PHOTOMETRIC STUDY OF THE PROFILES OF THE FRAUNHOFER LINES IN THE SOLAR SPECTRUM

PART I. Mg b. GROUP

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ABSTRACT. The paper consists of the results of the photometric studies carried out by the authors during the last year. After a brief description of the improvements and refinements perfected in the Direct-Reading Photo-electric Spectrophotometer described by Narayan and Ananthasubrahmanyam, the use of the instrument in the study of the line contours is discussed. Contours obtained by photographic photometry and this instrument are given.

Accurate measurements of the intensity distribution in the absorption lines in the solar spectrum at various points across the sun's disc are necessary for a correct appreciation of the mechanism of absorption in the solar atmosphere. All the strong lines in the solar spectrum have been studied by more than one author ; but the results of the different workers do not show the necessary degree of agreement that it calls for further work. In continuation of the work carried out by Royds and Narayan[1] on the strong lines of hydrogen and ionised calcium, a study of the mg. b group lines was undertaken

All the measurements of the intensity distributions in the absorption lines have been made till now by the method of photographic photometry. This method yields accurate results if suitable precautions are adopted. But it is involved and laborious requiring separate callibration marks, etc. In recent years attempts have been made by some physicists to use a photo-electric cell and an amplifier to measure the intensity distribution in spectral lines directly without recourse to photography. In a paper on " A Precision Reading Photo-electric Spectrophotometer " Narayan and Ananthasubrahmanyam[2] have described such a photo-electric photometer. The instrument was constructed by them at the Solar Physics Observatory and forms a permanent feature of the equipment of the Observatory. In the present paper the results obtained by the photographic method and with the direct-reading instrument are given. Since the instrument was set up, many improvements have been made in the light of experience. As this is the first paper reporting results with the improved instrument a short account is given of the modifications. The chief advantage of this method over photographic photometry lies in the saving of time.

DIRECT-READING PHOTO-ELECTRIC PHOTOMETER

The photo-electric current due to the light from any point in the spectral line is very minute and needs an amplification of many times. A single tube amplifier was first tried and found unsatisfactory. Fluctuations in the voltages of the filament and plate batteries cause a gradual drift in the zero reading of the galvanometer which measures the amplified current. Among the various amplification circuits tried, a two-tube balanced circuit described by Dubridge[3] has been found most satisfactory. When the circuit is properly balanced, variations of battery voltages do not affect the galvanometer and the measurements are thus more reliable. The circuit and the method of balancing are essentially the same as given by Dubridge and hence are not described here.

Osram electrometer triode tubes have been used in the amplifier circuit. They have a very high grid input resistance equal to 10^{16} ohms. On account of this very good grid insulation greater amplification can be achieved by using high grid leak resistances. Some difficulty was experienced in preparing suitable grid leak resistances high enough to take full advantage of the grid insulation of the valves. Resistances of the order of 10^8 ohms are usually made with xylol-alcohol mixtures enclosed in soft glass tubes with sealed-in platinum electrodes or by drawing Indian ink or lead pencil lines on paper or unglazed porcelain. The authors have tried all these and found them unsuitable due to residual and variable polarisation. The material finally employed is colloidal graphite. It forms a tenacious coating on glass, the resistance of which depends on the density and the thickness of the film.

A piece of pyrex rod about 8 mm. in diameter and 6 cm. long is ground for a space of few millimetres at each end by holding a piece of emery paper against the rod as it is rotated and a narrow longitudinal grinding is then made along the length. Fairly concentrated aqueous solution of colloidal graphite is applied on the ground portions near each end, of the rod. Brass caps with projecting wires for leads are then cast on the ends and a concentrated dispersion of colloidal graphite is then brushed on these caps and the rod down for a few millimetres. The fine longitudinal grinding is then brushed with a very dilute aqueous solution. In order to obtain adhesive and durable films the glass surface should first be carefully cleaned and dried in warm air. The colloidal graphite films function best after being baked at a sufficiently high temperature which ensures the removal of all moisture. The resistances are finally dipped in glyptal lacquer and allowed to dry. Tests made on these resistances indicate that they are free from polarisation, and have also a negligible temperature co-efficient.

As the amplification is very great it is necessary to screen the amplifier thoroughly. In this case the photo-electric cell with the amplifying valves and grid leak resistances is placed in a heavy cast-iron cylinder for the purpose of cutting out electrical and magnetic disturbances. The cylinder was then evacuated by means of Cenco HyVac pump. This evacuation removes any film of moisture from the valve surfaces and improves the insulation, resulting in a marked improvement in the performance and considerable increase in sensitivity. The amplification circuit so constructed was highly sensitive and steady.

The mechanical parts have been described in detail in the earlier paper. A scanning slit of adjustable width can be moved across the length of the spectrum by a micrometer screw worked by a divided drum head. The rotation of the drum head through each division displaces the slit through 0.005 cm. But the drum can be worked at smaller intervals. The light from the scanning slit is deflected by a right-angle prism and reaches the photo-cell. A sensitive galvanometer is fed with the amplified current and the deflection of the galvanometer is a measure of the current. If light from successive points in any absorption line is allowed to affect the photo-electric cell, the corresponding deflections of the galvanometer are proportional to the intensity at those points in the spectral line. The resolving power of the instrument depends on the width of the scanning slit which was kept sufficiently narrow.

EXPERIMENTAL

A 20-foot concave grating spectrograph in Eagle mount was employed in the photographic method. The photographs are made in the third order, giving a dispersion of 0.9 Å per mm. in the region 5100 to 5200 Å. Since stray radiations due to reflection and scattering by the optical parts are a troublesome source of error in this type of work, special precautions are taken to reduce it to a minimum. All the inner parts are painted dull black and several diaphragms are mounted inside so that there is no chance for any light to be reflected into the spectrum from the inner walls of the spectrograph. A double monochromator which allows only the small required region of wavelengths is used in front of a slit of the spectrograph. This device reduced the scattered light to the minimum. As the monochromator filtered out the other regions of the spectrum, overlapping of the different orders was also overcome by this device.

The Sun's image is formed by the 13-inch object glass of the Observatory fed from an 18-inch siderostat. The diameter of the image is about 60 mm. The Sun's image is formed on a plate in front of the vertical slit of the double monochromator. On this plate concentric circles were inscribed to facilitate accurate guiding of the Sun's image which was kept concentric with the circle. In order to obtain spectra from different points of the Sun's disc a series of small holes are drilled along a horizontal diameter of the circle and their positions are accurately measured. By displacing the slit plate horizontally so as to bring any of these holes exactly central on the slit of the monochromator, Sun's image also being displaced to be concentric with the inscribed circles, spectra would be obtained from different points on the Sun's disc.

A step wedge was used to record the standardising spectra in the photographic method. The wedge was always placed in front of the plate for which position it was also calibrated. All the spectra on any one plate had identically the same exposure. The necessary precautions have been adopted in the process of development. The plates were microphotometered with the Cambridge photoelectric microphotometer of the Observatory. The densities on the plate were converted into the intensities with the aid of the calibration marks.

In the measurements with the direct-reading instrument a glass littrow spectrograph giving a dispersion of 4.4 Å per mm. has been used. All precautions necessary to minimise scattered light were observed. But the monochromator was not employed with this method. The rest of the arrangement is the same as in the other method. The background in the neighbourhood of the b_1 line gives a galvanometer deflection of about 25 cm. with the scale at a distance of 1 metre. The drum head is set at successive intervals and the galvanometer deflection is noted in each position. 4 to 5 Angstroms on either side of the centre of absorption line, until the intensity reaches the background, are thus covered. Where faint absorption lines are present, observations are made at closer intervals. Knowing the dispersion of the spectrograph and the pitch of the screw, the drum readings can be converted into wavelengths. The galvanometer deflections plotted against the wavelengths give the intensity distribution in the spectral line.

By the photographic method four separate measurements are made and the mean values are reported. With the direct-reading instrument more observations (eight) could be made on account of the ease of operation ; the mean value is adopted. Observations were taken only under conditions of good sky. By the photographic method measurements were made upon the 3 lines at the centre of the sun's disc, equatorial and polar limbs and at other points across the disc. The studies by the second method were confined to the centre of the sun's disc.

RESULTS

(*a*) *Photographic Method.*—The intensity distributions in the b_1 line ($\lambda=5183.62$) of magnesium at the centre of the sun's disc and the equatorial and polar limbs are presented in Table I. The intensity at every point is expressed as a percentage of the background, which is chosen from a point free from absorption near the line. The absorption in the line is not symmetrical about the centre. The readings given in the table correspond to the mean of the intensities at equal distances on either side from the centre of the line. The distance from the centre is expressed in arbitrary units chosen for convenience. In the estimation of intensities faint absorption lines on the photometric trace are smoothed out.

TABLE I

Distance from the centre	Intensity at the centre of the sun's disc	Intensity at the equatorial limb	Intensity at the polar limb
0	15	21	23
10	25	35	36
20	35	46	46
30	43	53	54
40	51	60	60
50	57	65	65
60	63	68	69
70	67	73	74
80	71	76	78
90	75	79	81
100	78	81	84
110	81	84	86
120	83	86	88
130	85	88	90
140	87	90	92
150	89	92	94
160	91	94	95
170	94	96	95
180	96	97	97
190	96	98	98
200	98	98	98

The absorption is greater at the centre of the sun's disc than at the limbs. But it is evident that there is little difference between the equatorial and polar limbs. The distribution of intensity in the b_1 line at the limb and the centre is plotted in Fig. 1.

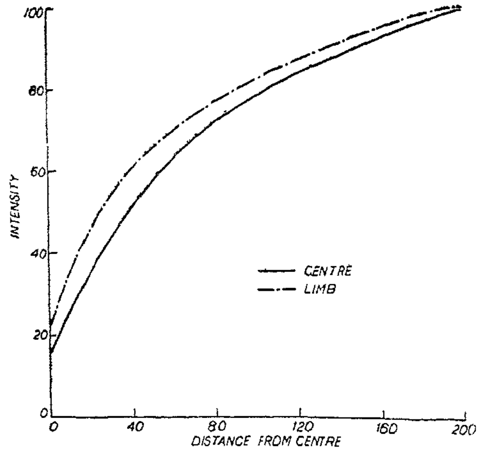

FIG. 1
Distribution of intensity in the b_1 line

The profiles of the lines, $\lambda = 5183.62$, 5172.70 and 5167.33 have been studied at the centre of the disc, the limbs and at four other points on the disc. Every line shows a progressive decrease in absorption as we proceed from the centre of the disc to the limb. The intensity distribution tables corresponding to different points on the sun's disc are not presented, as in the present state of the theoretical knowledge of absorption the equivalent width is more important than the actual profiles. The value obtained for the equivalent width of any line depends to a certain degree on the point to which the extreme extent of the line is judged to stretch. Care has been taken to estimate the extent of the wings as accurately as possible. Table II gives the equivalent width of $\lambda = 5183.62$ Å line at different points across the disc. The distance of the point from the centre is expressed as a fraction of the radius of the sun's image.

TABLE II

$\lambda = 5183.62$

Distance from the centre	Central intensity (% of background)	Equivalent width	NHf
0.00	15.5	1.46	4.90×10^{16}
0.36	18.7	1.45	4.84
0.55	19.0	1.40	4.51
0.70	18.9	1.42	4.64
0.96	20.6	1.34	4.13
0.98	24.2	1.17	3.20

TABLE III

$\lambda = 5172.70$

Distance from the centre	Central intensity (% of background)	Equivalent width	NHf
0.00	16.2	0.96	2.13×10^{16}
0.36	19.0	0.91	1.91
0.55	19.5	0.89	1.83
0.70	19.3	0.87	1.75
0.96	21.2	0.85	1.67
0.98	24.8	0.80	1.48

Tables III and IV are similar to Table II but correspond to the lines 5172.70 and 5167.33 Å. The equivalent width which may be considered to be a measure of the total absorption diminishes from the centre of the disc to the limb.

TABLE IV

$\lambda = 5167.33$

Distance from the centre	Central intensity (% of background)	Equivalent width	NHf
0.00	16.5	0.68	1.07×10^{16}
0.36	18.9	0.66	1.01
0.55	19.6	0.64	0.95
0.70	19.9	0.63	0.92
0.96	22.0	0.60	0.83
0.98	24.9	0.56	0.73

Unsold has derived the formula that in the case of absorption lines where the Doppler broadening is small the equivalent width is given by

$$W = \frac{\pi e^2}{mc^2} \lambda_0 \sqrt{\frac{2\pi}{3}} \sqrt{NHf} \qquad \ldots \qquad (1)$$

where W is the equivalent width, λ_0 is the wavelength at the centre of the absorption line, N is the number of absorbing atoms per c.c., f is the oscillator strength for the particular line and H is the height of the atmosphere. If the Doppler broadening is large enough to predominate to such an extent that radiation damping may be neglected altogether, the equivalent width is given by

$$W = \frac{\pi}{mc^2} \lambda_0^2 \, NHf. \qquad \ldots \qquad (2)$$

Neither of the equations correctly represents absorption lines in the solar spectrum where Doppler broadening is neither too large nor negligible. Where both types of effects are present, equation (1) gives the upper limit and (2) the lower limit of the number of atoms. The NHf values presented in Tables II, III and IV are calculated from equation (1) and hence represent the upper limit. From the equivalent width of any line at different points on the disc it is possible to calculate the density of atoms giving rise to the line at different heights in the sun's atmosphere, if f, the oscillator strength, is known. For the magnesium line, f has not been theoretically evaluated. So no attempt has been made to calculate the actual densities.

The sum rule of Burger and Dorgelo predicts for the intensity of the $M_{//}$-b lines, the ratio of 5 : 3 : 1. According to equation (1) there is direct proportionality between W and $\sqrt{NHf}$. For all the lines in a multiplet the thickness of the reversing layer, H, is the same. The value of Nf shall be proportional to the multiplet intensities. If, therefore, the square-root law is to hold, the observed total intensities (*i.e.*, the equivalent width) should be in the ratio of

$\sqrt{5}$: $\sqrt{3}$: 1. The ratio of the total intensities at the centre and the limb are shown in Table V. They do not correspond to the square-root law.

TABLE V

Ratio of Total Intensities

	b_1	b_2	b_3
Centre	1.15	1 41	1
Limb	2.09	1.43	1
Ratio of $\sqrt{5}$: $\sqrt{3}$: 1	2.24	1.73	1

(b) *Direct-Reading Method.*—The distribution of intensity in the b_1 line, as measured by the direct-reading method, is given in Table VI. The distances from the centre on each side (*i.e.*, increasing and decreasing wavelength) are expressed in terms of the drum readings.

TABLE VI

Increasing Wavelength		Decreasing Wavelength	
Distance from the Centre	Intensity	Distance from the Centre	Intensity
0	17.0	0	17.0
1	28.1	1	24.3
2	39.1	2	37.8
3	50.8	3	51.1
3½	54.2	4	66.5
4	59.2	5	78.2
4½	63 0	6	81.9
5	74.5	7	84.1
6	84 7	8	85.6
7	88.3	9	87.2
8	88.8	10	87.4
9	86.5	10½	85.1
10	84.7	11	88.5
10½	84.9	12	92.7
11	87.3	13	94 7
12	90.6	14	95.1
13	94.0	15	90.8
14	95 5	15½	86.5
15	97.4	16	90.1
16	98.9	17	96.1
—	—	18	99.7

The profile of the line is plotted in Fig. 2. The asymmetry of the line is seen clearly in the figure. For calculating the equivalent width the other absorption

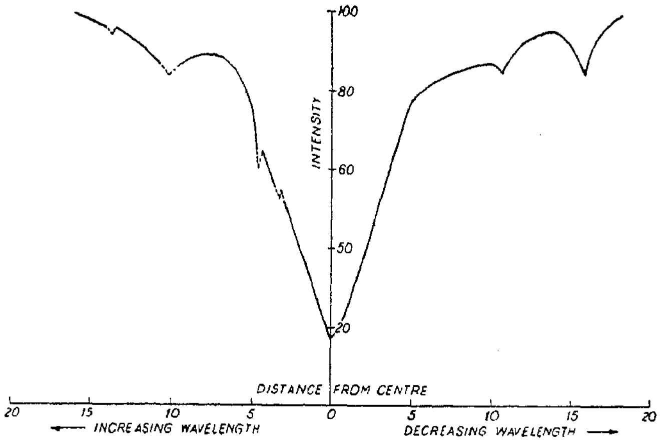

FIG. 2
The Profile of the line

lines seen in the graph are smoothed out and the area within that curve is computed. This gives an equivalent width of 1.63 which compares well with that obtained by the other method. The dispersion of the spectrograph used with the direct-reading instrument is smaller than that employed in the photographic method. Better agreement can be secured by using a spectrograph of higher dispersion with the direct-reading photometer. The detailed distribution in b_2 and b_3 lines is not given here but the equivalent widths calculated from the data are presented in Table VII.

A comparative table giving the equivalent width and central intensity obtained for the three lines by the authors and other workers is given below.

TABLE VII

Observer	5183.6		5172.7		5167.3	
	C. I.	E. W.	C. I.	E. W.	C. I.	E. W.
Kerff[4]	15	1.06	16	0.84	17	0.63
Plaskett[5]	16	1.54	16	1.08	—	—
Righini[6]	15	1.55	16	1.35	—	—
Allen[7]	11	1.60	12	1.20	16	0.75
Photographic method	16	1 46	16	0.96	17	0.68
Authors *(Direct-reading method)*	17	1.63	18	1.02	19	0.76

C. I. = Central Intensity expressed as percentage.
E. W. = Equivalent Width.

The authors have used a double monochromator besides adopting the other usual devices to minimise the scattered light. Spectrograph used in the photographic method is of a high dispersion. It can, therefore, be taken that the results of the authors are more accurate than those obtained by other workers.

The measurements by the direct-reading method illustrate the efficiency and dependability of the apparatus for studying the intensity distribution in the spectral lines. The use of the symmetrical balanced amplifier has overcome the tendency of zero drift and rendered the observations quite reliable. The accuracy of the measurements is as good as that by the method of photographic photometry. The labour involved in that method is saved and observations may be made with considerable ease and quickness. It is proposed to study the profiles of the strong Fraunhofer lines across the sun's disc and in sunspots with this instrument.

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