THE USE OF THE AO Spencer SPECTROMETER

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by

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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 wavelength 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, $m\mu$	Symbol	Element	Wave-length, $m\mu$
A	O	762.1	b_4	Fe	516.7
	O	759.4		Mg	
B	O	687.0	F	H	486.1
C	H	656.3	G’	H	434.0
D_1	Na	589.6	G	Fe	430.8
D_2	Na	589.0		Ca	
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

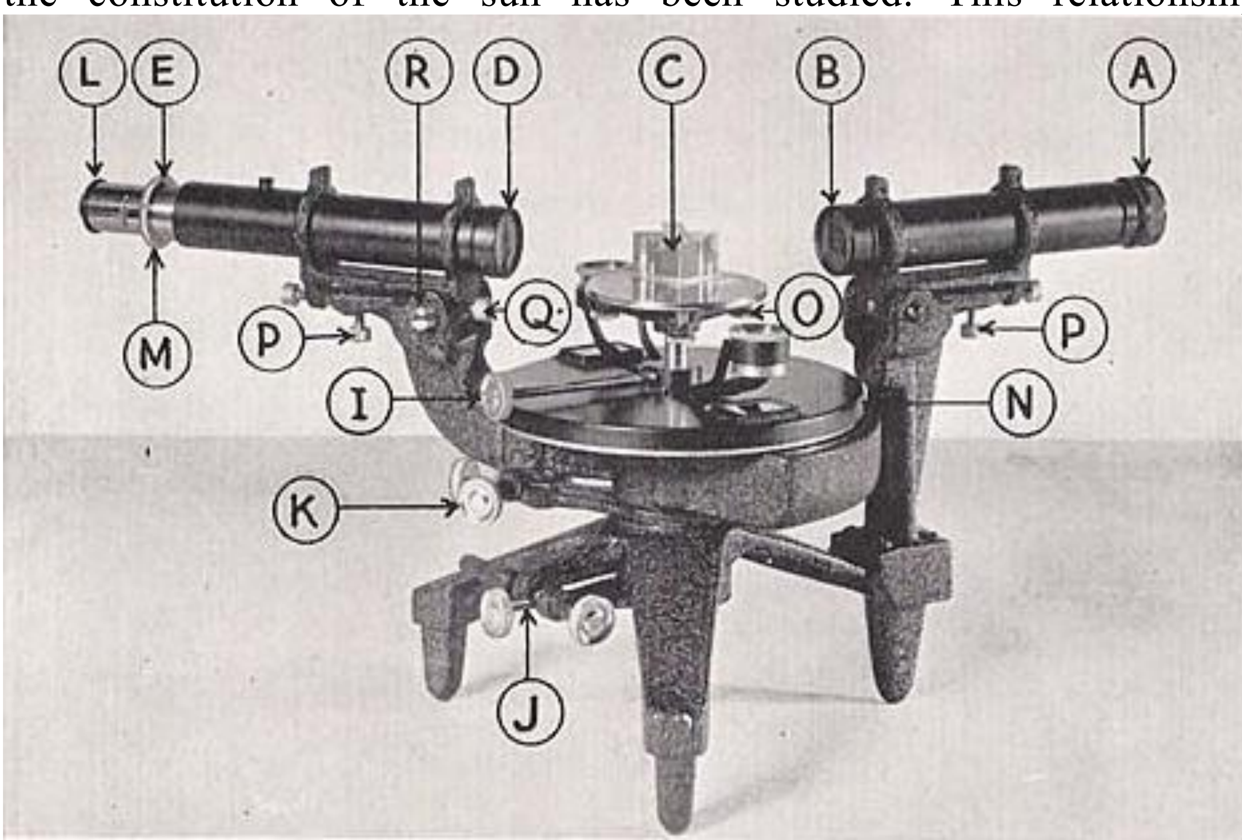

Fig. I. The Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; I—Prism Table Clamping Screw; J—Prism Table Clamping and Tangent Screws; K—Telescope Arm Clamping and Tangent Screws; L—Eyepiece Ring; M—Telescope Focusing Ring; N—Divided Circle Dust Cover; 0—Prism Table Leveling Screws; P—Collimator and Telescope Leveling Screws; Q—Telescope Bearing Front Screw; 12— 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-

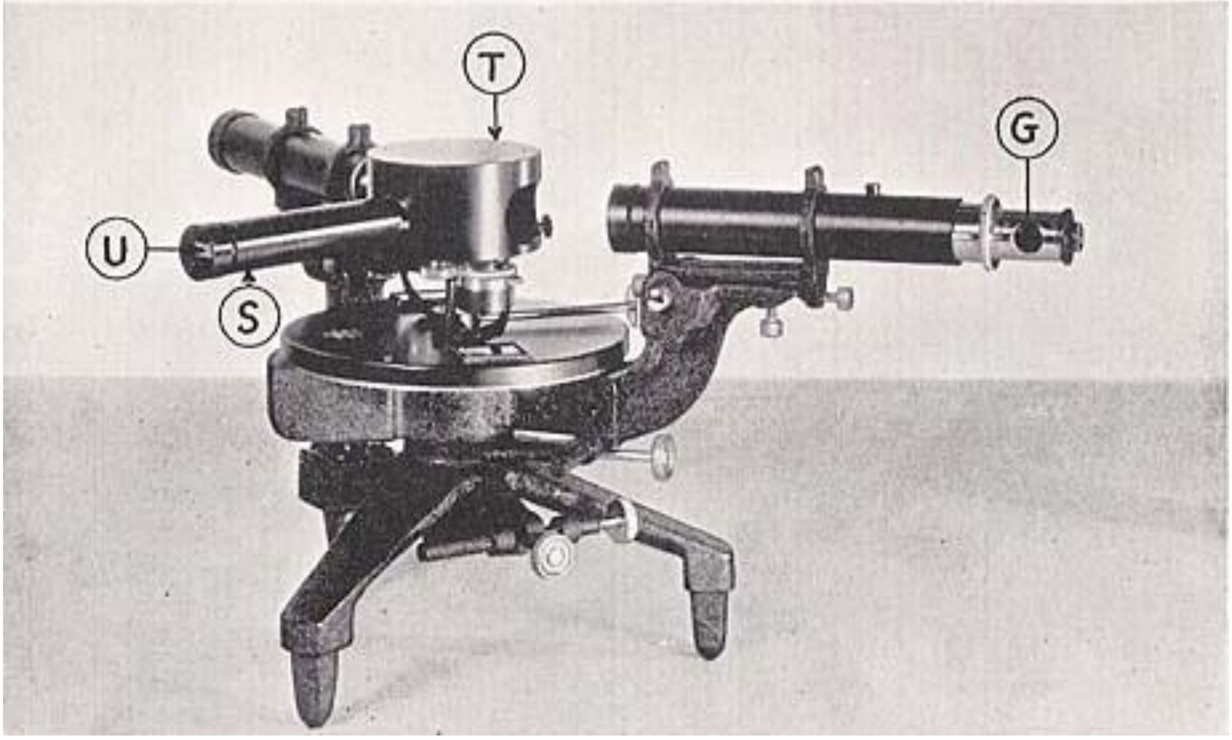

Fig. 21 The Spencer Bunsen Spectroscope Attachment. G—Send-transparent Diagonal Mirror; S—Bunsen Attachment Collimator; T—Bunsen Attachment Prism Table Cover; U—Wave-length Scale.

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 arc 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.

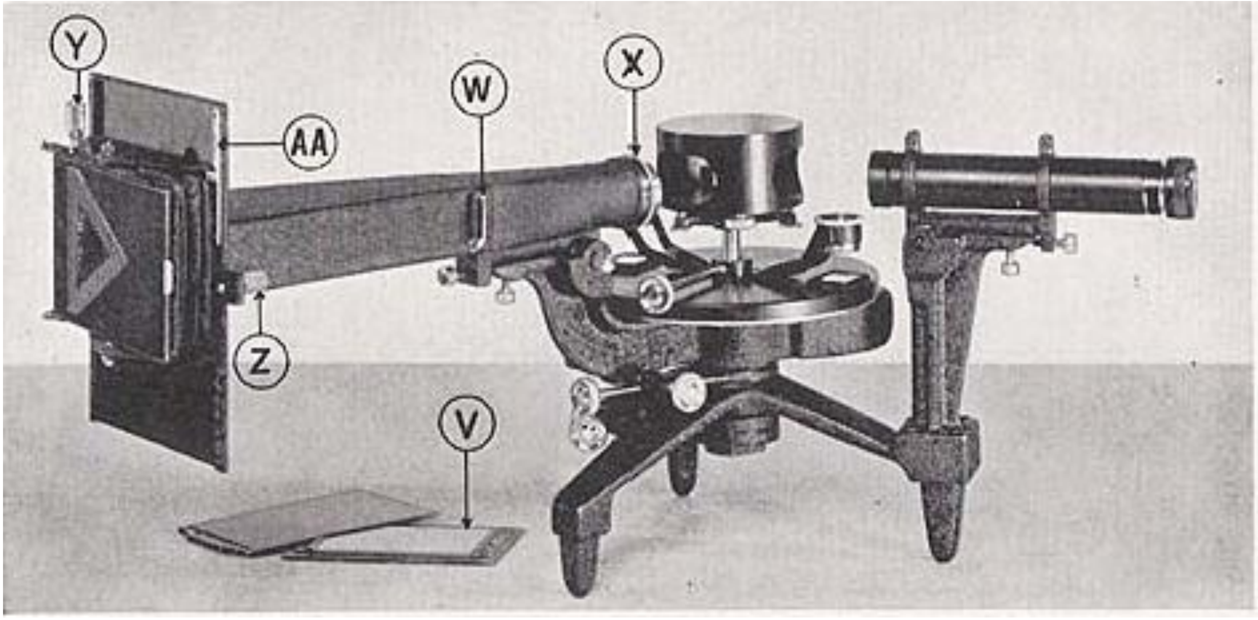

Fig. 3. The Spencer Spectrographic Camera. V—Focusing Screen; W --Shutter Handle; X—Camera Objective Draw Tube; Y—Tilt Clamping Screw; Z—Plate Slide Carriage Clamp; AA—Plate Carriage Scale.

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

$$\sin r = \frac{1}{n}\sin i \qquad (1)$$

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

$$i' = A - r \qquad (2)$$

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

$$\sin r' = n \sin i' \qquad (3)$$

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

$$D = i + r' - A \qquad (4)$$

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

$$i = r', \quad r = i' \qquad (5)$$

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

$$A + D_{\min} = 2i = 2r' \qquad (6)$$

$$n = \frac{\sin {}^1\!/_2(A+D_{\min})}{\sin {}^1\!/_2 A} \qquad (7)$$

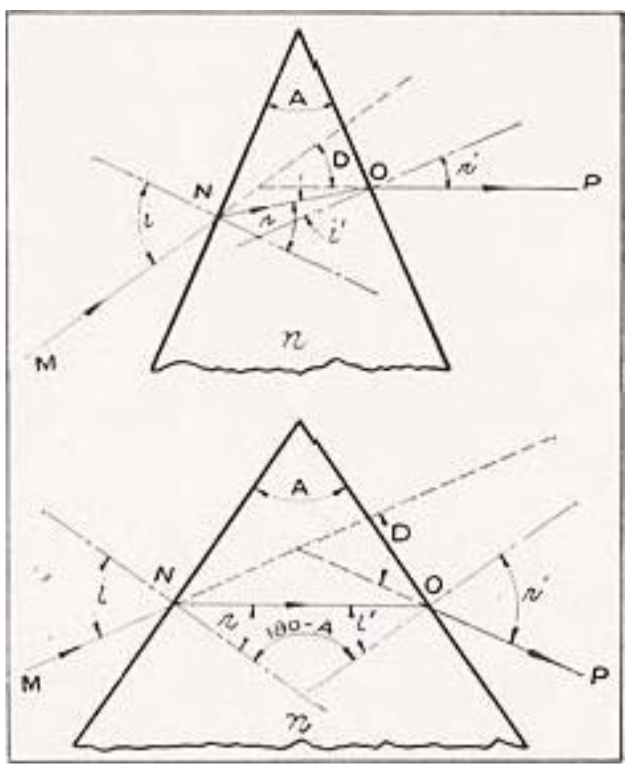

Fig. 4. Refraction of Light by a Prism

[1]See an optical text such 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).

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

$$A = \frac{n_1\lambda_1^2 - n_2\lambda_2^2}{\lambda_1^2 - \lambda_2^2} \quad (9) \qquad\qquad B = \frac{\lambda_1^2\lambda_2^2(n_2 - n_1)}{\lambda_1^2 - \lambda_2^2} \quad (10)$$

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, $m\mu$	*Index*	*Wave-length,* $m\mu$	*Index*
656.3	1.7147	486.1	1.7394
587.6	1.7218	435.9	1.7542
546.1	1.7277		

[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

$A = 1.6835$ $B = 134296$

n_{obs}	λ	λ^2	B/λ_2	n_{calc}	obs-calc
1.7147	656.3	430730	0.0312	1.7147	0.0000
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	0.0000

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.

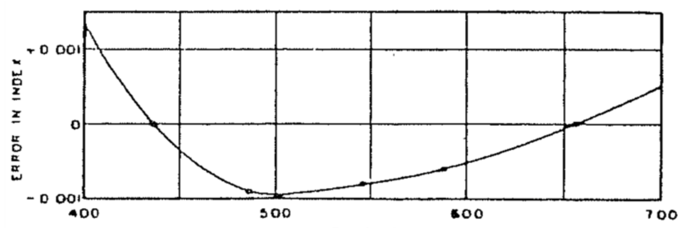

Fig. 5. Error Curve from Cauchy's Formula

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]

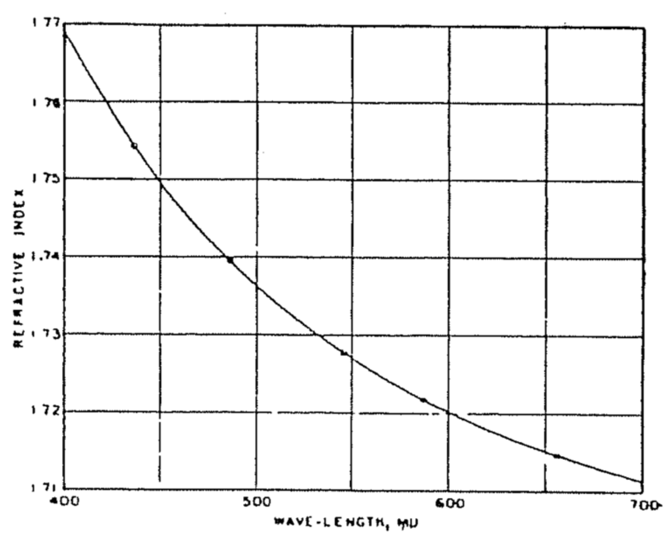

Fig. 6. Dispersion Curve for Extra Dense Flint

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.

[4]For the solutions see Sir Richard Glarebrook, "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

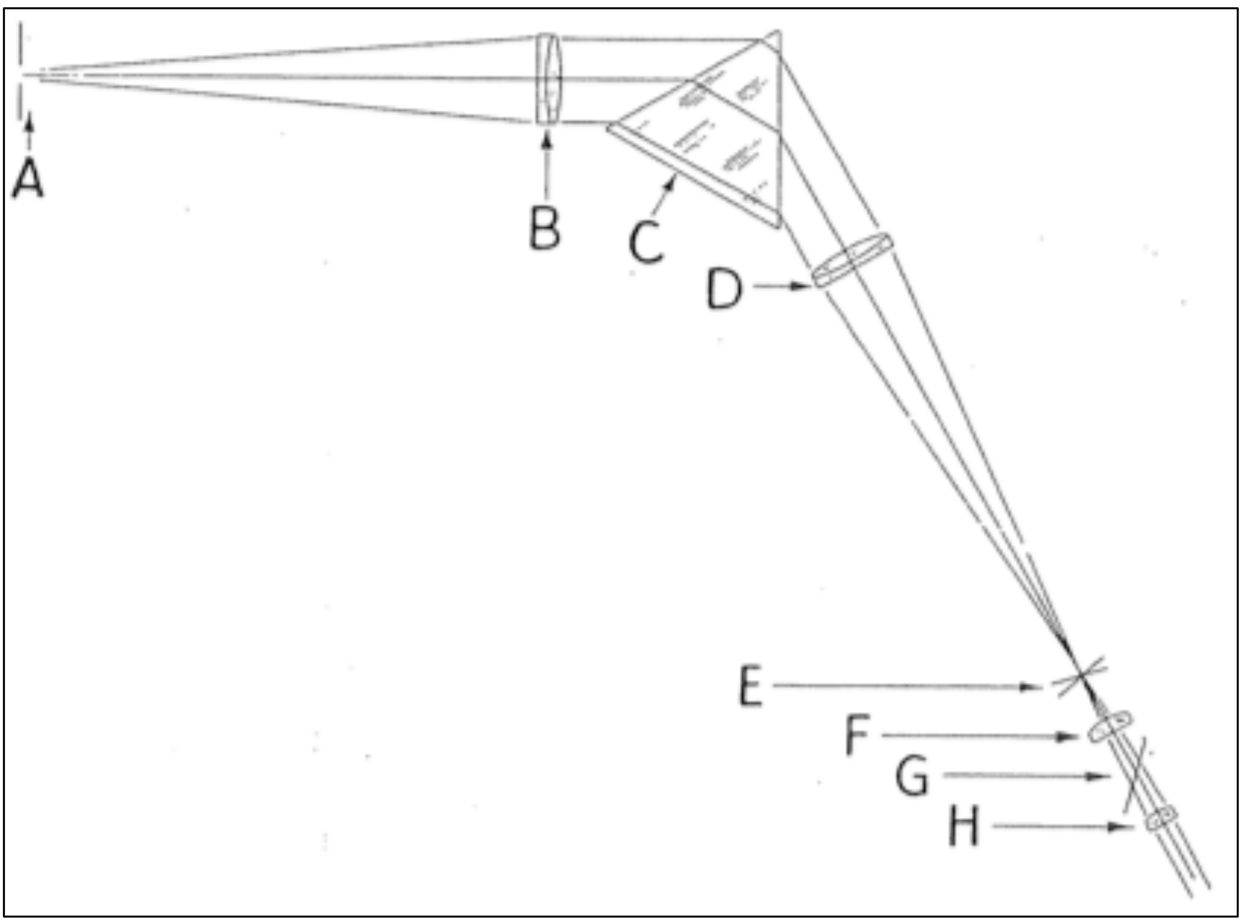

Fig. 7. Path of Rays through the Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; F—Eyepiece Field Lens; G—Semi-transparent Diagonal Mirror; H—Eyepiece Lens.

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 coining 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 arc 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 pres sure 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 care ful 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 instru ment parts which would disturb the delicate adjustments.

Focusing by Auto-Collimation

In focusing the telescope it is first necessary to focus the eye piece 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 he 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

[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 experimen tal 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. I) 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-

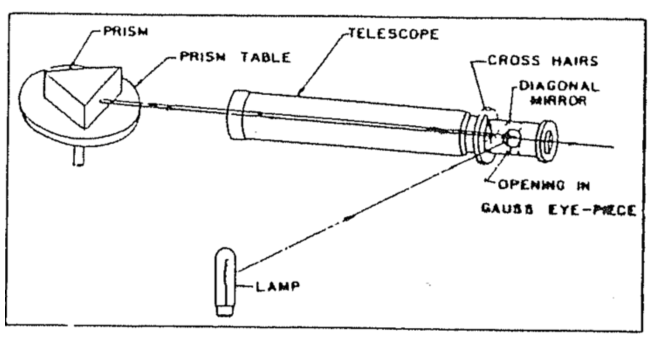

Fig. 8. Arrangement of Telescope and Prism for Auto-Collimation

[5]**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."

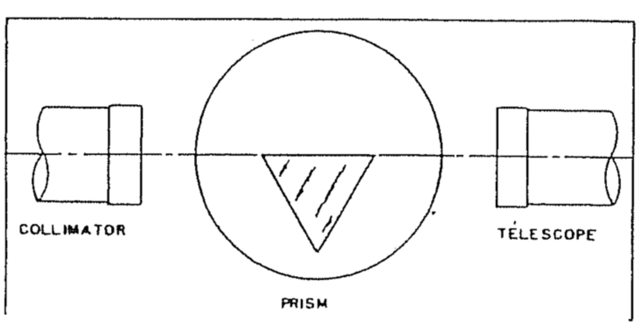

Fig. 9. Arrangement for Aligning Slit

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

[7]Interesting accounts of the instruments and methods used in dividing circles will be found in "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.

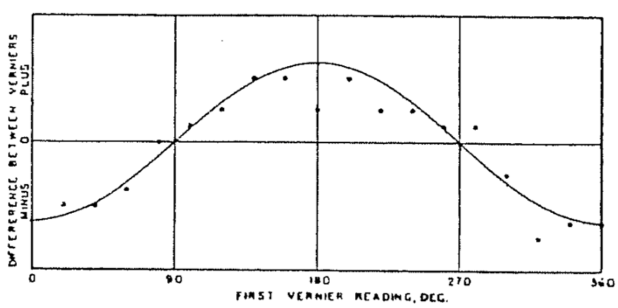

Fig. 10. Test of Divided Circle

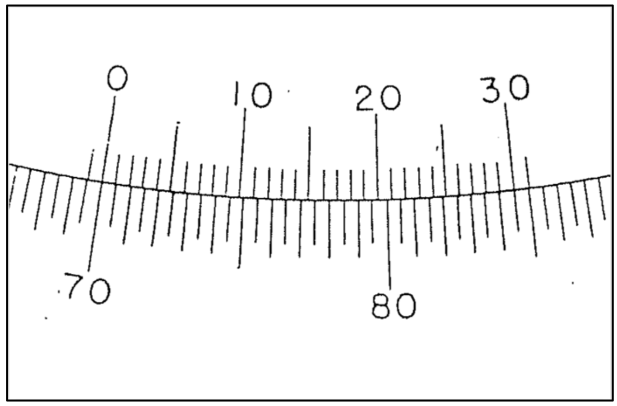

Fig. 11. Divided Circle and Vernier

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. I*	*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 MINIMIUM DEVIATION ON PRISM NO. 10042

	Telescope Left			*Telescope Right*			
Prism Apex	*Vernier*		*Scale Reading*	*Vernier*		*Scale Reading*	*2 D*
	No. 1	*No. 2*		*No. 1*	*No. 2*		
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 mm) 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.

$$n = \frac{\sin\frac{A+D}{2}}{\sin\frac{A}{2}} \tag{7}$$

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

[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,

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

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

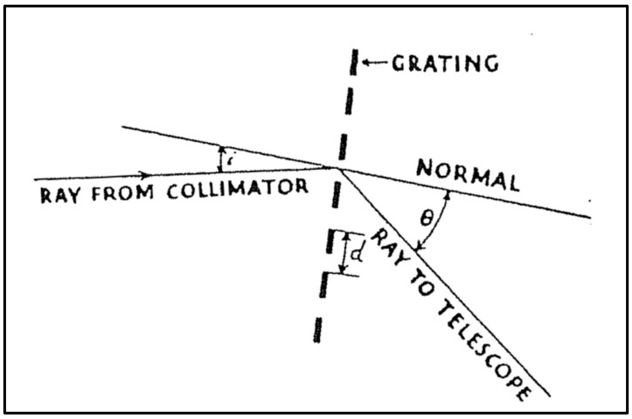

Fig. 25. Diffraction of Light by a Grating

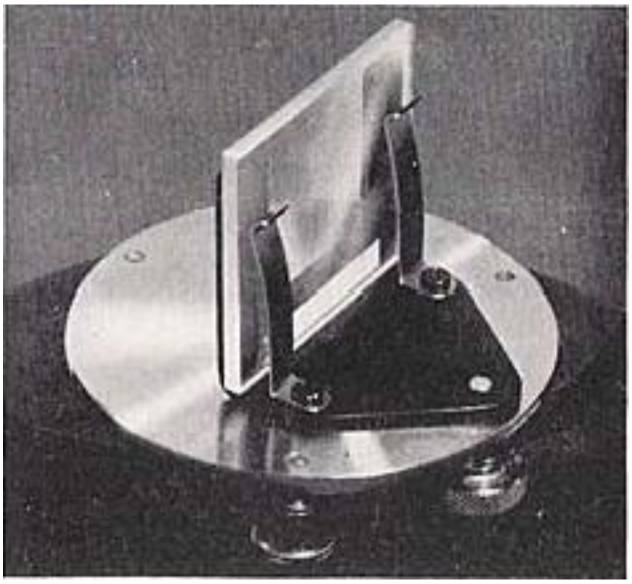

Fig. 26. The Diffraction Grating on the Spencer Spectrometer

[30]Central Scientific Co. Catalog 3136. 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 auto-collimation. 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* $\theta \pm$ *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'		

*Second order

TABLE NO. XIII

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 ± 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 mμ (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.

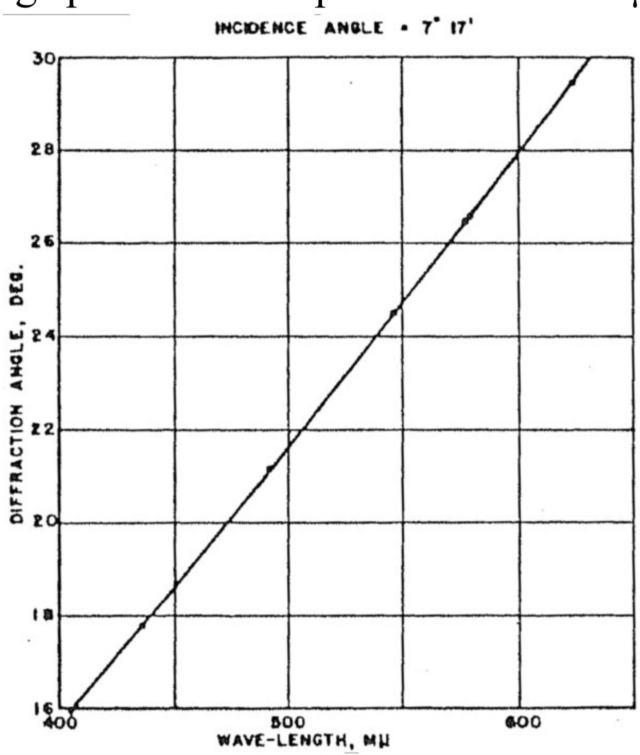

Fig. 27. Dispersion Curve for Grating

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 analogous 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. Analyti-cal 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

[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.

THE USE OF THE

AO Spencer SPECTROMETER

by

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LIST OF ILLUSTRATIONS

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 wavelength 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, $m\mu$	Symbol	Element	Wave-length, $m\mu$
A	O	762.1	b_4	Fe	516.7
	O	759.4		Mg	
B	O	687.0	F	H	486.1
C	H	656.3	G'	H	434.0
D_1	Na	589.6	G	Fe	430.8
D_2	Na	589.0		Ca	
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

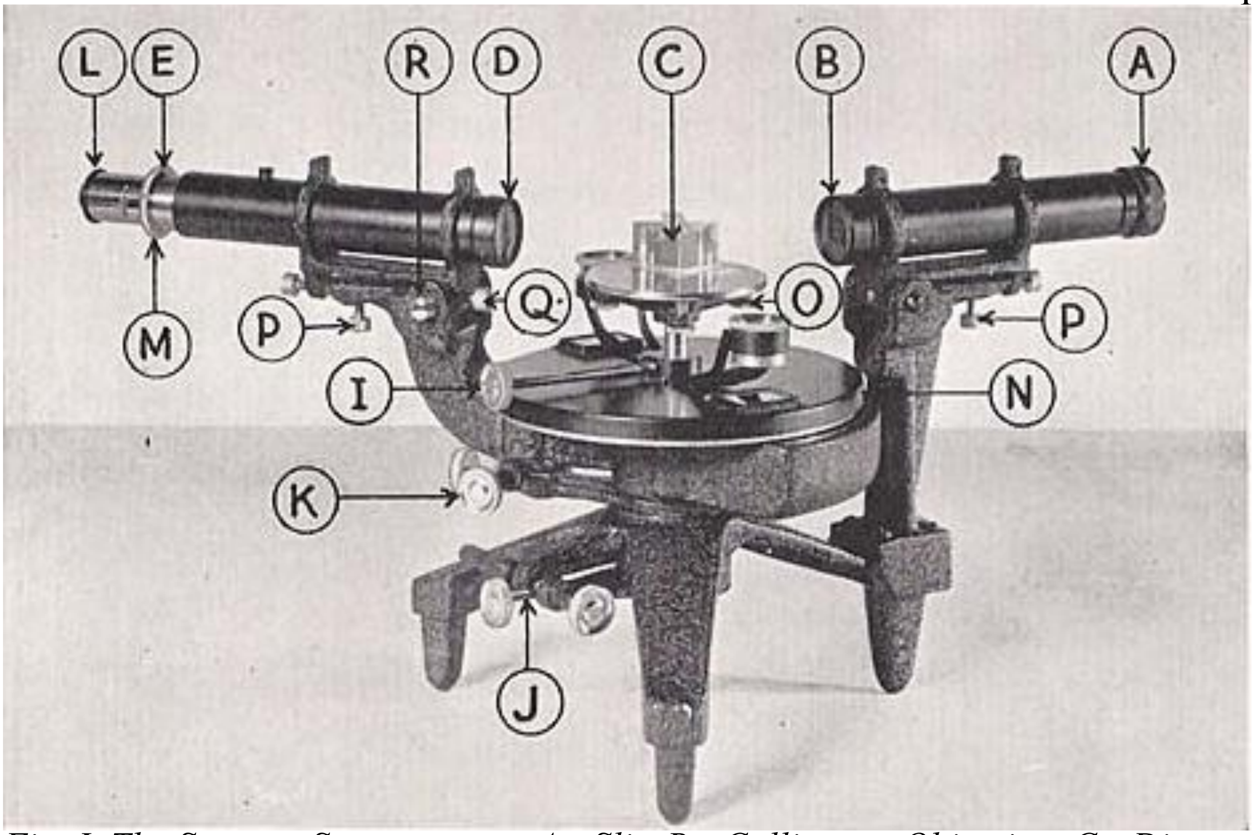

Fig. I. The Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; I—Prism Table Clamping Screw; J—Prism Table Clamping and Tangent Screws; K—Telescope Arm Clamping and Tangent Screws; L—Eyepiece Ring; M—Telescope Focusing Ring; N—Divided Circle Dust Cover; 0—Prism Table Leveling Screws; P—Collimator and Telescope Leveling Screws; Q—Telescope Bearing Front Screw; 12— 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-

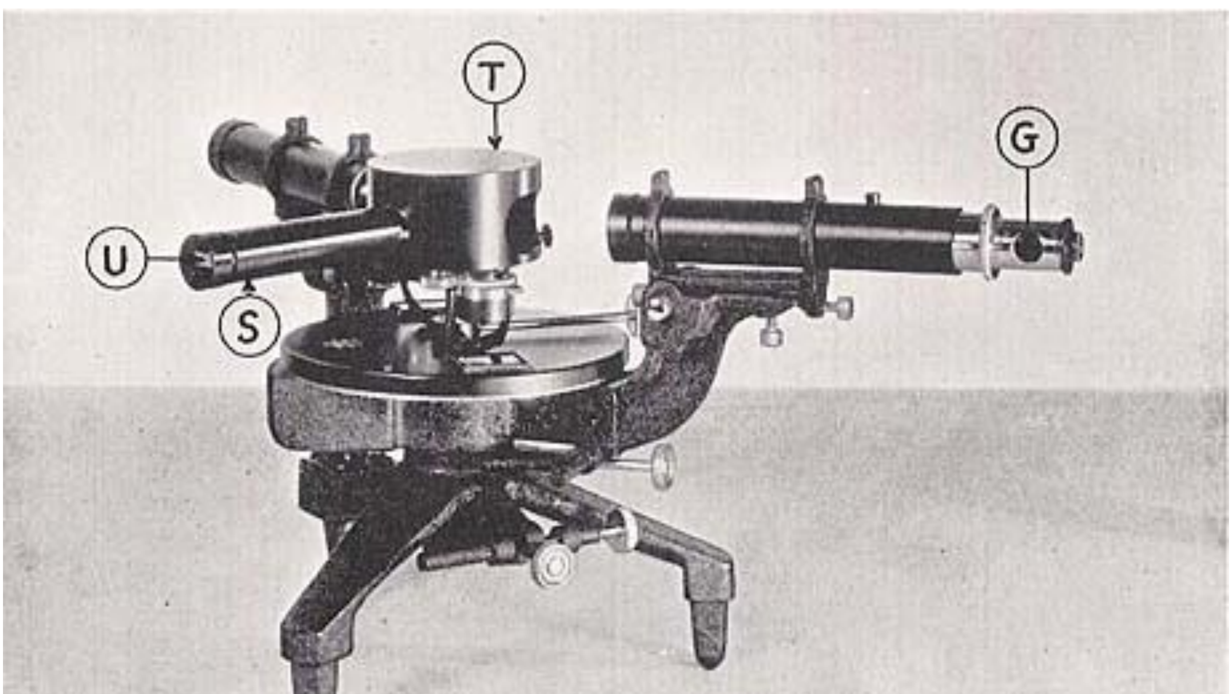

Fig. 21 The Spencer Bunsen Spectroscope Attachment. G—Send-transparent Diagonal Mirror; S—Bunsen Attachment Collimator; T—Bunsen Attachment Prism Table Cover; U—Wave-length Scale.

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 arc 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.

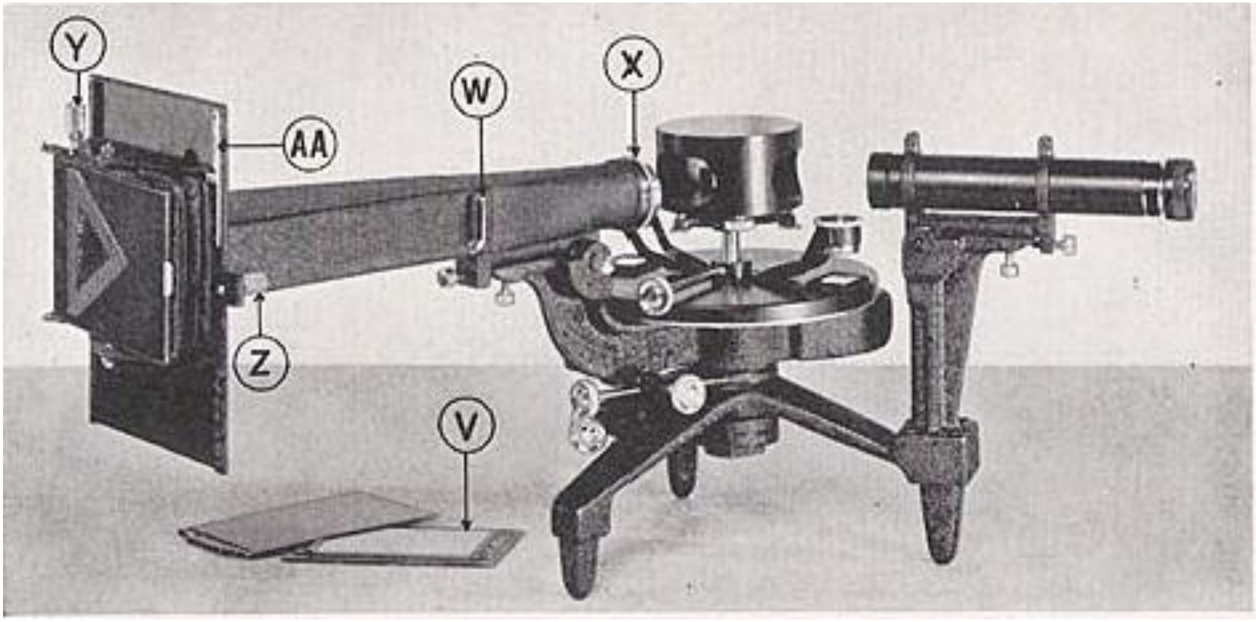

Fig. 3. The Spencer Spectrographic Camera. V—Focusing Screen; W --Shutter Handle; X—Camera Objective Draw Tube; Y—Tilt Clamping Screw; Z—Plate Slide Carriage Clamp; AA—Plate Carriage Scale.

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.

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

$$n = \frac{\sin {}^1\!/_2(A+D_{\text{min}})}{\sin {}^1\!/_2 A} \tag{7}$$

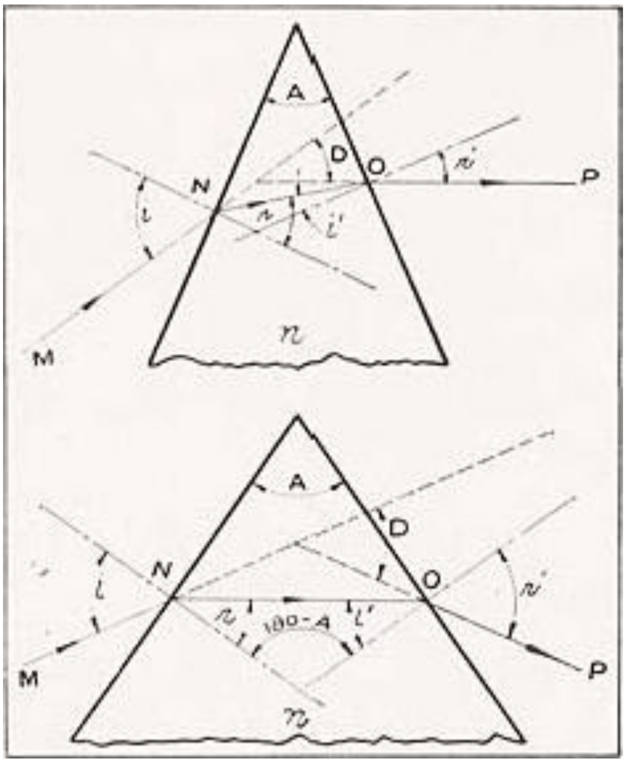

Fig. 4. Refraction of Light by a Prism

[1]See an optical text such 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).

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

$$A = \frac{n_1\lambda_1^2 - n_2\lambda_2^2}{\lambda_1^2 - \lambda_2^2} \quad (9) \qquad\qquad B = \frac{\lambda_1^2\lambda_2^2(n_2 - n_1)}{\lambda_1^2 - \lambda_2^2} \quad (10)$$

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, $m\mu$	*Index*	*Wave-length,* $m\mu$	*Index*
656.3	1.7147	486.1	1.7394
587.6	1.7218	435.9	1.7542
546.1	1.7277		

[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

$A = 1.6835$ $B = 134296$

n_{obs}	λ	λ^2	B/λ_2	n_{calc}	obs-calc
1.7147	656.3	430730	0.0312	1.7147	0.0000
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	0.0000

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.

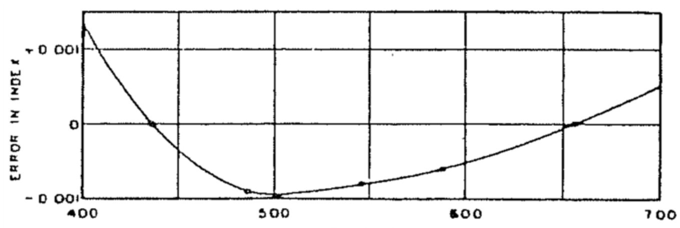

Fig. 5. Error Curve from Cauchy's Formula

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]

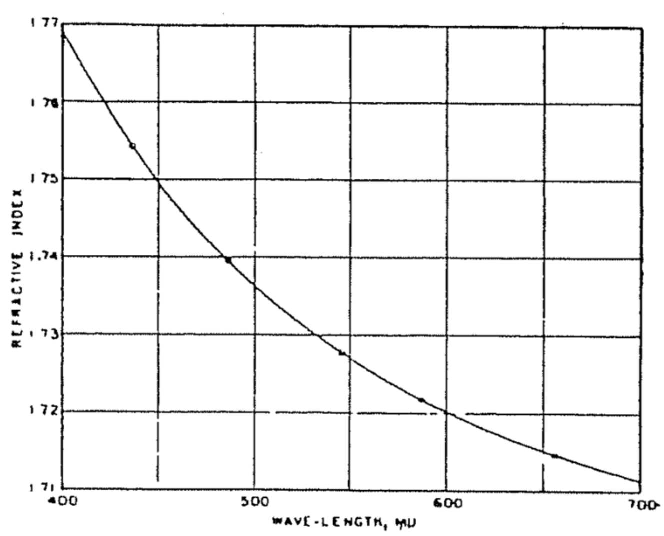

Fig. 6. Dispersion Curve for Extra Dense Flint

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.

[4]For the solutions see Sir Richard Glarebrook, "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

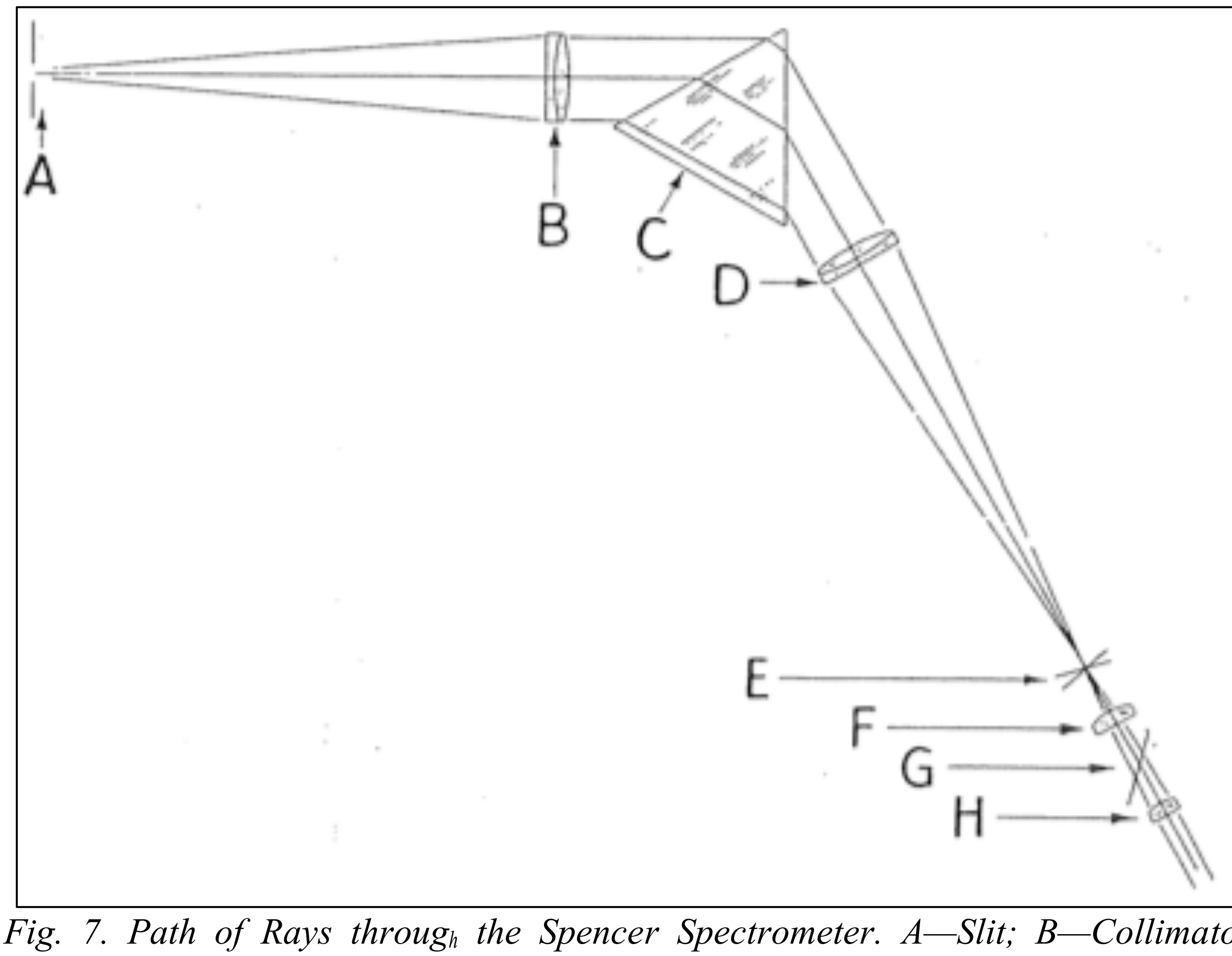

Fig. 7. Path of Rays through the Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; F—Eyepiece Field Lens; G—Semi-transparent Diagonal Mirror; H—Eyepiece Lens.

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 coining 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 arc 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 pres sure 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 care ful 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 instru ment parts which would disturb the delicate adjustments.

Focusing by Auto-Collimation

In focusing the telescope it is first necessary to focus the eye piece 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 he 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

[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. I) 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-

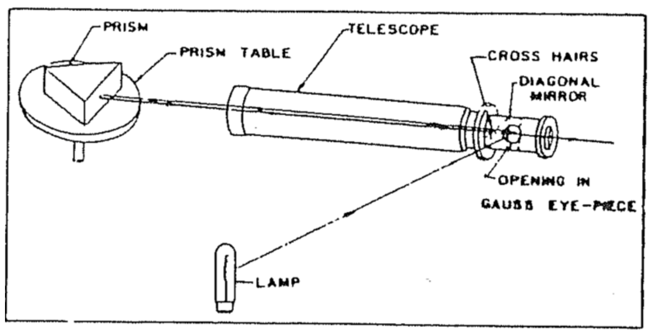

Fig. 8. Arrangement of Telescope and Prism for Auto-Collimation

[5]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."

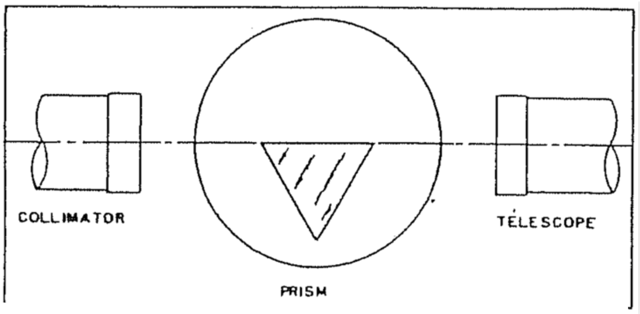

Fig. 9. Arrangement for Aligning Slit

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

[7]Interesting accounts of the instruments and methods used in dividing circles will be found in "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.

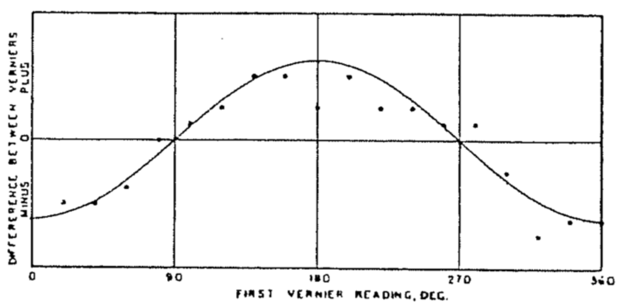

Fig. 10. Test of Divided Circle

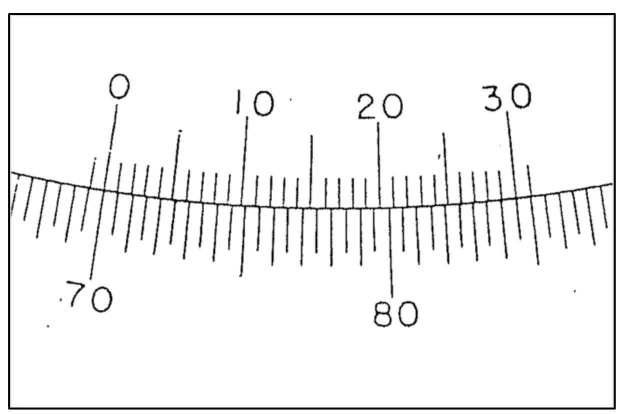

Fig. 11. Divided Circle and Vernier

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. I*	*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 MINIMIUM DEVIATION ON PRISM NO. 10042

Prism Apex	*Telescope Left*			*Telescope Right*			
	Vernier		*Scale Reading*	*Vernier*		*Scale Reading*	
	No. 1	*No. 2*		*No. 1*	*No. 2*		*2 D*
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 mm) 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.

$$n = \frac{\sin\frac{A+D}{2}}{\sin\frac{A}{2}} \tag{7}$$

Pages
16 - 32
intentionally
omitted

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,

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

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

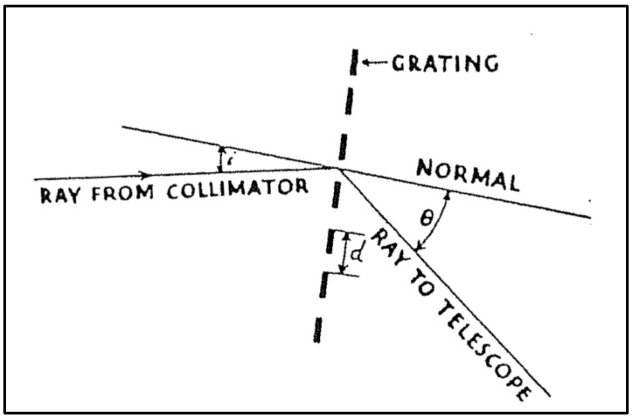

Fig. 25. Diffraction of Light by a Grating

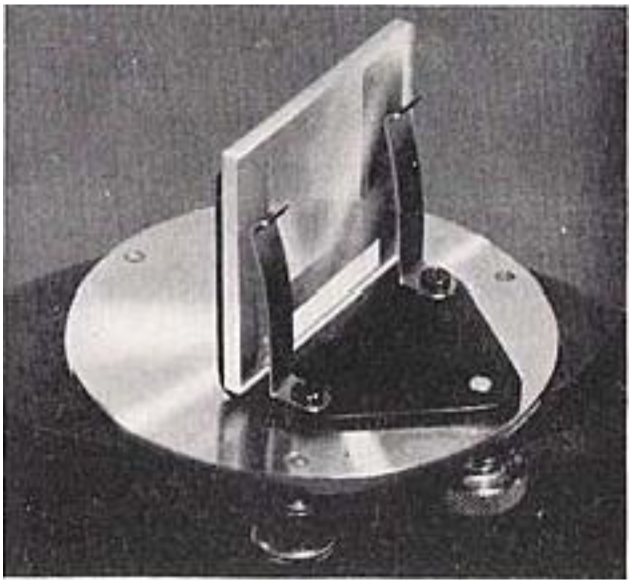

Fig. 26. The Diffraction Grating on the Spencer Spectrometer

[30]Central Scientific Co. Catalog 3136. 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* $\theta \pm$ *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'		

*Second order

TABLE NO. XIII

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 ± 0.2

*Second Order

These data determine the grating space. The equation used is

$$d = \frac{m\lambda}{\sin\theta \pm \sin i}. \quad (15)$$

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 mμ (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.

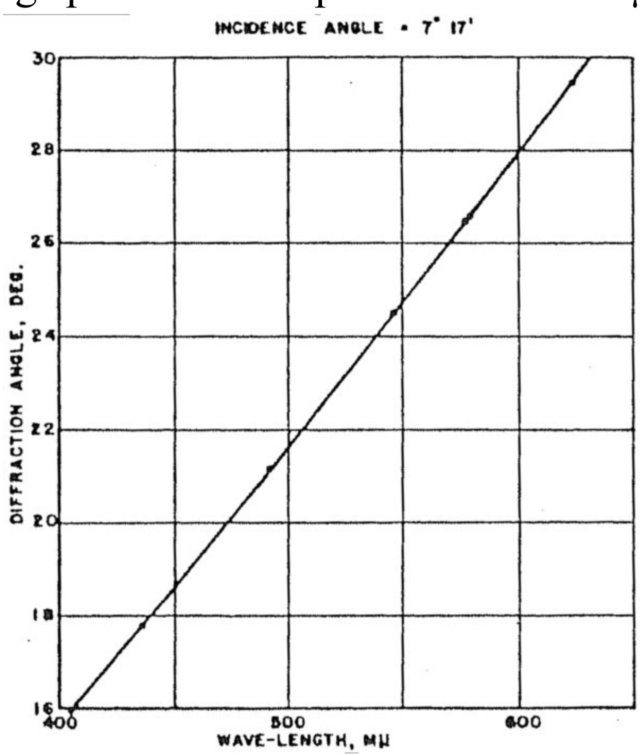

Fig. 27. Dispersion Curve for Grating

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 analogous 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. Analyti-cal 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

[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.

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