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TEMPERATURE CONTROL SPINDLE STAGE

D. JEROME FISHER, *Rosenwald Hall, University of Chicago, Chicago, Illinois.*

ABSTRACT

Herein is described a simple temperature control spindle stage, together with the recommended operation procedure. For accurate double variation work, it is considered that a stereogram with extinction curves would normally be required. It is recommended that for the sake of simplicity and easy visualization, the plane of the stereogram be normal to the spindle axis. This technique is illustrated by the study of a Black Hills morinite crystal, and new values for its indices of refraction are given. It is considered that the double variation spindle technique is much simpler, quicker, and definitely more accurate than the U-stage double variation method of index determination.

INTRODUCTION

The writer has long had a Vigfusson-type temperature control stage, modified slightly so that it sits down in the microscope stage when the central plate of the latter is removed (Fig. 1). Intrigued by the enthusiastic report of Wilcox (1959) on the value of the spindle stage for determining indices of refraction in anisotropic crystal grains, the writer had the temperature control stage converted to handle a spindle (Fig. 2) by cutting a V-notch in its upper plate and adding a support bar with bearing. The crystal is mounted on the slightly pointed end of a stiff steel wire (.018″ diameter and 37 mm long) using the 4 glue:1 molasses cement[1] recommended by Wilcox. This wire is held in the spindle by friction. The V-notch is cut practically to the level of the upper glass plate. In case one wishes to do *x*-ray work on the same crystal, the latter is mounted on a short glass capillary into which is stuck the end of a shortened and pointed piece of the .018-inch steel wire. The spindle can be rotated completely around, contrary to the stage of Wilcox, a necessary condition to attain accuracy, as is demonstrated later. The steel wire is held snugly in its notch by means of a spring bronze clip (Fig. 2) which is fastened in place by sliding it under a pair of screw heads. The upper glass plate of the stage has a couple of small thin glass squares cemented to it, similar to those shown in Hartshorne and Stuart (1960, Fig. 287), to support a small cover glass, but the latter is unnecessary when working with a high-power objective. The synchronous polar microscope (Fig. 1) is very handy in this work, not only because rotating the stage with its attached rubber hoses is a nuisance, but also because one has no trouble keeping the objective centered on the crystal as it is rotated on the spindle by slightly adjusting the centering screws on the nosepiece.

[1] This cement is very handy for originally mounting the crystal. However it should be armored with water glass if the crystal is to be studied at above-room temperatures.

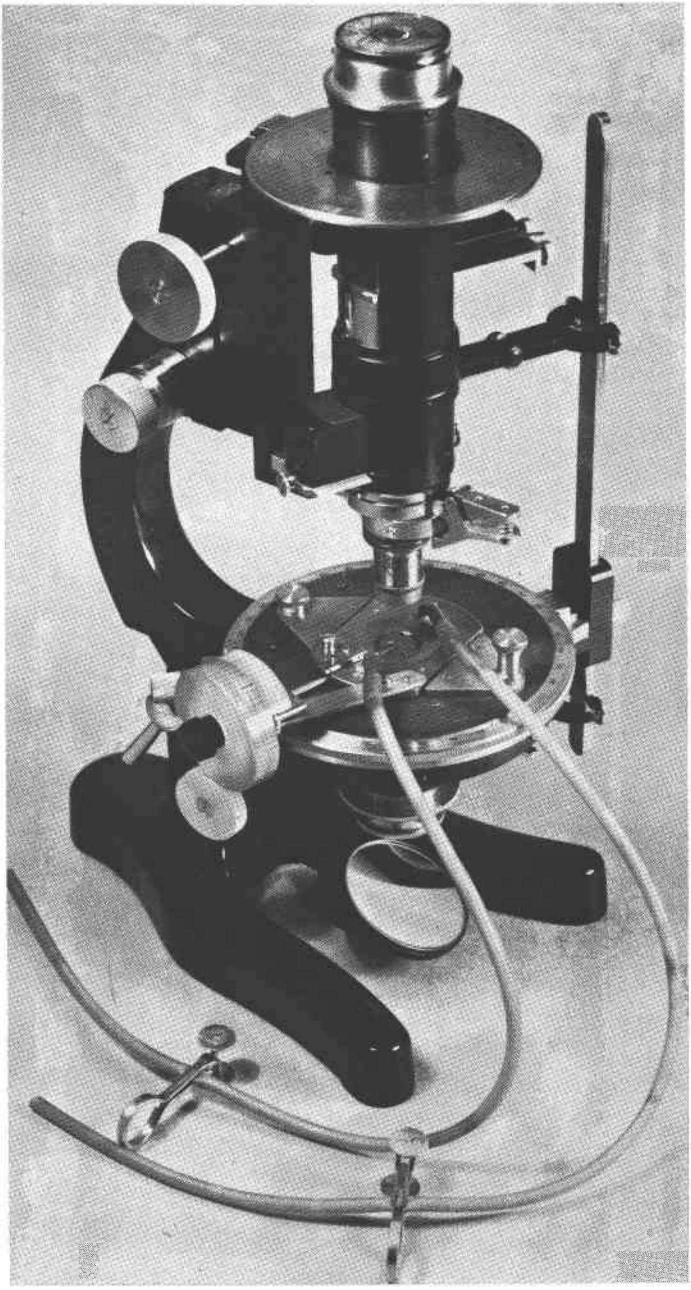

FIG. 1. Temperature control spindle stage mounted on a synchronous polar microscope.

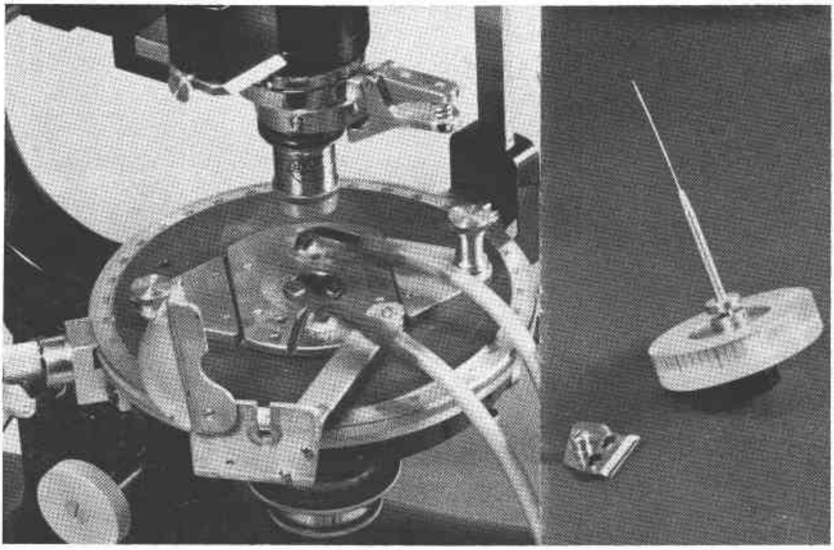

FIG. 2A. Detailed view of the temperature control spindle stage with the piece having the fiducial mark (with vernier scale) raised on its screw hinge, and the spring bronze clip and spindle with dial removed to the right.

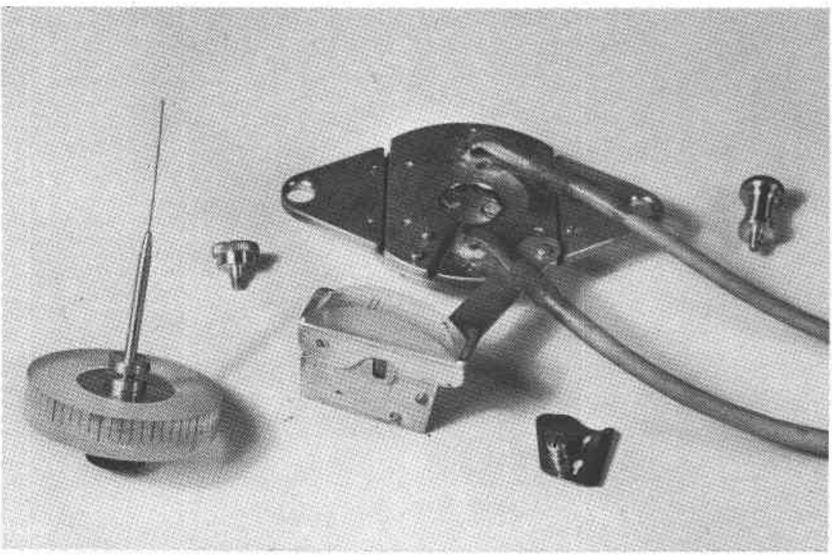

FIG. 2B. The dis-assembled temperature control spindle stage.

The writer considers this spindle stage technique the best one available for getting all three indices in a biaxial grain in the ordinary case. It is superior to the universal stage technique because it is simpler and quicker and probably is more accurate, since no glass surfaces of unfavorable index value not normal to the light path are involved. It is much easier to get (and keep) a grain centered; and when one needs to change the oil, it is far quicker.

Operation

When the cement holding a tiny crystal grain to the end of the piece of straight steel wire has set, proceed as follows:

1. Fasten the spindle stage to the microscope stage after removing the central plate from the latter. Very carefully and slowly put the converger up; if it strikes the lower glass of the stage cell, lower the substage slightly. If the glass is broken, replace it using Lakeside 70 cement[1] (melting point of this thermoplastic is 80° C.).
2. Using pliers, insert the steel wire in the spindle. To ensure a tight fit, a slight bend may be made in the wire about $\frac{1}{8}''$ from that end which is inserted in the spindle.
3. With the spindle in place, shift the stage as required to center the crystal under the cross-hairs (using an objective that has already been accurately centered) and fasten the spindle stage to the microscope stage by means of the two thumb screws.
4. Remove the spindle and replace it with a longer piece of the .018 steel wire. Note the stage vernier reading when the wire is parallel the east-west cross-hair. (If using the synchronous-polar microscope, note this reading when the synchronous-polar circle is set at 160°; note that on this microscope the *analyzer* vibration direction always points towards the vertical bar used to synchronously rotate the polars.)
5. Replace the spindle with the crystal stuck on the end of the wire.[2] Place a $\frac{1}{4}$ inch square cover glass over the crystal across the two glass blocks fastened to the upper glass of the temperature-control cell. Using a coarse hypodermic needle, inject a bit of the proper double-variation oil (Emmons, 1943, p. 63) under the cover glass, around the crystal between the two glass blocks.
6. Using a 6 mm objective (such as the Leitz P5 with a conoscopic angle of 81° and a free working distance of 0.75 mm) with the converger

[1] This Lakeside cement is slowly attacked by the immersion oils; therefore the outer edge of the top of the upper glass plate should be "armored" with the glue-molasses cement, or else a different thermoplastic seal should be used.

[2] If a little water is put along that part of the spindle which runs in the groove below the spring clip, it will prevent the embedding oil from being drawn into this groove.

in and the concave mirror,[3] determine both spindle and polars readings when a straight isogyre goes through the center of the field (the Lasaulx technique is generally more satisfactory than is the use of the Bertrand) parallel to the analyzer vibration direction (Rosenfeld, 1950, p. 904; or Wilcox, 1959, p. 1278). While rotating the spindle the grain may be kept centered under the cross-hairs by means of the two centering-screws on the objective nosepiece.[4] Note that on one complete rotation of the spindle axis, there should be six positions when this condition is satisfied for a biaxial crystal, unless the grain has an unusual orientation on the spindle. If one has trouble making out the details of the interference figure because the aperture is too small, then remove the cover glass (Paragraph 5) and use a 4 mm objective (such as the Leitz P6) as an oil immersion job. The aperture of the converger can be increased by placing a drop of oil between it and the lower window of the temperature-control cell. On the other hand if the interference figure is of the flash type, the isogyres may be so broad that an accurate reading is not possible. At this stage in the procedure no time should be wasted with interference figures hard to decipher or that yield results of doubtful accuracy.

7. If one has difficulty with the technique of the previous paragraph, a stereogram should be prepared as described in the next section. If only one or two critical directions are obtained with the technique of the previous paragraph, this (or these) may be superimposed on the stereogram; this will help in locating critical vibration directions.

8. Once the settings for measuring the principal indices of refraction are determined, the microscope is transferred to the temperature—wave length control bench, and the procedure follows the double-variation technique.

Stereogram

Theoretically the spindle technique should lead to three pairs of readings just 180° apart on the spindle dial, each pair giving the settings for measuring a principal index of refraction. Practically this result is not obtained because of 1) observational errors, and 2) errors inherent in the technique because of centering problems, lens problems, or the fact that the oil and grain do not have exactly the same index, and the grain usu-

[3] It may be necessary to have the cell filled with water in order to gain sufficient aperture to clearly make out the interference figure. The cell may be left filled with static water, having the hose ends clamped off.

[4] This method of optical decentering (though as noted later it may involve re-centering the Bertrand) is considered satisfactory because any adjustment needed is generally very minor. Of course one can try to move the spindle stage and reclamp it with no change in azimuth; or one may even mount the spindle stage on a mechanical stage oriented with one movement parallel to the spindle axis.

ally has an irregular surface. Therefore the writer considers that a stereogram should be prepared in all cases where one wishes to attain a high degree of accuracy.

The first step in preparing a stereogram is to measure the extinction angles at say 20° changes in the dial readings. For each extinction position take two readings (90° apart) to yield an average value. These readings are converted to angles off the spindle axis, positive if they are anticlockwise from the spindle, negative if clockwise (to follow Schuster's rule). In finding the extinction positions the standard orthoscopic technique may be used, but if one is looking down nearly along an optic axis, it is better to take the extinction position as that where an isogyre goes through the center of the field of view. To attain accuracy in this case it is important that the cross-hairs be almost perfectly centered. If one has kept the grain centered by adjusting the screws on the nosepiece, note that the Bertrand lens must be adjusted also. Use of a sodium vapor lamp is desirable, to avoid dispersion effects. In making this "survey" at 20° intervals, one can easily find the recognizable positions of the critical index directions (normal to a straight central isogyre parallel the analyzer vibration direction) and such positions should of course be noted with maximum accuracy.

The stereogram is prepared from the values of the extinction angles at the various spindle readings. One may employ the method of Joel and Garaycochea, but a much quicker and more readily visualized method is to have the plane of the stereogram perpendicular to the microscope stage and the spindle axis. This can perhaps best be described in terms of an actual example, using a crystal of morinite from the Black Hills, South Dakota. The spindle dial is graduated every 6°; a vernier may be added beside the fiducial mark to enable one to read to the nearest degree or two. When the dial is turned clockwise the spindle values increase; the fiducial mark is vertically above the spindle (Fig. 1).

Figure 3 is a stereogram prepared from the data in Table 1; its four cardinal points are marked, 0, 90, 180, 270 to correspond to spindle readings Σ. If one imagines this stereogram held close to and parallel the dial (spindle reading set at 90), with the 0–180 line horizontal and thus parallel the microscope stage, then as one looks down the microscope tube he is looking in the direction from 90° towards the center of the stereogram (where the center S represents the spindle axis) and he sees extinction angles ϵ of $-27°$ and $+63°$ (Table 1); these are plotted as points on the horizontal diameter 27° to the left and 63° to the right of the center, and these may each be marked 90, 270 (spindle readings). If now the spindle is set to read 130° and the stereogram is rotated clockwise 40°, one (in looking down the microscope tube) follows the 130° radius of the stereogram and along the diameter normal to this one plots the points 130, 310 out

TABLE 1. MEASUREMENTS ON MORINITE

Σ	Polars Readings (at extinction)		ε	ε′
10	184	94	23	−67
30	187	97.5	26	−64
51[1]	196.0	106.1[1]	36	−54*
70	205	115	45	−45
90	131.5	42	−27	63
110[1]	198.3*	107.8	38*	−52
130	131.5	40	60.5	−29.5
150	137	47	66	−24
170	139	48.5	67	−23
180[1]	139*			−21*
190	137.5	46.5	67	−23
210	134.5	44.5	64	−26
230	128	37	57.5	−32.5
248[1]	116.3	23.8[1]	45*	−45
270	186	96	27	−63
286[1]	130.9*	39.4	−30*	60
310	190	100	29.5	−60.5
330	185	95	24	−66
350	184.5	95	23	−67
360[1]	181*		21*	

[1] Spindle readings Σ at the critical index positions settings; asterisks are also present on the correct polars readings for measuring a principal index, and on the corresponding ε reading. The values shown for Σ readings of 180 and 360 are taken from the stereogram (Fig. 3).

Extinction angles (ε and ε′) measured against the spindle axis are obtained by subtracting the readings in the second column from 160 (or by subtracting 160 from these readings). If the microscope were a non-synchronous polar instrument, in place of 160 one would use the stage reading when the E-W cross-hair lay parallel to the spindle axis. Readings greater than 160 are positive and the ε-values are plotted along a horizontal radius (on the stereonet imagined to be under Fig. 3) out to the right from the center *S*. The ε and ε′ readings are averaged values; this also includes averaging the results for pairs of spindle readings 180° apart. The magnitude of the error involved in thus using average values (instead of drawing a pair of extinction curves) may be estimated from the data given by Gillberg (1960).

$+60\frac{1}{2}°$ to the right and $-29\frac{1}{2}°$ to the left (Table 1). Continuing in this fashion the extinction curves can be drawn in 5 to 10 minutes.

It is noticeable from Table 1 that spindle readings 110 and 286 (nearly 180° apart) were determined as the best values for critical index position settings; these are plotted in the stereogram as 108 and 288. But at these settings it was not possible to get accurate extinction readings, since one was then looking nearly along an optic axis. The other critical setting readings of Table 1, at 51 and 248 (=180+68) are quite a ways off from

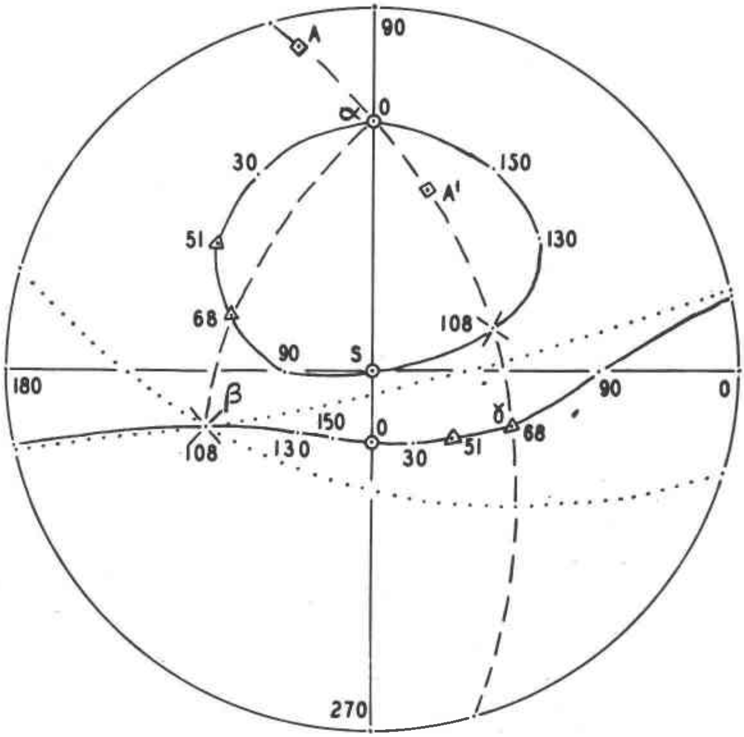

Fig. 3. Stereogram ("upper" hemisphere) with spindle S at the center, with the extinction curves obtained from morinite. The numbers show spindle readings (Σ). The extinction angle (ϵ) off the spindle direction is given by the central (angular) distance of any point on the extinction curves; such a radius cuts the primitive at 90° off the spindle reading. The traces of the circular sections are shown by the dotted arcs intersecting at β. The optic axes (A, A') do not lie on the extinction curves; therefore extinction is not parallel them when they are rotated into the plane of the microscope stage. Note that all points given with spindle readings along the extinction curves also have spindle readings of 180° plus the value listed.

being just 180° apart, so both sets were plotted in the stereogram. Since the optic triangle (the $\alpha\beta\gamma$ triangle; Fisher, 1952, p. 110) is an all-right angle equilateral triangle, it is clear from the stereogram that the position of a true critical setting can only be the one marked γ in Fig. 3, assuming the one marked β is approximately correct. The extinction angle for the one marked γ could be measured quite accurately, thus this was taken to be the best value, and where its polar cut the lower extinction curve located a slightly revised position for β. The polar of β intersects that of γ in the apex marked α, which lies on the upper extinction curve. On checking back on the crystal this setting was seen to be approximately correct for

α, but the figure was a flash type with broad isogyres, and no accurate setting could be obtained by observing it.

Since at spindle 108–288 one sees a nearly centered optic axis figure, there is no question but what this marks the position for measuring β. Since morinite is known to have $2V=40°$ and to be $(-)$, it is clear from Fig. 3 that the apex marked α is the acute bisectrix; thus the optic axes A and A′ and the traces of the two circular sections were added to the stereogram. Since A is 8° from the primitive (measured along the trace of the optic plane) it is assumed that with spindle settings of 108–288 the optic axis is 8° off center (in the grain). Had one not seen a melatope in the field of view, the proper designation of the apices of the optic triangle could no doubt have been determined by the judicious use of the quartz wedge or by the Becke test against the immersion oil.

By bisecting (angular measure) the segment of a diameter of the stereogram lying between the two points where it cuts the traces of the circular sections (construction according to the Biot-Fresnel law), a point on the theoretical extinction curve is located. Establishing several points in this manner shows close agreement between the extinction curves of Fig. 3 and the theoretical ones; some divergence was noted in the lower curve near the primitive. The measured value of parallel extinction was found at spindle settings of 102–282; the theoretical value is about 99–279. Near these settings a small change in the spindle value means a large change in the extinction angle. If 2V cannot be observed, its approximate value can be computed from the indices of refraction. Knowing this, the result could be refined by applying the Biot-Fresnel law to the measured extinction curves (Wilcox, 1960).

Joel and Garaycochea note that in general S always lies on one extinction curve (their "polar" one), and on this will also be found but one optic triangle apex (either α or γ). The other two apices lie on the "equatorial" extinction curve.[1] One of these curves lies in the acute angle between the circular sections, the other in the obtuse angle. The "ghost" optic triangle of these authors, which in Fig. 3 would have one of its apices where the equatorial extinction curve cuts the primitive, would appear to cause no trouble on a stereogram projected with S at its center. Their procedure of locating the optic triangle (by a graphical method of getting a "locus of points for the third apex" which cuts the polar curve at two points) seems both slow and inaccurate as compared to the isogyre technique of Rosenfeld, but is valuable where the latter technique cannot be applied. I would add one more generalization to their observations; namely, if the polar curve (and therefore S) lies in the obtuse angle between the two

[1] It may be noted in passing that the equatorial extinction curve for a uniaxial crystal is a great circle whose pole marks the c-axis.

circular sections, then the acute bisectrix is on the polar curve; if in the acute angle, then the obtuse bisectrix lies on the polar curve. The point S on the polar curve marks the spindle position when extinction is parallel to the spindle axis; the other (equatorial) extinction curve must go through antipodal points on the primitive for the same spindle reading.

These authors also discuss cases of special orientation which translated into a stereogram normal to the spindle axis might read as follows. If S lies along one side of the optic triangle (Duparc and Pearce), this side is the trace of a plane of symmetry bisecting the two extinction curves; this situation includes the special case where S coincides with an optic axis. If S is at an apex of the optic triangle, the polar curve becomes a point coinciding with S, and the equatorial curve is the primitive; this is the only case where β may lie on the polar curve; in this case one cannot determine the location of the other apices by means of extinction angles. If S lies on a circular section, the result is a polar extinction curve including the central part of the trace of the circular section, and an equatorial extinction curve including its outer portions (see the penultimate paragraph of this paper); if S also lies on one side of the optic triangle, the two extinction curves meet where the extinction angle is 45°; if in addition 2V = 90°, the two extinction curves consist of a circle of radius 45°, plus the trace of the circular section. In case S is on the circular section, the latter is in the plane of the microscope stage at the proper spindle setting; under these conditions one is looking down on a centered melatope, and so no extinction angle can be observed; the theoretical part of the extinction curve for this condition is the trace of the circular section through S. However even in this case with S in the circular section, the position of α or γ on the extinction curves can generally be established through isogyres, and if one of these can be located, the other two optic triangle apices are readily found on the stereogram. The case of morinite in Fig. 3 approaches this condition.

The six positions for measuring the critical indices of the morinite are readily visualized if one holds Fig. 3 close to and parallel the spindle dial. As the stereogram is rotated, each critical position is attained when an apex of the optic triangle lies on a horizontal diameter; *i.e.*, in the plane of the microscope stage. The value of the extinction angle (off the spindle direction) is measured by the distance from S to the apex. The sign is negative if the apex is to the left of S, positive if to the right. The results are given in Table 2. These values were checked by means of the isogyres. The final results thus obtained were $\alpha = 1.5530$, $\beta = 1.5653$, and $\gamma = 1.5670$ for $\lambda = 589$ (calc. 2V = 40°07′). $\alpha = 1.5573$ for $\lambda = 510$. Note that the value of α_{Na} is .002 higher than that given earlier (Fisher and Runner, 1958, p. 590). The writer had previously attempted to measure these indices using the double variation U-stage techniques, but had been unable to get a suitable check with the birefringence results obtained on the Umirg (Fisher, 1960). Thus he feels that the temperature-controlled spindle technique is more accurate, simpler, and quicker than the U-stage method for getting accurate n-values from biaxial crystals.

It is interesting to note that the three extinction angles listed in Table 2 are the angles between the spindle S and α, β, and γ. A simple check on the accuracy of the work is to draw small circles with these radii about the vertices of the optic triangle as shown in Fig. 4. This is easily done on an $r=5$ cm. stereogram using the projection protractor (Fisher, 1941, p. 300). These three circles should intersect at a common point S, from which one readily reads the polar coordinates in terms of the optic triangle. An alternative method of checking is to draw the small circle

TABLE 2—CRITICAL SETTINGS FOR MORINITE

n	ϵ	Σ	Polars*	ϵ	Σ	Polars*
α	69	180	139	−69	0	181
β	52	288	122	−52	108	198
γ	45	68	115	−45	248	25

* These settings are the complements of the ϵ-values (with their signs changed) off 160°, because a critical index is measured in a direction normal to that of a straight central isogyre parallel the analyzer vibration direction. Or put another way, for observing the critical index positions one adjusts the polars as if one were reading the points in Fig. 3 (indicated by appropriate symbols) which are respectively centrally distant 90° from the apices of the optic triangle.

centered at α (the center of the stereogram) and lay off the proper distances along great circles through first β and then γ to points lying on the small circle already drawn. Of course if the optic triangle in Fig. 3 is truly equilateral with 90° sides, the three arcs in Fig. 4 will meet in a point.

Just as α, β, and γ each comes to lie in the plane of the microscope stage twice on one complete rotation of the spindle, under the same conditions each of the two circular sections twice reaches a central vertical position, and here one might think it possible to measure (in the plane of the circular section) the value of $\beta'=\beta$. Of course under these conditions an optic axis lies in the plane of the microscope stage normal to the circular section. Such a condition can be recognized practically by rotating the spindle 90° from the position when an optic axis lies in a vertical plane which includes the spindle axis, a situation that can be observed commonly from the isogyres. However, when an optic axis lies in the plane of the microscope stage, in general extinction is not parallel to it as shown by the fact that the optic axes do not lie on the extinction curves; thus in this situation the light traversing the crystal does not

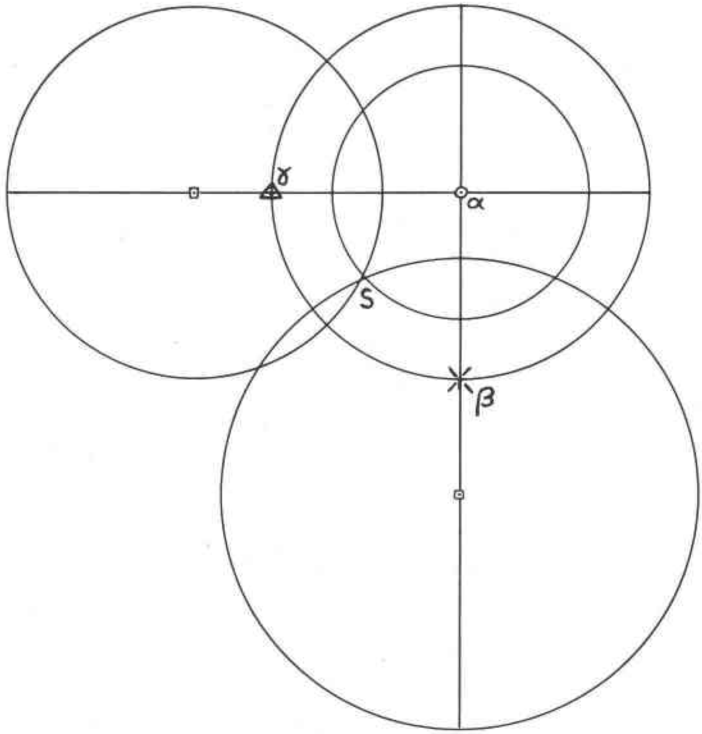

Fig. 4. Stereogram with small circles (having radii equal to the extinction angles, Table 2) centered on the apices of the optic triangle.

vibrate parallel a circular section, the condition essential for measuring β'.

In fact the fundamental principle behind the practical use of the spindle stage is that when a principal index direction lies in the plane of the stage, extinction is parallel to it. Thus α, β, and γ occur as points on the extinction curves. If one of these positions can be located accurately from the isogyres (or by the far more cumbersome method based on the determination of indices of refraction) then the other two can be determined easily graphically from the extinction curve stereogram as points 90° away (and also at right angles to one another).

In order to emphasize the differences between the Joel type of stereogram with its plane of projection parallel to the microscope stage and that used here (Fig. 3) with its plane normal to the spindle, the two types are drawn for the same crystal, a positive one with $2V=80°$. Let us imagine we start with the obtuse bisectrix normal to the plane of the stereogram and the optic plane in the position shown by the dotted lines (with the two optic axes marked by small squares along them) in Figs. 5 and 6. Let the random spindle axis S have $\phi=36°$ and $\rho=54°$ with reference to the optic plane.

In Fig. 5, S is first tilted in the αS plane to the primitive at S' and then the indicatrix is turned 90° clockwise (looking from S' towards S'') about the spindle axis, so that α lies on the primitive (and β and γ at the points indicated) when the dial of the spindle axis happens to read 240°. The extinction curves are drawn by means of the Biot-Fresnel law, and it is clear that α can be measured at this dial reading with polars set 54° off the spindle axis at S'. Rotating clockwise 50° farther, one can measure γ

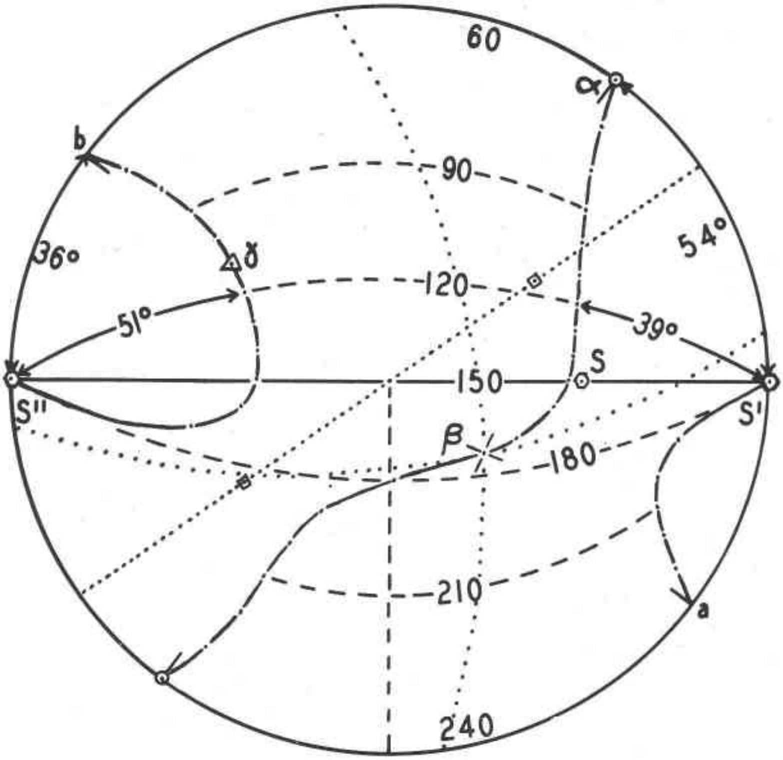

FIG. 5. Stereogram (upper hemisphere) parallel the microscope stage showing the extinction curves for a positive indicatrix (2V=80°) at a random setting (except that α lies on the primitive). Dial values (read by great circles parallel the spindle axis $S'S''$) are shown *without* the degree mark, extinction angles (measured against the spindle axis along great circles parallel this axis) *with* the degree mark. The traces of the circular sections are shown by dotted arcs intersecting at β. The dots along the extinction curves are at 10° intervals of dial readings.

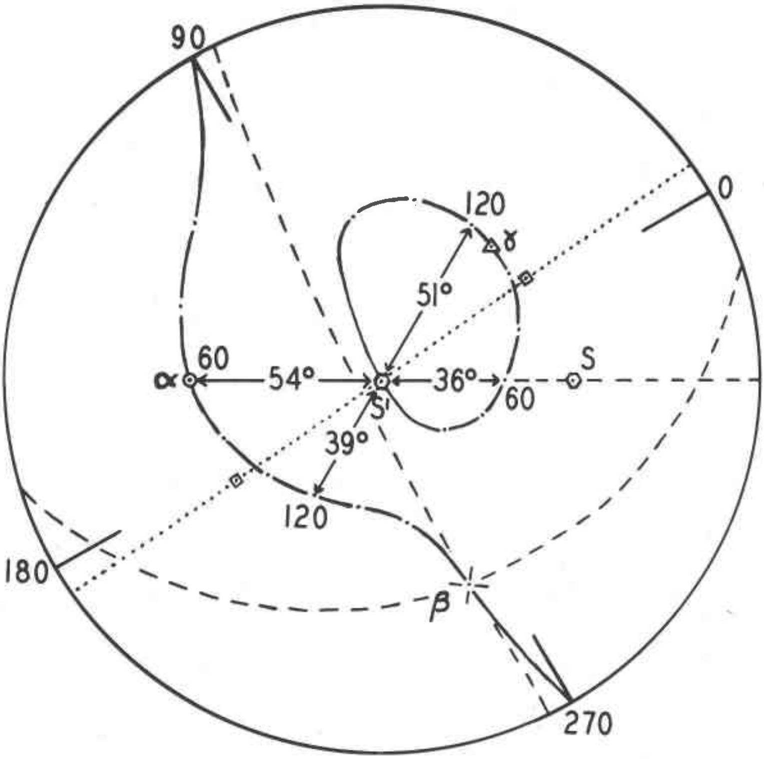

FIG. 6. Stereogram as in Fig. 5 except projected on to a plane normal to the spindle axis. The traces of the circular sections are shown by dashed arcs intersecting at β. The dots along the extinction curves are at 20° intervals of dial readings.

($\Sigma=290$, $\epsilon=49$), and by 63° more, β ($\Sigma=353$, $\epsilon=61\frac{1}{2}°$). When the dial reads 180°, extinction is substantially parallel the spindle.

In Fig. 6, S is tilted to the center at S', with the optic triangle apices going to the points shown, and the extinction curves are quickly constructed using the Biot-Fresnel law. When the spindle reading is 60°, α is in the plane of the microscope stage with extinction angles of $-54°$ or $+36°$. Spindle readings are marked to correspond with the values in Fig. 5 so that extinction is parallel the spindle at dial settings of 0–180°. Figure 6 can be converted to Fig. 5 or vice versa by a 90° rotation. Certain extinction angles corresponding to the same dial settings are marked in each figure, so that one makes easy comparison of the relative simplicities of the two modes of projection.

The special situation of the extinction curves when S is on or near the trace of a circular section is illustrated in the stereogram of Fig. 7 by three cases. In case 2 (S on the circular section) the polar curve includes the inner portion of the trace of this circular section, whereas its outer portions are part of the equatorial curve. In case 3 (S is 2° to the left of the circular section) the corresponding curves are rather similar to and close to those of case 2. However in case 1 (S is 2° to the right of the circular section) the equatorial curve has flipped across and is now close to but just outside of the polar curves of the other two cases; similarly the polar curve of case 1 is across (on the right side) of the circular section. This is in accord with the rule that the acute bisectrix lies on the extinction curve in the obtuse angle between the traces of the circular sections.

It should be mentioned that when working with a stereogram such as Fig. 3 or Fig. 6, since extinction angles are measured radially out from the center S, the use of an equatorial (polar) stereonet (Johannsen, Fig. 510) has advantages over those of the ordinary meridian (Wulff) net, but the

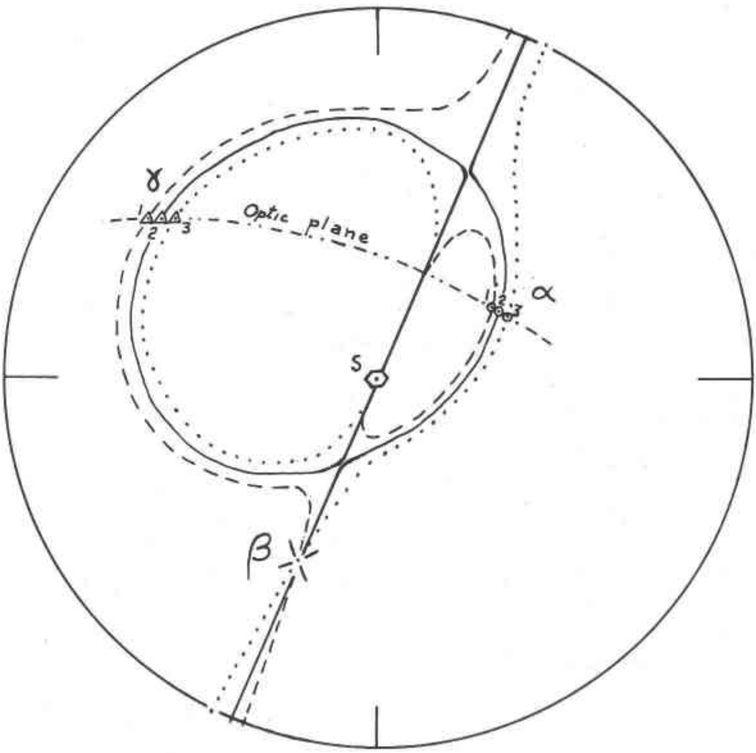

FIG. 7. Stereogram showing the extinction curves for a positive crystal (2V=46°) when S is on the trace of the circular section (case 2, continuous lines), and 2° to the right of it (case 1, dashed lines), or 2° to the left of it (case 3, dotted lines).

equatorial net is in no sense a necessity. It is of course obvious that the spindle technique can be applied readily using the Umirg (Fisher, 1960), but this latter microscope is less-easily subjected to temperature control and is more complex than the simple apparatus described herein. The writer is indebted to Ray E. Wilcox for the loan of his prototype model of a temperature control spindle stage and for constructive critical comments on the manuscript, and to W. F. Schmidt for overseeing the construction of the present stage and for the photography.

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