A MOLL-TYPE MICROPHOTOMETER AND ITS PERFORMANCE.

H. H. Plaskett.

The recording microphotometer designed by Moll * differed from the original Koch instrument † in two essential features. In the first place a thermocouple with galvanometer was used as the photometric receiver in place of Koch's photo-electric cell and electrometer, thus securing a constant and linear relation between incident light and recorded deflection; and in the second place a slit reduced the illuminated area on the photographic plate to the exact dimensions of the analysing beam, thus eliminating the error due to scattered light discovered by Schwarzschild and Villiger.‡ Actual experience with the Moll microphotometer at Harvard § and at Lick, || while fully confirming the advantages claimed for this type of instrument, has revealed certain imperfections in mechanical design and in exactness of adjustment. Advantage therefore has been taken of the opportunity of acquiring a microphotometer for the University Observatory, Oxford, to design an instrument of this type in which some of these difficulties have been avoided. This instrument, jointly designed by R. M. Abraham and the writer, and constructed by Casella & Co., has proved to be not only relatively inexpensive, but also accurate in use and easy of adjustment.

The present paper contains in the first section a brief description of the instrument and its adjustment, and in the second section an account of tests of the instrument, especially with regard to proportionality of linear displacement and resolving power. It is hoped that these tests may prove to be sufficiently revealing, though simple of execution, to justify their application to other microphotometers.

Section 1.—*The Instrument and its Adjustment*

1.1. *The Instrument.*—The optical system of the microphotometer is essentially identical with Moll's original design. The lamp house with its Zeiss condensing lens ($\times 8$) forms one unit, A (see Plate 2, fig. 1); a second unit, B, consists of one of four self-centring interchangeable slits ruled in silver on glass and a Zeiss apochromatic objective (primary magnification 10, numerical aperture 0·30), both mounted in the one microscope with tube length variable between 13 and 15 cm.; and the third unit, C, has an identical microscope objective and the Moll quick vacuum

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† *Ann. d. Phys.*, **39**, 705, 1912.
‡ *Astroph. Journ.*, **23**, 286, 1906.
§ H. H. Plaskett, *M.N.*, **91**, 882, 1931.
|| A. H. Farnsworth, *L.O.B.*, **16**, No. 456, 1933.

thermocouple (period 0·3 second) with horizontal and vertical adjustments within the mount but without the usual subsidiary slit, field lens and objective. Provision is made in each of these units for focussing, for independent rotation of the parts, and for placing the lamp filament, slit or thermocouple on the optical axis of the condensing lens or microscope objectives respectively. Each unit is held to a geometric slide, which is free to move or can be clamped at any desired position, on the optical bench, I, by two sets of three collimating screws which press on two coaxial circular rings on the unit.

The photographic plate, which can be taken in sizes up to $12{\cdot}5 \times 25$ cm. (5×10 in.) without cutting, is held by cork-tipped fingers to an inner stage which is adjustable for height. This inner stage is supported by flat leaf-springs under tension on the main stage, E, which in turn is pivoted to the carriage ; this mode of support ensures that a straight line on the plate can readily be made parallel to the direction of motion of the carriage. The carriage is another geometric slide which moves on ways consisting of two lapped silver steel rods with centres 16 cm. (6·5 in.) apart ; this broad base ensures that any microscopic irregularity in the ways produces the minimum disturbance in the motion of the plate. Four springs and rollers support three-quarters of the weight of carriage and stage, thus reducing wear at the five constraints (two *V*'s and a plane) and ensuring a smooth easy motion for the carriage on its ways. If desired the carriage and stage can be lifted as a unit off the ways.

The carriage is driven in one direction (away from the gear system) by the pressure of a bronze nut with a hardened steel abutment. This nut is carried forward by the rotation of its screw of tool steel, one-inch in diameter, with ten threads to the inch, and cut over a length of six inches ; the screw is held between 60° centres, as in cutting and grinding, and has on its shaft a small gear which engages with the gear F. The gear F may be turned either directly by the handle seen on the same spindle, or, by engaging the handle by means of a screw to the worm wheel, the gear F is turned by a motor drive through the pulley. The nut is prevented from turning with the screw, and so is moved forward to push the carriage, by a hardened steel finger from it which bears on a straight edge ; this latter could, if necessary or desired, serve as a corrector bar. The motor gives plate speeds ranging from 3 cm. to 24 cm. per hour ; the latter of these is nearly the maximum speed which should be used if thermocouple and galvanometer inertia is not to distort the record.

The gear F also serves, through the idler gear G, to drive the spindle which carries the gear H, which spindle is in line with and connected by means of a key to the hollow drum shaft. By means of a motion of this spindle either H may engage with a small gear which can be seen in the plate on G's spindle, in which case one revolution of the drum occurs for twenty-eight revolutions of the screw, or a gear behind H may engage directly with G as in the plate, in which case one drum revolution occurs in four screw revolutions. The actual magnification of the record on the drum over that of the object on the plate depends, of course, on the radius of the drum; the magnifications corresponding to these two spindle positions are, closely enough, 6·89 and 48·2.

The drum is provided with the usual slit and cylindrical lens, fixed in the lower case which carries the drum bearings. The excursion of the slit image given by a Moll micro-galvanometer (period 0·25 second), which is connected directly with the thermocouple, is recorded as a black line on a sheet of bromide paper 12·5 × 50 cm. (5 × 20 in.), clamped on the drum. In order to set up a co-ordinate system on this bromide paper record, which is independent of any subsequent changes in the dimensions of the paper on developing and fixing, and which is independent of errors in the gear train, a subsidiary lamp is erected beside the galvanometer and intermittently lit by a 6-volt transformer through the contact maker, to be seen in Plate 2 to the left and behind the gear F. This contact maker is actuated by one of two special gears on the screw shaft which are cut with ratchet teeth; by moving the contact maker to engage with the appropriate ratchet tooth gear black lines are printed on the record parallel to the drum axis for definite fractions of a screw revolution, and at the same distance apart, roughly 8·7 mm., for either magnification. A series of lines also at the same distance apart, but at right angles to the time marks, is produced on the record by means of fine slits engraved on a silver on glass scale set in the drum cover and continuously illuminated by a small lamp vertically above the scale. Fig. 2 (Plate 2) shows part of a microphotometer record of the solar spectrum near $H\gamma$ with this superposed grid [dispersion of spectrum 16 A. per mm.; microphotometer slit 10·4 μ; magnification of record 48·2].

1.2. *Collimation.*—On first setting up the microphotometer, and subsequently only if the lamp or the objectives are changed, it is necessary to collimate the optical system. Accurate collimation ensures first the critical definition, only attainable on the optical axis, which is necessary to reach the optimum resolving power; secondly, the maximum galvanometer deflection for a given energy output of the analysing lamp; and finally a symmetrical distribution of stray illumination, due to reflection off the various lens surfaces, about the analysing beam. A characteristic of the present instrument is the accuracy and permanence of its collimation.

In adjusting the instrument for collimation the following procedure has been found convenient:—

Unit A.—Rotation of the lamp house as a unit about the optical axis of the condensing lens immediately discloses, by a displacement of the image, any departure of the centre of the filament from this axis. Such departure may be corrected by the collimating screws which hold the lamp in position. When the lamp house has been collimated as a unit it only remains to make its optical axis parallel to the optical bench. A departure from parallelism is revealed by a displacement of the filament image as the lamp house on its slide is moved along the optical bench, and may be corrected by the six collimating screws which hold the lamp house to the slide.

Unit B.—Since the definition of the slit image, and consequently the resolving power of the microphotometer, depend upon accurately centring

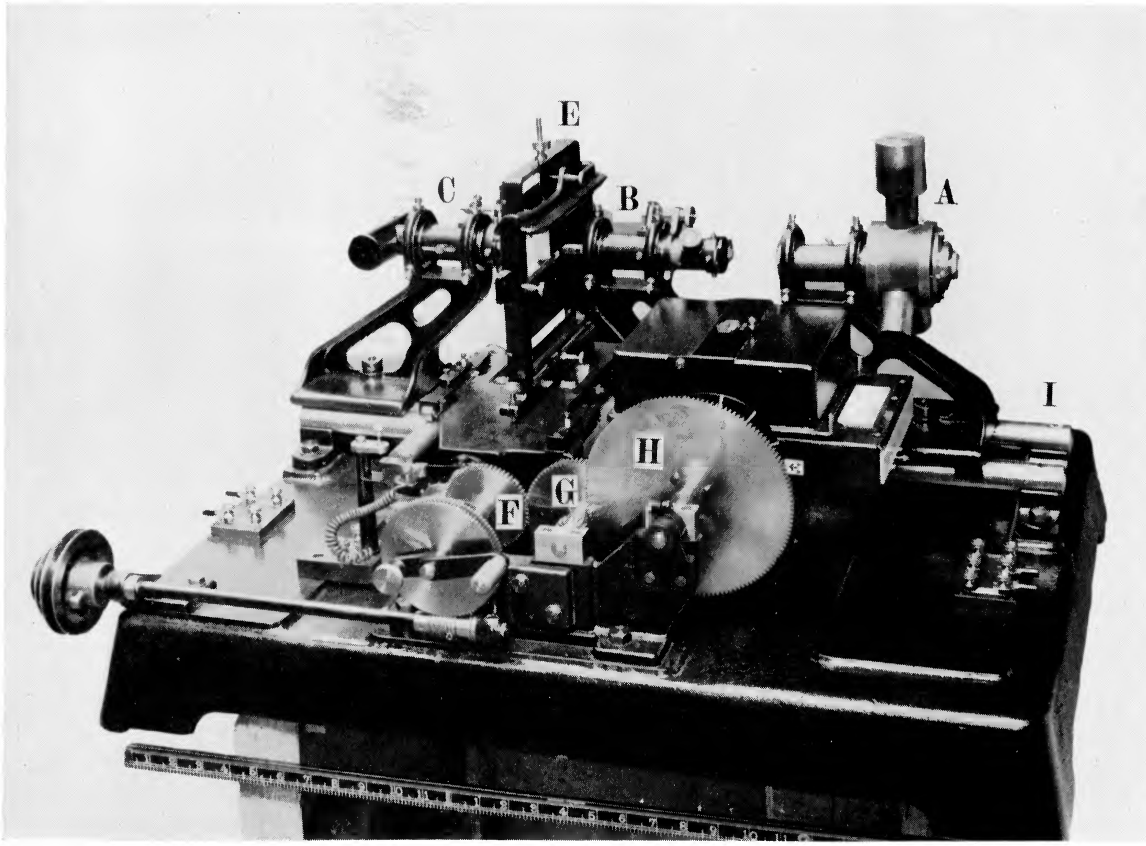

Fig. 1

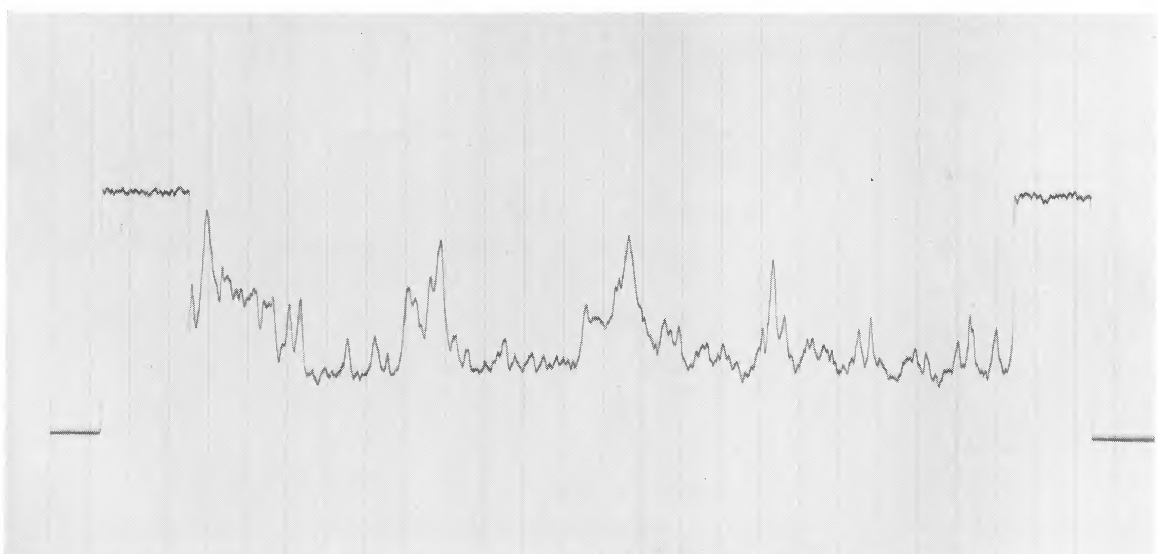

Fig. 2

H. H. Plaskett, A Moll-type Microphotometer.

the slit on the optical axis of the objective, a more sensitive test than is afforded by rotation is required for detecting lack of collimation. The first step in the adjustment is by varying the tube length to make the linear separation of the images of two marks on one of the slits exactly one-tenth their actual separation ; since the primary magnification of the objective is ten, this procedure ensures that the slit is at the optical tube length for which the objective is corrected, and that, consequently, when the slit is placed on the optical axis its image will be critically defined. The second step is to examine this image, as formed on a plate, with a low-power magnifier. If the slit is not centred, then surrounding the bright central image, but lying in slightly different planes, will be found a number of fainter images which arise from internal reflections within the microscope objective. Accurate centring is then secured by adjusting the collimating screws which hold the slit until the principal and the internally reflected images coalesce. The final step is to make the optical axis of the now collimated slit microscope coaxial with that of the lamp house ; this may be simply effected by adjusting the microscope as a unit until the filament image is centred on the slit, and at the same time, when the lamp house has been moved back on the optical bench, the narrow band of the extra focal patch, as limited by the slit, is centred on the front face of the microscope objective.

Unit C.—Since in this type of microphotometer definition and resolving power are essentially determined by the collimation of units A and B, it suffices to adjust unit C until the galvanometer deflection is a maximum, and then by means of the collimating screws which hold the unit to its slide to make its axis coaxial with that of the common axis of units A and B.

1.3. *Plate Adjustment.*—Before a photographic plate, carrying for example a spectrum, can have its transmission recorded by the microphotometer, it is necessary to be able accurately and quickly to align the spectrum and sharply to focus the slit image on the plate. With the aid of a positive eyepiece behind the thermocouple, with which can be seen the linear thermocouple strip and any real images formed in its plane by the objective of unit C, this alignment proceeds as follows :—

First microscope B is put out of focus to give a broad illuminated patch on the plate, and microscope C is focussed until the thus illuminated silver grains are seen through the eyepiece to be sharply focussed in the plane of the thermocouple. Then the plate carriage is moved in its ways, and, if necessary, the screws working against the flat leaf-springs, which hold the inner stage and the screw which determines the tilt of the main stage, are adjusted until the silver grains remain sharply in focus and the spectrum remains centred on the thermocouple strip through the whole motion of the carriage. Thus the spectrum is made strictly parallel to the direction of the carriage motion. Next, by means of a tangent screw, the thermocouple mount is tilted in unit C until the linear junction is parallel to the spectrum lines, and then the microscope B is focussed until the slit image is sharply defined, when, if necessary, the slit can be rotated in unit B until its image is parallel to the thermocouple. Finally, by means of the horizontal and vertical adjustments in the thermocouple mount, the linear junction is moved parallel to itself until the slit image is centred on it. The whole operation can be carried out both quickly and positively, and so satisfactorily do the apochromatic objectives define in both visual and infra-red that no change of these adjustments increases the galvanometer deflection.

Section 2.—Performance

A recording microphotometer for which the claim of precision is made should have three characteristics. It should give a relation between plate transmission and deflection which is independent of the time, or at least strictly reproducible; it should give an exact proportionality between displacement measured on the bromide paper record and displacement on the plate; and finally it should have high resolving power. Tests of the present instrument for these characteristics will now be described.

2.1. *Characteristic Curve.*—Since the photographic plate scatters rather than absorbs the light incident on it, the flux, T, transmitted by a given area depends upon the angular aperture and effective wave-length of the analysing beam. If, and only if, these variables are held constant, is T an invariant physical quality, and is equality of silver deposit measurable with the microphotometer. Assuming this to be the case, and it is easily effected, let the deflection which corresponds to T be y, measured on the record from the zero line ($T=0$), and let y_0 be the similarly measured deflection which corresponds to the unexposed part of the photographic plate. Then the functional relation between y/y_0 and T may be called the characteristic curve, and dy/dT the sensitivity of the instrument. For a given microphotometer in which the angular aperture and effective wave-length of the analysing beam are held constant, the characteristic curve and the sensitivity depend wholly on the characteristics of the photometric receiver and its associated electrical circuit.

In the present instrument the photometric receiver is a thermocouple with galvanometer, giving a linear characteristic curve. Such a receiver has the great advantage that its characteristic curve is independent of time, so that it is not necessary, as Lindblad and Stenquist * found it necessary with the Stockholm Koch-Goos microphotometer, repeatedly to standardize the instrument through the use of filters of differing transmission. The characteristic curve of this thermocouple, as contrasted with those of two photo-electric receivers, is shown in fig. 3, where the abscissæ are values of y/y_0 for the present instrument, and the ordinates of the filled circles are the corresponding y/y_0 for a Zeiss microphotometer, while the ordinates of the half-filled circles are the same quantities for a Cambridge microphotometer. The data for this figure were obtained from records made at Dr. Redman's suggestion and recently discussed by him.† The comparison, as a comparison of characteristic curves of different receivers, is only approximate because a photographic plate was used as a transmission standard, and because the angular aperture and effective wave-length of the analysing

* *Astronomiska Iakttagelser å Stockholms Observatorium*, **11**, No. 12, 1934.

† *The Observatory*, 57, 275, 1934.

beam were different in the three instruments. The figure gives, however, at least a qualitative idea of the performance of the receivers, and in particular shows the intentionally arranged high sensitivity of the Zeiss instrument for low transmissions as contrasted with the high sensitivity of the Cambridge instrument for large transmissions. From several points of view the linear characteristic curve of the thermocouple has something to commend it,

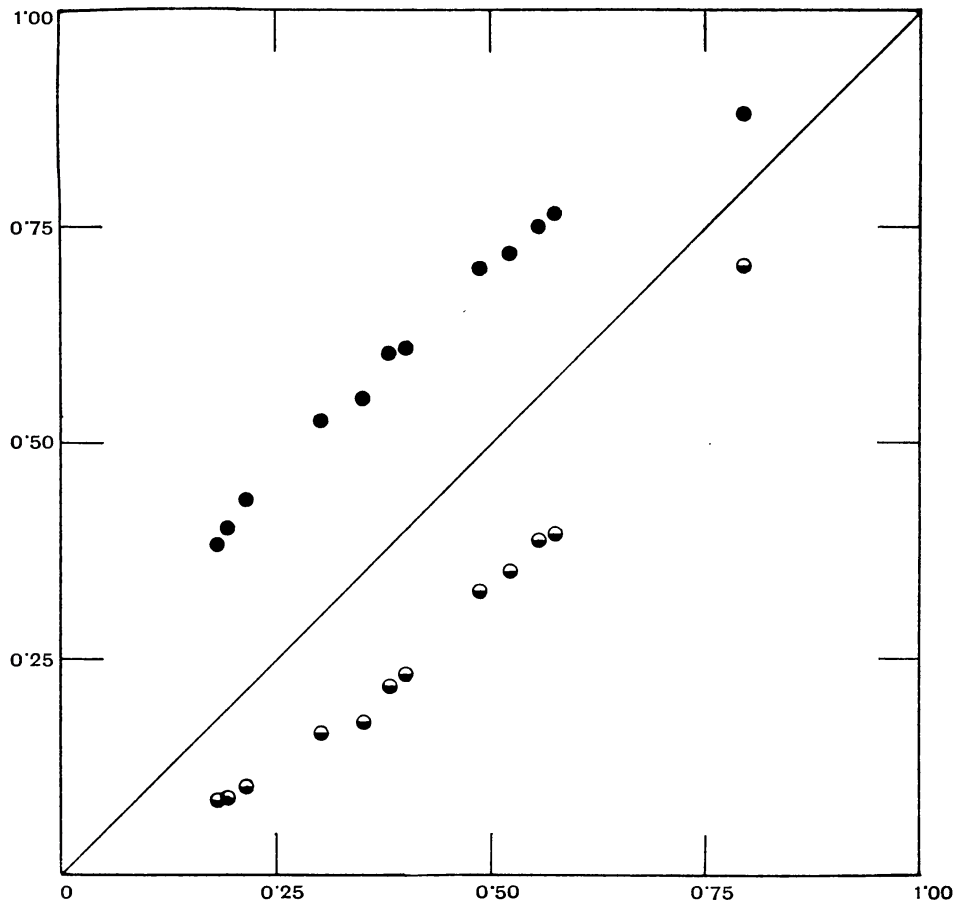

FIG. 3.—*Relative Characteristic Curves. Abscissæ are values of y/y_0 for Oxford Microphotometer, and ordinates of the filled and half-filled circles are the corresponding values of y/y_0 for the Zeiss and Cambridge Microphotometers respectively.*

but the chief advantage of the thermocouple undoubtedly lies in the constancy of this characteristic curve with time.

2.2. *Proportionality of Displacement.*—To obtain proportionality between displacements on the plate and the record to the requisite degree of accuracy imposes the severest demands both on the gear system and on the screw and straightness of the carriage ways. In order to test the gear system, records were made of the time marks, which, as has been described, are printed on the record for equal fractions of a revolution of the screw. If the bromide paper has not changed dimensions on development, and if the gear system is accurate, these time marks should be equally spaced. A sample of the results from the measures of one record is given in Table I, under the heading of Model I. The first column gives the number, *n*, of

TABLE I

Gear and Drum Errors

n	Model I				II	IA
	x	Obs.	Comp.	O – C	O – C	O – C
	mm.	mm.	mm.	mm.	mm.	mm.
0	13·8	13·8	13·8	± 0·0	± 0·0	± 0·0
4	48·7	48·8	48·8	± 0·0	– 0·7	± 0·0
8	83·7	83·8	83·8	± 0·0	– 1·2	+ 0·1
12	118·9	119·0	118·8	+ 0·2	– 2·1	+ 0·2
16	154·3	154·5	153·8	+ 0·7	– 2·3	+ 0·2
20	189·6	189·8	188·8	+ 1·0	– 2·4	+ 0·2
24	225·2	225·4	223·8	+ 1·6	– 2·3	+ 0·4
28	260·6	260·8	258·8	+ 2·0	– 1·8	+ 0·5
32	295·8	296·1	293·9	+ 2·2	– 1·2	+ 0·5
36	330·3	330·6	328·9	+ 1·7	– 0·4	+ 0·3
40	364·7	365·1	363·9	+ 1·2	± 0·0	+ 0·1
44	399·2	399·6	398·9	+ 0·7	+ 0·2	+ 0·3
48	433·7	434·2	433·9	+ 0·3	+ 0·4	+ 0·3
52	468·3	468·9	468·9	± 0·0	± 0·0	± 0·0

the time mark, the second its measured x in mm., the third this measured x corrected for a change in dimensions of the bromide paper (correction found from a pencil grid ruled on the back of the record and measured before and after development), the fourth column gives the position of the time mark computed from the expression $n(x_{52} - x_0)/52$, and the fifth column gives the residual O – C. From the run of the residuals, confirmed from other records, it was clear that there was eccentricity either in the drum or gears of Model I. Consequently Model II with a newly designed drum, and with gears mounted on heavy steel hubs on their several pinions and with teeth cut on a dividing engine with an accuracy of three seconds of arc, was put into operation in March. O – C residuals, derived in the same way as for Model I, are given under the heading II in the sixth column of Table I; it will be observed that, in spite of these precautions in construction, the errors in Model II are as large as those in Model I. From a scale engraved on the large gear, H, it was possible to show that of these large residuals only about 0·3 mm. was contributed by gear errors, and since the drum was accurately centred and turned, it followed that the residuals in the case of Model II, and possibly Model I, must have originated in the coupling between the gear spindle and the drum shaft.

This coupling is shown in section in fig. 4. Here O is the centre of the hollow drum shaft, O′ is the centre of the gear H spindle, and A is a key attached to the spindle which, when the spindle is moved perpendicular to the plane of the diagram in order to change gears, moves in a slot or keyway in the hollow shaft. If the spindle and shaft are not exactly lined up, that is $OO' = b \neq 0$, then when the spindle has turned through $\pi/2$ so that the key is at B, the drum shaft will have only turned through the angle $\frac{\pi}{2} - \sin^{-1}\frac{b}{r}$ (or, approximately, $\frac{\pi}{2} - \frac{b}{r}$), where r is the radius of the hollow drum shaft. Hence the drum will be out of position in angle by b/r, and the record will be linearly out of position by Rb/r, where R is the radius of the drum. From the dimensions of the parts it follows that the residuals shown for Models I and II would be produced if $b = 0{\cdot}13$ mm. (0·005 in.), a rather small quantity.

When it was realized where the source of the trouble lay, Model I was rebuilt with new gears, cut as in Model II, only with finer teeth so that gear

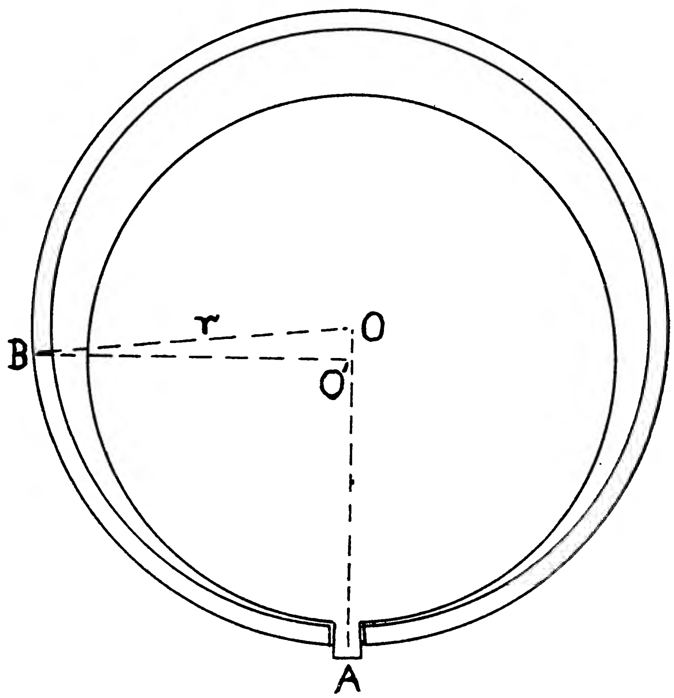

FIG. 4.—*Effect of Eccentricity of Gear Spindle in Drum Shaft.*

errors contributed less than 0·08 mm. to the residuals, with a new drum and with the drum shaft and gear spindle carefully aligned with the aid of a true arbor. In the last column of Table I the residuals obtained with this instrument, described as Model IA, are given from measures of the same type as for the two previous models. From these residuals—and five other records showed residuals smaller than these—it will be seen that the error between the screw and the drum has now been reduced to a satisfactorily small quantity—a quantity which is indeed comparable with the errors introduced by shrinkage and expansion of the bromide paper.

2.21. Having assured ourselves that the gears and drum in Model IA are sufficiently accurate, it now remains only to test the accuracy of the screw and the straightness of the ways. For this purpose a glass scale, ruled with fine divisions every tenth mm., was standardized at a number of divisions from measures with a Hilger micrometer by the method of repeated coincidences.* Table II contains in its first column the division number (in mm. from an arbitrary origin in the scale), and in the second column the correction in microns to be added to this division number to give the actual position of the division from the arbitrary origin; the corrections are the means from three independent sets of measures, and the attached errors are the standard deviations of these means. This standardized glass scale was set up on the stage of the microphotometer, and three records with a

TABLE II

Standard Scale

Divn.	Correction		Divn.	Correction	
mm.	μ		mm.	μ	
0	± 0·0	± 0·0	25	± 0·0	± 0·0
9	− 1·4	·3	26	− 0·7	·0
18	± 0·0	·5	27	− 0·7	·3
27	+ 0·1	·5	28	+ 1·0	·2
36	+ 1·6	·3	29	− 0·1	·2
45	+ 0·5	·3	30	+ 1·7	·3
54	± 0·0	± 0·0	31	± 0·0	± 0·0

magnification of 6·89 obtained. These records were measured from the co-ordinate system imprinted by the time marks, thus automatically eliminating any residual errors due to gears, drum, alignment and bromide paper; a glass reticule, accurately ruled for the specific purpose of measuring records made with Model IA, made measurement precise and rapid. The results are given in Table III, where the first column contains the position of the scale divisions on the glass scale (taken from Table II), the next three columns contain the measured positions of these divisions on three records (1, 2, 3) in units of time marks, and the fifth column contains the mean from these

TABLE III

Screw Errors with Magnification 6·89

Scale	1	2	3	Mean	Comp.	O − C
mm.					mm.	mm.
0·000	0·00	0·00	0·00	0·00	0·000	± ·000
8·999	7·08	7·09	7·09	7·09	9·002	− ·003
18·000	14·18	14·18	14·17	14·18	18·004	− ·004
27·000	21·27	21·27	21·26	21·27	27·007	− ·007
36·002	28·35	28·36	28·35	28·35	35·996	+ ·006
45·000	35·44	35·43	35·44	35·44	44·998	+ ·002
54·000	42·53	42·53	42·54	42·53	54·000	± ·000

* D. Gill, *M.N.*, **49**, 105, 1889; H. Jacoby, *Am. Journ. Science*, **151**, 333, 1896.

three records. Since 42·53 time marks on the record is equivalent to 54·000 mm. on the standardized scale, 1 time mark is equivalent to 1·2697 mm., and, using this factor, the mean measured positions on the records are converted into computed positions on the glass scale. The last column of the table contains the difference (O – C) between the actual positions, as given in the first column, and these computed positions. Since the error in measurement is 0·01 of a time mark, residuals up to 0·013 mm. may be expected from this source alone ; it will be noted that no residuals exceeding this quantity are found.

A more critical test is afforded by using the 48·2 magnification where the proportionality factor is 1 time mark = 0·1814 mm., and where consequently the accidental error of measuring a record, projected on the glass scale, amounts only to 0·0018 mm. Three records were made of the central part of the glass scale (divisions 25 to 31), one with the nut at the beginning of the screw, one with the nut near the middle, and one near the end of the screw. The results are given in Table IV where the first column gives the division position (taken from Table II), and the next three columns are the O – C residuals in microns (found as in Table III) from these three records (numbered 4, 5, 6). It will be noted that with the exception of division 27, and possibly division 30, the residuals are less than the accidental error of measurement. Since for the two exceptions the residual has the same sign

TABLE IV

Screw Errors with Magnification 48·2

Scale	Residuals O – C			
	4	5	6	Mean
mm.	mm.	mm.	mm.	mm.
25·0000	± ·0000	± ·0000	± ·0000	± ·0000
25·9993	+ ·0004	− ·0017	− ·0015	− ·0009
26·9993	− ·0028	− ·0027	− ·0038	− ·0031
28·0010	− ·0011	+ ·0004	+ ·0002	− ·0002
28·9999	+ ·0001	+ ·0001	− ·0004	− ·0001
30·0017	+ ·0012	+ ·0022	+ ·0019	+ ·0018
31·0000	± ·0000	± ·0000	± ·0000	± ·0000

and roughly the same size at three different parts of the screw and ways, it is not improbable that some of the error is inherent in the scale rather than in the instrument. Thus a slight irregularity in the carbon filling of a division mark, within 0·2 mm. of the height on the scale at which the records were made, would be recorded by the microphotometer, but would be averaged out in the visual standardization with the Hilger micrometer. Whether this be the interpretation or not, it is clear that the screw and the ways of the microphotometer have an accuracy of at least $\pm 3\ \mu$, possibly $\pm 2\ \mu$.

Since the errors in the screw and the ways of the instrument are of this order it follows that, from displacements measured with reference to the time marks over, if desired, the full 50 cm. of the record, the displacement computed on the plate will also be accurate to at least $\pm 3\ \mu$, possibly $\pm 2\ \mu$. This accuracy, it may be pointed out, is not far removed from the maximum accuracy which can be reached from direct measurement of a photographic plate, since distortions in the emulsion produce spurious displacements of the order of $\pm 1{\cdot}6$.*

It is of interest to compare the accuracy of this microphotometer with that of others on which actual tests have been carried out. The results of these tests are summarized in Table V. In each case the test has been made against a measured scale, but only in the present instance has this scale been

TABLE V

Errors of Microphotometers

Instrument	Error	Recording Drive	Observer	Reference
	μ			
Goos	$\pm$ 0·1	Rotating mirror	F. G.	*Zs. f. Inst.*, **41**, 313.
Koch-Goos	1	Steel bands	F. G., P. P. K.	*Zs. f. Ph.*, **44**, 855.
Oxford	2·5	Gears	H. H. P.	Present paper.
Cam. Sc. I. Co.	7	Friction drum	H. H. P.	Unpublished.†
Moll (Lick)	$\pm$ 25	Worm and gear	A. H. F.	*L.O.B.*, **16**, No. 456.

self-standardized by the method of repeated coincidences. The errors in the first three instruments are satisfactorily small and irregular, but in the last two the errors are periodic and unduly large. In a comparison of this kind ruggedness and permanence of adjustment should be taken into account as well as accuracy, and from these points of view the steel band and the friction drum instruments leave perhaps something to be desired. The present instrument appears to rank high both as regards accuracy and sturdiness.

2.3. *Resolving Power.*—A microphotometer of infinite resolving power may be defined as one which would record without distortion the transmission as a function of position on the photographic plate, no matter how the transmission and its successive derivatives with respect to position varied over the plate. Such infinite resolving power would be realized in the Moll-type microphotometer if the slit image on the plate were an infinitely narrow line. On account, however, of the width of the slit itself, and the distribution in the intensity of its image produced by diffraction and aberration, this slit pattern can never correspond to an infinitely narrow line, but only to a more

* H. Coburn, *A.J.*, **42**, 75, 1932.

† The usual co-ordinate system was not imposed on these records, so that the error is the sum of errors due to the ways, the screw and the drum.

or less concentrated intensity distribution. It is clear that the more concentrated this slit pattern becomes, the higher will be the resolving power of the microphotometer, so that any practical discussion of resolving power reduces immediately to an observational determination of the slit pattern. Given this, it is possible to find not only a purity or efficiency factor for the instrument, but also the instrumental conditions under which the transmission of a given photographic emulsion will be determined without distortion by the microphotometer.

2.31. *The Slit Pattern.*—In a Moll-type microphotometer let the slit image centred at ξ on the photographic plate (see fig. 5 (*a*)) have an intensity

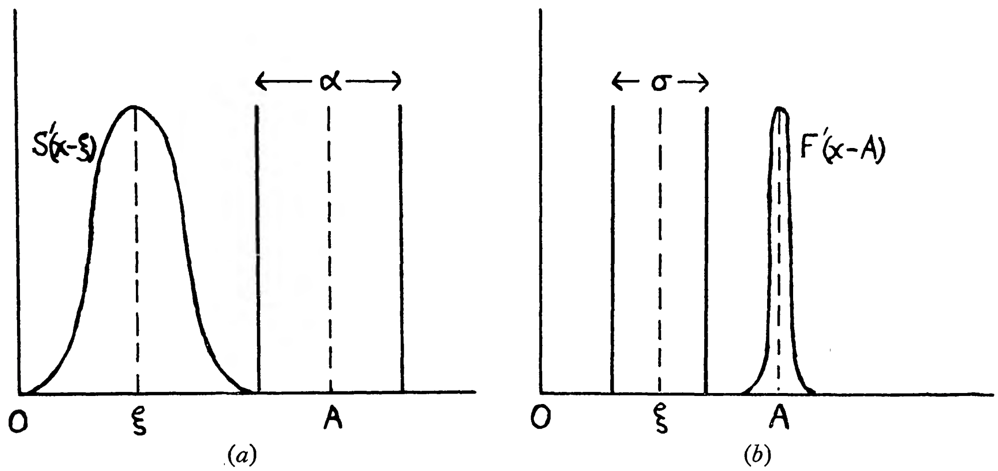

FIG. 5.—*Determination of Slit Patterns for* (*a*) *Moll- and* (*b*) *Koch-type Microphotometers.*

distribution $S'(x-\xi)$, where ξ is the centre of the slit pattern with respect to some arbitrary origin on the plate. As the plate is driven across the beam the effect is that the co-ordinate ξ increases uniformly. Now suppose our plate is an Abbe Test Plate consisting of narrow rectangular openings cut in silver on glass, and consider one opening of such a plate centred at A and of width α. Then for the position ξ of the slit the flux which reaches the thermocouple, supposed to be infinitely wide, will be given by

$$I'(\xi)=\int_{A-\frac{\alpha}{2}}^{A+\frac{\alpha}{2}} S'(x-\xi)dx=\int_{A-\frac{\alpha}{2}-\xi}^{A+\frac{\alpha}{2}-\xi} S'(u)du. \tag{1}$$

If, as is more usual, we measure not the flux but the transmission, then the transmission, $I(\xi)$, is given by the ratio of the flux reaching the thermocouple for the position ξ of the slit to the flux when the slit is centred on a large completely transparent part of the plate. Hence we have

$$I(\xi)=I'(\xi)\Big/\int_{-\infty}^{\infty} S'(x)dx=\int_{A-\frac{\alpha}{2}-\xi}^{A+\frac{\alpha}{2}-\xi} S(u)du, \tag{2}$$

where

$$S(x)=S'(x)\Big/\int_{-\infty}^{\infty} S'(x)dx,$$

and consequently
$$\int_{-\infty}^{\infty} S(x)dx = 1. \tag{2a}$$

Now differentiating (2) with respect to ξ we find immediately
$$\frac{dI(\xi)}{d\xi} = S\left(A - \frac{a}{2} - \xi\right) - S\left(A + \frac{a}{2} - \xi\right), \tag{3}$$
or if the centre of the Abbe Test Plate opening be made the origin of co-ordinates (that is, $A = 0$),
$$\frac{dI(\xi)}{d\xi} = S\left[-\left(\xi + \frac{a}{2}\right)\right] - S\left[-\left(\xi - \frac{a}{2}\right)\right]. \tag{4}$$
Thus by a graphical differentiation of the observed transmission curve $I(\xi)$ from an Abbe Test Plate opening of known aperture, it is possible by means of (4) to find the observed slit pattern. Obviously a similar treatment will yield the slit pattern from the transmission curve across a single straight edge.

It is of interest to note that a function $S(x)$, which plays exactly the same part for a Koch-type microphotometer, may also be found from an application of (4). The method of derivation arises from noting that if in the Moll-type microphotometer an infinitely narrow opening is situated at A in fig. 5*a*, then the flux reaching the thermocouple is $S'(A-\xi)$; provided such an opening could be experimentally realized it would afford an easy method of finding the slit pattern for a Moll-type microphotometer. In fig. 5 (*b*), which represents the focal plane of the second objective in a Koch-type microphotometer and therefore the plane of the slit, let the Koch slit of width σ be centred at ξ, and let the image centred at A of an infinitely narrow line have an intensity distribution produced by diffraction, aberration, and Schwarzschild-Villiger effect of $F'(x-A)$. As the plate is driven across the analysing beam the co-ordinate ξ uniformly increases, and for any given position ξ the flux which reaches the photo-electric cell situated behind the slit will, from analogy with the Moll-type case, be denoted by $S'(A-\xi)$, where
$$S'(A-\xi) = \int_{\xi-\frac{\sigma}{2}}^{\xi+\frac{\sigma}{2}} F'(x-A)dx. \tag{5}$$
Next suppose that we have an Abbe Test Plate opening centred at A and of width a, and consider an infinitely narrow line in that opening centred at x'. Then from (5) the flux which reaches the photo-electric cell from this line will be
$$S'(x'-\xi) = \int_{\xi-\frac{\sigma}{2}}^{\xi+\frac{\sigma}{2}} F'(x-x')dx,$$
and for the totality of such infinitely narrow lines the flux reaching the photo-electric cell will be
$$I'(\xi) = \int_{A-\frac{a}{2}}^{A+\frac{a}{2}} dx' \int_{\xi-\frac{\sigma}{2}}^{\xi+\frac{\sigma}{2}} F(x-x')dx = \int_{A-\frac{a}{2}}^{A+\frac{a}{2}} S'(x'-\xi)dx'. \tag{6}$$

This is identical with (1), and leads by the same steps to (4). Consequently the slit pattern $S(x)$ can be found from measures of the transmission of an Abbe Test Plate opening by means of (4) for either a Moll- or Koch-type microphotometer. It should be noted, however, that while the Moll-type microphotometer, on account of the linear characteristic curve of its thermocouple, gives this required transmission as a function of ξ directly from the record, with the Koch-type microphotometer it will in general be necessary

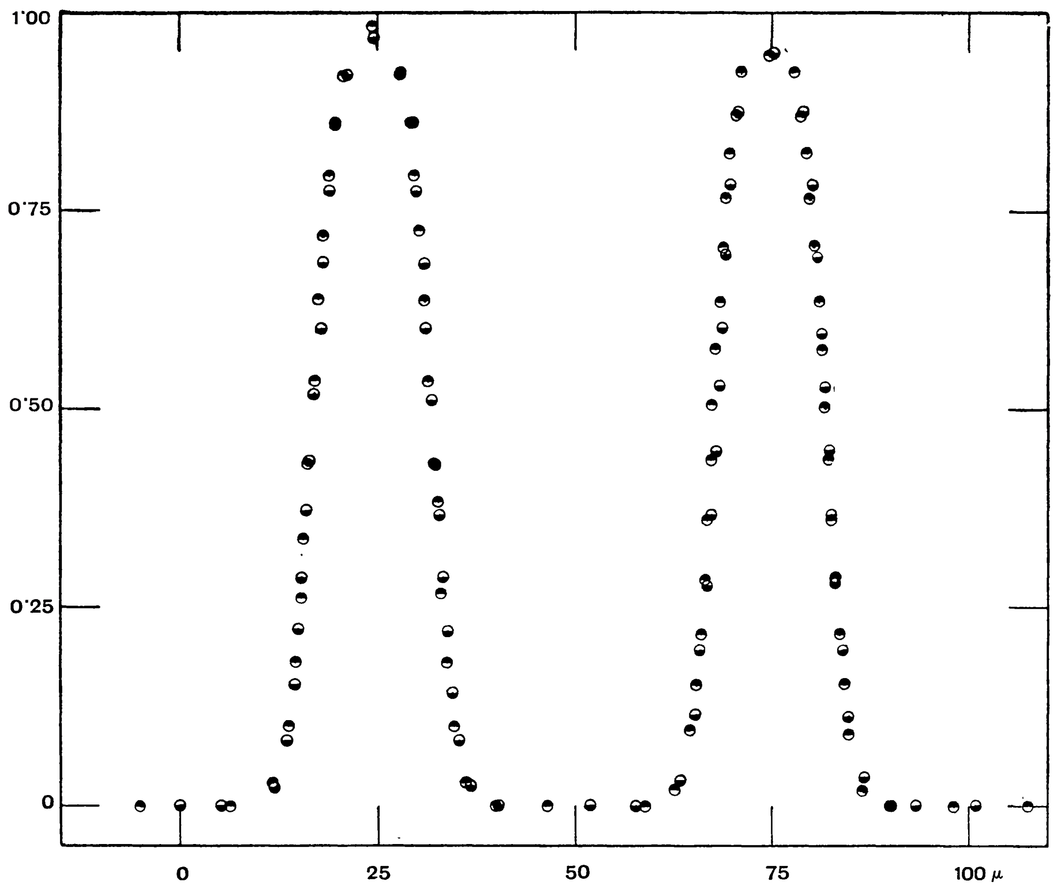

FIG. 6.—*Values of $I(\xi)$ for two successive openings of Abbe Test Plate. Circles filled at bottom are for plate travelling from right to left across microphotometer slit image (projected width 5·1 μ), and circles filled at top for plate travelling left to right.*

first to find the non-linear characteristic curve of its photo-electric cell, and then by its use to change recorded readings to transmissions before an application of equation (4) can be made.

In order to find the slit pattern $S(x)$ for the present instrument two successive openings of an Abbe Test Plate with widths $a=17{\cdot}2\,\mu$ and $a=15{\cdot}4\,\mu$, separated by an opaque space of $34{\cdot}2\,\mu$, were run through the microphotometer with magnification 48·2. The measured transmissions, taken from two microphotometer records for opposite directions of run, the x co-ordinates on which were measured on a Hilger micrometer, are shown in fig. 6 for a microphotometer slit width (projected) of $5{\cdot}1\,\mu$. It will be noted that the runs in opposite directions lie well on top of each other, showing the absence of inertia in the thermocouple and galvanometer and the symmetry in the slit pattern. $I(\xi)$ curves were also obtained for a microphotometer slit width (projected) of 10·4 μ.

Placing the origin in turn at the maximum transmission for each $I(\xi)$ curve, each branch of each curve may be graphically differentiated at a number of points to find the complete slit pattern $S(x)$ by means of (4). The resulting slit patterns for the two microphotometer slits used are shown

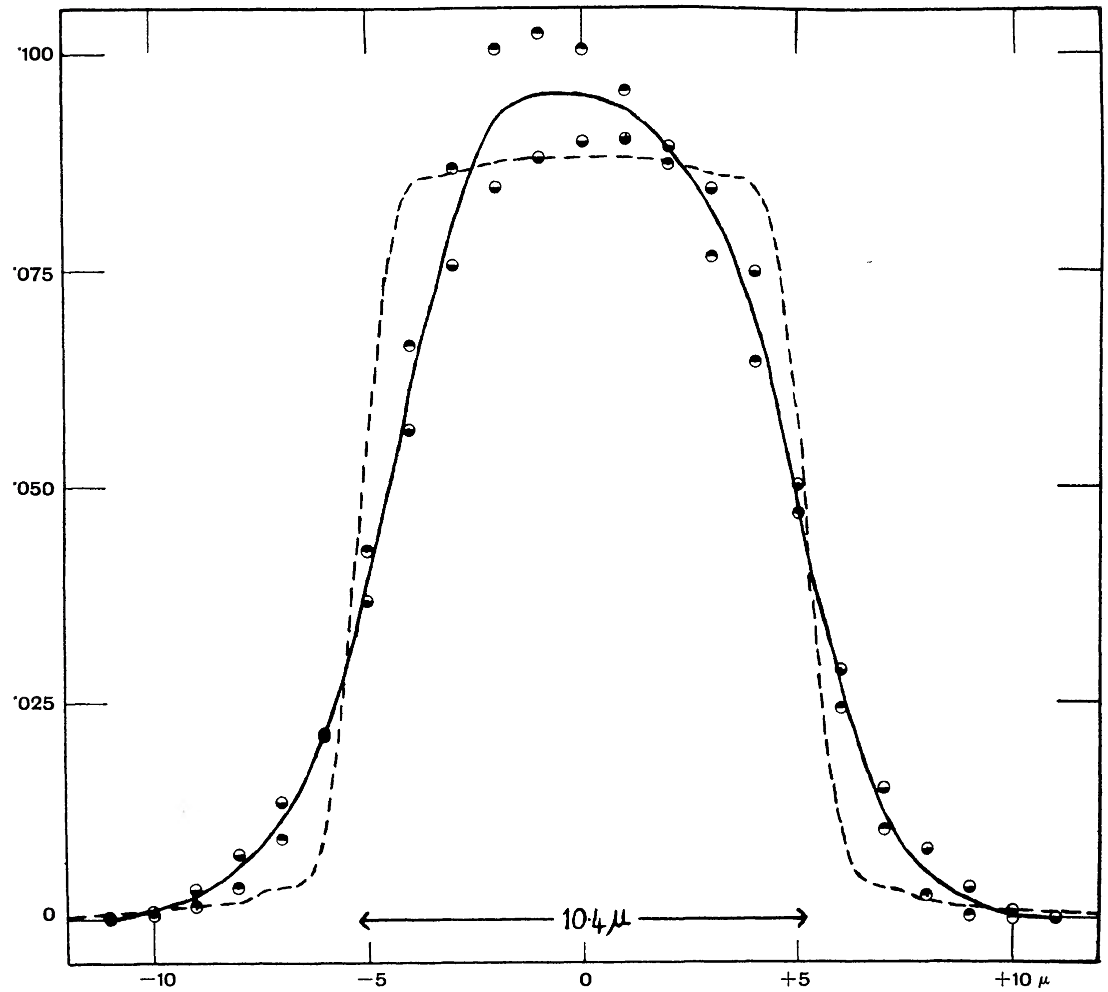

FIG. 7*a*.—*Slit Pattern for Microphotometer Slit* 10·4 μ. *Full line—observed pattern ; broken line—diffraction theory pattern.*

as full lines in fig. 7*a* and 7*b*, mean observed points from each record being shown by differently half-filled circles. These curves represent the actual distribution of light in the analysing beam as it falls on the plate. The areas of the curves are 0·94 and 0·92 (mean 0·93), and this number, as a moment's consideration will show, is the average transmission of the two Abbe Test Plate openings. If the latter had been transparent, the area under the slit patterns, in accordance with (2*a*), would have been exactly unity.

2.32. *Purity Factor.*—The theoretical slit pattern for a given microphotometer slit can be found from elementary diffraction theory. Assuming no phase relations between light from different parts of the slit,* as

* Lord Rayleigh, *Scientific Papers*, 4, 235–244, 1896.

illuminated by the lamp-house condenser, it may readily be shown for a microscope objective with rectangular aperture $a \times c$ (a sufficiently close approximation) that the theoretical slit pattern is given by

$$S_t(x) = \frac{ac}{\pi}\int_{v_1}^{v_2} \frac{\sin^2 v}{v^2}\,dv, \tag{7}$$

where

$$v_1 = \frac{2(\text{N.A.})}{\lambda}\left(x - \frac{\sigma}{2}\right)\pi \qquad v_2 = \frac{2(\text{N.A.})}{\lambda}\left(x + \frac{\sigma}{2}\right)\pi.$$

In this equation σ is the projected slit width, (N.A.) is the numerical aperture of the objective (in our case 0·30), and λ is the effective wave-length of the

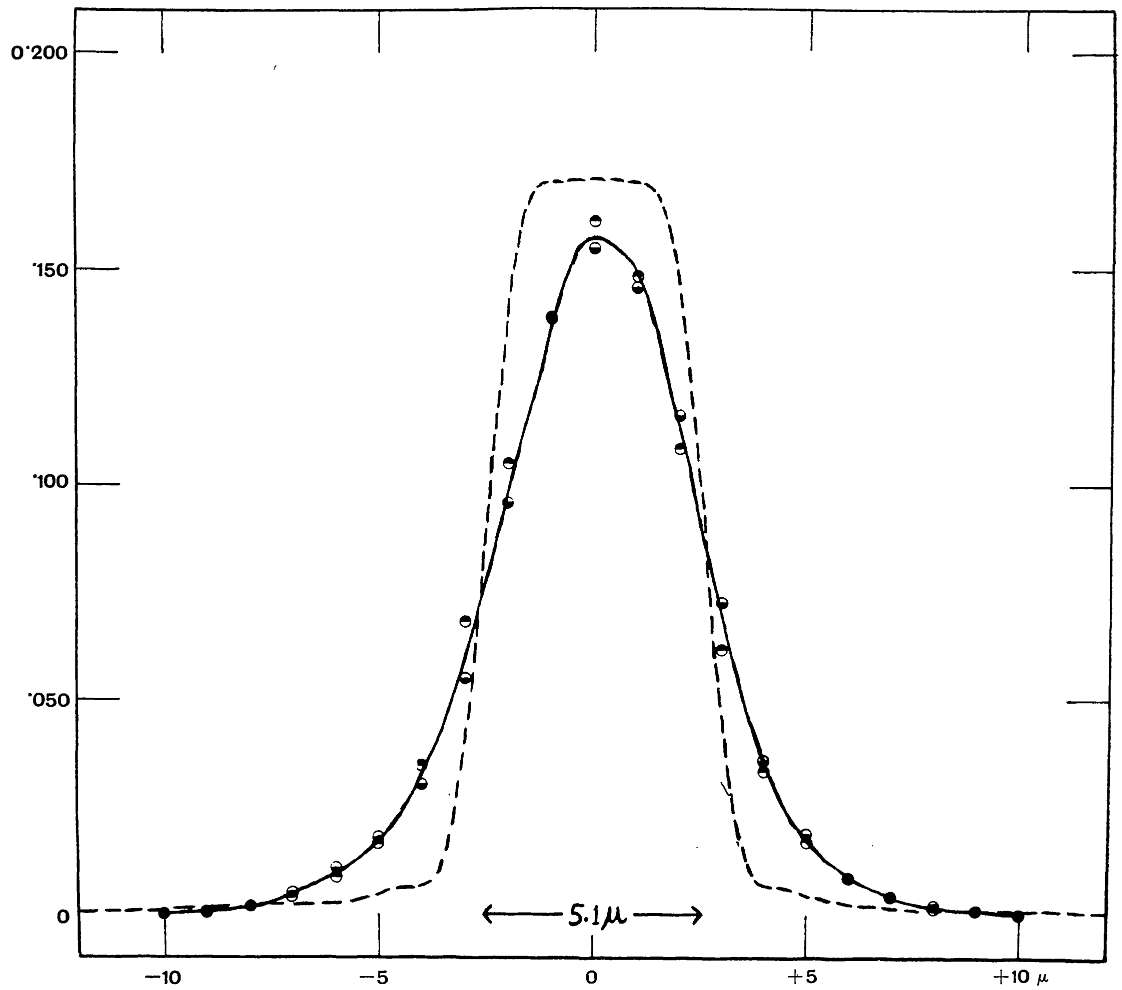

FIG. 7*b*.—*Slit Pattern for Microphotometer Slit* 5·1 μ. *Full line—observed pattern ; broken line—diffraction theory pattern.*

analysing beam which may be taken as 1 μ. The value of the integral was found from some new numerical integrations, and the resulting values for $S_t(x)$, with ordinates adjusted so that the area under the theoretical pattern is the same as that for the observed pattern, are shown as broken lines in figs. 7*a* and 7*b*.

It will be noted, though the differences are not large, that the theoretical pattern is in each case more concentrated than the observed pattern. This is well shown in Table VI, where the second and third columns contain the widths, for the observed and theoretical patterns respectively, within which the fraction 0·90 of the total light of the pattern lies. The increasing diffuseness of the observed pattern with decreasing slit width, which is shown in this table, is an effect produced by aberration of the optical system of the microphotometer; since the observed patterns are symmetrical within the errors of determination, this aberration presumably arises more from the chromatic difference of focus for 0·56 μ (the effective wave-length with which the plate is focussed) and 1 μ (the effective wave-length for which transmission is measured by the microphotometer) than from extra axial aberration originating from lack of collimation.

Table VI

Concentration of Slit Patterns

Microph. Slit	0·90 Width		Fraction of Total Light within Projected Slit Width		
	$S(x)$	$S_t(x)$	$S(x)$	$S_t(x)$	Purity
10·4 μ	11·0 μ	9·9 μ	0·879	0·925	0·95
5·1	8·2	5·6	0·720	0·859	0·84

Effects due to aberration must be present to a greater or less extent in all microphotometers, and it is these effects rather than the diffractional widening which impose a limit on the resolving power of the microphotometer. While the material in figs. 7*a* and 7*b* is sufficient to evaluate the amount of aberration present in the optical system of the microphotometer, what is needed is rather some simple criterion, applicable to all instruments, which yields a measure of the efficiency of the microphotometer. Probably the simplest of these is found by measuring with a planimeter the fraction of the total light of the observed and theoretical patterns which lies within the limits of the geometrically projected slit width. These fractions are given in the fourth and fifth columns of Table VI. For a given slit width the ratio of these fractions for an observed and theoretical slit pattern may be called the purity for this slit width; this purity factor is given in the last column of the table. For a microphotometer without aberration this purity factor for a given slit width would be unity, but for the same slit width this factor becomes smaller as the aberration makes its appearance and becomes larger. Microphotometers may then be compared as regards their freedom from aberration, or their efficiency as regards resolving power, by determining the purity factor for some standard slit width, say 5 μ. For the present instrument, as reference to Table VI shows, this purity factor is

0·84; it would be of considerable interest to know the purity factors for other microphotometers.

2.33. *Distortion by the Microphotometer.*—Suppose the distribution of transmission in the photographic plate is given by $\mathcal{J}(x)$, and the slit pattern is given by $S(x)$, then for either a Moll- or Koch-type microphotometer it may be shown that $I(\xi)$, the transmission registered by the microphotometer, will be given by

$$I(\xi)=\int_{-\infty}^{\infty}\mathcal{J}(x)\,.\,S(x-\xi)dx=\int_{\xi-\beta}^{\xi+\beta}\mathcal{J}(x)\,.\,S(x-\xi)dx, \qquad (8)$$

the limits of integration being changed, since for all practical purposes a distance β can be found such that $S(x)=0$ for $-\beta \geqslant x \geqslant \beta$. Since we know the slit pattern, $S(x)$, it would be possible to solve the integral equation (8) by successive approximations, and to pass from the measured transmission, $I(\xi)$, to the actual transmission, $\mathcal{J}(x)$, on the plate. In practice, however, such a procedure would be unduly laborious, and what is required is to choose a slit pattern so concentrated that the distortion produced by the microphotometer is negligible. One method of doing this, knowing something of the variation of $\mathcal{J}(x)$ beforehand, is to choose a slit pattern such that over its full extent the value of $\mathcal{J}(x)$ does not differ from its constant value in the middle of the range. In this case the integral equation takes the form

$$I(\xi)=\mathcal{J}(\xi)\int_{\xi-\beta}^{\xi+\beta}S(x-\xi)dx=\mathcal{J}(\xi)\int_{-\beta}^{\beta}S(u)du=\mathcal{J}(\xi) \qquad (9)$$

and microphotometer distortion is negligible.

Another method of wider applicability is to choose the slit pattern so that the distortion produced by the microphotometer is less than that already produced by the photographic plate, as a result of the turbidity of its emulsion and the finite size of the silver halide grains. In this case the limit on the accuracy of the transmission curves is that produced by the irremovable limitations of the photographic process, and has nothing to do with the finite resolving power of the microphotometer. In order to find a slit pattern which satisfies this condition it is sufficient to note that the distortion produced by the photographic emulsion is conveniently measured by the so-called photographic resolving power. Imagine a contact print to be made on the photographic emulsion concerned, of a silver on glass plate on which are ruled at regular intervals a number of fine parallel transparent lines; this contact print will show a number of equally spaced black lines. As the spacing of the lines on the silver plate is steadily diminished, a stage is finally reached where, on account of photographic distortion, the emulsion just fails to show separable lines in the contact print. The number of lines per mm. corresponding to this stage is termed the resolving power of the emulsion concerned. Mees, Ross and others at the Kodak Research Laboratory * have carried out a number of investigations on the subject of photographic resolving power, and have been able to show that its determination is independent of the widths of the rulings. The most recent results show

* F. E. Ross, *Physics of the Developed Photographic Image*, chap. iv, 1924.

that the photographic resolving power varies between 35 for fast, coarse-grained emulsions, to 80 for fine-grained process emulsions.* In order now to choose a slit pattern for the microphotometer which will produce less distortion than that already produced by the photographic plate, it suffices to choose a pattern which is adequate to separate more lines per mm. on a similarly ruled silver on glass test plate than the photographic plate can. Consider two such lines, regarded as infinitely narrow, with co-ordinates 0 and Δ; then the transmission curve given by the microphotometer will be

$$I(\xi) = S(-\xi) + S(\Delta - \xi). \tag{10}$$

It is a matter of only a few moments numerical trial to use the observed $S(x)$ and equation (10) to find for what value of Δ in microns the transmission curves show a double maximum. The results of such trials for the two slit patterns are given in Table VII, the first and fourth columns containing values of Δ, the second and fifth giving the position of the maxima, and the third and last containing the ratio of $I(\xi)$ at the minimum between the two maxima to $I(\xi)$ at the maxima. Since the microphotometer with slit width

TABLE VII

Microphotometer Resolving Power

Microphotometer Slit 10·4 μ			Microphotometer Slit 5·1 μ		
Δ	Maxima	I_{min}/I_{max}	Δ	Maxima	I_{min}/I_{max}
μ	μ		μ	μ	
9	4·5		4	2	
10	1·5 9·5	0·90	5	0 4	0·95
11	1 11·5	0·69	6	0 6	0·78

10·4 μ has a slit pattern sufficiently concentrated clearly to separate 100 lines per mm., it follows that even with this arrangement the distortion produced by the microphotometer is definitely less than that inherent in the fine grain process plates with a maximum resolving power of 80. For faster emulsions a slit with projected width of 20 μ would probably give a sufficiently concentrated pattern to give less distortion than that inherent in the emulsion on account of turbidity and graininess. These satisfactory results are due to the small aberration of the optical system, or, otherwise expressed, the high purity factor of the instrument, and the consequence of this is that no existing emulsion would justify the use of the very concentrated pattern given by the slit of projected width 5·1 μ.

Summary.—The Moll-type microphotometer described above has certain new mechanical features which make possible accurate collimation and precise plate adjustment. The thermocouple and galvanometer give a linear

* C. E. K. Mees, *Journ. Opt. Soc. America*, **21**, 753, 1931.

characteristic curve which is independent of time. From detailed tests it has been shown that the instrument may be used for the determination of linear displacements with an accuracy of $\pm 2{\cdot}5\ \mu$. Finally, it has been shown that the microphotometer has a high resolving power, so that even with a slit of projected width $10{\cdot}4\ \mu$ less distortion is produced by the instrument than is inherent in a fine grain process emulsion—a result due to the freedom of the optical system from aberration.

In conclusion I wish first to acknowledge a special grant from Oxford University which made possible the purchase of this instrument for the observatory, and secondly to express my thanks to R. M. Abraham, to whose ingenuity in design much of the satisfactory performance of the instrument is due.

University Observatory,
Oxford :
1934 *November.*

ON THE CONSTRUCTION OF A SPECTROHELIOSCOPE.

A. M. Newbegin.

It is well known that for many years the work of my observatory has been the observation of solar prominences and the spectrum of sunspots. For this latter work I made a Littrow-type spectroscope of 102 inches focus, fed with a 4-inch grating by Michelson of very fine quality, but the limitations of the usual methods of observation has hitherto prevented seeing prominences anywhere except at the limb of the Sun. When Professor Hale introduced his spectrohelioscope it was at once realised that here was an instrument capable of supplying the deficiences of the ordinary types of prominence spectroscope, and it was decided to install such an instrument at Worthing as soon as it was practicable. Unfortunately, circumstances hindered that ambition being fulfilled immediately, but ultimately the idea of building the instrument in the workshop suggested itself.

It cannot be claimed that the instrument about to be described embodies any new idea, but it is believed to be the first spectrohelioscope constructed in this country to the designs of Professor Hale and, therefore, some description may be acceptable to other workers in solar physics.

A certain amount of correspondence with Professor Hale, who from the outset evinced great interest in the project, led to his sending me a full set of blue prints of his latest design, which, in the main, have been adhered to, but a few alterations or improvements of a minor character have been introduced.

By the kindness of Sir Frank Dyson, then Astronomer Royal, I was able to examine the Greenwich instrument very thoroughly, and it occurred to me that instrument was somewhat light in construction, and in preparing my patterns I decided to make the main castings heavier with a view to reducing vibration to a minimum.