NEW MEASURES OF THE SODIUM LINE D_1 IN THE SOLAR SPECTRUM

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Summary

An extended series of measures of the sodium line D_1 in the solar spectrum compared with vacuum tube emission shows that sudden changes in the shift towards red of the solar line occur from time to time, at both centre and limb. These changes may be explained as due to varying movements of the sodium gas. The mean values of the shift Sun – vacuum tube show a small excess over the Einstein effect at the centre, and a larger excess at the limb, as occurs also in the *Fe* and *Ca* lines in the H and K region. The excess at the centre may be due to a general descent of sodium in the reversing layer, as is found in the higher levels of the solar atmosphere. But the mean excess at the limb is an outstanding discrepancy implying a larger shift of D_1 than relativity predicts.

The total shift of the line at the east and west limbs gives a value of the solar rotation at a high level in the reversing layer, and confirms previous results in showing an increase of angular speed with height above the photospheric level.

In a previous paper * I gave the results of measures of the sodium line D_1 compared with vacuum-tube emission, and I stated in the summary that "unlike the lines of iron or calcium, the sodium line is found to give the same shift towards red at the centre of the disk as at various points on the limb, and this shift agrees very closely with the Einstein relativity effect". These measures, made in the year 1937, were remarkably consistent, as is shown by the small probable errors resulting from a comparatively small number of spectra measured; and they agreed with previous measures made at Kodaikanal in showing no greater shift at the limb than at the centre of the Sun.

In a long series of subsequent measures of D_1 in spectra obtained with the multiple transmission liquid-prism spectrograph, it is now found that after a run of constant values a sudden change may occur in the shift or wave-length of the line, and this may occur in the spectra of the centre of the disk or in those obtained near the limb. Confining attention first to the centre of the disk, and to yearly values, I give the results shown in Table I.

From these figures it will be seen how greatly the shift varies from time to time. High values occur in May and June 1938, in May, June and the first half of July 1944, and February and March 1945. Low values closely follow the high in 1938 and 1944. In all three years the mean for the year is the same, and the general mean from all the spectra measured is +·0147 A. The relativity effect is +·0125 A., showing an excess of +·0022 A. I give in the fourth column the probable error of each set of measures in order to show roughly the consistency of each.

It is necessary to discover whether these variations are due to changes in the Sun or in the emission spectrum of the vaccum-tube. The D lines are sensitive to pressure, and according to measures by Humphreys at 3½ to 10½ atmospheres, the mean shift per atmosphere for D_1 is +·011 A. To confirm this I have compared the tube spectra assumed to be at a very low pressure with the open arc, and obtained a mean value, arc –

* *M.N.*, 98, 196, 1938.

TABLE I

Shift of D_1 at Centre of Sun

No. of Spectra	Date	Mean Shift A.	Probable Error
	Year 1938		
14	May 30 to June 10	+·0202	±·0006
8	June 14 and 24	+·0165	±·0008
11	July 3, 9 and 13	+·0090	±·0003
16	July 30, August 1, 3, 4, 5, 6	+·0121	±·0004
		+·0146	
	Year 1944		
29	April 30, May 3 to 28	+·0173	±·0018
10	June 19, 20, 22, 24	+·0152	±·0010
7	July 6, 13 and 14	+·0244	±·0016
11	July 15 to 20, and August 23	+·0061	±·0009
9	August 26 to 30	+·0123	±·0011
53	November 16 to December 29	+·0150	±·0004
		+·0147	
	Year 1945		
14	January 1 to 29	+·0122	±·0003
11	February 10 to March 12	+·0203	±·0001
31	March 13 to 30	+·0146	±·0005
23	April 3 to May 2	+·0139	±·0004
		+·0147	
	Mean of 252 spectra	+·0147 A.	
	Relativity effect	+·0125 A.	

tube, from 9 spectra of +·014 A. But it appears that the D lines are affected also by the density of the vapour, the co-called "pole effect". Thus when the density is great in the open arc and measures are made on the narrow self-reversals of the lines, the shift to red for both D_1 and D_2 is greater than when the emission lines are very narrow. In comparing the Sun with the vacuum-tube, there is also found to be a tendency to slightly larger values of the shift when the tube line D_1 is very narrow, and smaller values when it is wider than the solar line. I believe this is a density effect, and may have some slight influence in determining the amount of the shift of the solar line. It will not, however, account for the large changes seen in Table I, for on examination of the spectra giving the largest and the smallest shifts in the two years 1944 and 1945 there is found to be no relation between the shifts and the widths of the emission line.

There is the further possibility that rotation effects may come in if the slit of the spectrograph is slightly east or west of the centre of the disk, but any error in adjusting the Sun's image on the slit could scarcely equal one millimetre, and this amount of error in an image 60 mm. in diameter would give a shift of only ·0013 A., even in the most favourable conditions when the solar equator passes through the centre, whilst departures from the mean value may amount to as much as ·009 A. In other words, to account in this way for such a shift the slit would have to be at least 7 mm. from the centre, whereas it is certainly kept within 0·5 mm. during the short exposures.

These departures from the normal redward shift must therefore be due to changes in the Sun, and may readily be attributed to movements of the sodium vapour. The average excess over the relativity effect of ·0022 A. might be interpreted as a downward movement at this high level in the reversing layer, the sodium vapour descending on the average at about 100 metres per second, partaking therefore in the downward motion of the higher chromosphere represented by the lines H3 and K3 of calcium, in which the

TABLE II

Shift of D_1 near Limb of Sun

No. of Spectra	Date	ϕ	V_0 km./sec.	Mean Shift A.	Probable Error
	Year 1943				
29 pairs	Apr., May, June, July	2° to 30°	2·038	+·0175	±·0005
	Year 1944				
14 pairs	Apr. and Sept.	0° equator	2·034	+·0148	±·0010
32 pairs	Apr. to Sept. incl.	3° to 30°	2·028	+·0178	±·0004
22 pairs	Oct. to Dec. incl.	1° to 28°	2·015	+·0166	±·0005
19 single	Apr., Sept. and Dec.	90° north	...	+·0144	±·0010
23 single	Apr., Sept. and Dec.	90° south	...	+·0175	±·0006
68 pairs for rotation; 110 measures for shift			2·025	+·0166	
	Year 1945				
19 pairs	Jan., Feb., Mar., Apr.	0° to 30°	2·023	+·0180	±·0008
	Mean of 116 measures for V_0		2·028 km./sec.		
	Mean of 158 measures of shift		+·0169 A.		

excess shift over relativity implies a motion of 0·94 km./sec. descent.* This downward motion of sodium, however, is not constant, and may even be reversed for short periods.

Shifts at the Sun's Limb.—Coming now to measures near the Sun's limb, shown in Table II, these were undertaken to give values of the solar rotation at the level represented by the sodium lines, as well as the general shift towards red. The rotation is given by half the sum of the shifts at opposite ends of a diameter of the Sun's image, and the general shift to red by half the difference of the shifts, corrected by the equivalent in angstroms of the annual and diurnal motions of the Earth in the direction of the Sun, at the dates and times the spectra were photographed, as is of course necessary when any comparisons are made between solar and terrestrial wave-lengths. Every individual estimate of the shift depends therefore on measures of a pair of spectra, except in the case of the shifts at the Sun's poles, which were determined separately for each pole. For these, and for most of the spectra at the solar equator, a device for rotating the solar image through a measured angle was used, consisting of three plane mirrors placed some distance in front of the spectrograph slit.

The mean limb shifts for each of the three years 1943, 1944 and 1945, shown in Table II, are in good agreement, and the different series of measures during 1944 do not show any marked deviations from the mean value of all the measures. There are, nevertheless, large deviations within each series, especially those two which give the largest probable errors. These deviations might be accounted for as due to horizontal currents in the Sun. Errors of measurement by the positive on negative method are small, but perhaps they scarcely justify the inclusion of the fourth decimal in each series.

The mean shift of +·0169 differs from my previous results from 66 measures made in the year 1937, which was +·0123 A. I am unable to account for this difference: the 1937 plates are of first-class quality, with nothing to indicate that they might give low values, and a re-measurement of some of the plates confirms the previous results. In the case of the earlier Kodaikanal series of spectra, taken with the open arc, it is possible that a too small pressure correction had been applied to the shifts. According to my direct measures of the pressure effect of one atmosphere ·003 A. should be added, which would bring the result to +·018 A. for both centre and limb, but the Kodaikanal results are of low weight, owing to the small number of spectra measured and the relatively low dispersion of the grating plates.

It is probable that the mean value now obtained is itself an under-estimate, owing to

* *M.N.*, 91, 267, 1931.

the slight tendency of the D emission lines to move towards red after the tube has been running for many minutes, and especially in an old tube that is nearly worn out. In the 1945 series I have used a new tube, run for short intervals, and this may account for the larger values shown in the Table. If this value +·018 A. is the true limb-shift of D_1, it implies an excess over relativity of ·0055 A., which compares with the excess shift of the iron and calcium lines in the H and K region, which I have found to be ·006 A. Any excess shift near the limb, or "limb effect", cannot be explained as a Doppler effect, since that would imply a recession of gas at opposite points on the limb, in other words an Earth effect. It therefore remains an outstanding discrepancy, implying a larger shift than general relativity predicts.

The Solar Rotation.—The values of V_0 shown in Table II are the results of measures obtained at the solar equator and at various latitudes between 0° and 30°, and these last have been reduced to the equator by means of a table constructed from the formula $(1{\cdot}50 + 0{\cdot}54 \cos^2 \phi) \cos \phi$ which represents the change of velocity with latitude with sufficient accuracy. The results are in good agreement in the three years, the mean for the total of 116 measures being 2·028 km./sec. This, compared with 1·94 km./sec. obtained at Kodaikanal in 1922–23 from iron lines in the violet region and 1·92 km./sec. from the Mt. Wilson measures between 1919 and 1924, indicates the increase in velocity with height above the photosphere, the sodium lines representing a higher level in the reversing layer than the iron lines. This increase applies also to the angular speed, for if the sodium line represents an increase of the solar radius of as much as 5000 km. compared with the level represented by the iron lines, the daily angular motion at the sodium level would be 14°·25 compared with 13°·73 for the iron region. Still larger angular speeds I have found with the hydrogen line α in the chromosphere, and with H and K in the prominences.*

Large variations occur in each series of measures, ranging between 1·9 and 2·2 km./sec. These are due to abnormal values at one or both limbs; and there is a tendency for a succession of high or low values to last for several days when the climate allows of a continuous daily record. It has been found in previous measures of rotation at different levels in the Sun's atmosphere that turbulent motion, causing variations in rotation, increases with height above the photosphere, culminating in the prominence region where the highest mean angular speed is found, and also the greatest irregular motion.

The limb spectra have all been photographed a short distance within the limb, usually at 0·98 from the centre. They have been secured under favourable atmospheric conditions, when the sky was free from thin diffusive clouds which have the effect of superposing light from the much brighter central part of the Sun's disk on the fainter light near the limb; but how much the rotation figures given in the table may still be affected by atmospheric scattering, even in a pure blue sky, could only be determined by measures obtained at high mountain stations, where for instance the corona may be photographed by Lyot's method.†

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* *M.N.*, 85, 609, 1925, and 95, 509, 1935.

† The effect of atmospheric scattering in altering the position of D_1 in the spectrum of the Sun's limb would appear to be quite negligible when the sky is clear, from the following experiment: a full exposure is made on the limb spectrum, but with the slit of the spectrograph crossing the limb and extending out into the sky beyond. When there is no diffusive cloud, no trace of the sky spectrum will appear on the photograph outside of the well-exposed limb spectrum. The superposition on the limb, therefore, of sky light which is too faint to make any impression on the plate, could not, it would seem, affect the position of the D line.