THE USE OF THE

AO Spencer SPECTROMETER

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HISTORICAL INTRODUCTION

THE phenomenon of refraction has been known for hundreds of years and the law of refraction was discovered by Snell in 1621. It is therefore somewhat surprising that not until 1666 did anyone notice that different wave-lengths are refracted by different amounts. In that year Sir Isaac Newton, experimenting with the passage of sunlight through a glass prism, showed that white light incident on the prism is broken up into a bundle of colored rays by the action of the prism and that these rays are dispersed into a spectrum. This experiment marked the birth of spectroscopy.

Although Sir Isaac Newton later used a slit in his experiments, the complete prism spectroscope was developed by Fraunhofer. Fraunhofer was the first to use a telescope for examining the spectrum visually and with this apparatus was enabled to observe the solar spectrum in great detail. The spectrum of the light from the sun is not entirely continuous but is crossed by a series of dark lines whose direction lies parallel to the slit. Their relative position is characteristic of the solar spectrum itself and is independent of the type of observing apparatus employed. Realizing this, Fraunhofer saw the great importance of these lines as landmarks or standards of wave-length and spent a number of years mapping out about 700 of them. He published his researches in 1814 and to the most important of these lines he assigned the names of the letters of the alphabet beginning in the red with A and ending in the violet with H. These prominent lines in the solar spectrum are still called Fraunhofer lines and a list of the principal ones is given in the following table.

TABLE NO. I

FRAUNHOFER LINES

Symbol	*Element*	*Wave-length, mμ*	*Symbol*	*Element*	*Wave-length, mμ*
A	O O	762.1 759.4	b_4	Fe Mg	516.7
B	O	687.0	F	H	486.1
C	H	656.3	G′	H	434.0
D_1	Na	589.6	G	Fe Ca	430.8
D_2	Na	589.0			
E_2	Fe	527.0	g	Ca	422.7
b_1	Mg	518.4	h	H	410.2
b_2	Mg	517.3	H	Ca	396.8

It was soon discovered that these absorption lines appear at wave-lengths corresponding to emission lines in the spectra of terrestrial elements. By identifying these radiations in the laboratory the constitution of the sun has been studied. This relationship

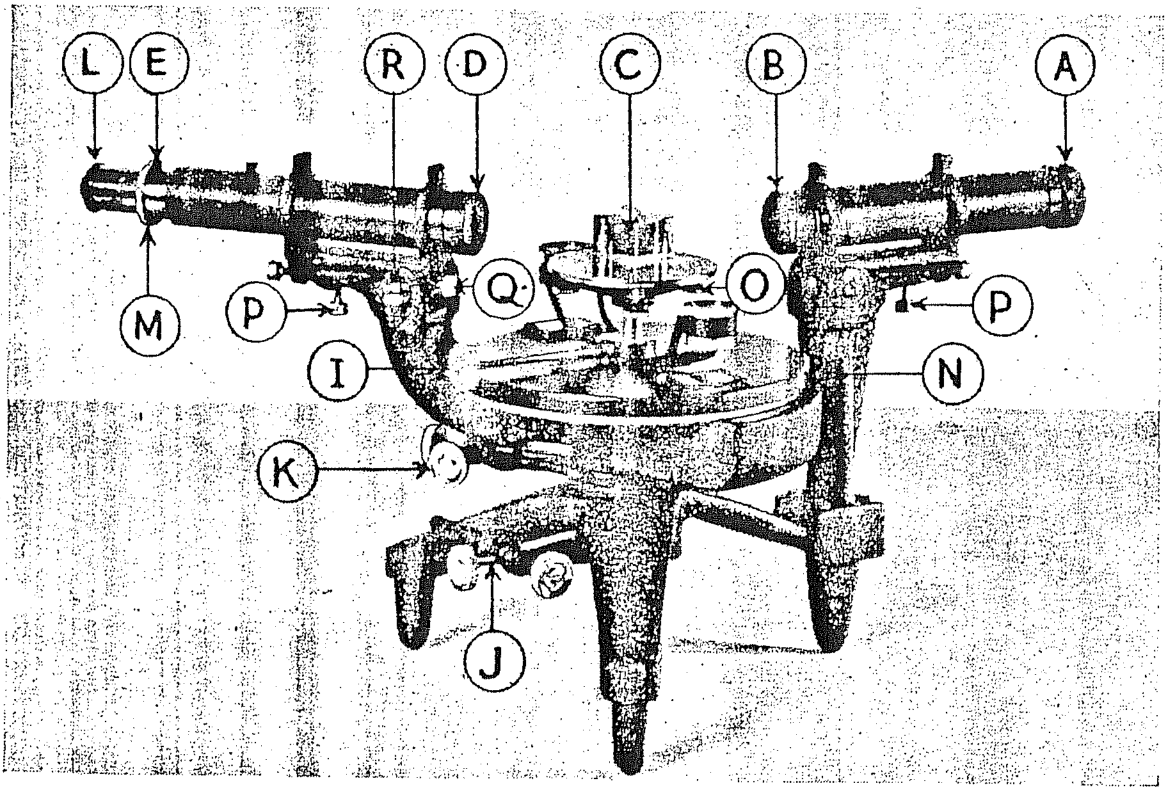

Fig. 1. The Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; I—Prism Table Clamping Screw; J—Prism Table Clamping and Tangent Screws; K—Telescope Arm Clamping and Tangent Screws; L—Eyepiece Ring; M—Telescope Focusing Ring; N—Divided Circle Dust Cover; O—Prism Table Leveling Screws; P—Collimator and Telescope Leveling Screws; Q—Telescope Bearing Front Screw; R—Telescope Bearing Side Screws.

between the constituents of the sun and of terrestrial sources was first investigated by Bunsen and Kirchhoff. These scientists studied the spectra of many substances which not only established the presence of many earth-known elements in the sun, but also formed a foundation for the entire science of spectroscopic analysis.

In the early days spectroscopes had two types of scales for recording the position of the spectral lines. In one type of instrument, represented by the Spencer spectrometer as its modern counterpart, see fig. 1, the position of the prism table and of the telescope can be determined by reference to a very accurately divided circular scale which is read with verniers. Instruments of this type have been developed to their highest precision for the purpose of making accurate measurements of the refractive index of transparent materials in prism form at various wave-lengths. In the other type of instrument, shown in the frontispiece and exemplified by the Spencer spectrometer used with the Bunsen spectroscope attachment, see fig. 2, an arbitrary scale suitably illuminated is reflected from the back surface of the prism and appears in the telescope superimposed on the spectrum being observed. The pioneers in spectroscopy were familiar with both these types of instruments and for wave-length studies and for the identification of chemical elements the second type was commonly em-

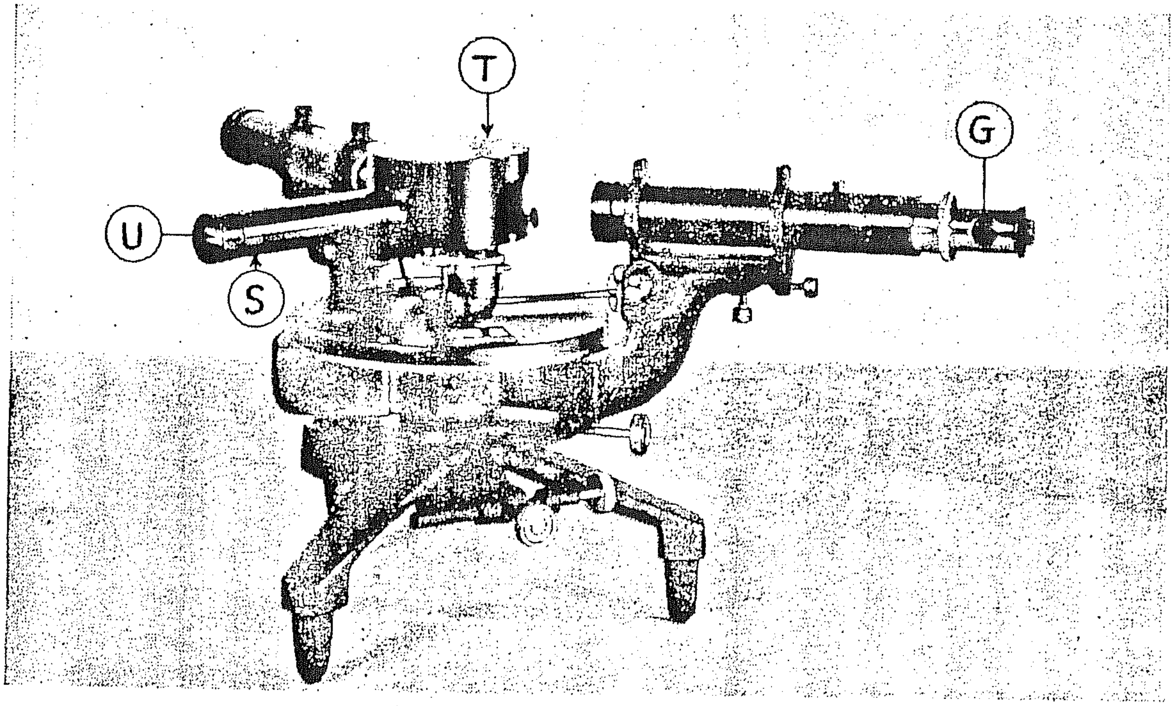

Fig. 2. The Spencer Bunsen Spectroscope Attachment. G—Semi-transparent Diagonal Mirror; S—Bunsen Attachment Collimator; T—Bunsen Attachment Prism Table Cover; U—Wave-length Scale.

ployed. In modern instruments designed particularly for the identification of wave-lengths, the wave-length scale is commonly built in and calibrated as a permanent part of the instrument.

Serious efforts to use the spectrometer for chemical analysis were first made about 1880 by Hartley who studied the successive disappearance of the lines in the spectrum of an element as its concentration in a mixture was gradually decreased. The persistence of spectral lines has been more or less continuously studied from that time until the present day. In the latter part of the 19th and the earlier part of the 20th century experimental methods and apparatus were developed for spectroscopic chemical analysis and extended tables of spectral lines were compiled from which the presence of minute traces of certain elements could be detected and the approximate amount of material estimated.

The three main applications of spectroscopy at the present time are in refractometry, wave-length determination and chemical analysis. The divided circle spectrometer is universally employed for refractometric measurements. Wave-length measurements are usually made with some form of constant deviation instrument having a permanent wave-length scale. A great many wave-length determinations are made by photographing the spectrum in some type of spectrograph and subsequently studying the spectrum on the photographic plate. This type of instrument is exemplified by the Spencer spectrometer with camera attachment, see fig. 3.

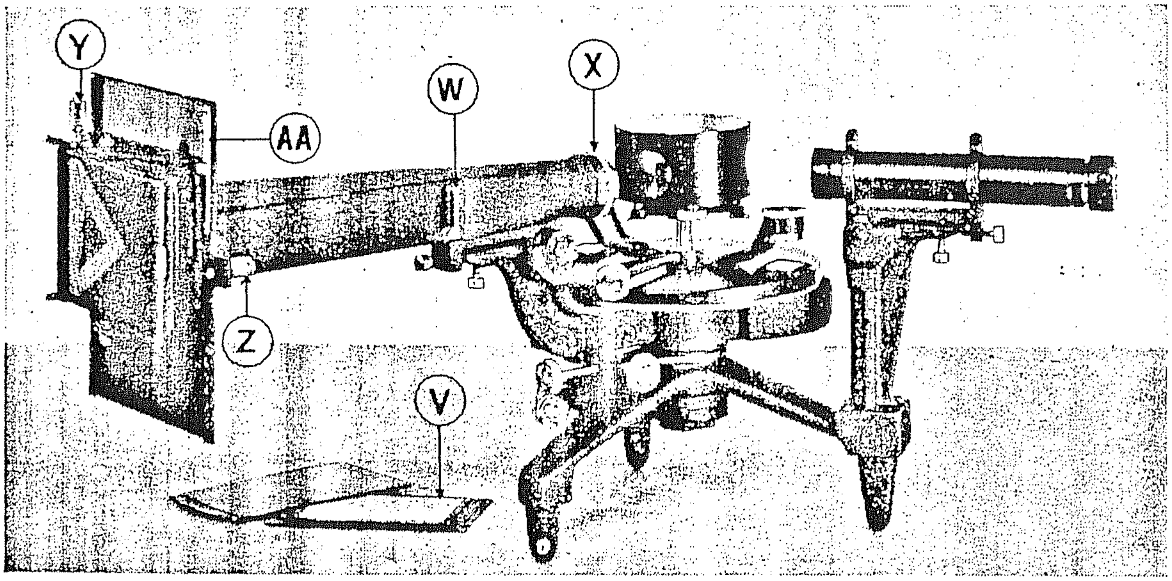

Fig. 3. The Spencer Spectrographic Camera. V—Focusing Screen; W—Shutter Handle; X—Camera Objective Draw Tube; Y—Tilt Clamping Screw; Z—Plate Slide Carriage Clamp; AA—Plate Carriage Scale.

REFRACTION OF LIGHT THROUGH PRISMS

General Case

The passage of a ray of light through a prism can be traced easily by the application of Snell's law at each of the two prism surfaces.[1] This is illustrated in fig. 4. The ray from M is incident on the first prism surface at the point N and makes an angle i with the normal to this surface. After refraction the ray proceeds in the direction NO through the material of the prism whose refractive index is n. The ray NO makes an angle r with the normal to the first surface given by

$$\sin r = \frac{1}{n} \sin i. \tag{1}$$

From the geometry of the figure the angle i' made by the ray NO with the normal at the second surface is

$$i' = A - r. \tag{2}$$

The ray is refracted at O and emerges into the air in the direction OP. The angle of emergence r' is given by

$$\sin r' = n \sin i'. \tag{3}$$

From these three equations any ray lying in a plane perpendicular to the intersection of the refracting faces can be traced through the prism. The total deviation is

$$D = i + r' - A. \tag{4}$$

Minimum Deviation

Some value of i can be found for which the deviation of the ray will be a minimum, the passage through the prism will be symmetrical and

$$i = r', \quad r = i'. \tag{5}$$

By substituting equations (5) in some of the earlier equations the following are obtainable.

$$A + D_{\min} = 2i = 2r' \tag{6}$$

$$n = \frac{\sin \frac{1}{2}(A + D_{\min})}{\sin \frac{1}{2} A} \tag{7}$$

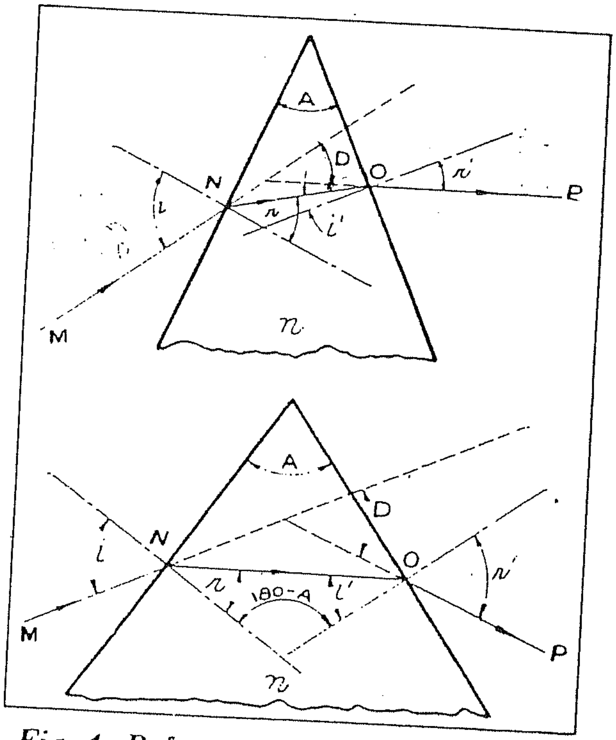

Fig. 4. Refraction of Light by a Prism

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[1] See an optical text as A. C. Hardy and Fred Perrin, "The Principles of Optics", pg. 545.

Equation (7) states that at minimum deviation the refractive index is uniquely determined by the deviation angle D_{min} and the prism angle A.

Curvature of Lines

The preceding discussion has assumed that all of the rays pass through the prism in a single plane perpendicular to the refracting edge. In practice, however, since any prism has a finite height, some rays will pass through the prism at an angle to this plane and will suffer correspondingly greater deviation. It is these oblique rays which cause the spectral lines observed in the telescope or photographed with the camera to appear curved. This curvature is approximately circular with a radius of about 4/5ths of the focal length of the telescope objective.[2]

Dispersion

The refractive index of ordinary transparent substances decreases with wave-length in a manner characteristic of the material. It is therefore necessary to take into account the variation of refractive index with wave-length in any complete account of the refraction of light by prisms. For a good many years efforts have been made to find a formula which would accurately match the dispersion curve of glasses over a useful range.[3] Cauchy's formula is the simplest and has considerable value when used over a short range of wave-length. This formula is given by equation (8) and the solutions for the constants by (9) and (10).

$$n = A + \frac{B}{\lambda^2} \tag{8}$$

$$A = \frac{n_1 \lambda_1^2 - n_2 \lambda_2^2}{\lambda_1^2 - \lambda_2^2} \tag{9}$$

$$B = \frac{\lambda_1^2 \lambda_2^2 (n_2 - n_1)}{\lambda_1^2 - \lambda_2^2} \tag{10}$$

Data for a glass of rather high refractive index are shown in table No. II.

TABLE NO. II

REFRACTIVE INDEX OF EXTRA DENSE FLINT GLASS

Wave-length, mμ	*Index*	*Wave-length, mμ*	*Index*
656.3	1.7147	486.1	1.7394
587.6	1.7218	435.9	1.7542
546.1	1.7277		

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[2] G. F. C. Searle, "Experimental Optics", pg. 38.
[3] R. W. Wood, "Physical Optics", pg. 469.

Using the data for 656.3 and 435.9 to compute the Cauchy constants, we can compute the index at the other wave-lengths. These calculations are shown in table No. III.

TABLE NO. III

CALCULATION OF INDEX BY CAUCHY'S FORMULA

$A = 1.6835 \qquad B = 134296$

n_{obs}	λ	λ^2	B/λ_2	$n_{calc.}$	o-c
1.7147	656.3	430730	0.0312	1.7147	0.0
1.7218	587.6	345274	0.0389	1.7224	–0.0006
1.7277	546.1	298225	0.0450	1.7285	–0.0008
1.7394	486.1	236293	0.0568	1.7403	–0.0009
1.7542	435.9	190009	0.0707	1.7542	0.0

The errors in the last column can be plotted as shown in fig. 5 and can be used to correct indices calculated for any wave-length in the range. The dispersion curve, fig. 6, is drawn through the original data shown by the circles and through additional points computed as just described.

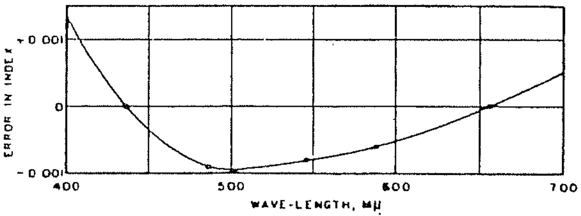

Fig. 5. Error Curve from Cauchy's Formula

The Cauchy formula, if used over a short wave-length range, is accurate enough for most work and because it contains only two constants is very easy to use. In cases where greater accuracy is required the Hartmann formula, equation (11), can be used. This formula

$$n = A + \frac{C}{\lambda_0 - B} \qquad (11)$$

has three constants which greatly increases the labor of computing.[4]

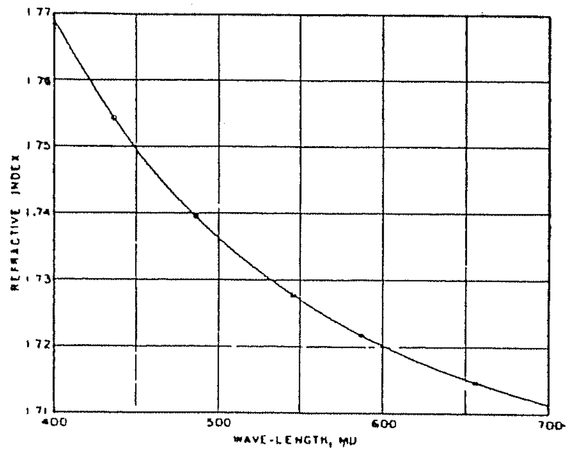

Fig. 6. Dispersion Curve for Extra Dense Flint

These formulas, with a suitable change in constants can be used with telescope angle or distance along a photographic plate as the dependent variable instead of index.

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[4] For the solutions see Sir Richard Glazebrook, "Dictionary of Applied Physics", Vol. IV, pg. 890, (1923.)

HOW TO USE THE SPECTROMETER

Description of Instrument

A practical spectrometer comprises devices to permit the substitution of bundles of parallel rays for the single rays traced in the preceding discussion of the theory of the dispersing prism, and devices for accurately measuring the angles involved. The photograph, fig. 1, and the diagram, fig. 7, show the general features of the instrument by the same letters. Monochromatic light from a source not shown illuminates the narrow slit A. The rays which pass through the slit diverge to the objective lens B. Since A is located exactly in the focal plane of B the combination, called a collimator, produces a bundle of parallel rays which traverse the prism C and are deviated into the direction D-H. D-H is a telescope which converts the parallel rays from the prism into an optical image of the slit. This image, produced by the objective D, is located in the plane of the cross hairs E. The cross hairs are in the focal plane of the objective. A magnifier or eyepiece comprising lenses F and H

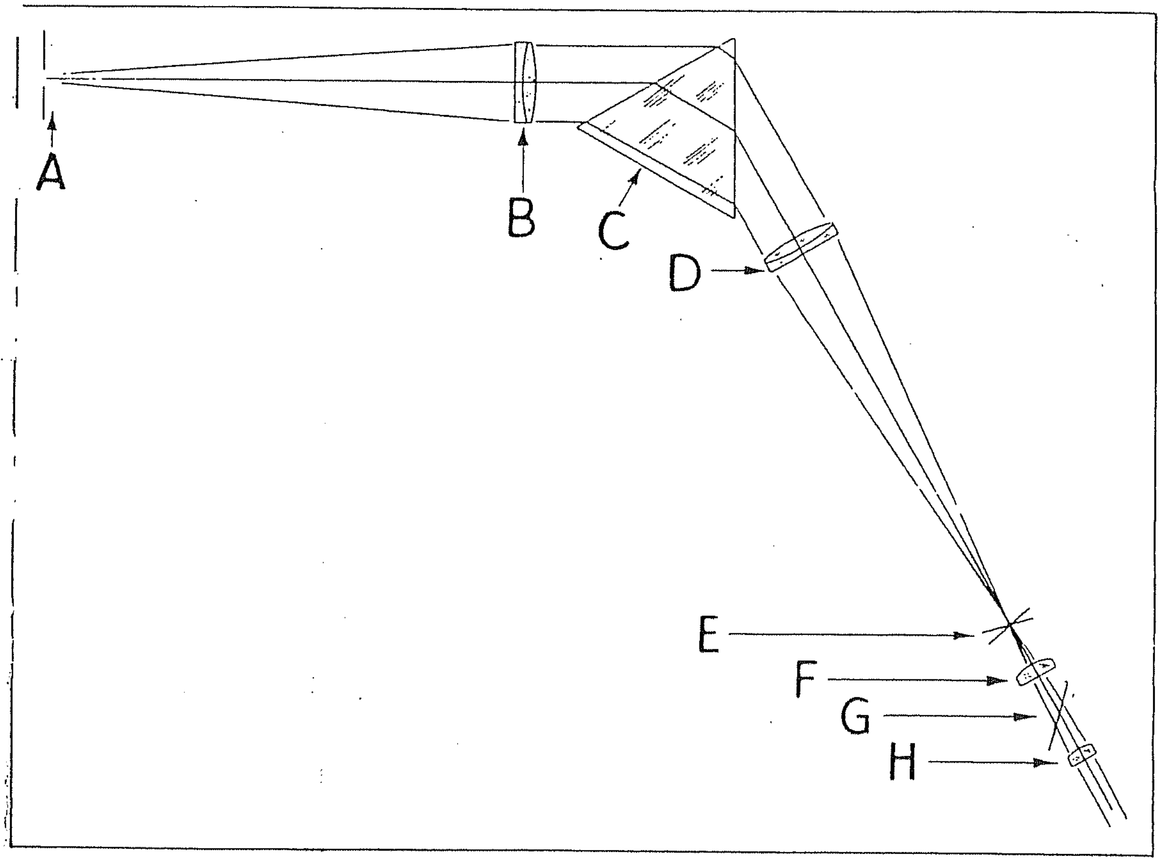

Fig. 7. Path of Rays through the Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; F—Eyepiece Field Lens; G—Semi-transparent Diagonal Mirror; H—Eyepiece Lens.

is used to observe both the slit image and the cross hairs which could otherwise be seen only with difficulty. Frequently the cross hairs receive adequate illumination from the light coming through the spectrometer. In using auto-collimation the cross hairs can be supplied with intense independent illumination by means of the Gauss eyepiece which contains an opening in the side of the tube giving access to the semi-transparent diagonal mirror G.

Permanent Adjustments

Several of the necessary adjustments are properly taken care of by the manufacturer. For example the axes of rotation of the telescope and prism table must be accurately coincident. This is assured by careful manufacture and no adjustment is provided or necessary. The axes of the collimator and telescope should intersect the axis of rotation. This adjustment is set correctly at the factory but since the adjustment of the telescope is disturbed when it is replaced by the camera, provision is made for resetting this adjustment with sufficient accuracy by moving the telescope laterally in its front bearing. Loosen screw Q in the front end of the telescope bearing and approximately center the axle between the screws R. Loosen clamp I and lift the prism table so that the unobstructed shaft can be seen by looking through the telescope from which the eyepiece has been removed. Line up the prism table shaft approximately over the center of the telescope objective by sliding the telescope mount. Tighten screw Q. Complete adjustment by loosening and tightening screws R. The camera does not require this alignment but the collimator can be adjusted if necessary by looking through the open slit and following the same procedure.

Working Adjustments

Before accurate results can be obtained from a spectrometer it is necessary to understand the functioning of its principal parts and to make sure that several adjustments are correct. The following will present the various features of the instrument and the working adjustments in a definite and orderly manner.

In fig. 1, the slit shown at A has two hardened metal jaws which are moved simultaneously by a cam attached to the outer knurled ring. The jaws are opened by the cam and closed only by the pressure of a delicate spring which prevents damage from closing the jaws too forcefully. Dirt on the slit is indicated by fine black lines which traverse the spectrum horizontally and which only appear when the slit is closed to the finest possible width. In order to clean the slit, open the slit wide and carefully stroke each edge of the slit jaws with a sliver of soft wood such as a clean match stick. In performing this cleaning operation, one must be especially careful not to rub the sliver of wood against the jaws in a direction parallel to the optic axis, but only in a direction parallel with the jaw edge and only with a very light contact.

A prism can be located on the prism table in a position appropriate to the experiment and fastened with the prism clamp. When it is desired to rotate the prism, the whole prism table and verniers are rotated by moving the scale cover N. The prism table rotation is controlled by the lower set of clamping and tangent screws J. Loosening the clamping screw permits free rotation. With the clamping screw tightened the tangent screw can be used to impart a very slow and delicate motion over a range of about ten degrees. The telescope is supported on a part of the same central bearing which carries the prism table. The divided circle rotates with the telescope arm and this rotation is controlled by a pair of screws K similar in function to the screws J just mentioned.

In any delicate instrument care should be taken not to clamp any of the parts any more tightly than necessary to produce the necessary rigidity in the instrument. Any clamping pressure beyond this point might introduce strain or slight bending of the instrument parts which would disturb the delicate adjustments.

Focusing by Auto-Collimation

In focusing the telescope it is first necessary to focus the eyepiece on the cross hairs. Pull the eyepiece almost out of the telescope by the ring L and insert it slowly until the cross hairs come into good focus with the eyes relaxed. In order to avoid eye fatigue the eyepiece should be in focus when the eye is focused for distance vision. This procedure makes it easier to make the focal adjustment. The cross hairs and eyepiece can now be brought to the focus of the objective by sighting on a distant object through an open[5] window or by auto-collimation. In either case the cross hairs position is adjusted by the knurled ring M until the image remains fixed against the cross hairs as the eye is moved slightly

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[5] Irregularities in a glass window pane lead to an inaccurate adjustment. The open window method can very seldom be used conveniently.

from side to side. When the cross hairs are outside the focal plane, the image moves in the opposite direction to the eye movement, but when the cross hairs are inside, the image and the eye move in the same direction. This method of focusing by the elimination of parallax is universal in the use of optical instruments.

Any prism face is used as a mirror in the auto-collimation method. Open the window G (fig. 2) in the Gauss eyepiece and illuminate the cross hairs with an auxiliary lamp. Place the prism surface perpendicular to the telescope axis and see both the cross hairs and their image in the field of the telescope.[6] The experimental set up is shown in fig. 8. Horizontal movement by tangent screws J or K and vertical adjustment by prism leveling screws O or telescope leveling screws P should suffice to bring the cross hairs and their image into superposition. Focus the telescope by parallax.

It also is necessary to set the collimator and telescope axes perpendicular to the bearing axis. This adjustment is first completed on the telescope. Move the 60° prism on the prism table so that it is centrally located with its corners bisecting the distances between the three leveling screws. Get the cross hairs and their image directly above one another by turning the back tangent screw. Correct half of their vertical separation with the telescope leveling screws P (fig. 1) and bring the cross hairs and image into exact coincidence with the back prism table screw O. Repeat this adjustment on each prism face in turn (rotating the entire prism table assembly and using a different leveling screw for the purpose) until the coincidence is perfect at all three prism faces.

The collimator can be adjusted for alignment and for focus by checking it against the adjusted telescope. Remove the prism and bring the telescope into line with the collimator. Turn the slit into a horizontal position by twisting the draw tube and bring it into approximate focus. Set the slit on the cross hairs with the collimator level-

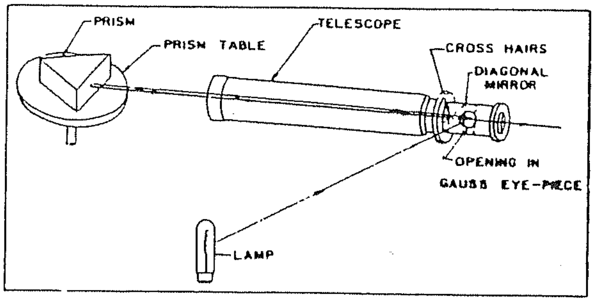

Fig. 8. Arrangement of Telescope and Prism for Auto-Collimation

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[6] In case of difficulty place the prism face against the end of the telescope and then gradually move it back onto the prism table while watching the image in the telescope.

ing screws P. Replace the 60° prism on the table in the position shown in fig. 9. Two intersecting images of the slit will be seen. When the slit is rotated into the vertical position, the images will be parallel. The direct image, which will move with the telescope but not with the prism table, should be set on the cross hairs and focused by parallax, making the adjustment with the draw tube and not the telescope. When the collimator is adjusted, the clamp S can be tightened and the slit should be vertical and in good focus.

Divided Circle and Verniers

The heart of the spectrometer is the divided circle from which all angular measurements are obtained. The circle is graduated with such accuracy that the error in the position of the various scale marks is much less than one minute of arc (the smallest interval readable on the verniers). In spite of years of experience, instrument makers have never found it possible to assemble the circle and verniers onto the instrument bearings with as great accuracy as can be obtained in the engraving of the scales themselves.[7] This minute departure from exact alignment produces small errors which are of opposite sign on opposite sides of the circle and are completely eliminated from the average of two opposite vernier readings. Recognizing this, Martin says,[8] "It is as well always to take opposite vernier readings for *any* work (students' experiments or the like). No student should be encouraged to think that two verniers are provided on a spectrometer because one may sometimes get too close to the collimator to be conveniently readable."

If the difference in vernier readings at various places around the circle is plotted against the complete scale reading for one vernier, the results may look like fig. 10. Since the vernier differences

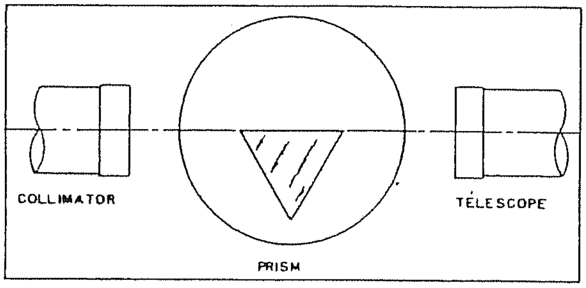

Fig. 9. Arrangement for Aligning Slit

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[7] Interesting accounts of the instruments and methods used in dividing circles will be found in the "Encyclopedia Britannica" and L. C. Martin, "Optical Measuring Instruments", pp. 45-60.

[8] L. C. Martin, "Optical Measuring Instruments", pg. 57.

vary between zero and a maximum, observations must be made at enough points to determine the maximum difference in testing the circle.

A vernier is a device for estimating fractional parts of the distance between two adjacent divisions on a scale. The vernier subdivides each main scale division into as many parts as there are divisions on the vernier scale. The full vernier scale has the same length as a part of the main scale embracing one fewer divisions than are contained on the vernier. The vernier and main scales are placed in contact with each other and the main scale is read to the nearest number of whole divisions using the zero on the vernier scale as the index. It is desirable to estimate approximately the fractional part of the main scale reading as a check on the more accurate reading to be made with the aid of the vernier scale. On the Spencer spectrometer, see fig. 11, the circle is divided into degrees and half degrees. The vernier scale is divided from 0′ to 30′, each division representing one minute of arc. At any given setting it will be noticed that the marks on the main and vernier scales are not in coincidence with one another except perhaps at one particular point. The mark on the vernier scale which most nearly coincides with a corresponding mark on the main scale represents the vernier reading (using the vernier scale numbers, of course). In the case of a scale divided to half degrees used with a vernier numbered from 0′ to 30′, it will be necessary to add 30 minutes to the vernier reading when the vernier scale index reads against the second half degree interval on the main scale.

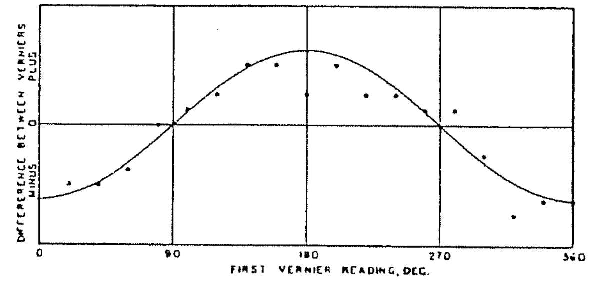

Fig. 10. Test of Divided Circle

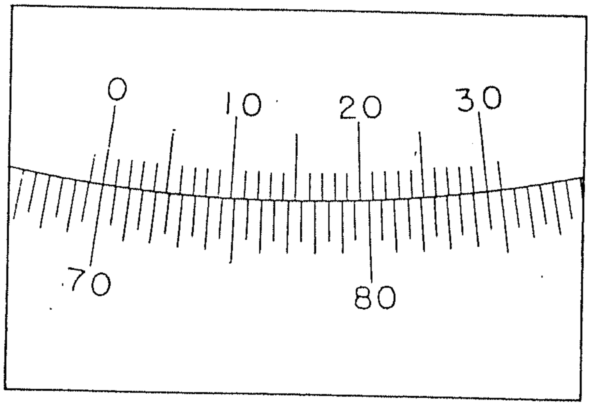

Fig. 11. Divided Circle and Vernier

Two examples will make this clear. Suppose that the index on the vernier scale lies between 7° and 7.5°. We look along the vernier scale and find a coincidence with the main scale at the 24th vernier scale division. The true reading of the instrument under these circumstances is 7° 24′. If, however, the index had been between 7.5° and 8° the scale reading would be 7° 54′. It will be observed that the selection of the line most nearly coincident is facilitated by examining the coincidence of adjoining vernier lines. Near the end of the scale opportunity to make this sort of comparison is afforded by engraving extra vernier scale lines beyond the 0′ and 30′ points.

REFRACTIVE INDEX MEASUREMENTS

Index of a Prism

In measuring the index of a prism, the angles *A* and *D*, fig. 4, are measured, using light of a particular wave-length for *D*, and the index computed from equation (7). Number the angles in pencil on the ground top surface of the prism selected for measurement. Clamp the telescope in a convenient observing position, set each prism face in turn perpendicular to the telescope by auto-collimation and note the circle reading. The angle between the two telescope positions is that marked 180° − *A* in fig. 4. A typical record is shown below. The fact that the sum of the angles of a triangle is exactly 180° may be used to test the results.

TABLE NO. IV

ANGLES OF NO. 10042 PRISM

Prism Face	*Vernier No. 1*	*Vernier No. 2*	*Scale Reading*
1-2	19° 21′	22.5′	19° 21.75′
2-3	139° 20′	19′	139° 19.5′
3-1	259° 16′	15′	259° 16.5′

Angle	*180° − A*	*A*
1	120° 5.25′	59° 54.75′
2	119° 57.75′	60° 2.25′
3	119° 57′	60° 3′

Place a sodium source, see pg. 18, in front of the slit and with the slit opened wide see that the central part of the collimator lens is filled with light. With the telescope and the prism in substantially the position shown in fig. 7, look in the telescope for a bright yellow vertical line which is the image of the slit. Slowly move either the telescope or the prism table through about 60° until this image is seen. Close the slit to give as narrow an image as possible. If everything is in good adjustment, the slit image will appear as two fine vertical lines spaced very close together. These lines are slit images of sodium light at two separate wave-lengths, 589.0 and 589.6 millimicrons. In making measurements of ordinary precision, the cross hairs can be set between the lines and the average wave-length, 589.3 millimicrons, assumed.

Rotate the prism table slowly. The slit image will move in the field of the telescope which should also be moved to keep the yellow line in view. The prism table and telescope should be moved in such a direction as to *increase* the angle ACH, fig. 7, (decrease the deviation). When this adjustment is approximately correct, clamping screws J and K should be tightened moderately and the final adjustment for minimum deviation made with the tangent screw J. The cross hairs should now be set exactly on the line with the telescope tangent screw K. When the adjustment is complete, read the verniers and record the results.

Repeat the experiment with the telescope and prism in a corresponding position on the other side of the collimator axis. Double deviation is the difference between the two telescope positions.

The measurements can be repeated on the other prism angles with results similar to those listed below.

TABLE NO. V

MEASUREMENT OF MINIMUM DEVIATION ON PRISM NO. 10042

Prism Apex	*Telescope Left*			*Telescope Right*			*2 D*
	Vernier No. 1	*Vernier No. 2*	*Scale Reading*	*Vernier No. 1*	*Vernier No. 2*	*Scale Reading*	
1	82° 35′	35′	81° 35′	201° 16.5′	15.5′	201° 16′	118° 41′
2	86° 23′	22′	86° 22.5′	207° 33′	33′	207° 33′	121° 10.5′
3	87° 44′	43′	87° 43.5′	208° 57′	56′	208° 56.5′	121° 13′

The refractive index for sodium light, (589.3 $m\mu$) can be found by substituting the values for A (prism angle) and D (deviation) in equation (7). The calculation using the data just obtained is shown in the table below.

$$n = \frac{\sin \frac{A + D}{2}}{\sin \frac{A}{2}} \qquad (7)$$

TABLE NO. VI

CALCULATION OF REFRACTIVE INDEX

Prism No. 10042 Sodium light, mean wave-length = 589.3 mμ

Prism Apex	*Angle* A	*Angle* D	$\frac{A+D}{2}$	$\sin \frac{A+D}{2}$	$\frac{A}{2}$	$\sin \frac{A}{2}$	n
1	59° 55′	58° 56′	59° 25.5′	0.86096	29° 42.5′	0.49558	1.7373
2	60° 2′	60° 35′	60° 18.5′	0.86870	30° 1′	0.50025	1.7365
3	60° 3′	60° 36.5′	60° 20′	0.86892	30° 1.5′	0.50038	1.7365

Observed value of n_D = 1.7368 ± 0.0004

The refractive index at other wave-lengths can be found by the same procedure, substituting other sources of monochromatic light for the sodium lamp.

The refractive index of a 30° — 60° prism can be found either by the method just described or by auto-collimation. Find the exact value of A (the 30° angle) by auto-collimation as described above. Illuminate the cross hairs with a sodium lamp and set the prism with reference to the telescope as shown in fig. 12. The rays from the illuminated cross hairs will be rendered parallel by the telescope objective, acting as a collimator, and will enter the prism at minimum deviation, be reflected from the back prism face and return along the same path. When the cross hairs are in coincidence with their image, the telescope is correctly set. The angle i can be measured by setting the telescope along the ray and also along the normal to the surface. The refractive index is obtained from the equation

$$n = \frac{\sin i}{\sin A} \cdot \qquad (12)$$

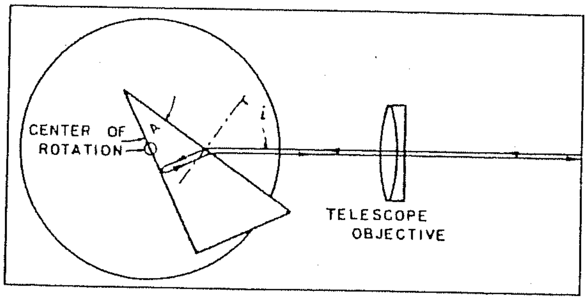

Fig. 12. Refractive Index Measured by Auto-Collimation

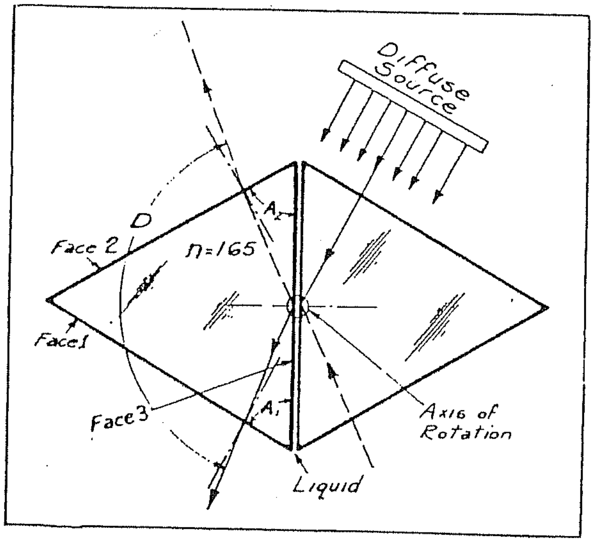

Fig. 13. Abbé Refractometer Demonstration

Index of Liquids

The spectrometer can be used to demonstrate the principle of the Abbé refractometer. Select a 60° prism for the refractometer prism whose refractive index and the angles A_1 and A_2 are known. Press a drop of the liquid to be measured against face 3 with an auxiliary prism. The arrangement is shown in fig. 13. Illuminate the auxiliary prism with a broad source of monochromatic light. Clamp the telescope and rotate the prism to bring the edge of the bright band of light emerging from face 1 onto the cross hairs. Repeat the setting by rotating the prism and moving the light source until the rays emerge in a similar manner from the face 2. Take the following data and substitute in equation (13).

$$n = \sin A \sqrt{n_p^2 - \sin^2 a} + \cos A \sin a \tag{13}$$

D = difference in the two prism positions.

A = average of prism angles A_1 and A_2.

n_p = index of the prism.

$a = \frac{D}{2} - A.$

n = refractive index of the liquid.

Complete details can be found in laboratory manuals describing optical experiments.[9]

The hollow prism can be used to measure the refractive index of liquids available in quantity. Since the rays are undeviated by passage through the plane-parallel glass sides of the hollow prism, the index is determined by the minimum deviation method first described. The refractive index of liquids changes rapidly with temperature and measurements over a range of temperature make an interesting experiment. Measure the temperature with a sensitive thermometer dipping into the liquid.

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[9] G. S. Monk, "Light, Principles and Experiments", pg. 367.
G. F. C. Searle, "Experimental Optics", pg. 81.

WAVE-LENGTH MEASUREMENTS

Light Sources

Radiations of definite character and wave-length are emitted by various types of light sources. Various incandescent solids, of which tungsten lamps are the most familiar example, emit a *continuous spectrum* which shows as an uninterrupted band of colored light. The continuous spectrum, having no structure of its own, is of particular value in studying the absorption of transparent colored materials.

When gas molecules are excited by electrical means or in a flame, light is emitted which has a banded spectrum. *Band spectra* are characteristic of individual molecules and may be used for chemical identification or for the study of molecular structure. Bands due to diatomic molecules have been studied in detail but polyatomic molecules either break down in the excitation chamber or produce complicated spectra which are very difficult to study. The blue cone of the bunsen flame shows bands due to CH. The carbon arc (flame, not crater) shows bands due to CN and CO.

Line spectra are the most common and easily excited of the spectral types. A line spectrum is caused by the excitation of atoms and is characterized by a succession of bright lines having an apparently random intensity and spacing but which is more or less individual in character. Sources whose lines are well separated for easy identification and use are of course most desirable and most commonly employed.

The sodium flame is the most common monochromatic light source. This yellow flame consists exclusively of light at 589.0 and 589.6 mμ. The flame spectrum of sodium or certain other salts can be easily obtained by supporting asbestos paper impregnated with the desired salt in the edge of the colorless flame from a Bunsen burner. More detailed methods have been described by Baly.[10] A list of selected elements and their more conspicuous radiations is given below. The elements are usually used in the form of the chloride because of the volatility of these salts.

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[10] E. C. C. Baly, "Spectroscopy", Vol. 2. pg. 55.

TABLE NO. VII

FLAME SOURCES FOR SPECTROMETER CALIBRATION

Wave-length, mμ	*Element*	*Wave-length, mμ*	*Element*
404.4	Potassium	589.3[11]	Sodium
460.8	Strontium	670.8	Lithium
535.1	Thallium	768.2[11]	Potassium

For certain purposes metallic arcs and sparks in air yield very useful spectra. The arc between iron electrodes has received the most study[12] and the iron spectrum is a recognized source of wave-length standards. This arc is very steady if maintained between a cooled upper electrode and a globule of molten metal in a depression in the lower electrode. The arc draws about 5-10 amperes from a d. c. circuit at 115 volts. A series resistance is required for control. The arc spectra of other metals can be produced by using an upper electrode of carbon and melting a bead of the desired metal in the depression in the upper end of the lower iron electrode. Such spectra of course will be contaminated with iron lines. Simple electrode holders for arc and spark spectra can be improvised or obtained commercially.[13] Touching the two electrodes with a carbon pencil serves to strike the arc without disturbing the electrode alignment.

High tension sparks between metallic electrodes frequently show the metallic spectrum on a background composed of many fine lines. These lines are due to the excitation of the air and may be reduced by adding self inductance to the circuit.[14]

Metallic arc and spark spectra have lines too close together for some experiments requiring monochromatic light but are exceedingly useful as wave-length standards or for the identification of chemical elements.

The enclosed metallic arcs are very convenient sources of monochromatic light. The mercury lamp is the most common and is available in many commercial forms which are convenient to use. High pressure lamps such as the type H-3 and H-4[15,16] produce

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[11] Close pair of lines.

[12] A. H. Pfund, Astrophys. Jour., 27, 298 (1908).

[13] Central Scientific Company. Catalog No. 87118.

[14] F. Twyman and D. M. Smith, "Wave-length Tables for Spectrum Analysis".

[15] These lamps are manufactured by the G. E. Co. and Westinghouse Lamp Co.

[16] B. T. Barnes and W. E. Forsythe, "Characteristics of Some New Mercury Arc Lamps" J. O. S. A. 27, 83 (1937).

broad lines at full pressure and should be operated at currents reduced sufficiently to produce sharp spectral lines. The most prominent line groups in the mercury spectrum are listed in table No. VIII.

TABLE NO. VIII

WAVE-LENGTH OF MERCURY LINES

Wave-length, mμ	*Conspicuousness*	*Color*
404.7	(5)	Violet
407.8		
433.9	(3)	Blue
434.7		
435.8		
491.6	(4)	Blue
496.0		
546.1	(1)	Green
577.0	(2)	Yellow
579.1		

Lamps are also available containing a mixture of mercury and other metals which supply additional lines in the spectrum.[17]

The sodium lamp[18] is a very convenient laboratory source and exhibits not only the very intense sodium lines but a few of the more prominent neon lines. These are very faint, of course, because of the small proportion of neon present in the lamp.

Gaseous discharge tubes of various sorts are also used as spectroscopic sources. Tubes containing the rare gases are readily available.[17] Hydrogen and helium spectra are commonly used for refractive index measurements.

Caution

Metallic arcs and sparks and the quartz mercury arcs emit a dangerous quantity of ultra-violet radiation. A sheet metal shield should be arranged to prevent any of these rays from reaching the eyes of the experimenter. When necessary to look directly at the light source, a piece of window glass or plate glass should be interposed. The radiation is naturally less dangerous to the skin but exposures of 10 - 15 minutes to the iron arc particularly will cause erythema (sunburn).

Wave-length Tables

The first efforts to identify wave-lengths took the form of maps of the solar spectrum on which the prominent lines were identified alphabetically. Subsequently these radiations were identified in

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[17] See for example Central Scientific Co. Catalog J136, pp. 1519-1520.

[18] The Sodium Lab-Arc is manufactured by the G. E. Vapor Lamp Co.

terms of wave-length expressed in linear measure, using a sub-multiple of the meter as a unit. In the field of physics, spectroscopists usually express wave-lengths in Angstrom units, abbreviated A. U. or more recently I. A. (International Angstroms). Chemists, engineers, the medical profession and workers in colorimetry prefer to use millimicrons, abbreviated $m\mu$.[19] Infra-red spectroscopists and workers in temperature radiation theory commonly use a larger wave-length unit, the micron, abbreviated μ. 1 micron = 1000 millimicrons = 10,000 Angstroms. The visible region extends from 4000 to 7500 Angstroms, 400 to 750 millimicrons or 0.4 to 0.75 microns.

The principal lines in the spectra of most elements have been measured and their wave-length and intensity tabulated. A selection of such tables is given below.

1. "Handbook of Chemistry and Physics", Charles D. Hodgeman, The Chemical Rubber Publishing Co., Cleveland, Ohio. This readily available book gives about 80 pages of tables which while not exhaustive are complete enough for many purposes.
2. "Atlas Typischer Spektren", J. M. Eder and E. Valenta, A. Hoelder, Wien, 1928. This work contains wave-length tables but its great value lies in the 50 odd plates illustrating the arc, spark, flame and discharge tube spectra of about 70 elements.
3. "Tabelle der Hauptlinien der Linienspektra aller Elemente", H. Kayser, Julius Springer, Berlin, 1926. Nineteen thousand lines are listed in order of wave-length.
4. "Wave-length Tables for Spectrum Analysis", F. Twyman and D. M. Smith, Adam Hilger, Ltd., London, 1931. This book is of particular value to the analyst.
5. "International Critical Tables", Vol. 5. McGraw-Hill, New York. These are reprinted in the Handbook of Chemistry and Physics.

The books in the preceding bibliography have been listed in the order of their importance to a student first becoming acquainted with spectroscopy.

Wave-length Calibration of a Prism

The use of a prism at minimum deviation is always an advantage because since the incidence and emergence angles are equal the

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[19] The prefix "milli-" means "one thousandth" and is properly abbreviated by "m". The symbol "μ" is the abbreviation for "micro" or "micron", meaning "one millionth" or "one millionth of a meter" respectively. This shows that there is no defense for the illogical and meaningless symbol "$\mu\mu$" sometimes ued as an abbreviation for millimicron. The symbol taken literally would mean the absurdly small quantity, a micro-micron.

deviation depends only on the prism angle and the index of the prism at the wave-length involved. In the study of a spectrum, resetting the prism at every line is too tedious and it is justifiable to set the prism at minimum deviation at only one standard point. Illuminate the slit with light from a mercury lamp. Set the prism at minimum deviation on the mercury green line, 546.1 mμ. The violet, blue and yellow lines can also be easily identified and the telescope set on them. The resulting data will be similar to table No. IX.

TABLE NO. IX

TELESCOPE SETTINGS IN THE MERCURY SPECTRUM

Prism No. 10040. Minimum Deviation at 546.1 mμ.

Wave-length, mμ	*Telescope Position*	$\frac{1}{\lambda^2}$	*Wave-length, mμ*	*Telescope Position*	$\frac{1}{\lambda^2}$
404.7*	73° 20.5′	6.106x10⁻⁶	546.1*	70° 4′	3.353
407.8*	73° 14.25′	6.013	567.6	69° 47.75′	3.104
435.8*	72° 15.25′	5.265	578*♯	69° 41.25′	2.993
491.6	70° 54.5′	4.138	623.4	69° 16′	2.573
496.0	70° 49.75′	4.065	690.7	68° 48′	2.096

* = Easily identified

♯ = Average of two lines at 577.0 and 579.1

A tentative curve plotted through the points mentioned will probably suffice to identify the line at 491.6 and the weaker one at 496.0 but may not identify the closely spaced lines in the red. A curve between telescope position and $1/\lambda^2$ (see discussion of Cauchy formula on page 6) will be nearly linear and will be very helpful in settling doubtful identifications. Compute $1/\lambda^2$ for all useful wave-lengths to have them available. As more lines are identified the curves can be altered to suit. The selection of additional wave-lengths from mercury or other spectra will permit the calibration curve to be drawn as accurately as may be desired. Two such calibration curves are shown in fig. 14.

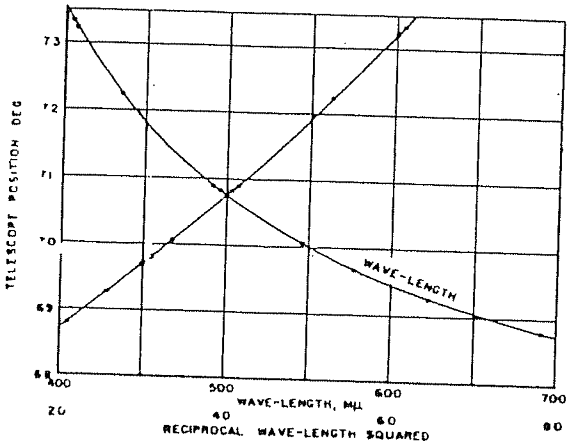

Fig. 14. Calibration of No. 10040 Prism

These calibration curves will always fit the prism for which they were made if in replacing the prism on the spectrometer the telescope and prism table are first clamped at the telescope position corresponding to 546.1 and the prism set to minimum deviation by loosening clamp I and very carefully adjusting the prism table with respect to the circle and verniers.

Constant Deviation Prisms

It is frequently desirable to have the collimator and telescope in a fixed relation to each other and many schemes have been devised by which this can be done. Perhaps the simplest method is to use a 30° — 60° prism as shown in fig. 15. The light incident on the short face is refracted into the prism. It is totally reflected from the long side and emerges from one end of the hypothenuse face. The internal reflection balances the refractions so that rays which pass through the prism at minimum deviation are deviated through 60° regardless of their wave-length. Thus the collimator and telescope can be permanently set at 120° included angle. Rotating the prism table through about four degrees permits the entire visible spectrum to be seen. This prism can be calibrated by the method described previously. First set the telescope 120° from the collimator and clamp it. Locate the prism on the prism table so that the center of rotation passes through the long side at its intersection with the bisector of the 60° angle. This position can be located well enough by eye. Work out a table showing prism table positions and wave-lengths similar to the previous table. A calibration for this prism is shown in table No. X amd fig. 16.

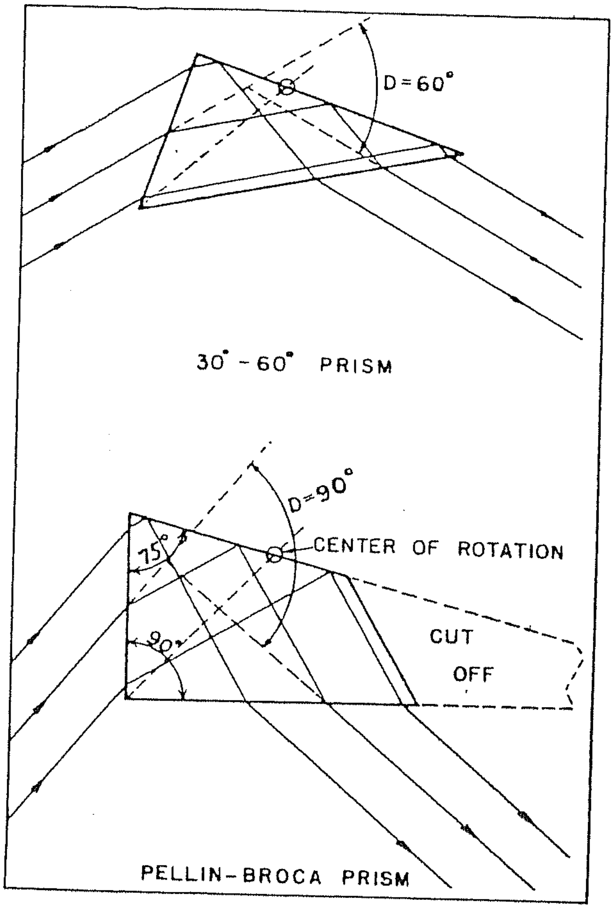

Fig. 15. Constant Deviation Prisms

TABLE NO. X

CALIBRATION OF CONSTANT DEVIATION PRISM

Prism No. 10041 589.3 mμ = 70° 03′

Element	Wave-length, mμ	Prism Position	Element	Wave-length, mμ	Prism Position
Copper	402.2	67° 21′	Copper	521.8	69° 26′
Mercury	404.7	67 23	Mercury	546.1	69 42
Copper	406.3	67 27	Mercury	577.0	69 57
Copper	424.9	68 00	Sodium	589.3	70 03
Mercury	435.8	68 11	Mercury	607.3	70 10
Copper	458.7	68 45	Mercury	612.3	70 12
Copper	465.1	68 45	Neon	614.3	70 14
Mercury	491.6	68 45	Mercury	623.4	70 17
Neon	503.4	69 13	Mercury	690.7	70 34
Neon	520.6	69 25			

The Pellin-Broca prism shown in fig. 15 deviates the ray through 90° and is very frequently used in spectroscopic instruments. This is essentially a triangular prism having angles of 75° and 90°. The portion shown by a dash line in the diagram is not used by the light and is usually cut off. Triangular prisms having a wide choice of angles have the constant deviation property if they cause two refractions separated by an internal reflection. Uhler[20] has shown that the 30° — 60° prism and the Pellin-Broca prism are merely special cases. In all such prisms the rotation should take place about the intersection of the reflecting surface with the bisector of the angle between the refracting surfaces.

Constant deviation of practically any angle also can be obtained by the use of an external front surface mirror as first described by Wadsworth[21] and subsequently discussed in various texts.[22,23] This type of mounting makes an interesting experimental set-up. The two arrangements shown in fig. 17 deviate the ray through 0° and 90° respectively. Notice that even though the reflection is

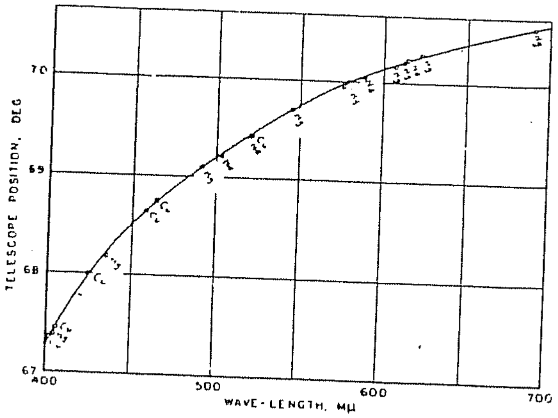

Fig. 16. Calibration of Constant Deviation Prism

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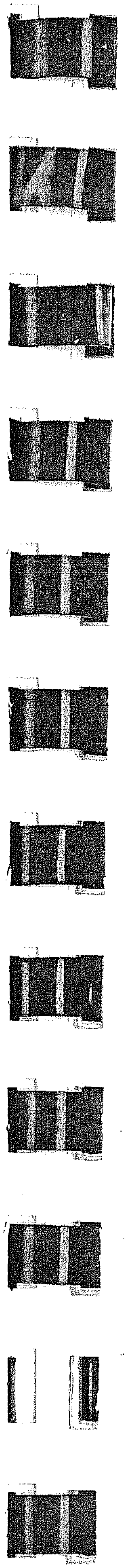
[20] H. S. Uhler, "Generalization of the Problem of the Rotation of Prisms Producing Constant Deviation by Two Refractions and One Internal Reflection", Astrophys. J., 47, 65 (1918).

[21] Wadsworth, Phil. Mag. 38 337 (1894).

[22] W. E. Forsythe, Ed., "Measurement of Radiant Energy", pg. 119, 135.

[23] A. C. Hardy and Fred Perrin, "The Principles of Optics", pg. 554.



external, the axis of rotation is still located at the intersection of the bisector of the refracting angle with the plane of the mirror.

Comparison Prism

The procedure, recommended on the opposite page, where unknown or uncertain lines are identified by gradually extending the list of known spectral lines is facilitated by the use of the comparison prism. This is a right-angled, total reflection prism, see fig. 18, which can be used to pick up light from one source located at the side of the spectrometer and direct it along the collimator axis above the direct beam from a second source located directly in front of the collimator as usual. The two spectra will be seen one above the other in the eyepiece. Thus the prominent features of each spectrum help to eliminate uncertain identifications in the other.

Bunsen Spectroscope Attachment

The methods just described for measuring wave-length are capable of high precision and entail a corresponding amount of labor and care. Where an arbitrary scale is desired for approximately locating the position of spectral lines and where simplicity and ease of adjustment and use are essential the Bunsen spectroscope attachment will be found of value. This attachment consists of an auxiliary collimator S mounted in the side wall of a prism table cover T which can be fastened to the prism table, see fig. 2. The collimator carries a scale U at its outer

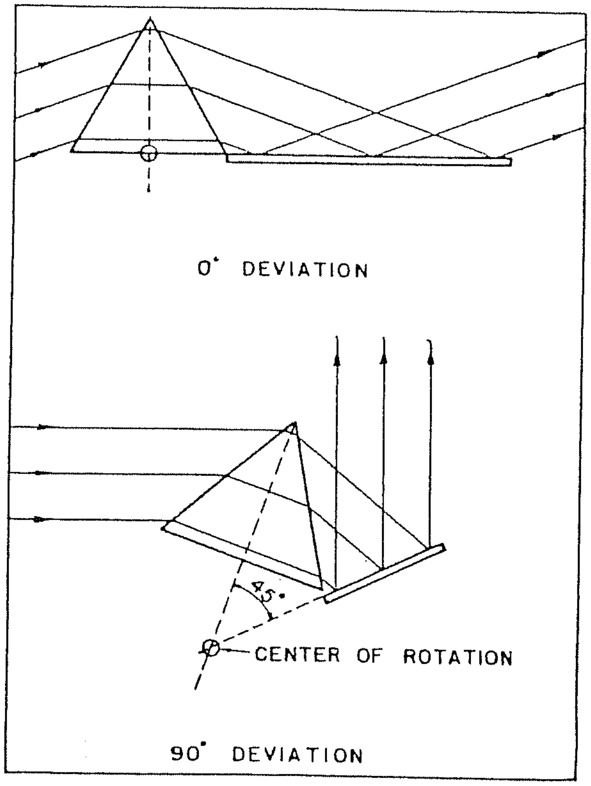


Fig. 17. Constant Deviation Prisms Using Wadsworth Mirror

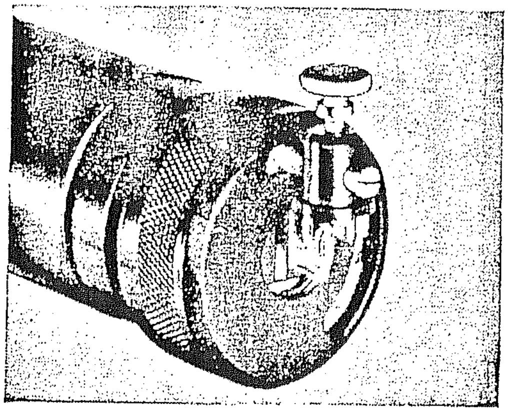


Fig. 18. The Comparison Prism

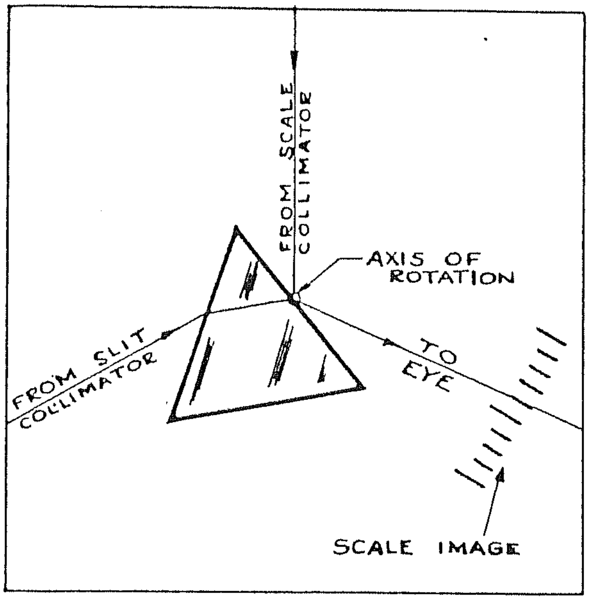


Fig. 19. Passage of Rays Through Bunsen Spectroscope

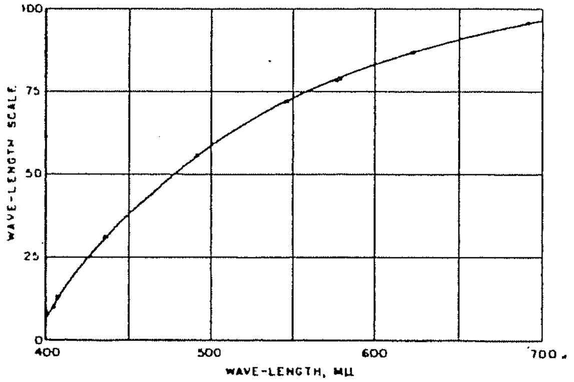


Fig. 20. Calibration of Bunsen Spectroscope

end which is illuminated by some external source. Rays from the scale are rendered parallel by the collimator and after reflection from the second prism face enter the telescope along with the spectrum forming rays and are focused by the eyepiece. The prism must be set to one side substantially as in fig. 19 in order that the scale forming rays may enter the telescope. After locating the prism on the table, adjust the instrument to show a good spectrum in the telescope. Clamp the prism table. Without moving the eye, swing the telescope to one side and see the spectrum directly in the prism. Still keeping the eye fixed, put the attachment in place and turn the prism table cover on the table until the scale is super-imposed on the spectrum and is right side up. Swing the telescope back into position to view the spectrum. The scale will also appear unless it is out of focus. If necessary, adjust the draw tube S to focus the scale. If the above procedure has been followed, the scale should appear in the telescope field without the necessity of additional lateral adjustments of the entire attachment.

The position of known spectral lines can be determined in terms of the scale and a calibration curve can be drawn between scale divisions and wave-length as shown in fig. 20. This curve will serve to identify unknown radiations.

If the attachment, or, more particularly, the prism were moved and replaced, it would probably be difficult to repeat the old calibration and a new one would be required.

SPECTRUM PHOTOGRAPHY

The Spectrographic Camera

Before attempting to assemble the camera on the spectrometer the collimator should be in proper alignment and in good focus for parallel light. This latter adjustment is particularly important because the image quality suffers when the rays traversing the prism are not parallel.

The Spencer spectrographic camera can be substituted for the telescope by loosening the telescope screws P and Q and the screw on one end of the axle R. Withdraw the axle to free the telescope. Assemble the camera in place of the telescope by threading the axle R through the front bearing. It is sufficient to center the camera bearing by eye in the middle of the fork before tightening the front screw Q. With the slit suitably illuminated and no prism in the light beam swing the camera into line with the collimator. An image of the slit will be found on the ground glass V mounted in the plate holder slide of the camera. The slit image can be centered in the middle of the slot in the back of the camera housing by adjusting the camera levelling screws P, thus aligning the camera with the collimator axis. The image is brought into focus by sliding the objective draw tube X. The flap shutter W controls the passage of light through the camera. Although the sharpest images are produced with the prism at minimum deviation, the spectrum is relatively compressed. Setting the prism slightly off minimum deviation produces a longer spectrum and need not deteriorate the image unduly.

Place a 60° prism having an index of about 1.72 on the prism table and line up the prism and camera substantially as shown in fig. 7 (the camera replacing the telescope). Illuminate the slit with a mercury lamp. Locate the spectrum on the ground glass. Rotate the prism table until the green or yellow lines are approximately at minimum deviation. Rotate the prism table to swing the back edge of the emergent face of the prism toward the camera lens. This will lengthen the spectrum. Rotation the other way would move the spectrum across the field but not increase its length materially. Lengthen the spectrum to about 35mm. between the blue line at 435 mμ and the yellow lines at 577,579 mμ. Move the camera to bring the blue line to the middle of the plate.

It may be well to move the prism slightly on the prism table to take in all of the beam from the collimator and to fill the camera lens. Sometimes it also is advantageous to move the camera to one side in its support at R.

Set the slit rather fine and bring the line at 435 $m\mu$ into good focus by adjusting the camera lens position. Without changing the camera lens adjustment, focus the yellow lines by adjusting the tilt (controlled by clamping screw Y). If desired, this visual adjustment can be made more accurately by using a magnifier to judge the position of best focus. For higher precision, a succession of small variations in camera lens position and in tilt position can be made, taking a separate photograph at each setting. The best focus and tilt adjustments can be determined by examining the finished plate with a magnifier. When focusing by photography it is convenient to use a source like the copper arc which has more lines in the spectrum than has mercury. When a detailed study of a particular spectral region is contemplated, it may be worthwhile to focus that region in the middle of the plate. Since permanent rigidity is desirable in spectrum photography, it is desirable to screw up the tangent screws J and K to their limit, thus holding the camera and prism table in more secure alignment.

The plate holder takes either glass plates or cut film, 6.5 x 9 cm. in size. Plates cut 2½x3½ inches will also fit the holder. After one or two preliminary trials the plate holder can be easily loaded in total darkness. With the dark slide removed, a nickel clamp will be seen which can be withdrawn slightly. This frees one end of a hinged metal frame which holds the plate or film in place against the spring back. The emulsion side of the plate should face the opening.

Making the Exposure

The spectrum photograph is a picture of the separate slit images formed by the various wave-lengths of light emitted by the source. Since the camera lens has twice the focal length of the collimator, each slit image is twice the height and twice the width of the slit itself. The height of the slit, which controls the height of the spectrum, can be reduced from 9 mm. to 3 mm. by using the two aperture diaphragm, fig. 21. The principal use of this diaphragm is in photographing two sources so that their spectra are in close juxtaposition on the plate to permit the relative wave-length positions of lines in the two spectra to be compared. This method of comparison is much more accurate than sliding the plate holder between exposures because the possibility of even a minute lateral movement is avoided. The spectra can be photographed in contact, one above the other, by photographing one spectrum through the upper and the second through the lower aperture without moving the plate holder. The plate position is controlled by the clamp Z and indicated on the scale AA. If the diaphragm is used, giving spectral lines 6 mm. high, well separated spectra can be made by lowering the plate about 1 cm. between exposures.

When the slit is fairly wide open, the spectral line images are correspondingly wide. As the slit width is reduced the lines get narrower until a limit is reached dependent on the light scattered from the slit jaws and on the minimum width of the photographic image. Narrower slits than this rapidly reduce the intensity of the spectrum but cannot sharpen the lines. Once the exposure appropriate to a given slit width is determined, the slit should not be changed without again checking the exposure time.

The exposure should be adjusted to show the desired detail. If it is only necessary to identify the strong lines on a plate, use a short exposure to suppress the background. Conversely a long exposure is required to record the weaker lines. Since long exposures broaden the strong lines too much to measure their position, it is often desirable to make a short and long exposure through the two aperture diaphragm. A plate of trial exposures in which each exposure time is increased by 2 or 2.5 will usually show at least one satisfactory spectrum on the plate.

The Condensing lens

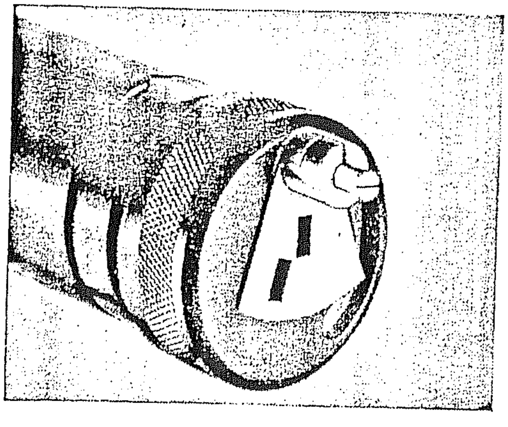


Fig. 21. Two-Aperture Diaphragm

The mode of illuminating the slit has a profound effect on the resulting spectra.[24] A small source located at a distance illuminates only the axial portion of the optical system thus failing to take advantage of the resolving power and light gathering capability of the full aperture. A

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[24] D. C. Stockbarger and Laurence Burns, "Line Shape as a Function of the Mode of Spectro graph Slit Irradiation", J. O. S. A 23, 379 (1933).

source of large projected area can sometimes be brought close enough to the slit to completely fill the collimator lens. The same result can frequently be more easily obtained by projecting an image of the source onto the slit with a condensing lens, fig. 22. In order to produce a real image, the source to slit distance must be at least four times the focal length of the condenser. When the distance is greater than four focal lengths there are two condenser positions where the source may be imaged on the slit. When the condenser is close to the source, the image is enlarged but the cone of rays entering the collimator is small. Placing the condenser close to the slit produces a small image and a widely diverging cone of rays. These principles can be used to guide the choice of source and condenser position so as to obtain an image large enough to cover the whole slit and composed of rays just filling the collimator. Rays more divergent than required are diffusely reflected from the collimator tube and produce stray light which veils the spectral lines and reduces the contrast.

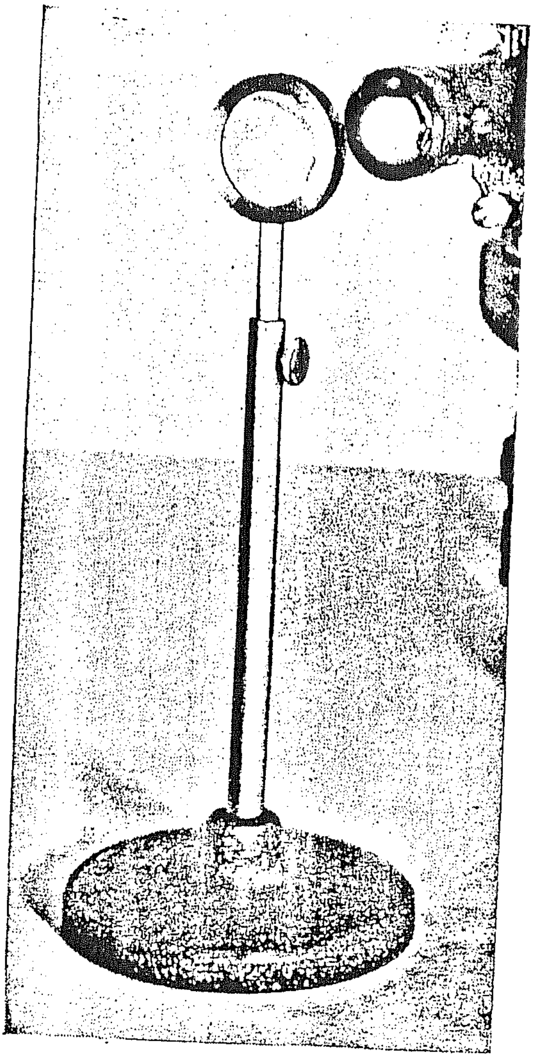

Fig. 22. The Condensing Lens

The condensing lens can be used to isolate and examine localized portions of a light source. In an open arc, for example, the radiation near the electrodes has a different character from that in the middle of the arc flame.

Plates and Developing

The emulsions used should be selected for their fine grain and color sensitivity. Speed is of no consequence. Wratten M plates (Eastman Kodak Co.,) are very satisfactory for general use in the near ultra-violet and visible regions between 350 and 600 mμ. The special plates which are required for the near infra-red also can be obtained from the same manufacturer.[25]

Plates usually are obtainable in the 6.5x9 cm. size but when necessary larger plates can be cut down. It is comparatively easy to cut photographic plates in the dark after a little practice. Prepare two guides as indicated in fig. 23 such that the distance from the back stop to the wheel of a glass cutter held against the open edge is just 6.5 and 9 cm. respectively. The plate is laid emulsion side down on a clean paper with its edge fitted into the corner of the guide and cut with a wheel glass cutter. Handle the plates only by the edges to avoid finger marks on the emulsion surface.

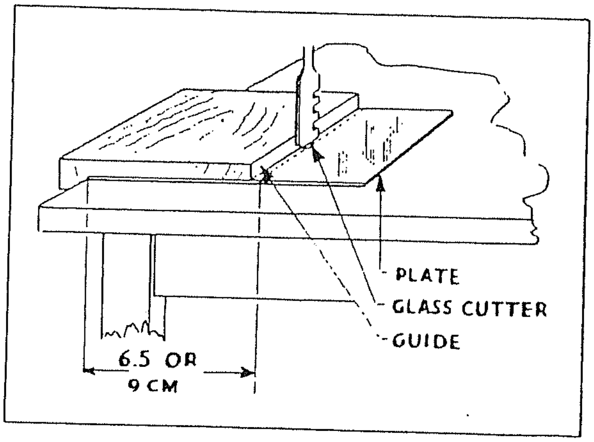

Fig. 23. Guide for Cutting Photographic Plates

The plates should be developed to the highest contrast compatible with a clear background. Use a contrast developer recommended by the plate manufacturer and develop by time and temperature. Most workers do not bother with safelights but develop the plate in the dark.

Eastman formula D-11 is a popular developer for spectroscopic plates. Formula D-19 is especially recommended for producing high contrast on Wratten M plates. These formulas are given in table No. XII.

TABLE NO. XII

DEVELOPING FORMULAS

Chemical	*Formula D-11*	*Formula D-19*
Water (about 125° F.)	500 cc.	500 cc.
Elon	1.0 grams	2.2 grams
Sodium Sulphite, desiccated	75.0 grams	96.0 grams
Hydroquinone	9.0 grams	9.0 grams
Sodium Carbonate, desiccated	25.0 grams	48.0 grams
Potassium Bromide	5.0 grams	5.0 grams
Cold water to make	1000 cc.	1000 cc.
Developing time at 65° F.	5 min.	4-6 min.

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[25] "Photographic Plates for Use in Spectroscopy and Astronomy".

Reading the Plate

It is obviously futile to attempt to identify every line appearing on a plate. Familiarity with one or two characteristic spectra, mercury and copper, for example, will supply known wave-lengths at frequent intervals. In this way if one of these spectra is photographed in contact with an unknown, the prominent features of the latter can be identified. A plate containing a few landmarks can be calibrated in as great detail as required by the procedure described previously and saved for subsequent comparison with other plates. Measure the position of the principal lines from one edge of the plate and interpolate graphically or with the Cauchy formula. The measurements should be made with a high grade scale preferably graduated to half millimeters to facilitate estimating tenths. Where higher precision is required, plates are measured with a traveling microscope, reading to 0.01 or 0.001 mm. and interpolations are made by the Hartmann formula. Compute the dispersion (mμ/mm.) on different parts of the plate to help keep the available wave-length accuracy in mind. For example on a certain plate the violet mercury lines were 1.7 mm. apart. The wave-length interval is 407.8 − 404.7 = 3.1 mμ and the dispersion 1.8 mμ/mm. Differences less than 0.2 mμ in this region would be unmeasurable with a scale (but could be observed with a micrometer microscope).

A wave-length scale is easy to prepare and is a valuable aid in identifying unknown lines. Plot a good curve relating plate distance and wave-length. A wave-length scale can be laid off from the curve. Since the dispersion changes rapidly the number of subdivisions on the scale will change correspondingly. If, due to change in the instrument adjustment, the scale does not fit all plates exactly, it will fit over the short distance between landmarks and is useful for quick interpolation. Fig. 24 shows the copper arc spectrum

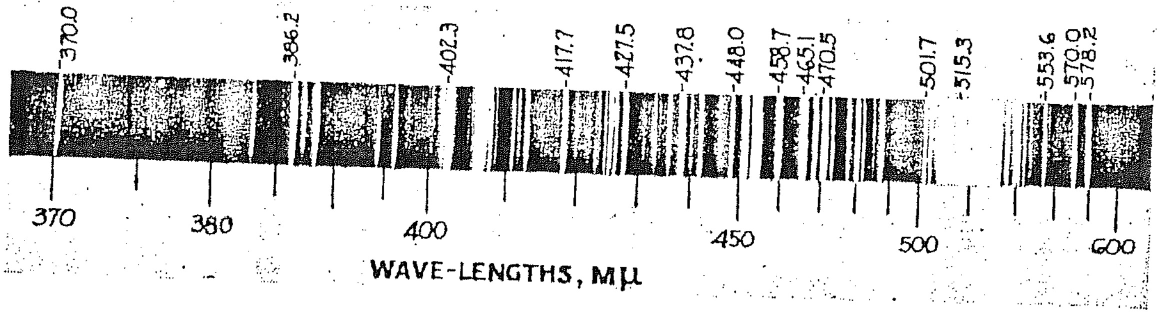

Fig. 24. Prismatic Spectrum of the Copper Arc

with a number of lines identified and with a wave-length scale adjoining which was prepared by the method just described.

DIFFRACTION GRATING MEASUREMENTS

Description of the Grating

A diffraction grating consists of a surface closely ruled with lines. In a transmission grating the lines are engraved on glass and the light passes through the spaces between the rulings. A reflecting grating is ruled on a metallic mirror surface which may be either plane or concave with a long radius of curvature. In the latter case the need for lenses is eliminated because the curved reflecting surface collimates the incident beam and focuses the emergent beam into an eyepiece or onto a photographic plate.

Gratings are ruled on highly precise machines[26] which advance the blank in minute steps by means of a lead screw. The lines are engraved with a diamond point. It is particularly important to minimize wear on the diamond which would decrease the uniformity of the line shape, to avoid temperature or other changes in the machine which would gradually change the grating space, and to eliminate all periodic errors in the lead screw which would produce periodic variations in the grating space, causing faint spectral lines to appear out of their proper place. The irregularities in the ruling of a grating give rise to false images or ghosts of the stronger spectral lines. Rowland ghosts are symmetrically grouped about the lines and Lyman ghosts may appear in neighboring parts of the spectrum.

Difficulties in the preparation of diffraction gratings and their scarcity have stimulated various efforts to make copies. Very successful grating replicas can be made by flowing the surface of the original with purified collodion and subsequently stripping and mounting the hardened film produced.

Grating Experiments

The detailed theory of the diffraction grating has been fully discussed in the literature.[27,28,29] Elementary theory describes the

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[26] Sir Richard Glazebrook, "Dictionary of Applied Physics", pg. 30 (1923).

[27] R. W. Wood, "Physical Optics", pg. 242 (1934).

[28] George S. Monk, "Light, Principles and Experiments", pg. 194 (1937).

[29] A. A. Michelson, "Studies in Optics", pg. 86 (1927).

action of a transmission grating by the equation, see fig. 25,

$$\sin \Theta \pm \sin i = \frac{m\lambda}{d}. \tag{14}$$

i = angle of incidence
Θ = angle of diffraction
m = order
λ = wave-length of light
d = grating space.

Mount a transmission grating replica[30] in the grating clamp and mount the unit on the prism table of the spectrometer as indicated in fig. 26. The surface of the grating should coincide with the spectrometer axis. The spectrometer collimator and telescope should be in adjustment as described on pg. 10. Before measurements can be made, the rulings must be made parallel to the spectrometer axis and the slit must be made parallel to the rulings. Illuminate the slit with a mercury lamp and look into the telescope. When the telescope is in line with the collimator, the central image due to undiffracted light is seen. At about 35° on either side the spectral lines due to the first order of diffraction appear. The second order is fainter and appears at greater angles. Cover the lower half of the slit with the two aperture diaphragm. Adjust the back leveling screws until the upper ends of the spectral lines appear the same height in the eyepiece when the telescope is turned to either side of

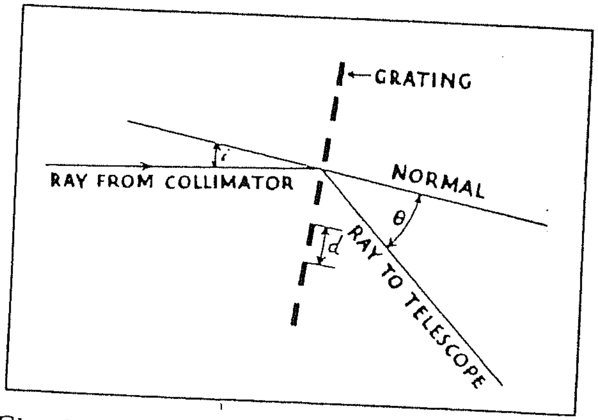

Fig. 25. Diffraction of Light by a Grating

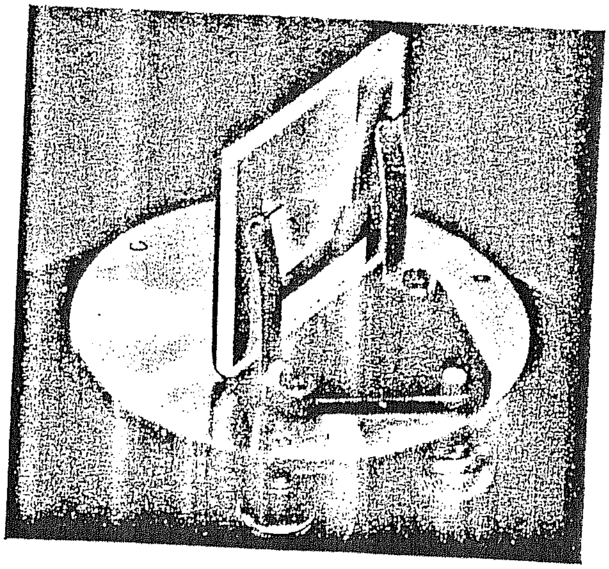

Fig. 26. The Diffraction Grating on the Spencer Spectrometer

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[30] Central Scientific Co. Catalog J136, pp. 1501-1502.

the central image. The rulings are now parallel to the bearing axis. Close the slit or block off the light transmitted through the the grating and bring the grating surface perpendicular to the telescope axis using the front levelling screw and testing by autocollimation. If the collimator has previously been set with its slit parallel to the bearing axis, it will now be parallel to the rulings.

Clamp the prism table with the grating approximately perpendicular to the incident rays. Swing the telescope through two orders of the spectrum on either side of the central image. A typical set of data is shown in table No. XIII. The angle of incidence is the difference between the pointing on the central image and along the perpendicular to the grating. The angle of diffraction is the angular difference between the grating normal and the spectral line. After similar quantities have been averaged, the results can be recorded as in table No. XIV.

TABLE NO. XIII

GRATING MEASUREMENTS IN THE MERCURY SPECTRUM

Wallace Replica of Michelson Grating Ruled 25,110 Lines per Inch

Wave-length, mμ	*Circle Reading*	θ	*sin* θ	*sin* θ ± *sin i*
407.8*	278° 26.5′	69° 19.0′	0.93555	0.80877
404.7*	277 30.5	68 23.0	0.92967	0.80289
579.1	253 38.5	44 31.0	0.70112	0.57434
577.0	253 28.0	44 20.5	0.69893	0.57215
546.1	251 3.5	41 56.0	0.66827	0.54149
491.6	247 2.5	37 55.0	0.61451	0.48773
435.8	243 6.5	33 59.0	0.55895	0.43217
404.7	241 0.0	31 52.5	0.52806	0.40128
Central Image	216 24.5			
Grating Normal	209 7.5			
404.7	193 9.0	15 58.5	0.27522	0.40200
435.8	191 21.0	17 46.5	0.30528	0.43206
491.6	187 58.5	21 9.0	0.36081	0.48759
546.1	184 37.5	24 30.0	0.41469	0.54147
577.0	182 39.5	26 28.0	0.44568	0.57246
579.1	182 32.0	26 35.5	0.44763	0.57441
404.7*	166 34.0	42 33.5	0.67634	0.80312
407.8*	166 6.5	43 1.0	0.68221	0.80899

Angle of incidence = i = 7° 17.0′

sin i = 0.12678

* Second order

TABLE NO. XIV

DETERMINATION OF GRATING SPACE

Observed data from preceding table.

$$d = \frac{m\lambda}{\sin \Theta \pm \sin i}.$$

$m\lambda$, $m\mu$	*$\sin \Theta \pm \sin i$*	*d, $m\mu$*	*$m\lambda$, $m\mu$*	*$\sin \Theta \pm \sin i$*	*d, $m\mu$*
815.6*	0.80888	1008.3	546.1	0.54148	1008.5
809.4*	0.80300	1008.0	491.6	0.48766	1008.1
579.1	0.57438	1008.2	435.8	0.43212	1008.5
577.0	0.57230	1008.2	404.7	0.40164	1007.6

Avg. $d = 1008.2 \pm 0.2$

*Second Order

These data determine the grating space. The equation used is

$$d = \frac{m\lambda}{\sin \Theta \pm \sin i}. \tag{15}$$

When the telescope and collimator are on the same side of the normal to the grating use the positive sign. Once the constant d is determined for a particular grating, it can then be used to measure the wave-length of spectral lines. The replica grating used to obtain the preceding data is a copy of a grating having 25,110 lines per inch. The observed grating space on the replica of 1008.2 $m\mu$ (0.0010082 mm.) corresponds to 25,193 lines per inch. Replica gratings always have more lines per inch than their originals because of a slight shrinkage of the film during manufacture.

The data also serve to plot a dispersion curve, fig. 27, from which the wave-length of unknown radiations can be obtained graphically. It is interesting to compare the dispersion of the grating with that of the prism, fig. 6.

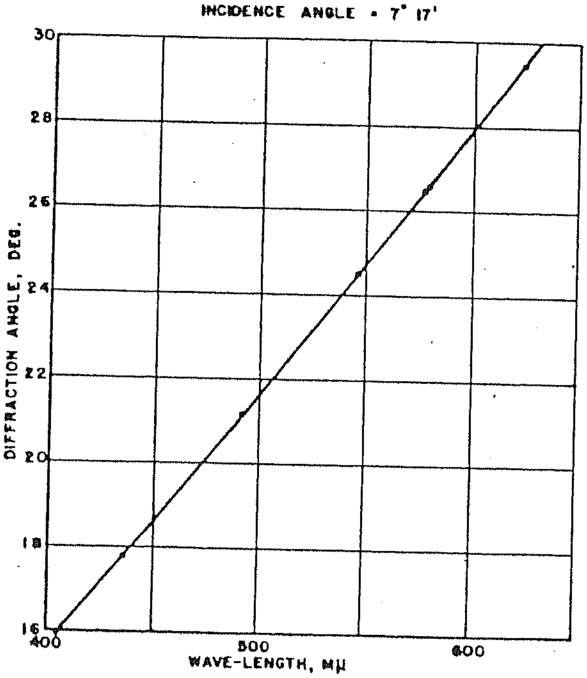

Fig. 27. Dispersion Curve for Grating

The telescope can be replaced by the camera attachment and the spectrum photographed with the grating. The camera is adjusted for focus and tilt in a manner analagous to that used with the prism. In making photographs, the prism table and grating must be covered with a black cloth to prevent the fogging of the plate by stray light. Since the grating yields higher dispersion than the prism, only a portion of the spectrum can be photographed at one setting.

CONCLUSION

The preceding pages have served not only as an introduction to a very interesting instrument but also as an introduction to the science of spectroscopy. Spectroscopy appeals because of its accuracy. Probably the most accurate measurement ever made in the field of physics is the wave-length of a certain line in the cadmium spectrum, measured by spectroscopic methods and assigned the value of 6438.4696 I. A.[31]

Refractive index of glass has been measured to six decimal places by prism methods.[32] Inhomogeneities in the glass prisms make futile any efforts toward higher accuracy.

The diffraction grating merits respect because of the accuracy of its manufacture and the versatility of the spectrometric apparatus of which it forms a part. Through the use of higher orders the available dispersion is increased and the complex nature of many spectral lines can be disclosed.

In astronomy the capabilities of the spectroscope are remarkable. By studying small shifts in the identifiable lines in star light the velocity of the stars and of the galaxy can be determined. Analytical study of stellar and solar spectra discloses the composition of the most remote corners of our universe.

To the chemist the spectrum discloses the presence of traces of metallic materials too small to be detectable by other means. For example, in solution, 0.001% of magnesium, cadmium, aluminum, copper, silver and some other metals may be detected. This has led

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[31] Value quoted from C. D. Hodgman, "Handbook of Chemistry and Physics", pg. 1604 (1936). Method described by A. A. Michelson, "Studies in Optics", pg. 46 (1928).

[32] L. W. Tilton, "Prism Refractometry and Certain Goniometrical Requirements for Precision", B.S.J.R. 2, 909 (1929).

to the preparation of a few "spectroscopically pure" metals in which the total contained impurities may be only 0.001%.

To the physics student, the spectrometer has a particular interest because it opens an acquaintance with a science of very broad scope and more particularly because of a gratification in the accuracy with which spectrometer experiments can be performed. The calculations shown in this booklet show checks in the fourth or fifth significant figure and call for computations with logarithms or a computing machine. The student feels respect for such experiments and confidence in the physical laws they demonstrate.