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ON THE CHANGE OF WAVE-LENGTH OF THE IRON LINES IN PASSING FROM THE CENTRE OF THE SUN'S DISC TO THE LIMB,

BY J. EVERSHED, F.R.S., AND T. ROYDS, D.SC.

Following on our researches on the displacements of the solar iron lines at the centre of the sun's disc and at the limb, we now give the results of measures of the change of wave-length of some selected lines in passing from the centre of the disc to the limb.

It has been shown in Kodaikanal Observatory Bulletin No. XXXIX that if we select certain lines of iron which in the arc spectrum are not subject to the density shift near the negative pole, and compare them with the same lines at the centre of the sun's disc, a total of 45 lines gives an average displacement of + 0·0094A, whilst near the limb the displacement of the same lines is + 0·0150A, showing a difference of shift, or increase of wave-length, in passing from the centre to a point about one-thirtieth of the radius inside the limb of 0·0056A. The question whether this increase occurs gradually or suddenly as the limb is approached is a crucial one with regard to the hypothesis which ascribes the limb shift to a difference of pressure between the effective regions of absorption at the centre and at the limb ; and the form of the curve representing the change of wave-length between centre and limb should also throw light on the question whether the redward shift at the centre of the disc is due to a downward movement radial to the sun.

In many individual cases the difference of wave-length between centre and limb is much greater than that indicated above, and in others it is less. In the case of the lines at 6301·718 and 6302·709, which were used by Dunèr and Halm in their measures of the solar rotation, the difference exceeds 0·01A. Unfortunately these lines are amongst those which are displaced near the negative pole in the arc, and we cannot state precisely what their displacement is at the centre of the disc. However, for the purpose of this investigation, we have used these lines, and the line at 6280·833, as they are most conveniently situated with regard to the telluric oxygen lines of the *a* group, which form standards of reference from which the change of wave-length in the iron lines may be readily determined in spectra extending across the sun's disc. In addition to these lines in the red, it seemed desirable also to measure some lines in the ultra-violet, which probably represent a much higher level in the solar atmosphere, and for which the limb — centre shift is much smaller. As there are no telluric lines in this region, it was necessary to impress upon the plates emission lines from an arc spectrum to form standards of reference.

The method is to project a small solar image on the slit of the spectrograph, centring it precisely so that the wide spectrum obtained represents a diameter of the sun. An exposure is then made, sufficient to give a strong image of the spectrum of the more feeble light from the limbs ; and in order to reduce and graduate the exposure for the central parts of the image a small strip of metal is held in front of the slit and moved up and down by hand during the exposure. With this simple device only a small amount of practice was needed to obtain sufficiently uniform density in the photograph.

In regions of the spectrum where there are suitable telluric lines, this procedure is all that is necessary to obtain photographs which will yield the required data. It is only necessary to measure the intervals separating the selected solar line from one or more telluric lines at the centre and at a number of points equidistant from the centre of the wide spectrum. The solar line will in general be inclined to the telluric lines by an amount depending on the latitude of the points of intersection of the slit with the sun's limb, this inclination being of course due to the Doppler shift of the solar rotation ; but in addition the measures will show that the line curves slightly towards the red at each end, and it is the nature of this curvature that is the subject of this investigation. A curvature in the same sense due to the action of the grating, being identical for both solar and telluric lines, does not affect the results.

In the more refrangible parts of the spectrum, where there are no telluric lines, we have found the arc spectrum of iron to be the most suitable substitute, because the iron spectrum has been more studied than any other, and it is very necessary to guard against errors due to the displacements of unsymmetrical arc lines near to the poles, which one of us has ascribed to a density effect. In the long arc necessary to impress the plate right across the wide solar spectrum, the wave-length of certain lines will change considerably as one pole or other is approached ; but by selecting symmetrical lines, it seems safe to assume that the wave-length will remain constant at all points, especially as the further precaution was taken of moving the arc continually up and down along the slit during the exposure, and reversing the poles so that half the exposure was made with the negative pole near the upper end of the slit, and half near the lower end. A difficulty in the use of the iron arc to determine the shifts of the solar iron lines is that the emission lines fall upon and obliterate the solar lines that it is desired to measure. This was overcome by the simple process of displacing the emission lines through a few angstroms by rotating the grating through an angle of one or two minutes of arc between the exposures on sun and arc. There is no danger in this procedure of changing the inclination of the arc lines.

Apparatus.—The large spectrograph described in Kodaikanal Observatory Bulletin No. XXXVI was used in this research, the only modification needed being the provision of an adjusting and guiding arrangement in front of the slit to ensure perfect bisection of the sun's image. A 3-inch lens of 5-feet focus was mounted in the beam of light from the siderostat, and the small solar image (14 mm. diameter) was projected on the slit by a reflecting prism. Immediately covering the slit-plate there was mounted a thin plate of brass with fine circular concentric lines engraved on it of diameters approximating to those of the greatest and smallest diameters of the sun's image. A slot about 1 mm. wide and 16 mm. long was cut in the plate along the vertical diameter of the circles to admit light to the slit, and the plate was then carefully adjusted by screws, so that the centre of the slot was coincident with the slit. To adjust the image concentrically with the circles, a telescope provided with a collimating lens is mounted so as to view the engraved plate, greatly magnified by the eye-piece. With the aid of the electric controls of the siderostat, the image viewed with the telescope may be kept as accurately concentric during an exposure as the definition of the sun's limb will permit.

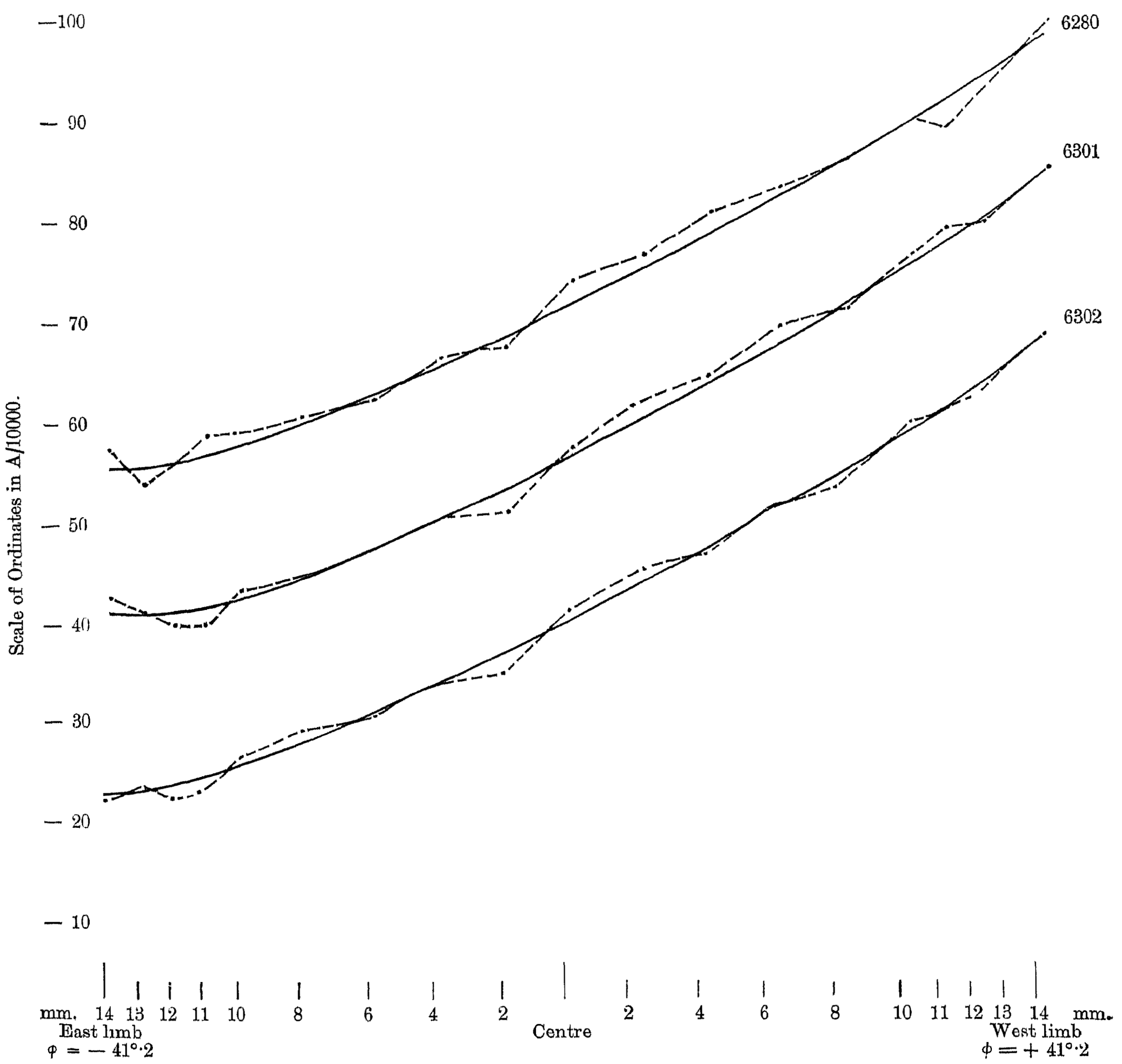
Measurement of the spectra.—As high resolving power and linear dispersion are necessary in dealing with wave-length differences of less than 0·01A, the third and fourth orders of spectra given by the new Anderson grating were used, and these naturally involved rather long exposures both on sun and arc. Sixteen minutes were required to get dense images of the solar limbs in the third order red region, and almost as much in the fourth order violet at λ 4380, where the dispersion is 2·4 mm. to the angstrom ; but in the ultra-violet at λ 3928 good images of both sun and arc were obtained with six minutes' exposure. In the third order red the linear dispersion is 2·1 mm. to the angstrom, and in the fourth order violet at λ 3928 it is also slightly over 2 mm. to the angstrom. The resolving power may be judged from the definition of the very homogeneous oxygen lines in the a group : the first line of this group, 6276·815 of Rowland, is barely resolved into two lines with separation 0·030A ; and the line at 6278·303 is a clearly separated double with components at 6278·276 and 6278·330. Apparently not much would be gained by further increasing the resolving power, since the iron lines suitable for measurement in this region vary from 0·08 to 0·11A in width, and it is this, and the diffusive character of their edges, which sets a limit to the accuracy of the measures.

The three lines measured in this part of the spectrum are all within the group of telluric oxygen lines, and are well adapted for the positive on negative method of measurement described in Kodaikanal Observatory Bulletin No. XXXII. They have a large limb — centre shift, but probably a very small or even negative centre — arc shift. For the line 6280 it is a small positive shift but for the other two at 6301 and 6302 it is negative in all the arc and sun comparisons we have made, even when the centre of a long arc is used, but the unsymmetrical nature of the lines makes it difficult to determine how far this may be due to a displacement in the arc.

At the other end of the spectrum we have taken, amongst others, the symmetrical Fe lines 3928·075 and 3930·450, which have a small limb — centre shift, but a large centre — arc shift. The narrow chromium line at 3928 783 was also measured, and the narrow spark lines of Fe and Ti at 4385·548 and 4387·007, which according to Adams have a relatively large limb shift for this part of the spectrum. For all but the red lines, the positive on negative method of measuring was found difficult to apply, and recourse was had to the ordinary method of bisection with a spider-thread, taking the mean results from the original negative and from a positive copy.

For the measurement of these spectra, which have a width of about 28mm., a special cross slide provided with a millimetre scale was constructed for the micrometer, and for the positive on negative measures a cross slide had to be provided for both positive and negative images. In either method of measuring, the plate or

FIG. 1.—DISPLACEMENTS OF FE LINES ACROSS SUN'S DISC.



plates have to be moved across the field of view in the direction of the spectrum lines by successive measured intervals from one edge of the spectrum to the other, the field of view being limited to a narrow strip, either by a mask placed over the plate, or in the positive on negative measures by a mask placed in the eye-piece. The movement is made by a screw bearing on the edge of the sliding plate-carrier.

As the change of wave-length in passing from the centre of the spectrum to the edge is most rapid near the edge, the 14 mm. representing the solar radius is divided into 2 mm. intervals as far as 10 mm. from the centre, and thence into 1mm. intervals, to 13 mm. The final measure is made at a point 0 25 mm. within the limb. In this way, including the measure of the central strip, a series of nineteen determinations of the relative positions of the solar and telluric, or solar and arc lines, is obtained, representing points on the sun's disc the heliographic co-ordinates of which can be determined from the known position-angle of the slit at the time the plate was exposed. The measured intervals between solar and reference line, or their differences, are then plotted, and a smooth curve drawn, from which a small correction to the central interval is obtained, and the other intervals are freed from accidental errors of measurement and possible real irregularities of wave-length. This smoothing process might however have been omitted altogether without seriously affecting the mean results obtained from several plates: its main purpose is to get a corrected value of the wave-length at the centre of the disc, and hence more correct values of the shifts between limb and centre. There is some evidence of real, though unsystematic, irregularities of wave-length confirmed by the different lines on a plate, and amounting at the most to $\pm$ 0·002A. We give as an example of this the curves in fig. 1, representing the measures of the lines 6280, 6301 and 6302, on the date November 14, 1914. At 2 mm. east of the centre the wave-length of all three lines is in defect, whilst at the centre and at 2 mm. west it is in excess of the values derived from the smooth curve. As different reference lines were used for each of the three iron lines, this is good evidence of real variation, especially as the lines are best defined near the centre, and the variation is about four times greater than the probable error of measurement.

However disconcerting such fortuitous irregularities may be, they are of interest in showing the slight instability of the lines of the solar spectrum, and the need for great caution in interpreting the results from a single plate in all researches connected with line displacements in solar spectra, and especially in solar rotation work.

In the reduction of the measures it is generally necessary to compute the component in the line of sight of the rotation velocity for each point measured. At times when the solar equator passes through, or very near, the centre of the disc, this is not essential, since the plus and minus velocities on the east and west halves of the diameter then cancel one another: when, however, the sun's axis is inclined to the direction of the earth there are appreciable differences, and although these are small, it was considered worth while to compute by an appropriate formula the corrections to be applied to the observed displacements in order to remove the effect of the solar rotation entirely. A comparison of the observed and computed velocities could then be used as a check on the general reliability of the measures.

Adopting Adams' formula for the sidereal solar rotation as correctly representing the change of velocity with latitude, the complete formula used for finding the component in the line of sight of the synodic rotation velocity at any position on the sun's disc is :—

$$(1\ 507 \cos \phi + 0{\cdot}456 \cos^3 \phi - \mathrm{C}) \sin \lambda . \cos \mathrm{D}.$$

The latitude, ϕ, is determined graphically by plotting the positions of the measured points on the appropriate solar chart, of which the Observatory possesses an excellent set, carefully constructed by the Rev. Father Beaurepaire. C is the correction found from Dunèr's solar tables for converting sidereal into synodical velocity. This is an unnecessary refinement, but its inclusion enables us to compare readily the observed with the computed line shifts. Sine λ (the heliographic longitude) is obtained by the formula :—

$$\text{sine}\,\lambda = \text{central distance} \times \text{sine angle between sun's axis and slit} \times \text{secant}\,\phi$$

D is the inclination of the sun's axis to the line of sight.

In our experience during the years of sunspot minimum, the constants in Adams' formula generally give too large a value for the solar rotation; but since we are only concerned here in finding the difference of shift between points east and west of the centre, any errors in these constants will have no appreciable effect.

In fig. 2 we give a smoothed curve representing the measures of the line 6302, on the date November 24, 1914 when the latitude of intersection of the slit and limbs was 37°·7. The curve of computed displacements due to the solar rotation is also given, slightly displaced with regard to the other curve, to show the parallelism of the two near the centre, and their departure as the limb shift begins to be manifest. In this particular plate the results of the rotation shift are in remarkably close agreement with the computed shifts from Adams'

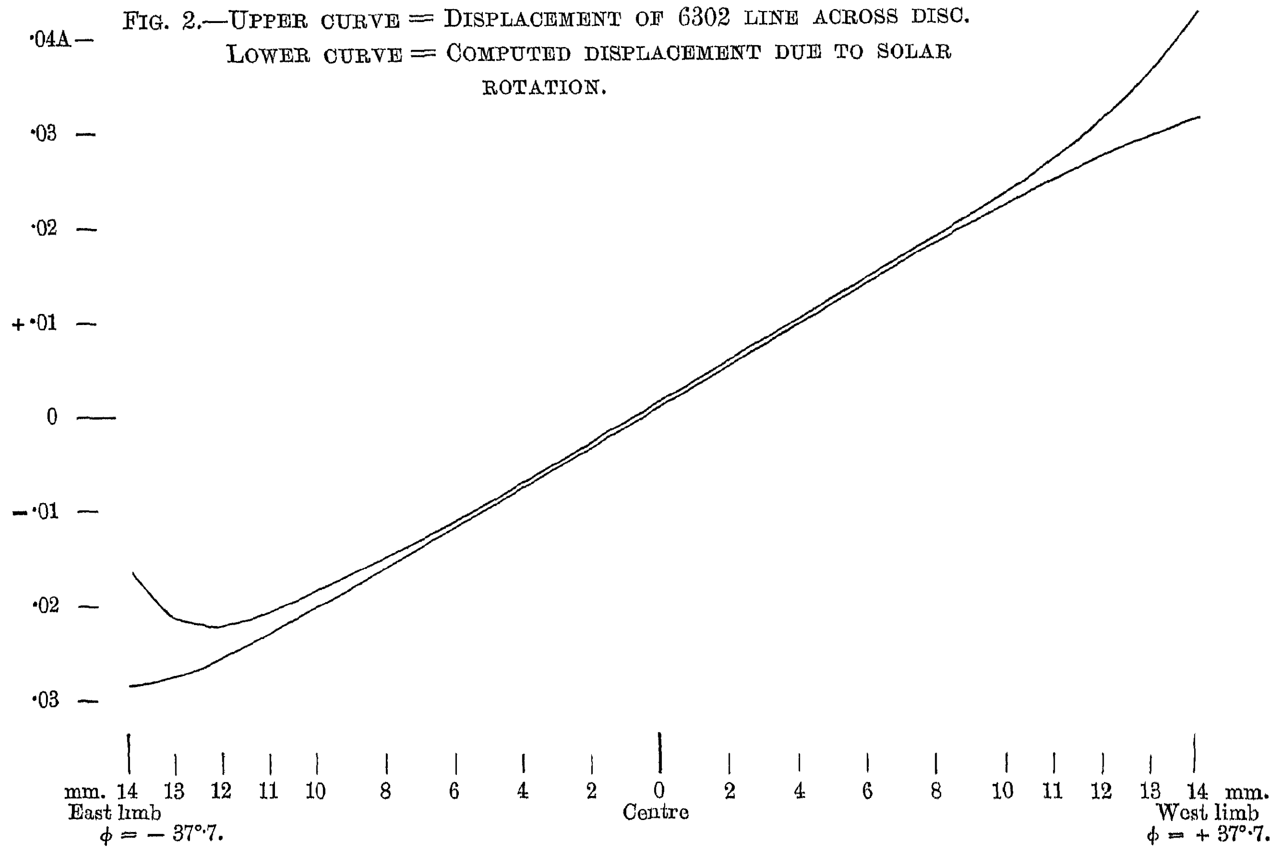


FIG. 2.—UPPER CURVE = DISPLACEMENT OF 6302 LINE ACROSS DISC.
LOWER CURVE = COMPUTED DISPLACEMENT DUE TO SOLAR ROTATION.

formula. In comparing these, we take the mean of the shifts at corresponding points east and west of the centre, both for the observed and computed shifts, in this way eliminating the limb shift. In table I we give the results for the three lines measured on the above date. In the mean values for the three lines the largest residual is only three in the fourth decimal, and the mean percentage difference about ¼ per cent under the computed values.

TABLE I.

Shifts of iron lines between centre and limb, due to component of solar rotation. In A/10000. (ϕ at limb = 37°·7.)

Central distance.	6280	6301	6302	Mean.	Computed.	O — C	Percentage difference.
MM							
2	46	45	45	45	45	0	0
4	90	87	87	88	88	0	0
6	134	130	130	131	132	−1	−0·76
8	174	168	170	171	172	−1	−0·58
10	211	208	211	210	211	−1	−0·47
11	233	229	231	231	234	−3	−1·28
12	254	249	252	252	251	+1	+0·40
13	269	269	268	269	268	+1	+0·37
13·8	278	282	270	277	276	+1	+0·36
				Mean percentage difference		..	−0·22

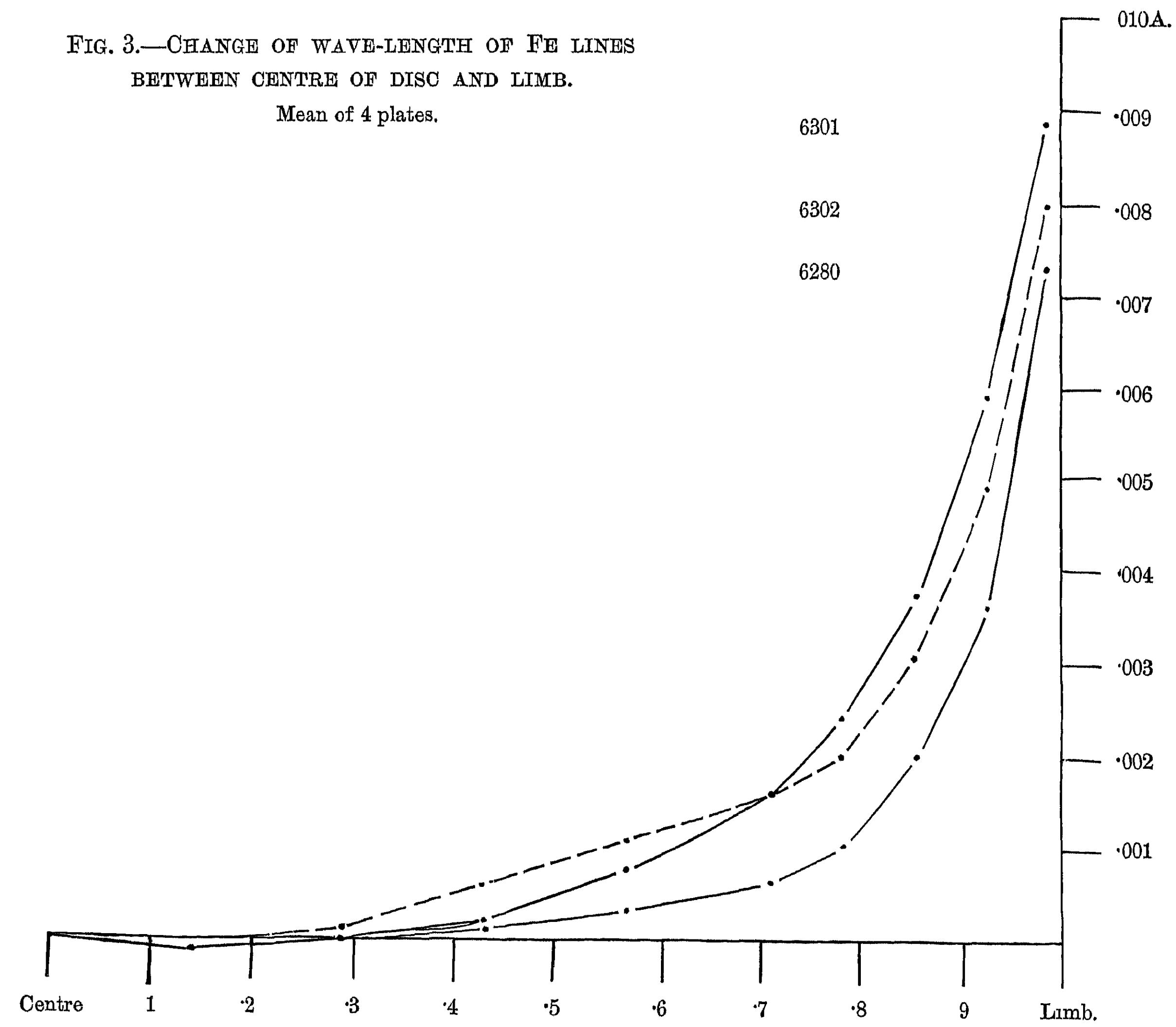
About the same order of accuracy is shown by the positive on negative measures of the three plates obtained on November 14, 1914, but in these the mean rotation values are about 2½ per cent smaller than those derived from Adams' formula.

These results serve to indicate the accuracy attained in the measurement of these rather wide lines by the positive on negative method. Measures have also been made of the same lines in other plates by the ordinary method, and by another measurer, and whilst the general form of the curve representing the shift across the disc is the same, there is a less satisfactory accordance in the rotation shifts. The same remark applies also to the ultra-violet lines measured in the ordinary way, the chromium line at 3928·783 and the Fe and Ti lines at 4385·548 and 4387·007 giving the best results, on account of their narrowness and well-defined character.

The stronger ultra-violet lines measured are those at 3928·075 and 3930 450. These give very small limb shifts, and in some plates it appears to be a negative shift : the displacement is towards violet instead of towards red. As these lines are rather wide, and the measures are difficult, we have some doubt as to the reality of the negative shifts. It suggests a variability of the limb shift, of which we have indications also in some of the measures of the red lines.

Results of the measures.—Leaving the question of the negative shifts for further investigation, we now proceed to give the results of the measures, after elimination of the rotation shift, and taking the mean of the east and west displacements. The diagram fig. 3 exhibits the mean change of wave-length between the centre of the disc and the limb of the Fe lines 6280, 6301, and 6302. These are derived from four plates

FIG. 3.—CHANGE OF WAVE-LENGTH OF FE LINES BETWEEN CENTRE OF DISC AND LIMB.
Mean of 4 plates.



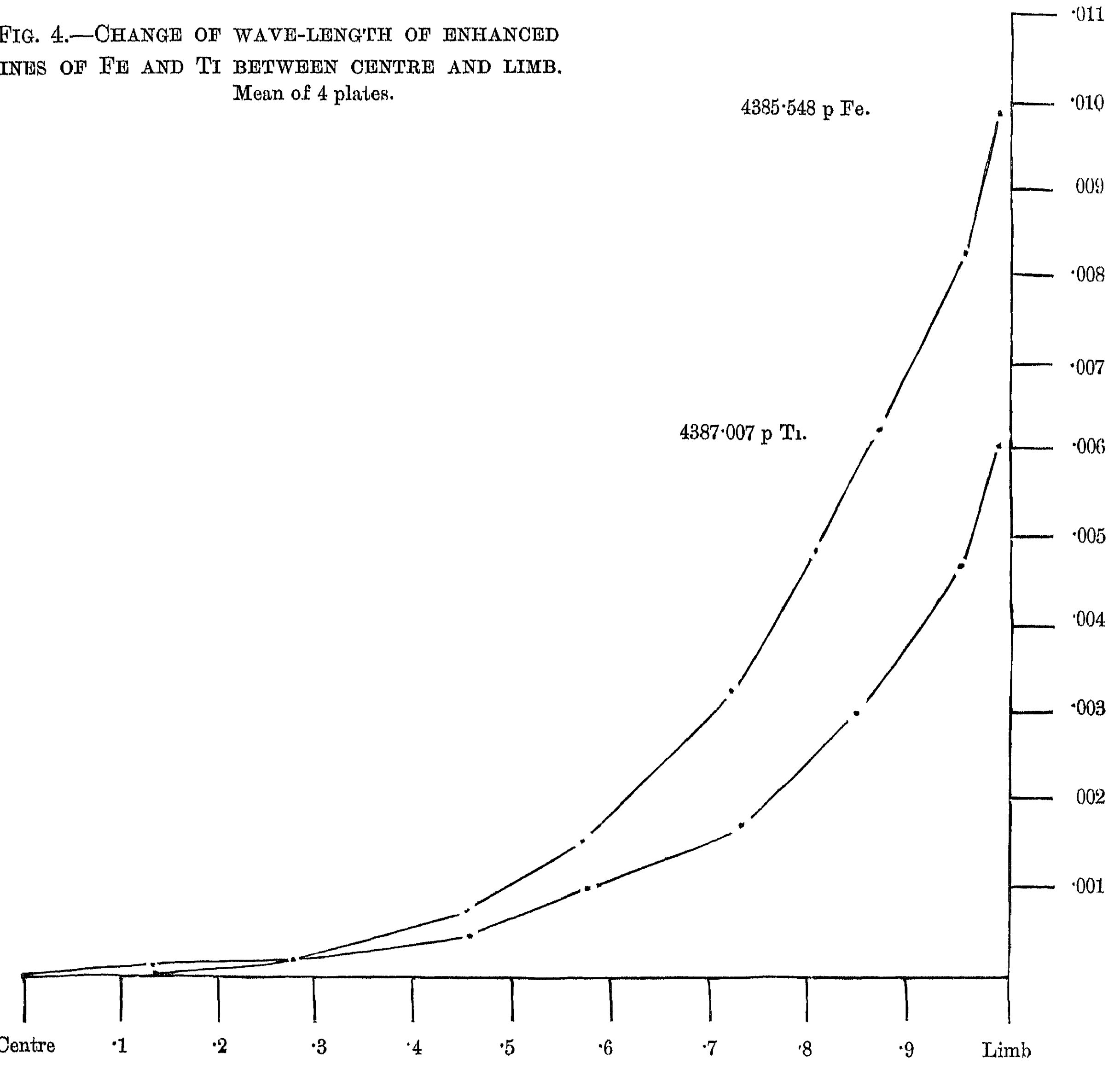
measured by the positive on negative method. The abscissæ are here given in tenths of the solar radius, and the ordinates in angstroms. The latitudes of the points of intersection of slit and limbs varied between 26°·4 and 41°·2, the mean being 35°·6. The plates were secured on dates November 14 and 24, 1914, under practically perfect atmospheric conditions.

The outstanding feature of the curves is the small distance from the centre at which the limb shift begins to manifest itself. This begins at approximately 0·3 of the radius from the centre for all three lines, but the curve for the 6280 line falls below the other two, the increase of wave-length being at first less rapid than for the line 6301. There is also a slight indication of a decrease of wave-length for the line 6301 at the point measured nearest to the centre. This decrease does not exceed 0·0002A, and must be considered doubtful. Three of the four plates measured give minus values, and one a plus value.

Two other plates taken on March 18 and 19, 1915, at latitudes 82°·3 and 86°·9 (the slit being almost coincident with the sun's axis) were measured by the ordinary method. Taking the mean results of a positive and a negative image, these show rather larger limb shifts for the lines 6301 and 6302, but a smaller shift for the line 6280. The rates of increase between centre and limb are however very similar to those given in the curves. It cannot be said that latitude has any appreciable influence on the limb shifts, which appear to be the same at all points on the circumference of the sun. But, as already mentioned, there is some evidence of variability of the limb shift on plates taken on different dates, which needs further investigation. For instance, a plate taken on December 25, 1914, at latitude 69° 1, yields remarkably small limb shifts for all three lines, the values being about one half of those usually obtained. It may be added that all of the plates were taken under conditions of exceptional purity of sky, although the definition of the sun's image may have varied considerably.

Fig. 4 shows similar curves for the lines 4385·548 and 4387·007. These lines were selected because they have relatively large limb shifts for this part of the spectrum, and they fall near to the strong Fe line

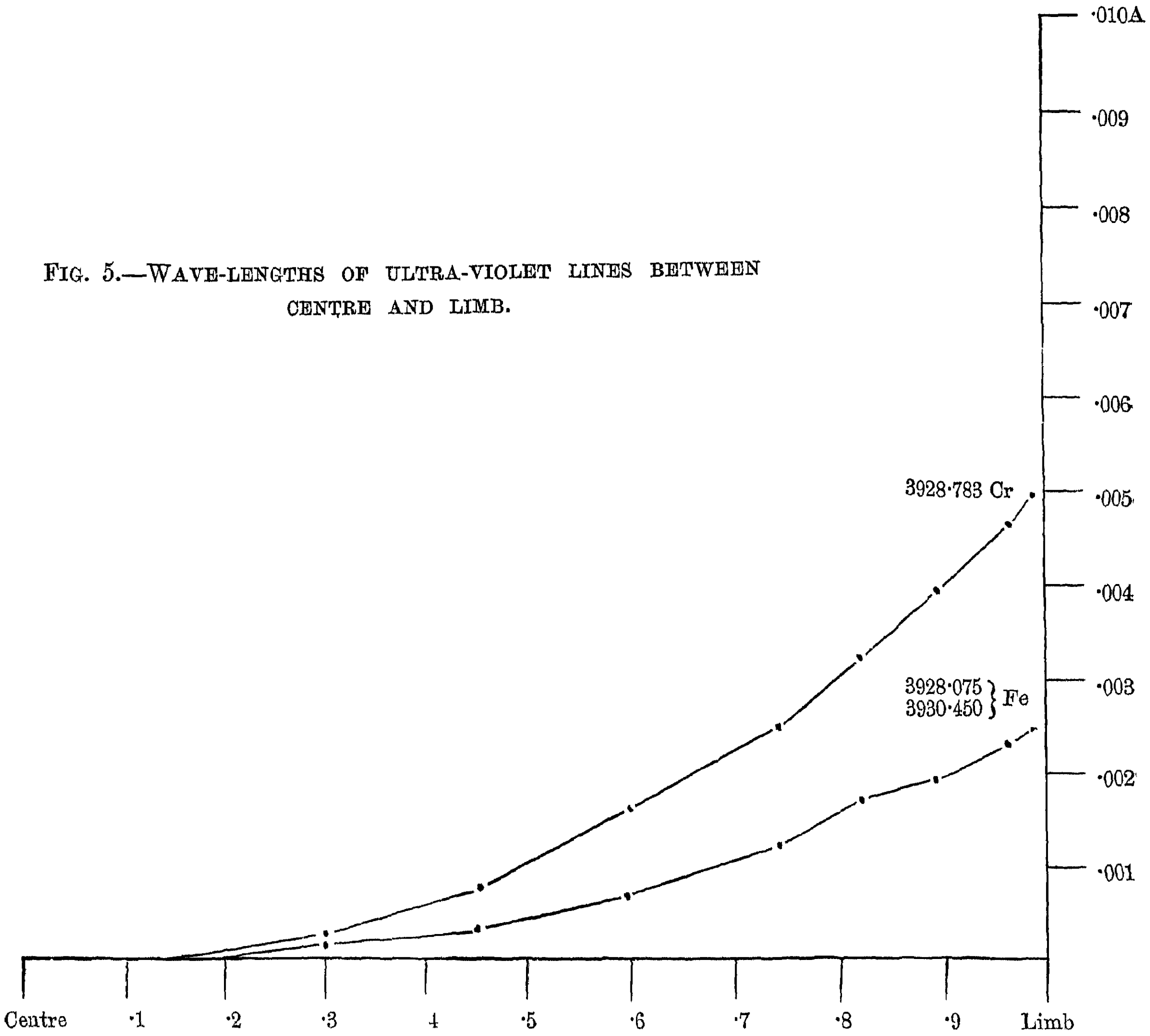
FIG. 4.—CHANGE OF WAVE-LENGTH OF ENHANCED LINES OF FE AND TI BETWEEN CENTRE AND LIMB.
Mean of 4 plates.



4383·720, a symmetrical line which is readily reversed in the arc, the absorption line forming an excellent line of reference. They are due to enhanced Fe and enhanced Ti respectively. Four plates were exposed on October 9, November 19 and 23, 1914, the latitudes of intersection of slit and limb being 27° 3, 55°·6, 50°·4 and 51°·7.

Fig. 5 shows the ultra-violet lines measured. The lower curve is the mean result obtained for the two strong iron lines 3928·075 and 3930·450. These lines, as already stated, have a very small limb shift and

FIG. 5.—WAVE-LENGTHS OF ULTRA-VIOLET LINES BETWEEN CENTRE AND LIMB.



a large centre — arc shift. As there is no appreciable difference between them, the mean of the two is given, from two plates. The upper curve in this diagram is the narrow chromium line 3928·783, the mean of four plates. The data for this diagram are derived from plates taken on December 25, 27 and 28, 1914, and January 8, 1915. The latitudes range from 40°·4 to 81° 2.

Comparing these ultra-violet lines with those at the red end of the spectrum, we find the increase of wave-length begins at about the same distance from the centre in both ; but the ultra-violet lines, and especially the strong iron lines, show a very much smaller rate of increase near the limb than the red lines. The enhanced lines in fig. 4 give essentially the same type of curve as the red iron lines.

Discussion of results.—In Kodaikanal Observatory Bulletin No. XLVI the question was raised as to whether the general movement of recession indicated by the displacement of the iron lines towards red at the centre of the sun's disc was the result of a circulation of the solar gases in a direction radial to the sun, or was part of a general movement of recession from the earth. The present series of measures appears to show that the displacements at the centre are not due to a radial circulation on the sun, but are probably part of a general displacement increasing from the centre towards the limb. If the descending movement at the centre of the disc were due to a circulation radial to the sun, the component of motion in the direction of the earth would diminish from the centre towards the limb in proportion to the cosine of the angular distance from the centre, and this would be apparent in an initial decrease of wave-length, most marked for those lines having a large centre—arc shift. This decrease would continue until counteracted by the increasing limb shift, producing a displacement curve across the disc very different in form from that actually found. So far as we have gone, the line 6301 is the only one which shows any tendency to a decrease of wave-length, but this line has a very small, or possibly a negative, shift at the centre of the disc, while the strong lines in the ultra-violet which have a mean centre—arc shift of 0·016A exhibit no diminution of wave-length, but a continuous increase from a point not very far from the centre.

In Kodaikanal Observatory Bulletin No. XXXIX it was shown that the relative shifts between the limb and centre cannot be explained by a difference of pressure in the effective regions of absorption at the limb and at the centre of the disc, and the displacement curves now found afford additional evidence in the same sense, as the following considerations will make clear.

According to Halm's hypothesis, at the limb the path of the light through the lower layers is increased in greater ratio than that through the upper layers. It is easily seen, however, that owing to the slight depth of the reversing layer this effect can only be appreciable very near to the limb. It is sufficient to calculate the ratio between the thickness of a layer at the bottom of the reversing stratum and one at the top, since for these extreme layers there is the maximum possible difference. In fig. 6 let O be the centre of the sun, and P the centre of the disc seen from the earth. A ray of light starts towards the earth from A on the photosphere at

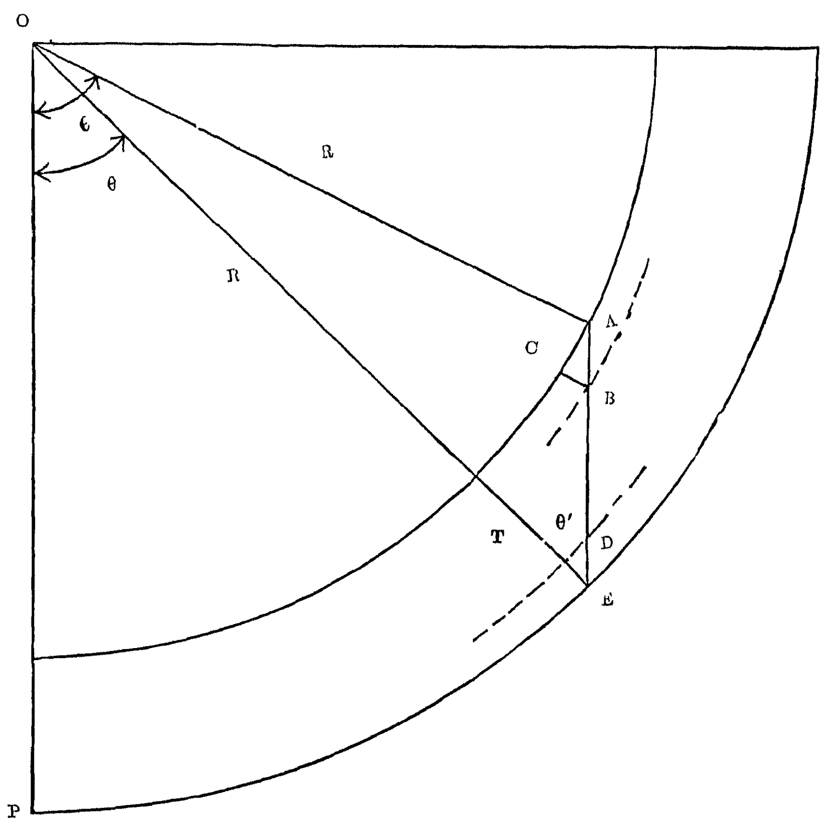


FIG. 6.

angular distance θ from the centre of the disc, and emerges from the reversing layer at E, at distance θ' from the centre of the disc. Then θ' is given by the relation

$$\sin\theta' = R.\sin\theta/R + T \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where R equals the radius of the sun, and T equals the total thickness of the reversing layer. Now the length of path AB of the ray through a thin layer of thickness BC = d at the base of the reversing layer is $d/\cos\theta$, and similarly the length of path DE through an equally thick layer at the summit is $d/\cos\theta'$. The relative increase in the lowest layer is therefore

$$\cos\theta'/\cos\theta$$

This ratio is given in the following table, obtained with the help of equation (1), assuming that the sun's radius equals 960″, and the total thickness of the reversing layer equals 2″.

TABLE II.

θ	$\cos\theta$	$\sin\theta$	$\sin\theta' = 960/962 \times \sin\theta$	θ'	$\cos\theta'$	$\frac{\cos\theta'}{\cos\theta}$
0°	1·0000	0·0000	0·0000	0° 0′	1·0000	1·000
45°	0·7071	0·7071	0·7067	44° 53′	0·7083	1·001
70°	0·3420	0·9397	0·9377	69° 40′	0·3474	1·016
75°	0·2588	0·9659	0·9640	74° 34′	0·2661	1·028
80°	0·1736	0·9848	0·9827	79° 20′	0·1828	1·053
82°	0·1392	0·9903	0·9882	81° 12′	0·1530	1·099
85°	0·0872	0·9962	0·9942	83° 47′	0·1083	1·242
88°	0·0349	0·9994	0·9973	85° 48′	0·0732	2·097
90°	0·0000	1·0000	0·9979	86° 18′	0·0645	∞

Whatever assumptions we may make as to the difference of pressure in the upper and lower layers, and also as to the effect of the difference of path on the pressure displacement of a line, it is evident from this table that no difference of path is appreciable except between 85° and 90° from the centre, and therefore no change of wave-length can occur except quite close to the limb. Thus, at about 85°, or 0·996 of the radius from the centre, we might expect a line to begin to be widened on the red side, the violet edge remaining in its normal position owing to the absorption at the highest level. This widening would be of a diffuse character, since the rays of light would traverse successive layers of decreasing pressure and temperature. The effect of a higher temperature in the lowest strata would indeed tend to neutralize the increased absorption due to a longer path, and it is by no means clear that any displacement whatever would be observed. However this may be, as all the displacement curves agree in showing that the shift is continued far within the limb, it cannot be due to the effect of pressure differences. The pressure theory of both limb and centre shifts is also difficult to reconcile with recent views as to the effective depths in the reversing layer where absorption occurs. For we now believe that the fainter lines originate at greater depths than the stronger lines, consequently they should give larger shifts at the centre of disc because of the greater pressure, and smaller limb — centre shifts because of the smaller difference of path for radial and tangential rays. This is just the opposite of what is actually found ; on the average the fainter lines have smaller centre — arc shifts and larger limb — centre shifts than the stronger lines.

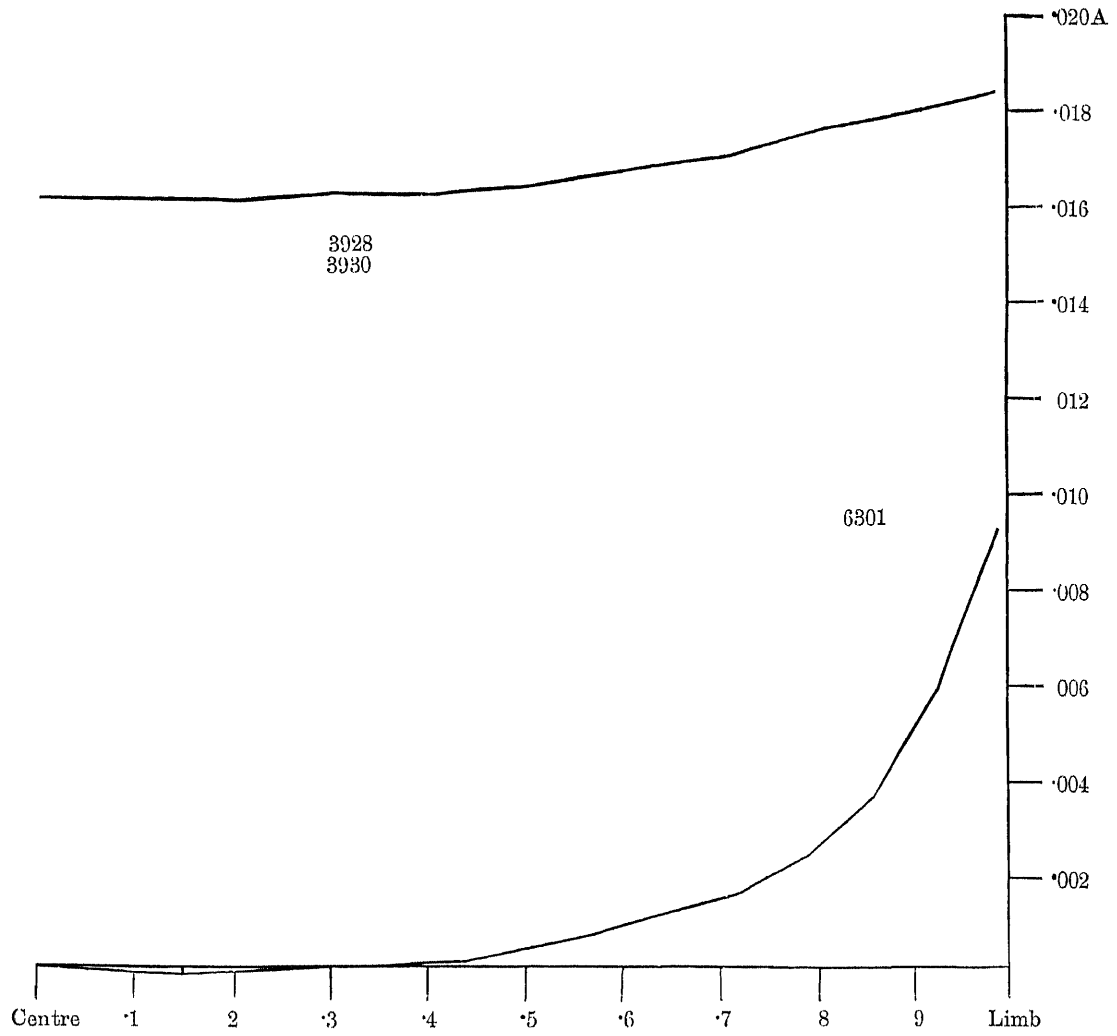
Owing to the remarkable inverse relation between the limb shift and the centre shift which has been shown to exist (Kodaikanal Observatory Bulletin No. XXXIX), we seem justified in assuming tentatively that both are due to a single cause, and one in which pressure plays no part. But the centre shifts have been interpreted as due to descending movement, which is greatest in the higher levels, and decreases, possibly to zero, in the lower levels of the reversing layer [1] ; and this interpretation has been endorsed by Dr. St. John.[2] If the limb shift is also a Doppler effect we may add the two shifts, and represent the change of wave-length between centre and limb as in the diagram fig. 7, in which the upper curve represents the ultra-violet lines 3928·075 and 3930·450, and the lower curve the red line 6301·718, which we will assume has a zero centre—arc shift.

If we accept St. John's conclusions as to the different levels represented by lines in different spectral regions, the ultra-violet lines represent a high level, and therefore show the large descending velocity of which the ordinate 0·016A is the equivalent. The red line, on the other hand, represents a very low level, and is produced in a region where this downward movement is arrested. At the limb, however, there is much less difference in the displacements, the wave-length of the red line being increased by 0·010A, and the wave-length

[1] Kodaikanal Observatory Bulletin Nos. XXXVI and XXXIX. [2] Mt. Wilson Annual Report, p. 256, 1914.

of the violet lines by 0·002 only. The velocities at the limb will then be for the red line 0·5 km/sec, and for the violet lines 1·4 km/sec.

FIG. 7.



We thus see that at the limb a great depth of the reversing layer is affected by the movement, while at the centre of the disc only the upper layers are in motion. If we could conceive of the Earth exerting a repulsion on the solar gases, this behaviour of the high-level and low-level lines becomes intelligible ; for at the centre of the disc the resistance of the denser layers and of the photosphere itself would arrest any downward movement, while at the limb the entire stratum would be more or less free to move tangentially to the solar surface.

The velocity interpretation of the limb shifts inevitably leads to an Earth effect, even if we assume a combination of radial and surface currents on the sun to account for the observed displacement curves. Formulæ combining a radial and a surface current can be constructed to fit the displacement curves satisfactorily, but the surface current must be towards or away from the centre of the disc, a point on the sun which has no significance except in relation to Earth. Also as the radial currents involve an ascending motion, whilst we find a descending movement, it seems futile to discuss these formulæ.

To escape from the hypothesis of an Earth effect, we must assume that the solar line shifts depend upon the direction which the rays of light take in traversing the reversing layer, the shift being least for rays passing normally through it, and most for the tangential rays. The effects of anomalous dispersion will no doubt appeal to many as giving a probable explanation of the facts, and doubtless the anomalous dispersion theorv would lend itself admirably to this problem as to so many others.

We consider nevertheless that the Doppler hypothesis should not be lightly discarded until indisputable evidence is forthcoming that anomalous dispersion is really an effective agent in displacing solar lines. The recent work of Albrecht in regard to this appears to us to be entirely discounted by our measures of close double lines in sun and arc,[1] and by the subsequent disclosure of very large overestimates in Rowland's measures of the separations of many solar double lines. The actual close agreement in the separations of arc and solar double lines seems indeed to rule out anomalous dispersion as an effective agent in displacing solar lines.

It remains to mention a crucial experiment which would decide the question whether the displacements are due to motion radial to the Earth, and affect only that side of the sun directed toward the Earth, for by the aid of the planet Venus we can compare the generalized spectrum of a hemisphere of the sun turned 90° or more from the Earth with the hemisphere facing the Earth. If the displacement of the solar lines affects only the hemisphere facing the Earth, there will be a difference of wave-length between the lines of the planet's spectrum, when corrected for her motions in the direction of Earth and sun, and those of ordinary sunlight.

It is probable that with modern instruments the line-of-sight velocity of Venus could be readily determined with a probable error as small as ± 0·2 km/sec, while the difference of wave-length expected corresponds to from 0·6 to 1 km/sec, according to the lines chosen.

If there is no such difference of wave-length between the light from the two sides of the sun, then it will be necessary to find some explanation of the line shifts other than motion in the line-of-sight.

SUMMARY.—(1) The first part of this paper describes the method of obtaining spectra representing a diameter of the sun, and the use of the telluric lines at the red end of the spectrum, and the reversals of the superposed arc lines of iron at the violet end, as reference lines for determining the displacements of the solar lines across the disc between centre and limb.

(2) The methods of measurement and reduction are described, and the accuracy of the positive on negative method of measuring is illustrated by comparing the observed with the calculated shifts due to the components in the line-of-sight of the solar rotation movement.

(3) Small irregularities disturbing the smoothness of the curve which represents the change of wave-length between centre and limb are indicated.

(4) Diagrams are given showing the change of wave-length between centre and limb of the red lines 6280·833, 6301·718 and 6302·709, of the violet lines 4385·548 and 4387·007, and of the ultra-violet lines 3928·075, 3928·783 and 3930·450.

(5) The form of these curves indicates that the redward shift, or downward movement, at the centre of the disc is not due to a radial circulation of the solar gases, but is probably part of the general displacement increasing towards the limb.

(6) It is shown that a difference of pressure between the effective region of absorption at the limb and at the centre of the disc will not account for the displacement curves, since the limb shift continues for a long distance within the limb, while a pressure effect could only be appreciable from ·996 radii from the centre to the limb.

(7) It is suggested tentatively that both limb shift and centre shift are due to a single cause, a general movement directed away from the Earth, all over the disc. This movement affects only the higher parts of the reversing layer at the centre of the disc, because of the resistance offered to a downward movement by the lower layers or the photosphere : at the limb the movement affects the lower strata also, because there is little resistance to a movement to the solar surface.

(8) It is suggested that observation of the wave-length of the lines in the spectrum of Venus would decide the question whether the shifts are due to a recession from the Earth.

J. EVERSHED.
T. ROYDS.

THE OBSERVATORY, KODAIKANAL,
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[1] "The Observatory," January, 1916

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