate *R*, but not *S*, is tunable and of the wide-field form.

Axis orientations are shown by the arrows.

At a fixed temperature and wavelength, a simple element has transmittance $\cos^2 \varkappa\pi$, where $\varkappa$ is the retardation in wavelengths. The variation in $\varkappa$ with angle to the normal limits the angular field. If this variation is not to exceed $0 \cdot 1$, then for quartz and calcite retardation plates the semi-fields are both very nearly $40\varkappa^{-\frac{1}{2}}$ degrees; this amounts to about $\frac{1}{4}°$ for a $\frac{1}{8}$ Å simple element. Lyot described several methods of increasing the field; in his type I wide-field form, a retardation plate is split into two equal parts, with axes crossed, and separated by a $\frac{1}{2}\lambda$ plate with axes at 45° (Fig. 2 (*b*)). For quartz and calcite plates, the field is then increased by factors of $18 \cdot 6$ and $4 \cdot 4$ respectively.

Evans's scheme of split elements, used extensively in the $\frac{1}{8}$ Å filter, enables one retardation plate to be placed between the two halves of another, with polarizers outside the combination (Fig. 2 (*c*)). The total number of polarizers is then nearly halved, considerably reducing absorption losses if sheet polarizers are used. The inner plate and the outer half-plates can themselves be made in Lyot's type I wide-field form.

Elements may also incorporate "tuning systems", as described by Lyot and Evans. We have used a system consisting of two $\frac{1}{4}\lambda$ plates with axes crossed and separated by a $\frac{1}{2}\lambda$ plate whose rotation through an angle ψ changes the retardation of the element by $2\psi/\pi$ wavelengths. This system can replace the $\frac{1}{2}\lambda$ plate in a wide-field element (Fig. 2 (*d*)); or can follow a single plate, in which case the second $\frac{1}{4}\lambda$ plate may be omitted if it is followed immediately by a polarizer.

The filter (Fig. 1) contains basically 12 elements, the five pairs of split plates of highest retardation being of calcite, the remainder of quartz. The semi-field is limited to $1 \cdot 13°$ by the thickest calcite element; all calcite elements and the two thickest quartz elements are of the wide-field type, the semi-field of the next thickest quartz element, $2 \cdot 86°$, having negligible influence on the field of the filter as a whole. Each of the five sections lying between consecutive polarizers starting from the left-hand side of Figure 1 is of Evans's split element type, and contains two elements, the central one being wide-field and tunable. The fourth section is modified so that the outer element is also tunable (but not wide-field). The last two sections of the filter contain single wide-field tunable elements.

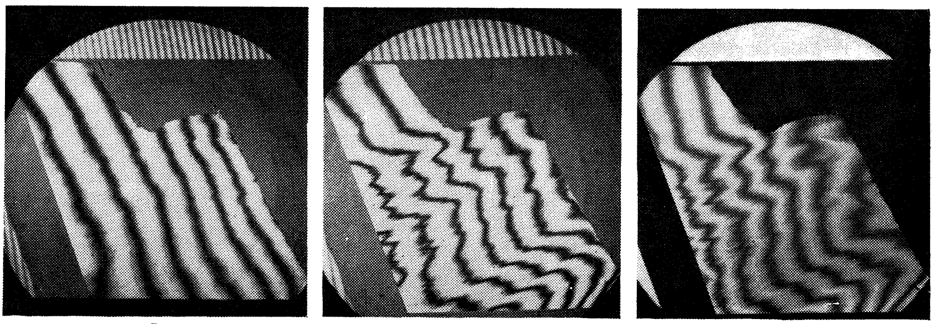
Wavelength variations are achieved by rotating the various $\frac{1}{2}\lambda$ plates in the ratios shown. The whole filter assembly is immersed in oil at a temperature of $40 \pm 0 \cdot 01$ °C.

The optical tolerances require strict attention. For wavelength uniformity across the filter aperture, a high degree of parallelism is needed in every plate; we have attempted to keep the retardation uniform to within $0 \cdot 02\lambda$. Similar tolerances apply to the retardations of untuned plates; these are all outer components of split elements, and the tolerances apply for each half separately as well as to the combination. Giovanelli and Jefferies (1954) have shown that errors of $0 \cdot 5°$ in the alignment of crystal and polarizer axes about the filter axis are negligible; in practice, these errors can be reduced to nearer $0 \cdot 1°$. More stringent tolerances apply to the alignment of the crystal optic axis in the surfaces of wide-field elements, errors causing great asymmetry in the field; nominal tolerances are listed in Figure 1.

III. Optical Construction

While quartz of fairly good homogeneity is available, high quality calcite in the sizes required is virtually unobtainable ; and it has been a major task to make use of imperfect material.

The starting point has been to examine the optical homogeneity of the quartz and calcite interferometrically, the slabs being plane parallel, with the optic axes lying approximately in the surfaces. The thinner quartz plates have been selected from almost perfect material, but almost all the calcite, and to a lesser extent the thicker quartz slabs, though highly transparent and superficially of good appearance, showed serious optical defects of one form or another (Fig. 3). The calcite defects appear mainly in the extraordinary ray, the waveform for the ordinary ray being much the superior in all cases.



(a) (b) (c)

Fig. 3.—Optical quality of one of the calcite crystals with plane parallel faces. (*a*) Interference fringes, ordinary ray. (*b*) Interference fringes, extraordinary ray. (*c*) Birefringent fringes (see text).

After selection, the plates are polished flat* and parallel, slightly oversize, the optic axis being aligned in the surface by trial and error. The test for the latter is the centering of the isochromatic fringe system, checked by rotating the crystal in the plane of its surface ; with sufficient care, the required accuracy can be obtained. With poor material, some prior figuring may be required, as described below, to obtain uniform retardation across the surface.

The optical inhomogeneities can be corrected only by first figuring to achieve uniform retardation ; this results in equal distortions of both ordinary and extraordinary rays. These distortions are then corrected together, as described later. To test for uniformity of retardation, the plate is placed between polarizers and examined in collimated light. A Twyman interferometer was converted for the purpose by covering the comparison mirror (Fig. 4) and inserting a polarizer before the entrance pupil and one near the eye, both with axes at 45° to those of the plate under test. Fringes of equal retardation are then obtained (Fig. 3 (*c*)). This system has an advantage that light passes twice through the plate, thus

* A method of polishing blemish-free high quality optical surfaces on calcite is described by Smartt (1961).

doubling the sensitivity. The crystal is then figured to a uniform appearance. It is helpful at times to place a thin quartz wedge before the plate to provide, say, 5 fringes across the field, any deformations being due to the plate. As light

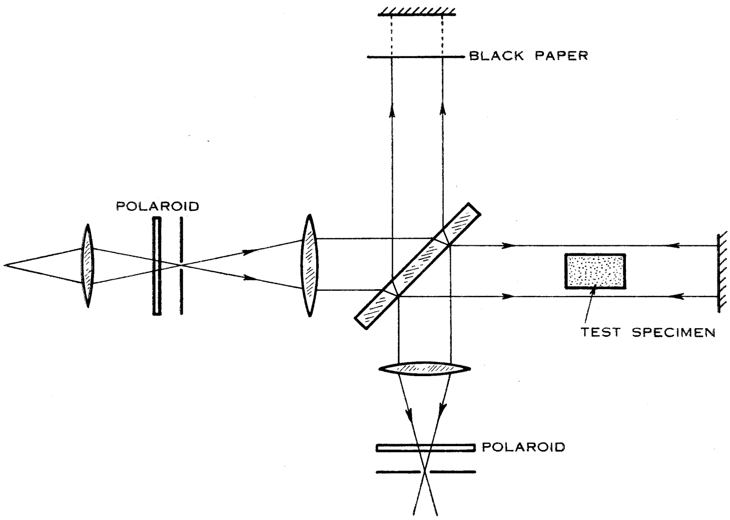


Fig. 4.—Twyman interferometer modified for viewing birefringent fringes. Polarizers are inserted before the entrance pupil and near the eye, with axes at 45° to those of the test specimen. The comparison mirror is covered with black paper.

source, a cadmium lamp with red filter has been used, giving a sharp line close to Hα ; laboratory Hα sources yield lines too broad for satisfactory contrast on thick calcite plates. Figure 5 shows two of the components after figuring.

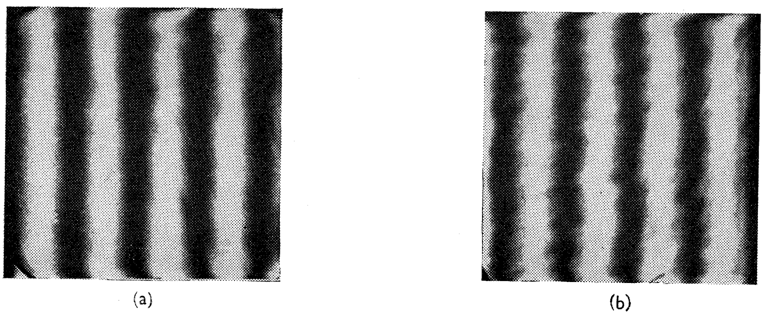


Fig. 5.—Birefringent fringes (double transmission) of each of the two thickest (46 mm) calcite components. A thin supplementary quartz wedge provides several fringes across the surface. The right-hand component is the worst in the whole filter.

In general, unfigured calcite showing a deformation of not more than one-half a birefringent fringe on double transmission, as described above, has proven to be quite satisfactory material, all but one of the 10 calcite components being of this quality or better. The remaining calcite component, one of the two thickest, showed a deformation of nearly two birefringent fringes; exceedingly difficult to figure, its residual errors dominate the wavelength non-uniformity of the filter as a whole.

Adjustment of thickness has been by polishing on the unfigured face. The thinnest elements were made to thicknesses computed from available refractive index data; this subsequently proved a cause of strong secondary spectral maxima, owing to imperfect birefringence data, though measurements by Smartt and Steel (1959) have now provided more accurate values. Elements of intermediate retardation were checked at 40 °C by visual spectroscopic intercomparison of the channel spectra. For the highest retardations, inadequate spectral resolution was available, and checking was made at 40 °C with a Babinet compensator. The latter has special advantages where components are made in pairs, as here; for when crossed their retardations should cancel, giving a central black fringe with collimated white light, while separately they should cancel the sum of the two thinner components. This technique is also valuable in the transition from the quartz to the calcite retardation plates; because of their differing dispersions, matching can be achieved only in a restricted spectral range, but the relevant " white light " fringe can still be identified using a suitable red filter. The accumulation of errors from plate to plate can be eliminated by ensuring an integral number of wavelengths retardation with an Hα source. The Babinet compensator is undoubtedly the simplest and best of the test instruments for adjusting retardation plates of all thicknesses.

The $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$ plates were originally intended to be of mica, but we had great difficulty in splitting mica in parallel sheets without scratching. At one stage it was proposed to cement the mica plates between cover glasses using a mixture of Aroclor 4465 and Canada balsam, of refractive index intermediate to those of mica, to reduce scattered light; but this cement showed a tendency to become cloudy owing to crystallization. An alternative plan had been to immerse the filter as a whole in a fluid of this index. This scheme met with difficulty in the selection of immersion liquids which would attack neither the laminated polarizers nor the sealing gaskets. Mica plates were finally abandoned and replaced by pairs of quartz plates, differing in retardation by either $\frac{1}{4}\lambda$ or $\frac{1}{2}\lambda$ and mounted in opposition. These have the advantages of freedom from scratches, better transparency than mica, and, in the outer 3 mm, better optical performance than a cemented plate, which usually shows marked variations in optical path near the edge. The problem of producing scratch-free mica plates was ultimately solved, nevertheless, and will be described elsewhere by Smartt and Mugridge.

The transparency of the filter depends almost solely on that of the Polaroid polarizers used in it. Very high transparency Polaroid does not polarize completely, though Giovanelli and Jefferies (1954) showed that under some conditions advantage could even be taken of this to reduce parasitic light; it has been impossible to obtain Polaroid having such optimum properties near Hα and remaining satisfactory at longer wavelengths. We have used unlaminated Polaroid K sheet selected by Dr. Schurcliff of The Polaroid Corporation, with a transmittance of 0·89 at Hα for plane polarized incident light (neglecting surface reflections). The immersion fluid (Dow Corning silicone oil 702) has been chosen so that its refractive index (1·512) matches that of the Polaroid (1·50) fairly closely, thus eliminating optical defects due to surface ripples.

The final stage in optical construction is the correction for wave-front distortions introduced in figuring the retardation plates. We have already mentioned that the ordinary ray is scarcely affected by crystal inhomogeneities so that, in principle, the wave-front could be restored by the use of a liquid or cement matching the refractive index of the ordinary ray. No satisfactory liquids or cements of this high index have been found, though wave-front distortions are reduced considerably on immersion even in the lower index silicone oil. Three glass plates, refractive index 1·65, have been distributed through the filter, figured to correct for residual defects in neighbouring components.

IV. Assembly

The optical components are mounted in a cell, temperature controlled to $40\pm0\cdot01$ °C, containing suitable gearing for rotating the various $\frac{1}{2}\lambda$ plates for varying the wavelength. The four thickest calcite elements are tuned from the one shaft, the remaining tuned elements from another, and the two shafts can be rotated independently or together to give rapid or fine variation of wavelength over a range of 16 Å on either side of Hα.

The assembly has been monitored in detail by examining the spectrum of the light transmitted by the separate elements ; this has enabled the adjustments of the rotatable $\frac{1}{2}\lambda$ plates to be optimized individually. The ability to do this has an important bearing on the accuracy of retardation required for the quartz and calcite plates, for the transmittance of any tunable element can be maximized on Hα. Even so, it is necessary to control the element thickness to some extent, for parasitic light can otherwise become serious. A tolerance of $\pm\frac{1}{4}\lambda$ on the sum of the retardations of the two halves of each tunable element is adequate, ensuring a displacement of no more than $0\cdot02\lambda$ in the retardation at the next primary maxima ; for various reasons, manufacturing tolerances were kept much below this value. In practice, the major source of parasitic light has originated from small errors in the retardations of the thin untuned elements.

The large number of re-entrant parts in the filter cell has necessitated considerable care in the elimination of air bubbles, and deep channels have been needed in the cell to allow for ready penetration of the oil and escape of air. Provision has been made for thermal expansion of the oil by attaching a flexible Nylex tube, sealed at one end, to an outlet in the cell wall. Neoprene has been chosen, after considerable testing, as the most suitable material for the various seals around the end windows and control shafts.

V. Performance

Interferometer tests on the transmitted wave-front with an incident plane wave show deformations of a somewhat irregular nature amounting to nearly $\frac{1}{2}\lambda$ across the full aperture. These arise almost entirely from deformations of the end windows, particularly the one nearer the $\frac{1}{8}$ Å element. While they could undoubtedly be largely eliminated by reassembly, they are harmless in view of the particular way the filter is to be used, with only a narrow cross section to any image-forming cone of rays.

The spectrum shows a number of subsidiary maxima at multiples of 32 Å from Hα, arising from the untuned elements, and the next primary maximum near 6100 Å has a much poorer profile than that at Hα. On the long wavelength side of Hα, the subsidiary maxima become very strong, owing to the falling off in quality of the polarizers. An auxiliary narrow-band red interference filter, centred on Hα, is needed to remove this parasitic light; the present filter has a half-width of about 180 Å (central transmission 89%), appreciably reducing though not completely eliminating the stray light.

Wavelength uniformity across the filter is difficult to test directly, and is probably easiest assessed from the residual retardation defects in the poorer of the thickest calcite components (Fig. 5). These are about $0 \cdot 1\lambda$, corresponding to wavelength fluctuations over a range of 1/80 Å.

The profile of the principal maximum near Hα has been examined with a Fabry-Perot interferometer constructed by Dr. C. F. Bruce for length-standard determinations. The detailed analysis needed for the wings and secondary maxima has not yet been undertaken, but over the main part of the principal maximum the profile is close to theoretical.

The transmittance maximum has been measured without the final polarizer; it is 13%. With either a further Polaroid or a polarizing beam-splitter this would be reduced to 12%.

VI. Simultaneous Observations in Two Wavelengths Spaced $\frac{1}{8}$ Å Apart

For some purposes it is desirable to make observations in two wavelengths simultaneously, so that atmospheric distortions are identical on each. This can be done for wavelengths $\frac{1}{8}$ Å apart as follows.

If the final polarizer is replaced by a polarizing beam-splitter which separates two beams plane polarized at right angles to one another, the final element produces two sets of complementary channel spectra with maximum $\frac{1}{8}$ Å apart. These are each superimposed on the transmission spectrum of the remainder of the filter, which has a bandwidth of $\frac{1}{4}$ Å at half-intensity. On turning the final $\frac{1}{2}\lambda$ plate through $22\frac{1}{2}°$ from its normal position, the two beam-splitter images are centred $\pm\frac{1}{16}$ Å from the nominal wavelength.

The beam-splitter is shown in Figure 6. A layer of calcite is sandwiched between two glass prisms at such an angle that total internal reflection occurs for the extraordinary ray (R.I. 1.485) but not for the ordinary ray (R.I. 1.654), which passes through the calcite. The glass, Schott SF17 (R.I. 1.645), has been selected so as to avoid appreciable reflection of the ordinary ray. It was originally intended to oil the prism assembly together with a liquid of the same refractive index, but it has proven impracticable to secure a surface on the long thin calcite component sufficiently flat to avoid distortion of the reflected image. The calcite has therefore been contacted optically onto the flat face of the front prism, the remainder of the assembly being oiled together with Aroclor 1254 (R.I. 1.64).

VII. Discussion

In retrospect, we must admit that the design of the filter could have been improved in many ways. Some modifications could be incorporated if the filter cell were redesigned; others are only possible in a completely new filter.

The most important modification would be to tune the quartz and calcite sections separately from outside. These sections could be adjusted independently at any temperature during assembly, and could subsequently be matched at any other convenient temperature; in the present filter, the quartz and calcite elements match only at 40 °C. Also, as much of the light transmitted outside the central band is due to errors in retardation of the untuned elements, a completely tuned filter is worth consideration.

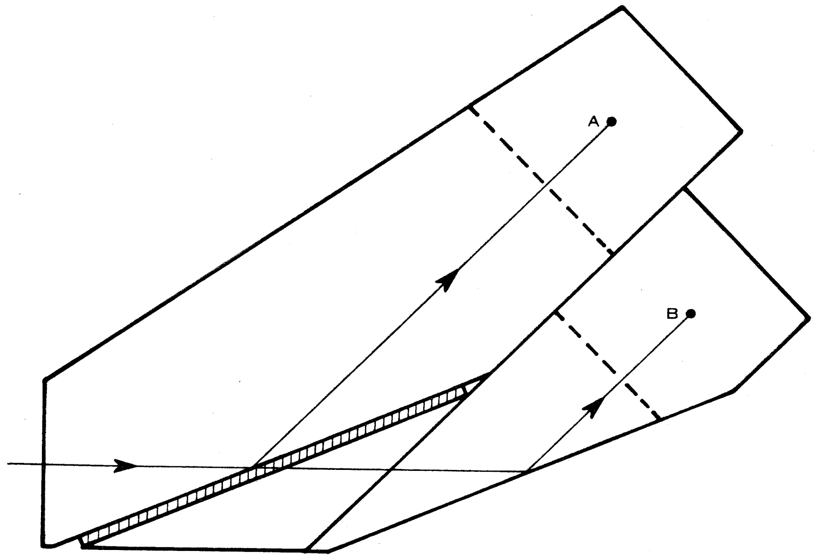


Fig. 6.—Polarizing beam-splitter. A plate of calcite (hatched), with its optic axis perpendicular to the plane of the diagram, is sandwiched between glass prisms, the extraordinary ray being reflected and the ordinary ray transmitted. Faces at 45° reflect the two rays upwards (perpendicular to the plane of the diagram) at A and B, the dimensions being such that the two images are in focus simultaneously on a plane parallel to that of the diagram.

A filter combining these two modifications could be tuned over a wide range of wavelengths, as the separate tuning would allow correction to be made for the differing dispersions of birefringence of quartz and calcite. The tuning range would be limited by the variation of retardation of the $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$ plates with wavelengths, though these can be reduced by using " achromatic " combinations of plates as proposed by Pancharatnam (1955) and Koester (1959). Such composite wave plates could even be tuned themselves to ensure correct retardation at any wavelength; the tuning would be very complex in practice, but in principle a filter could be made to tune to any wavelength.

In any future design of a narrow-band birefringent filter, the use of natural calcite should be avoided if possible. It seems likely that artificially grown crystals would have fewer imperfections. An obvious possibility is sodium nitrate with $1\frac{1}{2}$ times the birefringence of calcite, but further work is required on techniques for producing optical surfaces and controlling the thickness of a crystal of such high water solubility.

VIII. Acknowledgments

The construction of this filter has involved the closest cooperation of many colleagues who have made major contributions to its success. The optical assembly and most of the experiments on materials were undertaken by Mr. G. Norton and Mr. E. G. V. Mugridge. Mr. J. T. Jefferies assisted in various aspects of optical tolerancing and assembly. Mr. A. F. Young has supervised the various electronic controls involved in the final filter unit and in test equipment. The mechanical design of the filter cell is due to Mr. R. Riches, its mechanical construction to the Laboratory's workshop staff. Dr. R. G. Wylie made available a precision temperature controller and assisted materially in problems concerning thermal insulation. Dr. C. F. Bruce, of the Division of Metrology, kindly made a Fabry-Perot interferometer available for profile measurement.

IX. References

Allen, C. W. (1934).—*Mem. Commonw. Solar Obs. Aust.* **1** (5) : 65.

Evans, J. W. (1949).—*J. Opt. Soc. Amer.* **39** : 229.

Giovanelli, R. G., and Jefferies, J. T. (1954).—*Aust. J. Phys.* **7** : 254.

Jones, R. C. (1941).—*J. Opt. Soc. Amer.* **31** : 488.

Koester, C. J. (1959).—*J. Opt. Soc. Amer.* **49** : 405.

Lyot, B. (1944).—*Ann. Astrophys.* **7** : 31.

Öhman, Y. (1938).—*Nature* **141** : 157.

Pancharatnam, S. (1955).—*Proc. Indian Acad. Sci.* **41A** : 130, 137.

Smartt, R. N. (1961).—*J. Sci. Instrum.* **38** : 165.

Smartt, R. N., and Steel, W. H. (1959).—*J. Opt. Soc. Amer.* **49** : 710.

Steel, W. H. (1961).—C.S.I.R.O. Aust. Nat. Stand. Lab. Tech. Pap. No. 17.