

Kodakikanal Observatory.

BULLETIN No. CIX.

PHOTOMETRIC STUDY OF THE LINES OF HYDROGEN AND OF CALCIUM IN THE FRAUNHOFER SPECTRUM AT DIFFERENT POINTS OF THE SUN'S DISC,

BY

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SUMMARY.

By means of photographic photometry, the contours of several strong lines in the sun's spectrum have been obtained for various points of the sun's disc between the centre and the limb, and the equivalent widths have been derived from the contour curves. The lines studied were $H\alpha$, $H\beta$, $H\gamma$, $H\delta$, the H and K lines of ionised calcium and the 4226 line of neutral calcium.

It is found that the residual intensities in every part of all the lines studied are greater as the limb is approached than at the centre of the disc. This is consistent with our previous knowledge of the tendency of the wings of lines to disappear towards the sun's limb, but the common appearance of lines becoming wider at the limb is partly due to the relative insensitiveness of the eye to the faint wings, for actually both in the core and in the wings the residual intensity is always (for the lines studied) greater towards the limb.

The residual intensities, equivalent widths and corresponding number of atoms lying above 1 cm^2 of the sun's surface are given for different points on the sun's disc in Tables I to VII.

It is of interest to compare the effects of the greater inclination to the vertical of the path through the atmosphere for the case of terrestrial lines produced by the earth's atmosphere, with the limb effect for solar lines. Using 9 lines of the B band due to terrestrial oxygen it was confirmed that their equivalent width increases proportionately to the square root of the number of absorbing molecules, the residual intensity in the lines being decreased at all points of the contour with increasing zenith distance. In the sun the effect is in the opposite direction as the inclination of the path through the reversing layer increases (as occurs towards the limb), and the difference is due to the fact that near the limb of the sun the effective level of the photosphere is higher than at the centre of the disc, whereas in the case of terrestrial lines the background of continuous spectrum is unchanged for both high and low sun.

The change in contour of solar lines as the limb is approached is the combination of two opposite effects, namely (1) an increase in the number of effective atoms due to the greater length of path when it is inclined to the vertical, tending to strengthen the line and increase its equivalent width, and (2) a decrease in the number of atoms due to the fact that the effective level of the photosphere is higher at the limb, tending to weaken the line and decrease its equivalent width. The first effect can be allowed for from geometric considerations so that the second effect can be measured from the changes in the contours towards the limb. Hence we have derived the concentration of atoms at different levels in the sun's reversing layer as given in Table X.

The electron pressure derived from the ratio of neutral to ionised atoms, is about 2×10^{-6} atmospheres at all the levels considered.

(375)

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All the Fraunhofer lines in the solar spectrum are not equally dark at all points of the sun's disc. It is well known that the contours of the Fraunhofer lines are not identical all over the sun. The Fraunhofer lines become wider near the limb of the sun although the width of the Fraunhofer lines does not appear to change near the limb. As will appear later in this bulletin the difference in the contours of the Fraunhofer lines as the limb is approached are largely due to the change in the effective level of the sun's photosphere. The photometry of absorption lines enables the number of absorbing atoms to be determined. Hence it is to be expected that a photometric study of the contours of the Fraunhofer lines at different points of the sun's disc will in consequence of the above mentioned change in the effective level give a measure of the number of atoms lying above the different levels and consequently also give the density between the different levels which are available for study. From this point of view photometric measurements have been made at the Kodaikanal Observatory of the lines of hydrogen and of calcium in the sun's spectrum from different points on the sun's disc the results of which are reported in this bulletin.

Many observers have made photometric studies of the lines of hydrogen and of calcium in the Fraunhofer spectrum and it will have been measured not only at the centre of the sun's disc but also at other points on the sun's disc. It is well known that the contours of the Fraunhofer lines are not identical all over the sun's disc. The Fraunhofer lines become wider near the limb of the sun although the width of the Fraunhofer lines does not appear to change near the limb. As will appear later in this bulletin the difference in the contours of the Fraunhofer lines as the limb is approached are largely due to the change in the effective level of the sun's photosphere. The photometry of absorption lines enables the number of absorbing atoms to be determined. Hence it is to be expected that a photometric study of the contours of the Fraunhofer lines at different points of the sun's disc will in consequence of the above mentioned change in the effective level give a measure of the number of atoms lying above the different levels and consequently also give the density between the different levels which are available for study. From this point of view photometric measurements have been made at the Kodaikanal Observatory of the lines of hydrogen and of calcium in the sun's spectrum from different points on the sun's disc the results of which are reported in this bulletin.

The spectrograph employed was the large grating spectrograph of the Observatory which has been described elsewhere³. Briefly this spectrograph uses a large plane grating and it can be used with a slit of all lengths of 13½ feet lies at an angle of about 60° to the collimator. The dispersions of the spectrograph in the region used in this research were as follows —

H α (1 1)	11 11 11
H β (3 1 1)	11
H γ ()	11
H δ ()	11
H & K ()	11

Special care was taken to reduce the internal reflection within the spectrograph by a treatment of the possible of internal reflection. Spectrograms have been obtained using a Michelson plane grating and also using a Rowland plane grating. With the Michelson grating it was necessary to cut down both the width and the length of the ruling in order to obtain the best definition. The results from the two gratings have been taken systematically and the averages for the two have been taken.

The sun's image was formed by a lens (lens loaned to the Observatory by the National Observatory, Hyderabad) fed from an 18 inch siderostat. The diameter of the sun's image was 14.4 mm.

1. *Phil. Mag.* 11 870 1931
 2. *Univ. of Astr. Physik* 1 111 1931
 3. *Munster and Houtgast / f. Astr. Physik* 1 81 1936
 4. *Phil. Mag.* 11 81 1936
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 99. *Phil. Mag.* 11 81 1936
 100. *Phil. Mag.* 11 81 1936

The sun's image was formed on a plate which could be displaced horizontally immediately in front of the vertical slit of the spectrograph. On this plate concentric circles were inscribed to facilitate accurate guiding of the sun's image which was kept concentric with the circles. In order to obtain the spectra from different points of the sun's disc, a series of small holes had been drilled along a horizontal diameter of the circles, and their positions relative to the circles accurately measured. By displacing the slit plate horizontally so as to bring any of these holes exactly central on the slit of the spectrograph, the sun's image being also displaced to be concentric with the inscribed circles, different points on the sun's disc from the centre of the disc to the limb could be photographed. Generally, eight different points between the centre of the disc and the limb were obtained on the same photographic plate, the point nearest the limb being as close to the limb as could be accurately measured and maintained.

The standardising spectrum for photometry was obtained on the same plate as the spectra to be studied and with identical exposures. In order to ensure uniform illumination along the whole length of the slit for the standardising spectrum, the object glass was temporarily removed so that parallel light from the object fell on the slit, in front of which was placed a calibrated step wedge. As a check, a standardising spectrum was also obtained by means of a step wedge immediately in front of the photographic plate. So that the standardising spectrum could have suitable density with the same exposure as the spectra to be measured, it was necessary to obtain the former with the first or second order spectrum when the latter were obtained with the second or third or higher respectively.

The photometric measurements were made with the Cambridge pattern microphotometer which, after the necessary exposures and being guided, was found to give reliable measurements when proper precautions are taken. The effective width of the photometer slit was about 0.005 \AA so that the loss of resolving power in the photometer was insignificant.

No reliance can be placed on photographic photometry unless certain essential precautions are taken. In making the photometric studies reported on in this bulletin, the two following precautions were rigidly adhered to. First, equal exposures were given to the standardising spectrum and those to be measured photometrically, in comparison with it. The standardising spectrum was exposed on the same plate which was developed with a bath in order to minimise the Elford effect. Secondly, the standardising step wedges were calibrated under exactly the same conditions as those in which they were used. This is most important at any rate for the type of wedge which has been used in this investigation. The wedges used were made by suitably exposing strips of a photographic plate. Photographically prepared wedges have the advantage that they can be made of sizes and densities to suit the object in view, but they have one great disadvantage in their graininess. This graininess introduces a very serious difficulty in their use. It is well known that the density of a medium depends on the optical arrangements when it is used. A wedge whose density values have been measured in one instrument cannot be used with these values in another instrument, nor used in another position in the same instrument. It was found, for instance, that when a wedge was used immediately in front of the photographic plate it gave entirely different densities from those when the same wedge was used in front of the spectrograph slit. This effect is considerable for photographically prepared wedges. The photographically prepared wedges used in this investigation were standardised in two ways for each optical arrangement in which they were used. One was by means of perforated screens with known ratios of the apertures of the perforations, and the other was by comparison with standard Ilford wedges used under conditions of the perforations, and the other was by comparison with standard Ilford wedges used under conditions similar to those for which the maker's certificate was obtained. The values obtained in these two ways were consistent with each other. Two step wedges were used, each with 10 steps ranging from clear glass to the greatest density which was found necessary. One step wedge was used immediately in front of the photographic plate and the other was used immediately in front of the slit of the spectrograph. In order to illustrate the

of the two wedges in the different positions the values of their transparency for a wave length of 1100 Å are given in the following table.

TABLE I TRANSMISSIONS OF SIMILAR STEEL WEDGES FOR $\lambda = 1100$

Wedge No.	Wedge thickness in cm	Transmission
1	100	9.3
2	87.7	89.3
3	81.7	90.8
4	63.1	41.9
5	44.1	1
6	31	14.4
7	13	9.1
8	1.1	1

If the two wedges referred to had been used in similar position their transmission would have been similar (although not identical) for they were constructed independently of each other but the values show how different are their effective transparencies due to their different positions in the different wedges. Yet in the result obtained there was satisfactory agreement in the content of the transmission wedges in these two different positions.

The theory of the formation of absorption lines has been formulated many times. We shall use the method of Unsöld⁴ which we find to deduce the number of absorbing atoms in tellurium plates. He made use of the value of the selective scattering coefficient given by Von Laue from the theory of scattering by bound electrons namely

$$\sigma = \frac{2\pi^2 e^2}{3m^2 c^4} \frac{\lambda^2}{(\lambda - \lambda_0)^2} N f \tag{11}$$

where σ is the scattering coefficient per cm length

λ is the wavelength of the centre of the absorption line

N is the number of absorbing atoms per cm³

f is the oscillatory strength for the particular line

and the remaining terms have their usual significance.

The above expression only applies in the absence of Doppler broadening due to the motion of the atoms in the line of sight in the absence of collisions between the atoms which is true for the absence of the Stark effect due to interatomic electric field. In the presence of Doppler broadening the expression may only be strictly applied to the wings of the absorption line which are relatively unaffected by the Doppler displacements which come into consideration.

⁴ Unsöld, Z. f. Physik, 44, 33, 19-6, Z. f. Physik, 46, 1-13

No exact expression has yet been given for the contour of an absorption line produced by an atmosphere of finite thickness. The best that can be done is to use approximations made under simplifying assumptions. Schuster showed that if we assume a definite photospheric surface at the base of a homogeneous scattering atmosphere, the contour of the resulting absorption line will be given by

$$r = \frac{1}{1 + \sigma H} \quad \dots \dots \dots (2)$$

where r is the ratio of the intensity in the line to the intensity of the photospheric radiation,
 σ is the scattering coefficient of the atmosphere,
and H is the height of the atmosphere.

Substituting Unsöld's expression for the scattering coefficient, it will be seen that the contour of an absorption line broadened by scattering will be of the form

$$r = \frac{1}{1 + \alpha/(\lambda - \lambda_0)^2} \quad \dots \dots \dots (3)$$

where $\alpha = 2\pi e^2 \lambda_0^2 N f H / 3m^2 c^4$.

The actual contours found for Fraunhofer lines do not follow the above form for r . Neither the contours which are published in this bulletin nor those which have been published by others resemble that given by the above equation (3). Unsöld and others have sometimes interpreted their results by taking the widths of lines at a certain value of r . This corresponds to selecting a point on the actual contour where it is cut by the theoretical contour given by (3). Naturally, the results obtained will depend on the value of r selected.

Also, the intensity at the centre of an absorption line predicted by equation (3) is not verified in the actual measures of absorption lines in the sun and stars. According to equation (1) the scattering coefficient at the centre of the line, where $(\lambda - \lambda_0)$ is zero, is infinitely large and therefore the absorption of photospheric radiation should be complete, making the central intensity zero. Actually it is found that the central intensities in Fraunhofer lines are considerable, being of the order of at least 10 per cent even for strong lines. It should be mentioned, however, that since the work published in this bulletin was completed, Thackeray,⁵ using a monochromator in front of the slit to reduce scattering in the spectrograph, has found much smaller central intensities particularly for the resonance line of neutral calcium, λ 4226. If the results of Thackeray are correct, they remain difficult to explain. Some attempts have been made by Woolley⁶ and by Strömgren⁷ to interpret the appreciable intensities found at the centre of Fraunhofer lines as fluorescence effects in the manner suggested by Rosseland. Whether these interpretations are well based or not, it is difficult to see why the calcium line 4226 should have the lowest central intensity as found by Thackeray. Whatever may be the processes in stellar and solar atmospheres which cause appreciable intensities in other lines, it is not easy to see why λ 4226 line should be an exception.

The evidence of the central intensity in the terrestrial lines in the Fraunhofer spectrum should not be neglected. It is shown later in this bulletin that the lines in the Fraunhofer spectrum which are most certainly conditioned solely by pure scattering are lines in the terrestrial bands due to absorption by gases in the earth's atmosphere. Take for instance the B band due to molecular oxygen. If any lines in the Fraunhofer spectrum should have the zero central intensity predicted by the scattering theory, they are lines such as those of the B band, the photometric results for which are given in a later section of this bulletin. Anticipating the results there given, we may state that the central intensities of the lines examined are of the order of 40 per cent of the sun's continuous spectrum. This deviation from the predicted zero value is so considerable that there is no possibility of explaining it as due to defective experimental conditions such as internal scattering within the spectrograph.

Notwithstanding the above mentioned discrepancies between the contours actually found in the Fraunhofer spectrum and that expected from the theory of scattering considerably more confidence has been placed in the latter than in the equivalent widths of absorption lines than in the deductions from actual contours. The equivalent width of an absorption line is defined as the width of continuous spectrum which would contain the same energy as the total energy absorbed in the line. It is expressed by $\int (1-\tau) d\lambda$. In the case where the Doppler width is small the equivalent width of a line is readily obtained from equation (3) and is given by

$$W = \frac{\pi e^2}{m^2} \lambda \sqrt{\frac{2\pi}{3}} \sqrt{V f H} \quad (4)$$

If the Doppler width is large enough to be the principal agent in broadening an absorption line the equivalent width is given by⁸

$$W = \frac{\pi}{mc^2} \lambda^2 N f H \quad (5)$$

Actually neither (4) nor (5) corresponds to solar conditions for the wide lines which we are considering in this bulletin. Under actual conditions where the Doppler widening is not negligible but not large enough to be the controlling factor we can only regard (4) as an expression for the upper limit of $V f H$ and (5) as the lower limit. It must also be noted that Unsold has shown⁹ that for the oscillatory strengths f terms which he has designated by f should be used. He has calculated the f values for H α , H β and H γ . For resonance lines such as the H & K lines of Ca and the 4226 line of Ca the f value are the same as the oscillatory strengths.

The line of the B band in the Fraunhofer spectrum have been variously used¹⁰ for the verification of the expression (4) for the equivalent widths of absorption lines as a function of the number of absorbing atoms when the lines are produced by pure scattering. In the case of Fraunhofer lines due to absorption in the earth atmosphere the Doppler widening, the effect of atomic collisions and the Stark effect can all be assumed to be negligible and we have in these lines an ideal case of absorption lines produced by pure scattering. The number of effective atoms varies with the altitude of the sun. All that is necessary for the tests is therefore to make photographic measurements of spectrum photographs taken at high and low altitudes of the sun preferably on the same day. As the previous results of different observers were not in exact agreement measures of some of the lines in the B band have been made at the Kodakanal Observatory in view of the importance of the matter. Photographs were taken of the B band with the sun at a zenith distance of 72 and at a zenith distance of 23 each with its own standardising spectrum for photometry. The lines chosen for measurement were the nine lines from $\lambda\lambda$ 687.7 650 to 687.0 959. Two photographs were taken at low altitude for zenith distances up to 72 the lengths of the paths through the air and consequently the number of absorbing atoms may be assumed to be proportional to the secant of the zenith distance. It is sufficient to quote the mean for the above 9 lines

Ratio of equivalent width to wavelength sun	1.4
Ratio of equivalent width to distance	1.0

This result shows that the proportionality of the equivalent width to the square root of the number of absorbing atoms is actually realised when the lines are conditioned by pure scattering. Although the results confirm the scattering theory in showing that the equivalent widths of the lines of the B band are proportional to the square root of the number of scattering atoms yet the central intensities in these lines are very different from the zero value predicted by the theory of scattering. With high sun the central intensities of the 9 lines in a used were 42 per cent of the continuous background and with low sun 76 per cent. Since absorption in the earth's atmosphere fulfils almost ideally the conditions required for the application of the theory of absorption by scattering and yet shows appreciable central intensities in the absorption lines it would seem that the central intensities in the Fraunhofer line may be due to the defects of the scattering theory rather than to obscure physical processes in the reversing layer.

Unold, St. and Lloyd, *Z. f. Astrophysik*, 1, 314, 1930

Z. f. Astrophysik, 1, 199, 1931

The photometric results for the various lines studied at the Kodakanal Observatory are given below in Tables I to VIII and in figs. 1 to 8, which are the averages from 5 or more plates. Since it was desirable to

TABLE I.—CALCIUM LINE λ 4226.

Residual intensity, Equivalent width, and Number of atoms above 1 cm² of photosphere.

Sin θ *	0	0.14	0.65	0.77	0.86	0.95	0.98
Cos θ	1.0	0.898	0.760	0.638	0.510	0.312	0.199
(λ λ_0) \S							
0	16.0%	18.8%	18.3%	18.8%	19.6%	20.9%	22.1%
\pm 5 \dagger	20.8	22.0	22.7	23.4	24.2	26.2	26.9
\pm 10 \dagger	26.2	27.8	28.3	29.9	31.6	35.1	36.7
\pm 15	31.6	33.8	33.7	36.6	37.2	42.2	44.8
\pm 20	37.7	39.7	38.7	41.0	42.5	47.9	50.9
\pm 25	44.1	45.9	45.6	46.4	47.3	51.9	55.3
\pm 30	50.5	51.1	49.1	51.4	51.6	55.8	59.2
\pm 35	54.5	55.7	53.6	55.3	55.1	58.8	62.3
\pm 40	58.0	59.4	57.1	58.3	58.4	61.4	64.7
\pm 45	60.9	61.9	59.9	61.0	60.6	63.4	66.7
\pm 50	63.2	64.2	62.2	63.3	63.4	65.5	68.6
\pm 60	67.7	68.5	66.6	68.2	67.6	69.8	72.0
\pm 70	72.3	72.6	71.1	73.3	72.0	74.0	75.8
\pm 80	78.4	78.7	76.2	78.0	77.9	79.1	79.3
\pm 90	85.2	82.8	81.5	82.9	83.3	83.8	83.0
\pm 100	87.5	85.1	84.6	86.0	86.3	87.7	86.1
Equivalent width	1.35 A	1.33	1.40	1.35	1.34	1.24	1.21
** NH per cm ²	3.10×10^{18}	3.02	3.35	3.09	3.05	2.64	2.49

* Sin θ = distance from centre of disc expressed in radii.

\S 100 units = 1.57 A, or 1 A = 63.6 units.

\dagger Contours for intermediate points near centre of line were determined but are not here reproduced.

** By formula (4); $f = 2$, \therefore NH = $W^2 \times 10^{18} / 0.587$.

TABLE II -H LINE OF IONISED CALCIUM

Equivalent width, and Number of atoms above 1 cm² of photosphere.

θ	0	0.33	0.65	0.77	0.86	0.91	0.98
ξ	1.0	0.898	0.760	0.638	0.510	0.312	0.199
θ	14.4%	15.4%	16.4%	17.4%	18.6%	21.1%	22.0%
5	19.5	21.1	22.0	23.0	23.6	28.6	30.0
10	24.4	26.7	27.2	29.9	29.6	37.2	38.2
15	28.3	31.4	31.3	34.2	33.4	42.1	41.1
20	32.6	35.2	35.6	38.6	37.0	45.9	49.0
30	41.8	44.2	43.8	47.5	44.3	51.2	71.0
40	51.0	54.0	53.6	56.2	53.7	61.7	91.0
50	59.2	63.2	62.5	63.5	59.6	69.0	90.5
60	66.2	70.3	68.2	69.3	65.6	73.0	74.8
70	76.0	75.7	74.6	75.0	69.5	78.0	78.7
80	81.3	81.5	81.1	83.0	74.3	82.6	82.4
Equivalent width	8.91 A	9.20 A	8.88 A	9.28 A	9.38 A	7.82 A	6.81 A
** NH per cm ²	9.30×10^{18}	9.93	9.25	10.10	10.34	7.17	6.44

* $\sin \theta$ distance from centre of disc expressed in radii.

§ 100 units = 8.25 A, or 1 A = 12.1 units.

† Contours for intermediate points near centre of line were determined but are not here reproduced.

** By formula (4); $t = 1/3$, $\therefore NH = W^2 \times 10^{18}/8.53$.

TABLE III.—K LINE OF IONIZED CALCIUM.

Residual intensity, Equivalent width, and Number of atoms above 1 cm² of photosphere.

Sin θ *	0	0.44	0.65	0.77	0.86	0.95	0.98
Cos θ	1.0	0.898	0.760	0.638	0.510	0.312	0.199
$(\lambda - \lambda_0)$ §							
0	14.0%	15.2%	16.7%	16.9%	18.2%	20.3%	21.2%
± 5 †	18.2	19.0	20.6	21.4	23.2	25.6	28.0
± 10 †	22.0	23.0	24.9	26.2	28.3	31.3	33.6
± 15	25.2	26.2	28.4	30.1	32.6	35.5	38.8
± 20	28.4	29.4	31.8	33.3	36.1	40.8	43.0
± 30	35.2	35.4	37.9	39.2	42.1	47.8	50.8
± 40	42.5	42.6	45.1	46.0	48.3	53.1	57.5
± 50	50.1	49.6	51.8	52.5	54.6	58.9	64.0
± 60	58.2	57.5	59.2	59.6	61.5	64.4	69.5
± 70	66.4	66.2	67.3	67.1	68.1	70.0	74.6
± 80	71.8	72.4	73.8	73.3	71.1	73.1	79.2
Equivalent width	10.77 A	10.74	10.60	10.44	10.09	9.68	8.54
** NH per cm ²	10.85×10^{18}	10.80	10.51	10.20	9.53	8.78	6.83

* Sin θ = distance from centre of disc expressed in radii.

§ 100 units = 8.32 A, or 1 A = 12.0 units.

† Contours for intermediate points near centre of line were determined but are not here reproduced.

** By formula (4); $f = 2/3$, \therefore NH = $W^3 \times 10^{18} / 10.69$.

TABLE IV.—H α LINE.*Residual intensity, Equivalent width, and Number of atoms above 1 cm² of photosphere.*

$\text{Sin } \theta$ *	0	0.44	0.65	0.77	0.86	0.95	0.98
$\text{Cos } \theta$	1.0	0.898	0.760	0.638	0.510	0.312	0.199
$(\lambda - \lambda_0)$ §							
0	25.1%	25.4%	26.4%	26.9%	27.9%	29.0%	29.1%
± 5 †	25.8	26.2	27.3	27.8	28.8	30.0	30.0
± 10 †	28.2	28.4	29.8	30.2	30.9	32.2	32.0
± 15	33.0	33.0	34.4	34.5	35.2	36.1	36.0
± 20	41.4	40.4	42.7	42.2	43.4	43.8	43.8
± 25	51.8	51.0	53.7	53.3	53.9	55.5	55.2
± 30	61.0	60.5	64.4	63.6	65.6	68.6	68.4
± 35	67.0	67.6	70.0	71.1	73.4	79.1	79.6
± 40	70.9	71.2	73.4	75.2	77.9	83.8	86.2
± 45	73.3	73.3	75.4	77.8	80.6	86.6	89.1
± 50	75.2	75.2	76.8	79.4	82.4	88.4	90.9
± 60	78.0	78.1	79.8	82.2	85.1	90.7	93.2
± 70	80.6	80.7	82.6	84.2	86.8	92.2	94.6
± 80	82.4	82.2	83.8	85.8	88.1	93.1	95.0
± 90	83.8	83.8	85.7	87.1	89.6	94.0	95.7
± 100	84.8	84.8	86.8	88.4	90.4	94.8	96.2
Equivalent width 0—105.	1.56 A	1.56	1.47	1.41	1.31	1.13	1.07
Do. 105—388	0.97 A	0.97	0.85	0.75	0.65	0.31	0.24
Total E. W.	2.53 A	2.53	2.32	2.16	1.96	1.44	1.31
Total number of atoms above cm ² of photo- sphere.	12.0×10^{15}	12.0	10.1	8.71	7.20	3.88	3.20

* $\text{Sin } \theta$ = distance from centre of disc expressed in radii.

§ 100 units = 2.22 A, or 1 A = 45.0 units.

† Contours for intermediate points near centre of line were determined but are not reproduced.

** By formula (4); $f' = 7.59, \dots \text{NH} = W^2 \times 10^{15} / 0.536$.

Residual intensity, Equivalent width, and Number of atoms above 1 cm² of photosphere.

Sin θ *	0	0.44	0.65	0.77	0.86	0.95	0.98
Cos θ	1.0	0.898	0.760	0.638	0.510	* 0.312	0.190
$(\lambda - \lambda_0)$ §							
0	24.1%	25.7%	26.6%	27.2%	27.0%	28.5%	29.2%
± 5 †	25.6	26.9	27.6	28.2	28.2	29.8	30.3
± 10 †	28.8	29.9	30.9	31.4	31.0	32.6	33.2
± 15	33.4	34.3	35.3	36.0	35.9	37.0	38.4
± 20	39.2	40.0	41.8	42.8	42.7	44.8	46.6
± 25	45.3	46.0	48.0	49.3	49.6	53.4	56.5
± 30	50.9	52.2	54.1	56.0	56.8	62.7	66.0
± 35	56.5	57.6	60.2	61.4	63.8	69.1	72.9
± 40	60.1	61.3	64.0	64.8	67.9	73.3	77.2
± 50	65.4	66.2	69.2	69.9	73.4	78.9	82.4
± 60	68.6	69.2	72.0	74.0	76.8	83.0	85.7
± 70	71.0	71.2	74.5	76.1	79.0	84.9	87.7
± 80	73.0	73.1	76.4	77.2	80.6	86.5	88.5
± 90	75.0	74.9	77.8	78.9	82.1	87.7	89.2
± 100	76.8	76.8	79.4	80.0	83.4	89.2	90.2
± 120	78.6	79.5	81.4	84.0	84.4	88.8	91.5
± 140	81.6	83.0	82.8	82.5	85.6	90.9	92.1
Equivalent width 0—150.	1.45 A	1.41	1.33	1.25	1.18	0.995	0.90
Do. 150—800	1.81 A	1.70	1.59	1.45	1.34	0.835	0.70
Total W.	3.26 A	3.11	2.92	2.70	2.52	1.83	1.60
Total number of atoms above 1 cm ² of photosphere.	4.04×10^{17}	3.66	3.24	2.76	2.40	1.27	0.97

* Sin θ = distance from centre of disc expressed in radii.

§ 100 units = 1.39 A, or 1 A = 71.8 units.

† Contours for intermediate points near centre of line were determined but are not here reproduced.

** By formula (2); $f' = 0.681$, $\therefore NH = W^2 \times 10^{17} / 2.64$.

TABLE VI.—H γ LINE*Equivalent width, Equivalent width, and Number of atoms above 1 cm² of photosphere*

θ	0	0.44	0.65	0.77	0.86	0.95	0.98
θ	1.0	0.898	0.760	0.638	0.510	0.312	0.193
(θ / θ_0)							
0	28.8%	27.5%	28.3%	28.9%	29.4%	31.6%	34.7%
5	30.6	29.2	29.8	30.9	31.5	33.5	36.7
10	35.0	33.4	34.8	35.4	36.8	38.9	44.0
15	41.2	40.4	41.9	43.5	45.0	48.4	53.4
20	48.0	47.6	48.8	51.4	53.1	58.4	63.6
25	53.9	53.6	55.6	58.4	60.8	66.0	72.6
30	58.4	58.2	60.6	62.8	65.7	71.7	79.8
35	61.3	62.0	63.4	66.0	68.8	74.8	83.2
40	63.6	64.2	64.8	68.2	71.0	76.3	84.7
45	64.8	65.8	66.0	69.3	72.0	77.2	85.3
50	66.2	66.6	67.2	70.2	72.5	78.0	85.7
60	68.4	68.8	69.3	72.4	74.2	79.0	86.7
70	70.9	71.1	71.4	75.0	76.6	80.6	87.8
80	73.6	73.7	73.9	77.2	78.4	82.2	88.8
90	77.0	76.2	76.4	80.0	80.6	83.4	90.0
≥ 100	79.2	79.4	78.8	82.9	83.0	84.5	90.8
Equivalent width 0-105	1.20 A	1.20	1.18	1.09	1.04	0.90	0.70
Do 105-400	0.96 A	0.94	0.98	0.78	0.79	0.60	0.45
Total W.	2.16 A	2.14	2.16	1.87	1.83	1.50	1.15
Total number of atoms above 1 cm ² of photosphere	7.92×10^{17}	7.79	7.92	5.94	5.70	4.00	3.17

* $\sin \theta$ -- distance from centre of disc expressed in radii.

§ 100 units = 1.52 A, or 1 A = 65.9 units.

† Contours for intermediate points near centre of line were determined but are not here reproduced.

** By formula (4), $f' = 0.191$, . . . $NH = W^2 \times 10^{17} / 0.589$.

TABLE VII.—H δ LINE.

Reproduced from the original, showing Equivalent width, and Number of atoms above 1 cm² of photo-sphere.

$\sin \theta$ *	0	0.44	0.65	0.77	0.86	0.91	1.00
λ (Å)	100	0.898	0.760	0.638	0.510	0.31	0.100
$(\lambda - \lambda_0)$ †							
0	31.5%	31.8%	33.0%	34.1%	35.7%	41.0%	41.5%
10	33.1	34.0	35.2	36.9	38.6	44.2	44.2
20	37.7	38.8	40.2	42.0	44.6	51.8	51.4
30	43.2	43.6	45.4	48.2	51.5	61.0	60.6
40	48.7	48.2	50.4	53.8	57.3	68.6	68.6
50	52.0	52.0	54.2	57.8	61.5	73.4	73.3
60	55.2	55.7	57.5	61.2	65.1	76.6	76.6
70	58.0	58.4	60.4	64.2	67.4	79.2	78.7
80	60.4	61.1	62.2	66.4	70.1	81.0	80.0
90	62.4	62.6	64.1	68.2	71.8	82.5	81.6
100	64.4	63.7	65.6	69.4	73.8	83.6	82.5
110	67.2	66.7	68.2	72.0	76.0	84.8	84.4
120	70.1	69.2	70.6	75.0	78.1	86.3	85.4
130	71.4	71.1	72.5	76.3	79.5	86.9	85.8
140	72.6	71.7	73.4	76.9	79.8	86.1	86.3
150	72.8	72.1	73.8	77.9	80.3	86.8	86.1
Equivalent width 0-105.	1.34 A	1.33	1.28	1.16	1.05	0.76	0.81
Do. 105-235	0.58 A	0.59	0.56	0.47	0.45	0.28	0.29
Total W	1.92 A	1.92	1.84	1.63	1.50	1.04	1.10
Total number of atoms above 1 cm ² of photo-sphere	13.4×10^{17}	13.4	12.3	9.6	8.2	3.9	4.4

* $\sin \theta$ = distance from centre of disc expressed in radii.

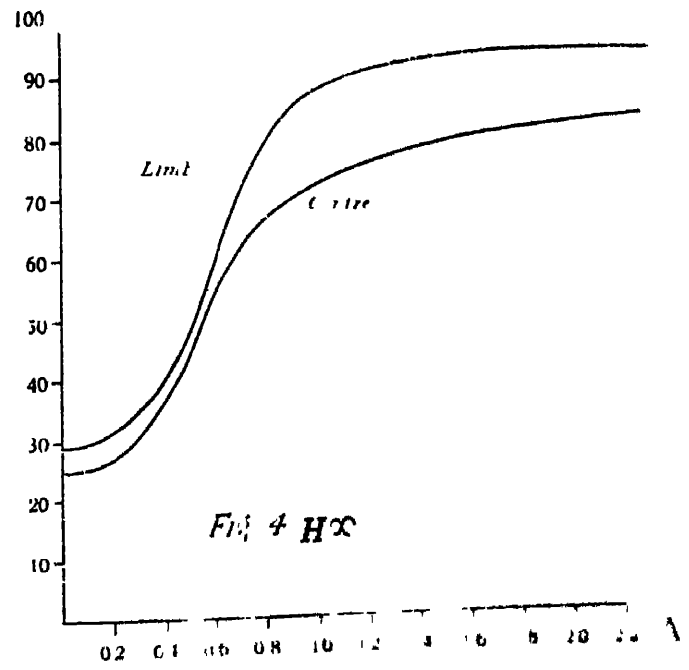
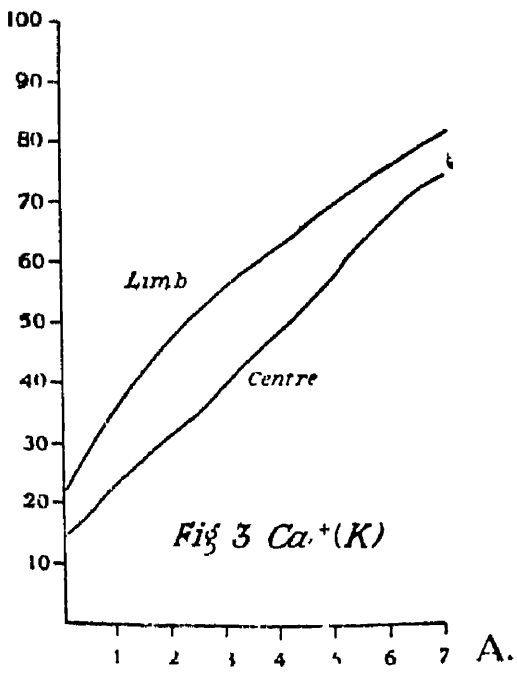
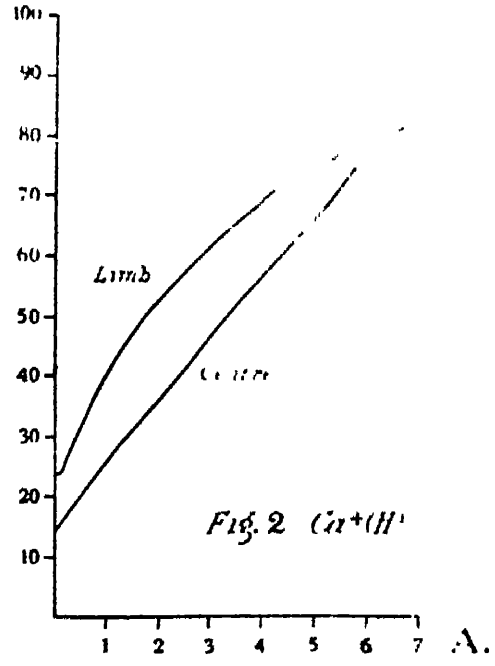
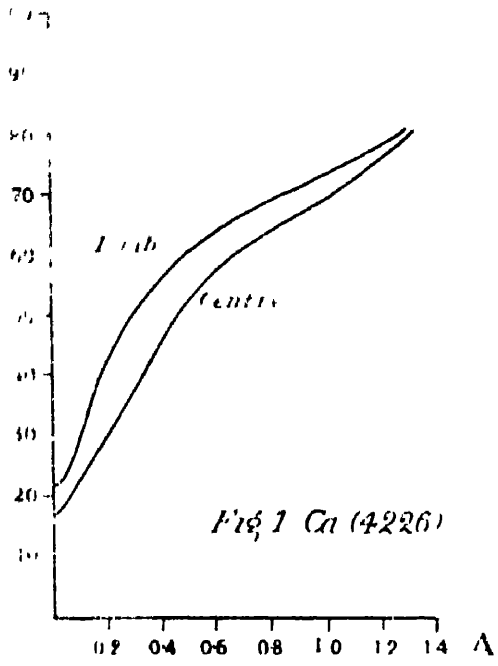
† 100 units = 1.604, or 1 A = 62.3 units

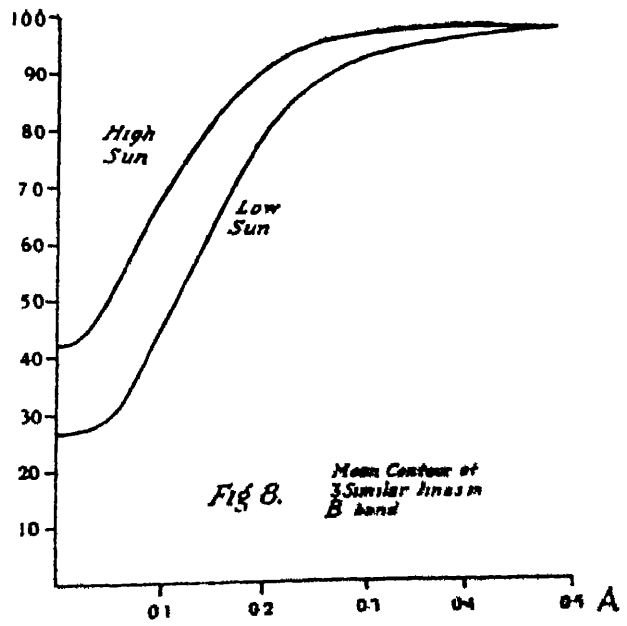
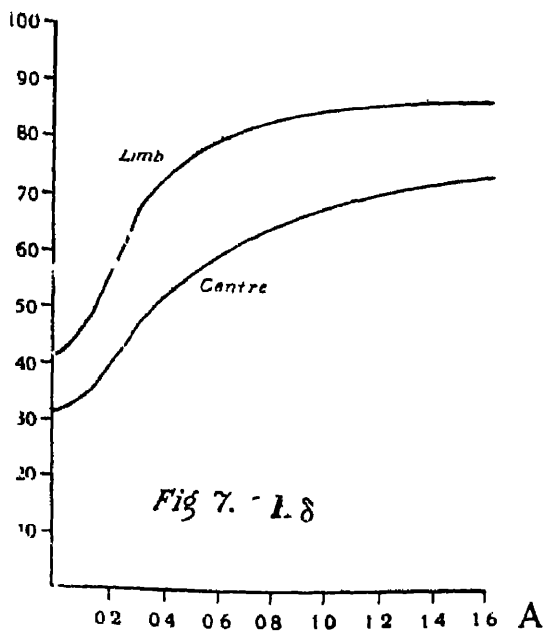
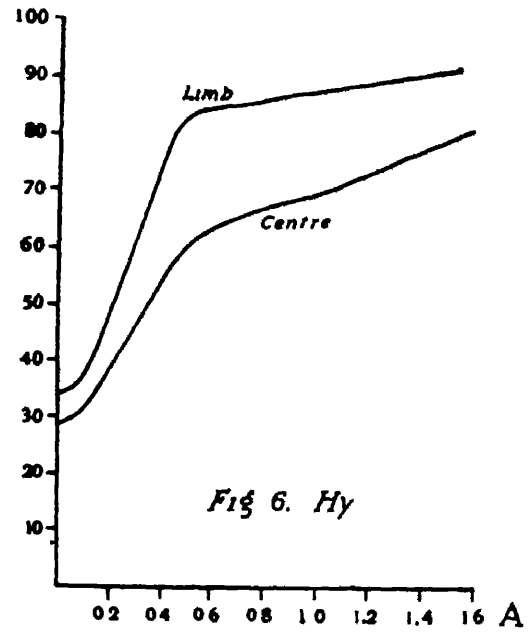
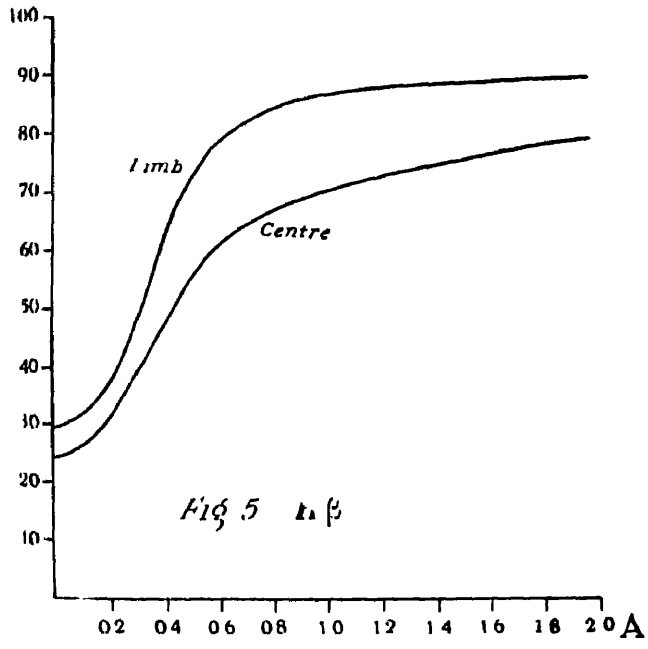
‡ Contours for intermediate points near centre of line were determined but are not here reproduced.

** By formula (4); $f' = 0.1$, $\therefore NH = W^2 \times 10^{17} / 2755$.

TABLE VIII.—MEAN CONTOUR OF 3 SIMILAR LINES IN B BAND.
Residual intensities expressed as percentages of continuous spectrum.

Distance from centre of line (10 units = 0.219 Å).	Secant of Zenith Distance.	
	1.09	3.34
$(\lambda - \lambda_0) \text{ \AA}$		
0	42.1%	26.5%
1	43.5	27.2
2	49.2	28.6
3	57.4	34.0
4	65.0	41.8
5	71.8	49.8
6	78.2	57.2
7	83.0	65.8
8	87.5	73.4
9	91.2	80.1
10	93.4	84.4
11	95.8	88.4
12	97.0	90.4
13	97.8	92.4
14	98.4	94.1
15	98.8	95.5
16	99.2	96.6
17	99.4	97.6
18	99.6	98.0
19	99.8	98.8
20	100	99.7
21	100	99.8
22	100	100





obtain photographs when the sky conditions were as nearly ideal as possible, the plates were used in succession at about the same time of the years 1934 and 1935, and the size of the sun's image was practically identical for all the plates taken. Consequently, the same holed plate in front of the slit as described on page 10 gave identical distances from the centre of the sun's disc for all the plates. The equivalent widths of the lines were obtained from the contour curves by determining the area of the space between the continuous spectrum and the contour curve over the whole width of the line. It should be noted that the value obtained for the equivalent width of these wide lines depend to a considerable extent on the point to which the extreme extent of the lines is judged to stretch, and consequently that it is necessary to estimate the limits of the width of the lines as accurately as possible. This estimation is largely a matter of judgment, especially in those regions of the spectrum which are rich in lines, in which case it is often difficult to decide the limits of the absorption line. In some cases where the red or the violet wing is less confused by foreign lines than the other, it is useful to assume that the real extent cannot be very different on the two sides. The importance of the contribution of the wings to the total equivalent width may be judged from the results given in the tables IV to VII. Although the amount of absorption in the wings is small, the extent of the wings may be so great that the contribution to the equivalent width becomes considerable. Looking at table IV for the $H\alpha$ line, the exact contours are given up to 100 units from the centre of the line, which is equivalent to 2.2 Å. At this point the intensity of the line has risen to 85 per cent. of the intensity of the continuous spectrum. The exact contour of the line beyond this point is unimportant but it is important to fix the total width of the line. It was found to be sufficient to determine this total width of the line independently of the contour of the central portion of the line. The contour of the central portion of the line was determined from a large scale photometric record, i.e., with the bromide paper on which the record is obtained moving at its maximum speed relative to the speed of the plate. As the exact contour in the wings is not important, the extreme width of the wings was estimated from records made with the minimum speed of recording so that a considerable length of the spectrum on each side of the line could be included in the record. Exact contours were thus obtained only for the central portions of the line, and approximate contours used for the wings, the limits of which were determined once for all for each position on the sun's disc from one photograph. No appreciable error in the equivalent widths can be introduced in this procedure. Reverting again to table IV for the $H\alpha$ line, the equivalent width within 2.30 Å from the centre of the line is 1.56 Å but the equivalent width beyond this point amounts to 0.98 Å. In the wings of the line it is not the exact shape of the contour which is important, but rather the great extent of the wing before the feeble absorption shades off into the continuous spectrum.

To derive the number of effective atoms in the sun's reversing layer from the equivalent widths in the above tables we adopt the method of Unsöld. Let us look first at the results for hydrogen. The f' values for the first 3 Balmer lines were calculated by Unsöld namely, 7.59 for $H\alpha$, 0.681 for $H\beta$ and 0.191 for $H\gamma$. Since the results for the higher members of the Balmer series will be neglected in the end, it is not worth while calculating the f' values for $H\delta$, but it has been taken as being of the order of 0.1.

Taking first the values for the centre of the sun's disc we see that as we ascend the Balmer series the values deduced for the number of effective absorbing atoms increase. This is because the conditions of pure scattering are seriously departed from in the sun, the cause being principally the Stark effect which is greater the higher we ascend in the Balmer series. The conditions of pure scattering are most nearly approached in the case of the $H\alpha$ line, and we shall take the values for this line as the nearest approach we can get to the number of hydrogen atoms in the 2-quantum state. Using formula (4), we obtain for the upper limit to the number of hydrogen atoms in the 2-quantum state in the sun's reversing layer the value 12.0×10^{15} atoms per square cm. of the sun's surface. This value being an upper limit there seems to be no good reason for departing from

the chromosphere is negligible compared with the number in the reversing layer, the actual proportion for Ca^+ being, according to Unsöld¹⁵, less than 1 : 10^6 .

TABLE X.—NUMBER OF ATOMS PER cm^3 IN REVERSING LAYER.

Heights above photosphere.	Number of atoms per cm^3		
	Ca	Ca^+	H (2-quantum).
0—136 kms.	11.3×10^9	3.68×10^{11}	6.13×10^9
0—287 kms.	9.05×10^9	3.40×10^{11}	3.61×10^9
136—287 kms.	6.95×10^9	2.55×10^{11}	2.61×10^9
0—600 kms.	5.2×10^9	1.7×10^{11}	2.0×10^9
287—600 kms.	1.6×10^9	0.4×10^{11}	0.2×10^9

It should be noted that the equivalent widths which we have found for the H and K lines of Ca^+ are not exactly proportional to the square roots of their oscillatory strengths, as found by Unsöld for their half widths. Indeed, Unsöld, Struve and Elvey¹⁶ have shown that the ratio of the equivalent widths of the H and K lines would be $\sqrt{2}$ for pure scattering, 2 for the case of Doppler broadening alone, and ~ 1 in the transition region, so that the ratio of their equivalent widths may be anything between 1 and 2. We actually find that the equivalent widths of the H and K lines are in the ratio 1.2, the ratio remaining practically constant across the whole disc. Consequently the number of atoms deduced for the two lines from formula (4) do not agree but are in the ratio $1.2/1.414=0.85$. It is therefore sufficiently accurate for our present purpose to take the mean value for the two lines as the number of Ca^+ atoms in the ground state.

It is well known that Saha's theory of ionisation enables the electron pressure to be calculated from the ratio of ionised to neutral atoms. The equation is¹⁷, in the usual notation, where x is the fraction of the ionised atoms of any element,

$$\log \frac{x}{1-x} = -\frac{5040 I}{T} + \frac{3}{2} \log T - 6.49 - \log P_e + \frac{3}{2} \log \frac{T_1}{T} + \log \frac{1}{4} + \log \frac{\sigma B'}{B}.$$

It seems clear that for T , the effective temperature, we should for our purpose take the effective temperature of the radiation from the centre of the sun's disc, and not from the disc as a whole. This temperature we have taken as 6070° , and for T_1 we have taken, from Chandrasekhar's tables, the mean temperature between the levels considered. For calcium, $I=6.09$, $\frac{\sigma B'}{B}=2$ and we have from the results in Table X, the following values for the ratio of ionised to neutral calcium atoms, giving the accompanying values of the electron pressure:—

TABLE XI.—IONISATION OF CALCIUM IN THE REVERSING LAYER.

Heights above photosphere.	0—136 kms.	136—287 kms.	0—287 kms.	Whole reversing layer.
$x/(1-x)$	3.29×10^2	3.63×10^2	3.40×10^2	3.25×10^2
Electron pressure in atmospheres	2.4×10^{-5}	1.7×10^{-5}	1.9×10^{-5}	2.1×10^{-5}

