1932MNRAS..92..196B

A PHOTO-ELECTRIC MICROPHOTOMETER USING VALVE AMPLIFICATION.

C. S. Beals.

The use of the photo-electric cell as a sensitive element for the measurement of the densities of blackening of photographic plates has become general of recent years, and a number of microphotometers have been built by different investigators in which the photo-electric cell is employed. These include the now well-known Zeiss instrument, the Koch and Goos * instrument, and the new microphotometer of the Cambridge Solar Physics Observatory.† These instruments are all of the self-registering type, and use electrostatic methods of recording.

The purpose of the present article is to describe an instrument recently built in the physical laboratory of the Dominion Astrophysical Observatory, which is of the direct-reading type and employs as a recording system a thermionic valve amplifier in conjunction with a galvanometer and scale. A limited amount of experience in the photometry of stellar spectra had suggested to the writer that for certain types of work a flexible and sensitive direct-reading instrument would be more convenient than one of the self-registering type. This idea was confirmed by correspondence with Dr. G. R. Harrison, who, with Hesthal,‡ had constructed a direct-reading photo-electric microphotometer for the purpose of measuring line intensities in laboratory spectra. Accordingly, an attempt was made to design an instrument which, it was hoped, would be specially suited for the investigation of certain astrophysical problems being studied at this observatory. The necessary requirements were as follows :—

(1) Convenience and simplicity of operation so that limited regions of the spectrum could be studied without elaborate preparation.
(2) Considerable sensitivity so that both low and high densities could be accurately measured.
(3) High resolving power for the measurement of narrow lines.
(4) Means for the precise determination of the wave-length of that part of the spectrum whose density was being measured.

The completed instrument is described in this paper. It is similar in principle to the microphotometer built by Hesthal and Harrison in which a valve amplifier with a galvanometer and scale was employed. It has proved to be reasonably inexpensive and easy to construct, and has more than fulfilled expectations in its performance. The writer is very much indebted to Dr. G. R. Harrison for a discussion of the physical principles

---

* *Zeits. f. Phys.*, **44**, 855, 1927.

† *M.N.*, **91**, 191, 1930.

‡ *Phys. Rev.*, **34**, 543, 1929 (abstract).

1932MNRAS..92..196B

involved in the construction of a microphotometer of this type. Thanks are also due to Dr. H. D. Arnold, Director of the Bell Telephone Research Laboratories, and Mr. P. Higgs, of the University of Washington, for suggestions relating to the use of a valve amplifier.

The Electrical System

Descriptions of amplifying systems similar to the one used here have been published by Brentano,* by Wynn-Williams,† and more recently by Nottingham.‡ Nottingham has discussed in some detail the physical characteristics of such an amplifier, so that only a bare description is given here. A diagram of the electrical parts is shown in fig. 1. Two thermionic valves form two of the arms of a Wheatstone bridge, while two resistances of from 8000 to 10,000 ohms form the other two arms. A galvanometer with shunt and damping coil is connected as shown in the diagram. One of the valves is made into a diode by connecting the grid and filament, while the grid of the other valve is connected to the photo-electric cells. A current flowing to the grid of the amplifying valve unbalances the bridge and causes a deflection of the galvanometer corresponding to an amplification factor of the order of 5000. Since the current is proportional to the light absorbed by the photo-electric cell, the galvanometer deflections provide

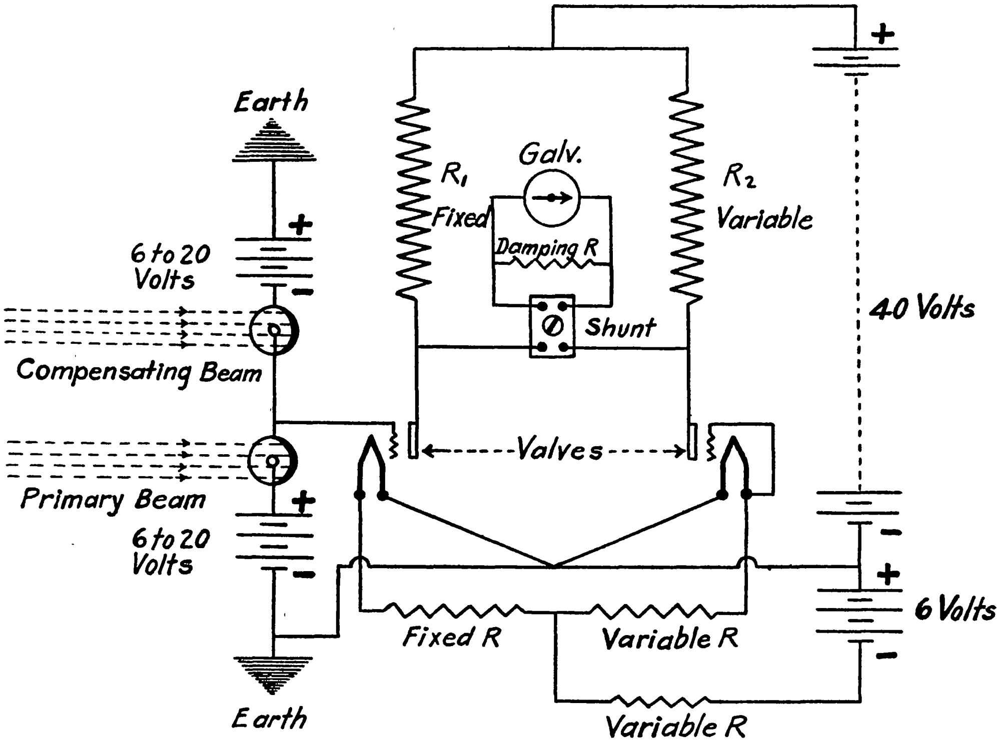

FIG. 1.—*Diagram of Electrical System.*

---

* *Nature*, 106, 532, 1921.

† *Phil. Mag.*, 6, 324, 1928.

‡ *Journ. Franklin Inst.*, 209, 287, 1930.

a measure of the intensity of the light, and, indirectly, of the density of the photographic plate or other absorber placed in the path of the beam.

The galvanometer is a Leeds and Northrup F4447 type B, and as supplied by the makers had a period of 6 seconds, a coil resistance of 500 ohms, and required 10,000 ohms external damping. Its characteristics have been changed by installing a suspension of period 1½ seconds. An Ayrton shunt of total resistance 10,000 ohms is used to vary the sensitivity, and an external damping coil of 2000 ohms provides practically complete damping.

The bridge resistances have each a total resistance of 10,000 ohms. One of them is an ordinary box-resistance with plugs for varying the total resistance in the circuit. The other is a variable resistance in a box with four dials having steps of 1, 10, 100 and 1000 ohms.

The valves used are of type Ux 201 A, with a plate impedance of the order of 10,000 ohms. They are used with a plate potential of 40 volts and a filament current of 0·15 amp. approximately. The filaments are lighted by a 6-volt automobile battery. A variable resistance is used for controlling the total current through the filaments, while two additional resistances, one fixed and one variable, make it possible to compensate for differences in valve characteristics by altering the current through the filament of one valve relative to that of the other. It is probable that almost any well-built radio valve could be used successfully in such an amplifier.

The photo-electric cells are Visitron type A.V. gas-filled cells manufactured by the G.M. Laboratories, Chicago. These cells are of the cæsium on silver type, and are highly sensitive in the visible and near infra-red region. They are operated on potentials of from 6 to 20 volts. Since these voltages are too low to produce the ionization currents on which the sensitiveness of a gas-filled cell depends, it is probable that vacuum cells would serve the purpose equally well. The cells are connected to the amplifier in the manner originally described by Koch,* which is illustrated in the diagram. The light from the lamp which provides the illumination for producing the photo-electric current is divided into two beams. The first beam passes through the photographic plate whose density is to be measured and falls on the first cell. The second beam, whose intensity can be varied by means of a diaphragm, follows a different path and by a series of reflections is caused to fall on the second cell. The second cell performs the function of a variable grid leak, and can be used to alter the sensitivity or to provide partial compensation for changes in the intensity of the source of light.

All parts of the electrical system, including batteries, resistances, valves, photo-electric cells and galvanometer, are enclosed in a single large sheet-metal box, which provides complete shielding from external electromagnetic disturbances. Control dials and switches are mounted in convenient positions in front of the box so that all necessary adjustments, such as balancing the bridge, altering the sensitivity, changing the zero point of the galvanometer, etc., can be performed without lifting the cover.

---

* *Ann. d. Phys.*, 30, 705, 1912.

The Optical System

The optical system is illustrated in fig. 2. An ordinary 30 c.p. automobile headlight is used as a source of light. It is fed by two large 6-volt storage batteries in parallel, and is satisfactorily steady if run for half an hour before the instrument is used. In front of the lamp is a glass condenser, consisting of two simple plano-convex lenses mounted with their convex faces inward as in a projection lantern. A converging beam from the condenser falls on the photographic plate, which is held in a micrometer carriage having two screw motions at right angles to one another. The plate is slightly behind the true focus of the condenser, so that a bright out-of-focus patch instead of a sharp image of the filament appears on the plate. The projector is a Dallmeyer cinematograph lens of F 1·5 aperture and 16 mm. focal length. It is set up in a micrometer-focussing mount, and has an extension consisting of a brass tube which enables the lens to be brought close to the surface of the plate and yet leaves room for convenient manipulations in focussing.

An image of the spectrum enlarged 17 times is projected on the screen, whose dimensions are 8 × 10 inches. In the centre of the screen is an accurately machined slit, variable both in length and in width. The variation in length is provided by the direct vertical motion of two celluloid strips above and below the slit. These strips have etched on their surfaces fine black lines which are continuous with the slit itself. These black lines serve the same purpose as the cross-hairs in an ordinary micrometer-measuring machine. With their aid it is possible to make accurate settings on the comparison lines on either side of the star spectrum and so to determine precisely the wave-length of the region of the spectrum under examination. The actual length of slit used varies with the width of the spectrum. It is usually about 5 mm.

The width of the slit, which opens symmetrically, is controlled by a micrometer screw, and slit-widths can readily be estimated to 0·01 mm. Since the magnification is approximately 17, a slit-width of 0·17 mm. corresponds to a distance on the plate of 0·01 mm. Owing to plate grain, smaller distances than this on the plate are usually of little significance, so that slit-widths of less than 0·1 mm. are seldom used. The light, after passing through the slit, falls on the photo-electric cell, which is 36 inches distant. No lens is used between the slit and cell, as the diverging beam from the slit forms a patch of light on the cell which is slightly smaller than the sensitive surface.

The path of the beam to the compensating cell is clearly shown in the diagram. Three mirrors are used, and a diaphragm enables the intensity of the compensating beam to be varied at will by the operator.

Method of Recording

The galvanometer is provided with a plane mirror and a lens of 1 metre focal length. For the purpose of making readings a semi-transparent celluloid scale is used. The scale is 60 cm. long, has millimetre divisions,

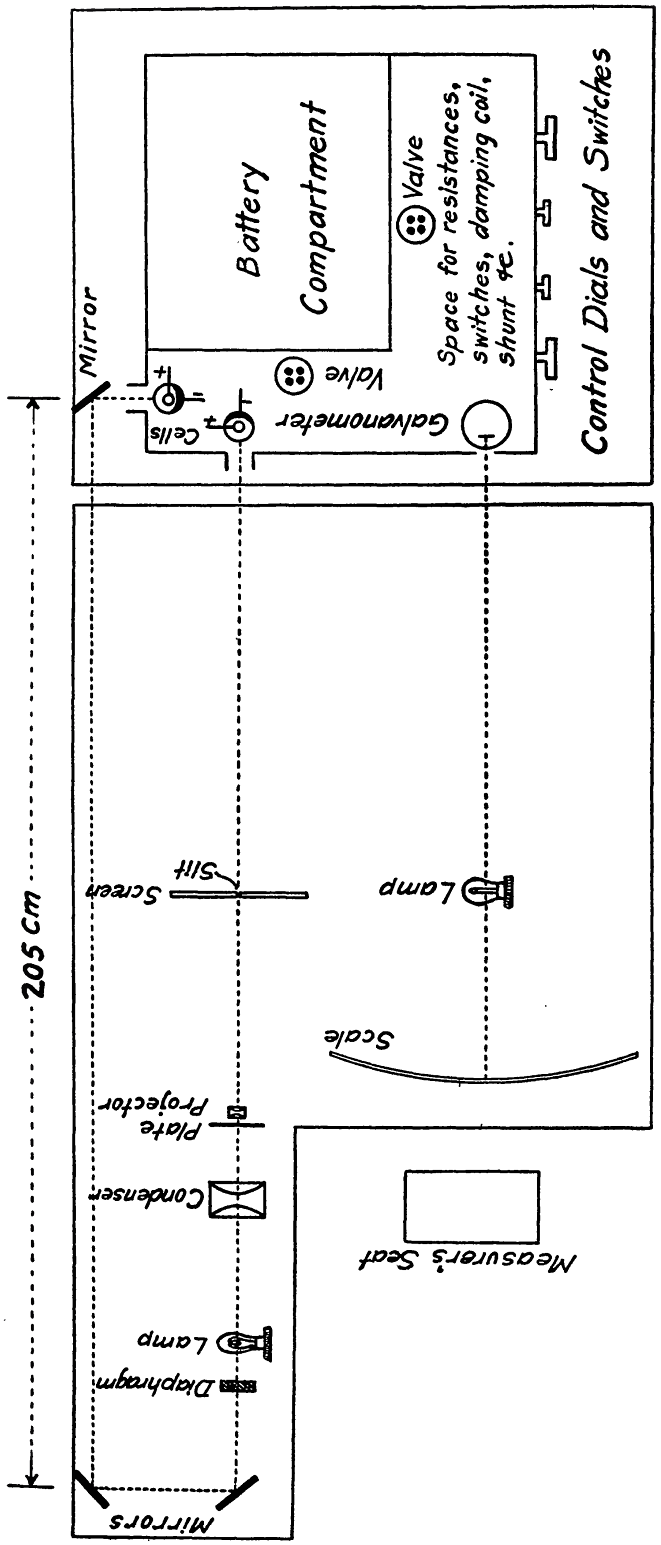

FIG. 2.—*Diagram of Microphotometer.*

and is used at a distance of 120 cm. from the galvanometer. The use of a lens necessitates a considerably curved scale, and somewhat better results might be obtained with a concave mirror. Contrary to the experience of Harrison and others, the writer has found the image of a vertical lamp filament by far the best and most accurate index to read. To make the scale more easily visible, a strip of white drawing paper has been placed behind and in contact with the etched figures and divisions. The scale is then illuminated from the front and is brought into high relief by the background of white paper. The image of the lamp filament appears below the scale, in the manner illustrated in fig. 3. The scale is placed directly in front of the operator, about 18 inches above the table, and in such a position that the eye can easily focus on the index and scale divisions. Fractions of millimetres can easily be estimated, but in practice readings are made to the nearest millimetre, the sensitivity being so adjusted that the range of density under measurement corresponds to a distance on the scale of about 300 mm.

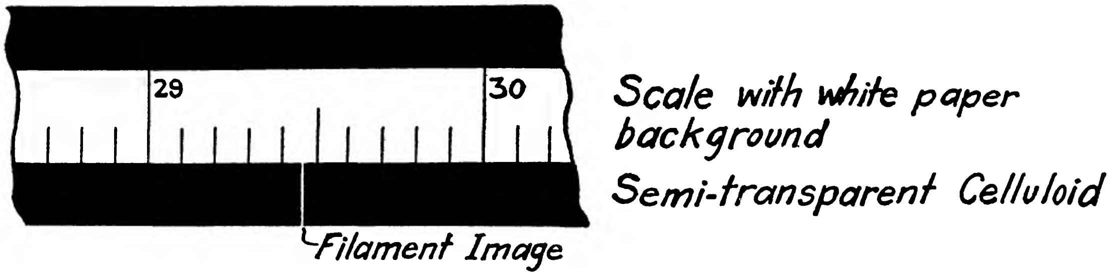

FIG. 3.—*Method of Using Lamp and Scale.*

The Instrument in Use

The instrument has proved to be very convenient in use, and has given comparatively little trouble. The only serious difficulties so far encountered have been due to insufficiently charged batteries and faulty soldered joints in the amplifier circuit. It is unnecessary to darken the room in which the instrument is used, and no difficulty has been encountered from electromagnetic disturbances. Some of the more important points concerning its performance may be outlined as follows :—

Steadiness of Zero.—In order to use successfully an amplifier of the type described here, it is necessary so to adjust the amount of light falling on the photo-electric cell and the sensitivity of the galvanometer that quick, irregular variations in the zero are inappreciable as compared with the magnitude of the galvanometer deflection being measured. These conditions have been attained in the present instrument by using the galvanometer previously described and reducing its sensitivity to 1/10 by means of the Ayrton shunt. With this combination irregular variations are reduced to a range of ±0·5 mm. With sensitivities ordinarily used, irregular variations in the photographic emulsion cause deviations of ±10·0 mm. in the readings, so that minute irregularities in the zero are of no significance.

A steady slow creep of the zero is generally observed during a run. It is usually small, and can be allowed for by checking from time to time during the course of a set of readings. For most purposes it is sufficient to check the zero at the beginning and end of a run and compute the corrections to be applied on the assumption that the creep is uniform. Since the instrument has been put in use, some 55 runs have been made of about 200 readings per run. The average creep has been 1·8 per cent. of the maximum deflection. Of the 55 runs, in 34 the creep has been 1 per cent. or less ; in 13 it has been between 1 and 2 per cent. ; in 5 it has been between 2 and 5 per cent. ; while in 3 it has been over 5 per cent. If the creep is less than 5 per cent. and if the corrections are carefully applied, it is believed that no error of importance is introduced. For precise work a run showing a creep of more than 5 per cent. is discarded.

Sensitivity.—The sensitivity of the instrument can be varied within wide limits, and can be made sufficient to cause a deflection of 50 mm. or more for the smallest difference in density that is clearly perceptible to the eye. The following means of altering the sensitivity are available :—

(1) Altering the intensity of the illumination on the compensating cell.
(2) Altering the slit width.
(3) Altering the voltage on the photo-electric cells.
(4) Altering the intensity of the source of light by changing the current through the lamp.
(5) Changing the sensitivity of the galvanometer by means of the Ayrton shunt.
(6) Changing the suspension of the galvanometer.

Usually only (1) or (2) is used, though for special work it may be necessary to employ any of the methods enumerated for altering the characteristics of the instrument.

The instrument can be adjusted for the accurate measurement of very high or very low densities. For the measurement of a plate showing very high contrast its accuracy is limited only by the length of its scale, which is 600 mm.

Resolving Power.—It is difficult to make quantitative tests of the resolving power of a microphotometer owing to the impossibility of securing a test object which reproduces the conditions encountered in measuring a photographic plate. The resolving power of the present instrument, however, appears to be considerably greater than that of the photographic plate, and when a very fine slit is used, deviations in the readings, due to the grain of the plate, become troublesome. In order to get even a moderately smooth record it is necessary to use a slit width of 0·2 mm., or greater. In order to facilitate comparison with other instruments, the diffraction pattern of the edge of a razor blade placed in the position of the photographic plate is shown in fig. 4. The image of the edge was brought into sharp focus on the screen, and the micrometer readings and galvanometer deflections were recorded in the same manner as in measures of photographic density. A slit width of 0·05 mm. was used.

Speed.—The time required to place a plate in position and make a run of

300 readings, which include the measurement of a strip of the spectrum and of a calibration strip, is about 45 to 60 minutes. Fortunately, the characteristics of the instrument are such that a rapid run increases rather than decreases the accuracy. As a consequence a comparatively large number of measures can be made in a short time, and the time taken in actually making the measures becomes small in comparison with that usually taken in reduction.

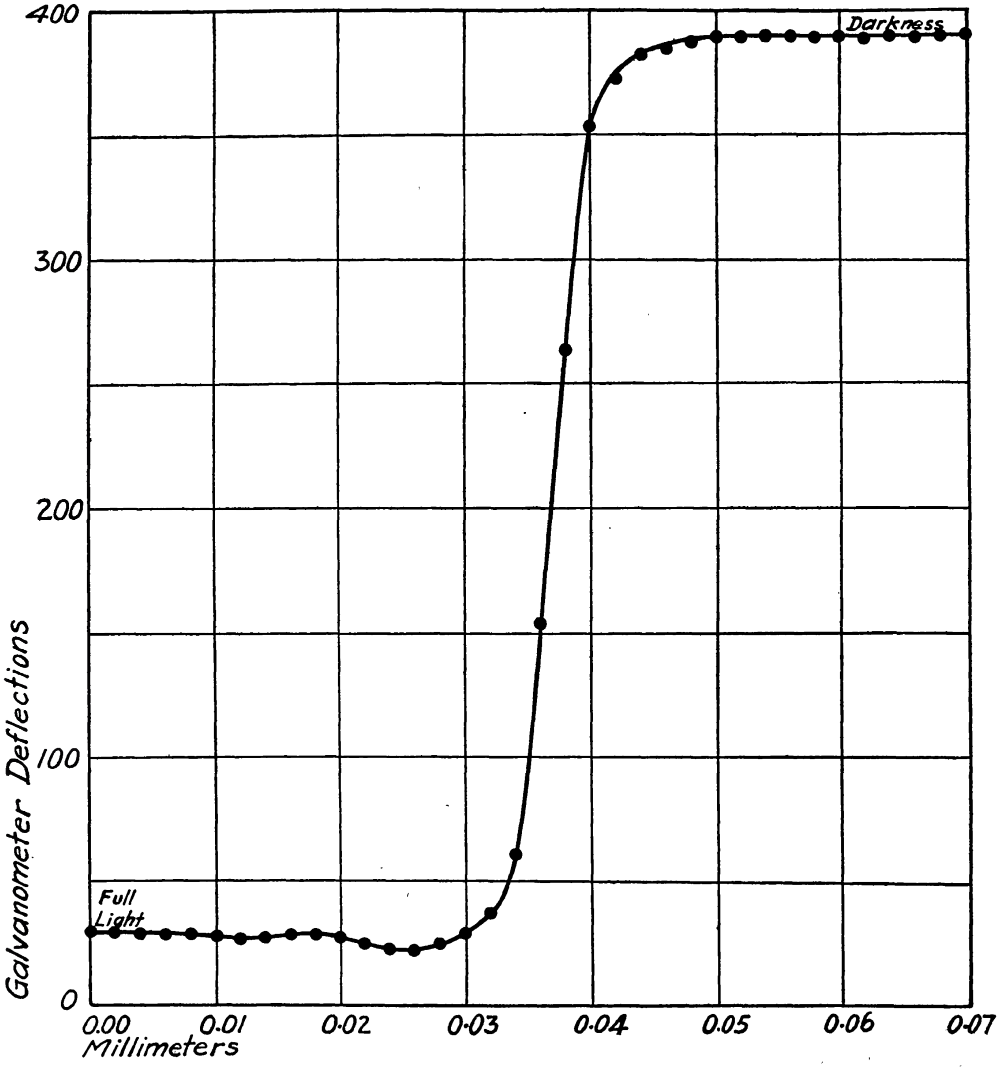

FIG. 4.—*Knife Edge Test.*

Examples of Actual Measurement

1. *Wolf-Rayet Band.*—Fig. 5 represents the contour of the emission band λ4686 in the star H.D. 192163. Intensities are given in relative units and have been referred to the top of the band considered as 10. Measures of density have been translated into relative intensities by means of the usual characteristic curves. These curves have been plotted from measures of calibration strips impressed on the plates by means of a neutral tint wedge used with an auxiliary spectrograph. The exposure times of the calibration

strips were made as closely as possible equal to the exposure of the star spectrum.

Six of the plates cover the range of intensity from the top of the band to intensity 3·5 approximately. One plate covers the entire intensity range from the top of the band to the extreme edges, while two plates cover the range from approximately 4·5 to the edges of the band.

The plates used were mainly E33 and Barnet, though one spectrogram was taken with an Ilford Empress plate. High contrast developers were used, one due to Ross and the other to Parkhurst.* The E33 plates were very satisfactory in their fineness of grain, but were too slow to record the extreme edges of the band. The Barnet plates (H and D 1500) gave reasonably satisfactory results in spite of a rather coarse grain, and their superior speed was a factor of great importance in recording the faint continuous spectrum on either side of the band. The Ilford Empress plates are unsurpassed for evenness and fineness of grain, but are too slow to be very practicable for any but rather bright objects. The upper part of the graph from the top of the band to intensity 3·5 has been plotted from measures of seven plates, and each point, on the average, is the mean of seven observations. Since the measures were satisfactorily accordant, a reasonable amount of confidence in the result seems justified. Below 3·5, measures are from three plates only, and each point is a mean of three observations. The three plates showed excellent agreement, however, and it is hoped that there are no serious errors. In making the measures the feature of the instrument that permits precise measurement of the wave-length of each point relative to the comparison spectrum has proved of very great convenience. It makes unnecessary the arbitrary process of "fitting" contours

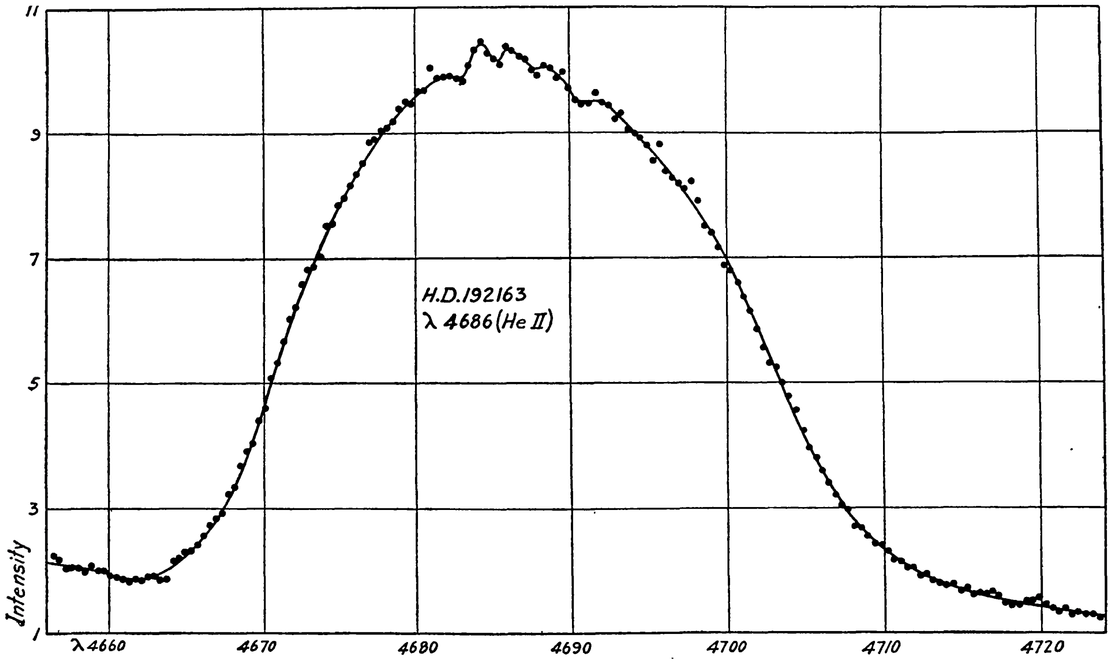

FIG. 5.—*Contour of Wolf-Rayet Emission Band.*

---

* *Pub. Dom. Obs.*, **8**, 121, 1924.

derived from separate plates, and not only adds to the accuracy but makes reduction much less laborious.

Theoretical predictions concerning the forms of Wolf-Rayet bands, as well as a number of actual measures, have already been published by the writer.* The band contour shown in fig. 5, however, brings into prominence two aspects not clearly shown in any previous measures.

The first of these is the appearance of complicated structural features on the top of the band, of a character somewhat similar to the structure that has been observed in bands in the spectra of novæ. This observation may be of considerable theoretical importance, since it suggests an additional indication of the fundamental similarity which the writer has endeavoured to establish between the spectra of novæ and Wolf-Rayet stars.

The second point, and one that is also of some theoretical importance, is the definitely asymmetrical character of the band as shown in the graph of fig. 5. According to the theory of Wolf-Rayet emission developed by the writer,† absorption would be expected on the violet edges of emission bands. In some cases such absorption has been observed to take the form of diffuse absorption lines bordering the violet edges of bands. It might be expected also that the absorption would act to add to the steepness of the contour on the violet edge, producing an asymmetry similar to that which is shown in fig. 5.

2. *Interstellar Calcium Lines.*—The graphs of fig. 6 show contours obtained for the two interstellar calcium lines H and K as well as the hydrogen line $H\epsilon$ in the spectrum of the star 9 Camelopardalis (H.D. 30614). In the case of the two interstellar lines the forms of the contours are almost undoubtedly due mainly to the properties of the spectrograph, and they have been determined for the purpose of obtaining accurate values of the total integrated intensities relative to the continuous spectrum. Three plates have been measured, and each point on the graph represents a single observation. In measuring such narrow lines it is necessary to use a narrow slit on the microphotometer. This greatly increases irregularities due to plate grain, and the scatter of the points on the diagram is due almost entirely to this cause.

The points due to different plates are clearly indicated on the diagram, and in spite of the relatively large scatter the agreement between plates is reasonably satisfactory. In determining the total integrated intensity of calcium H it is necessary to guess at the form of the violet wing of the line $H\epsilon$. It is naturally difficult to be certain of the magnitude of the errors introduced by an extrapolation of this sort. In this connection it is interesting to compare the value of the intensity ratio K/H with a value of the same quantity for this star determined by Struve and Elvey.‡ The actual quantities involved are represented by the integral

$$\int_{\nu_1}^{\nu_2} \frac{\partial I}{\partial x} \frac{\partial x}{\partial \nu} d\nu.$$

---

* *M.N.*, **91**, 966, 1931.

† *Ibid.*, **90**, 202, 1929 ; *Pub. D.A.O.*, **4**, No. 17, 1930.

‡ *Zeits. f. Astrophysik*, **1**, 314, 1930.

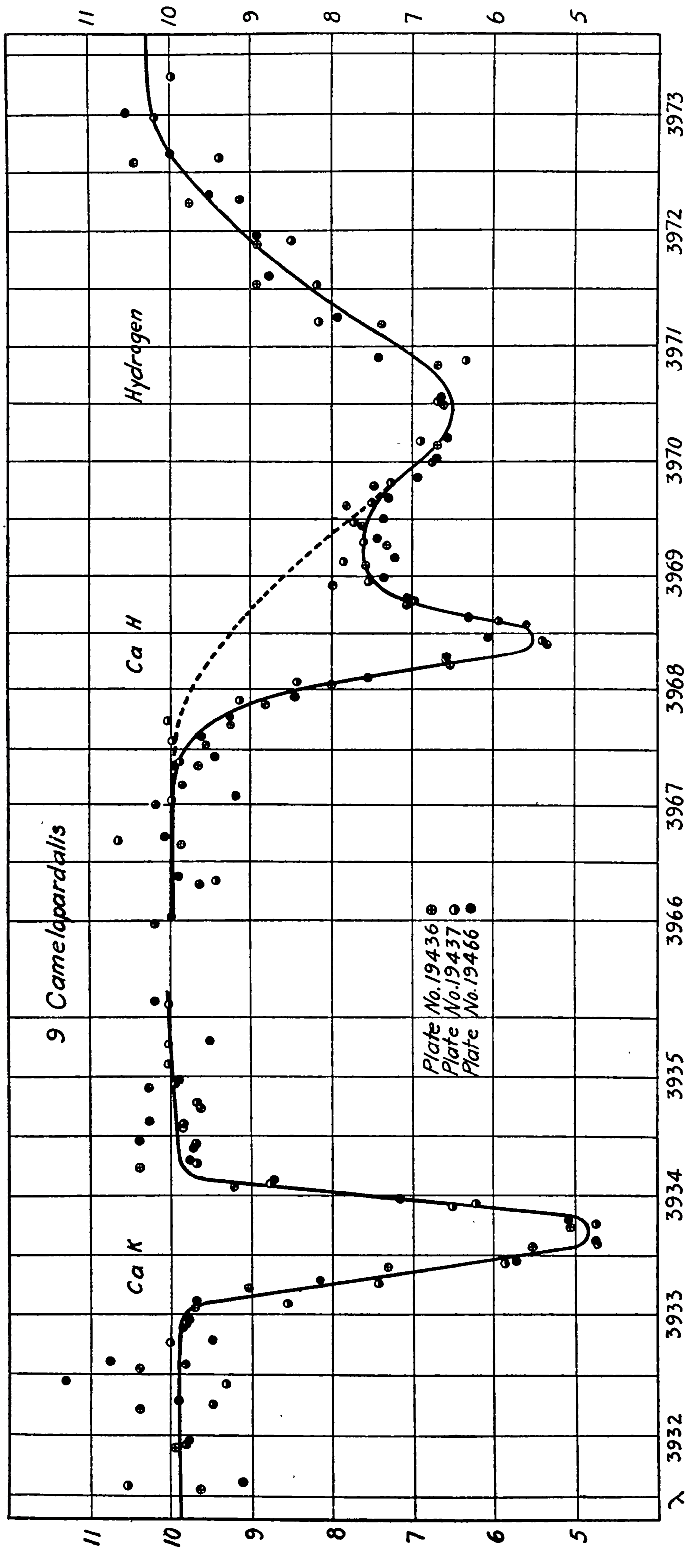

FIG. 6.—*Contours of Interstellar Calcium Lines and Hε.*