5. BIREFRINGENT FILTERS

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The birefringent filter is a relatively new instrument in solar research. Like the spectroheliograph and spectrohelioscope, it is a sharp-band monochromator for observing the sun in the light of a single line of the spectrum, but the principle on which it operates is totally different, with some substantial advantages and some limitations.

On the credit side, the birefringent filter transmits the whole image of an extended source simultaneously rather than by dissecting and reconstructing the image in a scanning process. It is much less difficult, therefore, to realize the best definition permitted by the inherent limitations of the optical system and the prevailing quality of seeing; and the image brightness is much higher than that of a scanning instrument (when integrated over a scanning cycle). The greater light transmission is helpful in prominence photography and quite essential in photographing the relatively faint emission corona through a coronagraph.

The birefringent filter is a comparatively simple instrument and correspondingly inexpensive. It is sufficiently compact to be readily attached
to an ordinary 4-inch equatorial telescope. In fact, such a combination constitutes a powerful research tool for studies of prominences and (provided that the transmission band width is less than 1 Å) for those investigations of the monochromatic features on the disk of the sun which can be carried out at a fixed wave length with little or no adjustment for radial velocities.

In its simplest form the filter suffers from two limitations. It can be made to operate at several fixed wave lengths of astrophysical interest, but it lacks the ready wave-length adjustment of the spectroheliograph. It also has a restricted field. Both limitations can be overcome by more complicated constructions, but a wide-field filter of adjustable wave length is several times as expensive as a simple filter.

Filters now in operation have effective band widths at Hα varying from 20 to 0.5 Å. Band widths up to 10 Å are excellent for prominence research, while the sharper bands are necessary for studies of flares, plages, dark filaments, and other phenomena on the disk of the sun.

The birefringent filter was first proposed by Lyot (1933). Öhman (1938) independently invented it and made the first operating sample in 1938, with an effective band width at Hα of 20 Å. Lyot (1944) and Evans (1949) have published the most complete discussions of the theory of the simple filter and of the more complicated forms, which give wide-field and wave-length adjustment. Evans included also a split-element form, which uses only half as many polarizers as the simple filter, greatly enhancing the light transmission. Billings (1947) has also discussed wave-length adjustment and has proposed an electrical method of "tuning." The practical details of the construction of a simple filter of quartz are described by Dunn (1951).

The following discussion deals with the simple filter only and takes, as an example, one that has been effective in observing prominences since 1942, mounted on the 5-inch coronagraph at the Climax, Colorado, station of the High Altitude Observatory. Its transmission band at Hα has an effective width of 4.1 Å. Figure 17 shows a prominence photographed through this filter.

Figure 18 is a diagram of the Climax filter. The b-elements, b₁ to b₆, are cut from crystal quartz with the optic axis parallel to the end surfaces within 0.001 radian. The first element, b₁, has a thickness, d₁ = 1.677 mm. The thicknesses of successive elements increase in powers of 2, and d₆ = 53.658 mm. All the b-elements are mounted with their crystal optic axes parallel. Between them, and at each end, are polaroid films, p, oriented parallel to each other, with the plane of polarization at 45° to the direction
Fig. 17.—Prominence photographed through the Climax birefringent filter
of the optic axes of the \( b \)-elements. The outside piece at each end is a simple glass window. Adjacent surfaces are immersed in liquid balsam to reduce intersurface reflections.

The theory of the filter is quite simple. Because of the difference in the rate of propagation of the ordinary and extraordinary waves in the birefringent medium, interference occurs. The transmission of an element, \( b_i \), of thickness \( d_i \), mounted between polarizers, is

\[
\tau_i = \cos^2 \pi n_i,
\]

where \( n_i \) is the order of interference, given by

\[
n_i = \frac{d_i}{\lambda} (\epsilon - \omega).
\]

Here \( \epsilon \) and \( \omega \) are, respectively, the extraordinary and ordinary refractive indices of the birefringent material. Since \( d_i = 2^{i-1} d_i \), the transmission of an assembled filter of \( l \) elements is

\[
\tau = \cos^2 \pi n_1 \cos^2 2\pi n_1 \ldots \cos^2 2^{l-1}\pi n_1.
\]

In the Climax filter \( l = 6 \), \( n_1 = 23 \), and \( n_6 = 736 \) at \( Ha \).

The characteristics of \( \tau \) as a function of wave length are exhibited in Figure 19. For simplicity, only three \( b \)-elements are considered. Curves \( a \),
\( b \), and \( c \) represent the transmissions of \( b_3, b_2, \) and \( b_1 \) individually. Curve \( d \) is the transmission of the three combined. The effects of adding further \( b \)-elements with thicknesses increasing in powers of 2 will be evident.

The transmission curve for the whole filter consists of widely separated sharp transmission bands, the effective widths of which are the half-widths of the maxima due to the thickest element alone (curve \( a \)). Let the effective width by \( \delta \lambda \). Then

\[
\delta \lambda = \frac{\lambda}{2 n_e} \kappa, \tag{4}
\]

where

\[
\frac{1}{\kappa} = \frac{\lambda}{\epsilon - \omega} \frac{\partial (\epsilon - \omega)}{\partial \lambda} - 1. \tag{5}
\]

![Diagram showing transmission curves for a three-element filter](image)

FIG. 19.—Transmission-curves for a three-element filter: each element separately and combined effect.

The factor \( \kappa \) takes account of the dispersion of \( \epsilon - \omega \) and is always in the neighborhood of 0.9 numerically.

The bands coincide with the maxima of \( b_1 \) (curve \( c \)) and are interspersed with \( 2^t - 2 \) secondary maxima. The aggregate graphical area of the secondaries between two successive bands in the transmission curve of a filter of four or more \( b \)-elements (corresponding to curve \( d \)) is about 0.11 the area of a single principal maximum.

Equations (2), (3), and (4) suffice for the design of a simple birefringent filter. The wave lengths of the transmission bands are fixed by \( b_1, \) and the band width by the order of interference in the thickest \( b \)-element. The thickness of \( b_1 \) should be sufficiently small to separate successive bands.
enough to permit the suppression of all but the particular band for which the instrument is to be used. This is accomplished by inserting appropriate glass or gelatin filters or one of the sharper interference filters, as have recently become available.

In designing the optical system, certain restrictions on the directions of the light entering the filter must be observed. Let \( \varphi \) be the angle in air between a ray and the instrumental axis, and \( \theta \) the azimuth of the plane of incidence, measured from the direction of the crystal optic axis of the \( b \)-elements. The wave length of the center of the transmission band varies appreciably with \( \varphi \) and \( \theta \). The wave-length shift, \( \Delta \lambda \), is given by the relation

\[
\Delta \lambda = \frac{\varphi^2}{2\omega} \left( \frac{\cos^2 \theta}{\epsilon} - \frac{\sin^2 \theta}{\omega} \right) \quad \text{(for positive crystals), } \quad (6)
\]

or

\[
\Delta \lambda = \frac{\varphi^2}{2\omega} \left( \frac{\sin^2 \theta}{\epsilon} - \frac{\cos^2 \theta}{\omega} \right) \quad \text{(for negative crystals). } \quad (7)
\]

For most purposes a maximum \( \Delta \lambda \) about one-fifth of the effective band width can be tolerated. This sets a definite maximum to the value of \( \varphi \) in a circularly symmetrical optical system. As long as this restriction is observed, the filter can be placed in either collimated or convergent light. The best polarizing films have some optical imperfections and scatter a certain amount of light. The objectionable effects of these faults will be minimized if the filter is placed in convergent light as near an image plane as possible and if its full aperture is utilized (rather than a small central portion) in either convergent or collimated light.

Figure 20 shows various optical arrangements which are in use with birefringing filters. Modifications are, of course, possible.

The Climax filter is mounted in convergent light in an arrangement similar to Figure 20, a. The maximum permissible \( \Delta \lambda \) is 0.8 A. The corresponding value of \( \varphi \) (max.) is 0.025 radian. Accordingly, the convergent beam entering the filter can have a focal ratio as large as \( f/20 \), provided that a field lens imaging the entrance aperture at infinity precedes the filter. Actually, it works at \( f/33 \) to provide an image large enough to fill the filter aperture. In collimated light (Fig. 20, c) the angular radius of the field as seen from this filter would be restricted to 0.025 radian.

Temperature variations are a disturbing factor in the operation of a birefringing filter. In a quartz filter the wave length of the transmission band shifts 0.7 A per 1° C change in temperature. Hence the temperature must be controlled to about 0.5° in the Climax filter. This is accomplished by mounting the filter elements in a thick aluminum shell, around which
heater wire is wound. A thermostat in a well in the aluminum controls the electric current to the heater wire to hold the temperature at 35°5 C. The arrangement is shown in Figure 18.

Since \((e - \omega)\) is not always known with sufficient accuracy to fix the position of the transmission band within a fraction of 1 A, the fine adjustment of the temperature control is useful. This is particularly so when more than one of the transmission bands is to be used, since it is generally impossible to design a filter with more than one band at exactly specified wave lengths. Small deviations can be corrected by changes in temperature.

![Diagram of optical arrangements with birefringent filter](image)

**Fig. 20.**—Optical arrangements with birefringent filter; (a) usual arrangement at Climax, (c) collimated light.

A disturbing influence in the temperature control of the filter is the heating due to the absorption of practically all the incident sunlight. The absorption takes place in the polarizers, each of which absorbs half the light incident on it and dissipates the resulting heat by warming the adjacent \(b\)-elements. One can minimize this effect by inserting the auxiliary filters ahead of the birefringent filter and placing the thin elements of the latter first, since they are comparatively insensitive to the small shifts in wave length due to solar heating. By the time the light reaches the more sensitive thick elements, it has been so diluted by the preceding polarizers that the heating effect is negligible.

Although any optically clear and homogeneous birefringent crystals, either uniaxial or biaxial, can be used for the \(b\)-elements of a birefringent filter, some have more favorable characteristics than others.
To the writer's knowledge only quartz, calcite, and laboratory-grown ammonium dihydrogen phosphate (ADP) have so far been used. The relevant optical characteristics of these materials at the wave length of $H\alpha$ are shown in Table 2 for a temperature of 18° C. Both $\epsilon$ and $\omega$ vary only slightly with wave length.

Quartz is excellent for filters with band widths down to about 3 Å. It is easy to work, and the tolerance in the thickness of a $b$-element is ±0.0015 mm. The thicknesses begin to be inconveniently large, however, for smaller band widths. Calcite does the same work with only about one-eighteenth the thickness and is excellent for the high-order elements in filters with $\delta \lambda$ as small as 0.3 Å. However, it is more difficult to work than quartz, and the tolerances are only one-eighteenth as large. In spite of the difficulties, successful filters with transmission bands of less than 1 Å have been made, with quartz in the low-order elements and calcite in the high-order elements, by Lyot and at the High Altitude Observatory.

Ammonium dihydrogen phosphate has a favorable value of ($\epsilon - \omega$), intermediate between quartz and calcite. Unfortunately, it is very difficult to work accurately, being highly soluble in water and rather soft. Once an ADP filter is made, it is difficult to use because of its extraordinary sensitivity to temperature variations. However, some ADP filters with $\delta \lambda = 1.25$ Å are in service for solar-flare studies at the Sacramento Peak Station of Harvard College Observatory and at the United States Naval Observatory.

The usefulness of the simple filter is enhanced if it is designed for more than one line of importance. Lyot discovered that if $N_1 = 15\frac{1}{2}$ at $H\alpha$ (and $b_1$ is placed between crossed polarizers), the bands can be brought into coincidence with no less than 6 lines of major interest. The Climax filter, with $n_1 = 23$ at $H\alpha$, also transmits the λ 5303 coronal line. Another High Altitude Observatory filter with $n_1 = 22$ at $H\alpha$ transmits the K line.

In prominence observation an occulting disk in the primary image, cutting off the intense photospheric light, is a great advantage. The eyepiece

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**Table 2**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\epsilon - \omega$</th>
<th>$\omega$</th>
<th>$\Delta \lambda / \Delta T^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz...</td>
<td>+0.009030</td>
<td>1.541899</td>
<td>-0.7</td>
</tr>
<tr>
<td>Calcite...</td>
<td>-.16977</td>
<td>1.65438</td>
<td>-0.4</td>
</tr>
<tr>
<td>ADP.......</td>
<td>-0.0444</td>
<td>1.5212</td>
<td>-7.0</td>
</tr>
</tbody>
</table>

* Units 1 Å and 1° C.
or camera is placed at a second image. Without the occulting disk the photospheric light is scattered over the entire field by the polaroid films, drowning out all faint detail.

A similar effect occurs when the filter is used with mirrors, either in a coelostat or in an objective. The reflecting surfaces scatter intensely at small angles to specular reflection. The contrast we obtained with the best mirrors was far inferior to that obtained with an ordinary achromatic lens. Similar experiences have been reported by Lyot.

The quantity of scattered light from within the filter or from reflecting surfaces is much reduced when the effective band width is less than 1 A. This is particularly so when the band is centered on a heavy absorption line like Ha, since the photospheric light transmitted by the filter is then greatly reduced. An occulting disk is then less important, and the filter works well with a reflecting system.

The transmission curve of a birefringent filter resembles that of a Fabry-Perot interferometer, and the idea of using an interferometer in series with a birefringent filter or a pair of interferometers in series must have occurred to many investigators (Evans, 1940). The practical difficulties of adjustment and stability and the low transmission of the interferometers have so far hampered application. However, recent experiments with solid Fabry-Perot filters by B. H. Billings show decided promise. The most important factor in these experiments is the use of highly efficient reflecting “surfaces” composed of multiple evaporated layers of dielectric materials of alternately high and low index of refraction. The layers are deposited in controlled thicknesses so gauged that the waves reflected from the interfaces emerge in phase. The reflecting power thus attained is around 0.99 over a fairly broad spectral region, and the absorption losses are negligible. A Fabry-Perot interferometer made with these surfaces has an extraordinarily small ratio of band width to separation and very little residual transmission between bands. The transmission in a band is 0.7 or better, which is a vast improvement over the usual 0.01 or 0.02 of the conventional interferometer.

If we are to use such an interferometer as a filter for solar research, we still face a difficult mechanical problem. In order to space successive transmission bands sufficiently far apart in the spectrum, the thickness of the interferometer must be only about 30 wave lengths or 0.02 mm in air, and, of course, it must be very constant. Billings has solved this problem by making a solid interferometer consisting of a carefully cleaved sheet of mica with reflecting surfaces on both sides. The whole thing is cemented to
an optically flat glass surface. If the cleaving is skilfully done, the mica sheet has a very uniform fixed thickness.

Since no way has been found to cleave the mica to an accurately predetermined thickness, it is impossible to make an interferometer with an on-axis transmission band centered on a given line like Ha. The interferometer can be tuned to some extent by tilting it off-axis. This moves the transmission bands to shorter wave lengths but reduces the angular field over which the wave-length variations remain within the tolerance. One of these experimental solid interference filters with a 3 A band has been successfully tried for prominence observation, and another one with sharper bands is being prepared for the solar disk itself.

There is reason to hope that before long it will be possible to produce solid interference filters at a lower cost than equivalent birefringent filters. The small field will, to some extent, be compensated by the greater transmission and the shorter exposures required for faint objects like the corona. A scanning mechanism might be devised for photography of large areas. Since it need not involve image dissection and reassembly, such scanning need not have any adverse effects on definition.

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6. THE CORONAGRAPH

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The basic difficulty in the observation of the solar corona without an eclipse is due to the presence of an intense spurious halo around the sun, produced by light from the solar disk scattered in the terrestrial atmosphere and in the observing telescope itself. At a distance of 1 minute of arc from the sun’s limb, the brightness of this scatter halo is ordinarily about 1000 millionths the average brightness of the sun, while in white light the corona, which must be seen through it, has a brightness of only 1