On some Spectrographic Measures of the Solar Rotation, made at the Kodaikánal Observatory. By J. Evershed and T. Royds, D.Sc.

During the dry seasons of 1911 and 1912 advantage was taken of days of exceptional clearness, when the sky appeared quite free from diffusive cirrus cloud, to obtain high dispersion spectra of the east and west limbs of the Sun and of the centre of the disc, for the purpose of studying the displacements towards the red of certain lines of iron and nickel at the Sun's limb.

The method of successive exposures was adopted, a plate being given a short exposure to the centre of disc spectrum, then a long exposure to the limb spectrum, and finally a second short exposure to the centre spectrum. The solar image was moved on the slit plate to the required position for each exposure, and Rowland's device of a movable slot immediately in front of the photographic plate was used to prevent overlapping of the limb and centre spectra. In this way two spectra representing the centre of the disc were obtained on either side of a central strip representing the limb.

Two series of exposures were made on each plate, one giving the spectrum of a point near the east limb, and the other a point nearly opposite on the west limb. Owing to the general displacement of the lines in the spectrum of all parts of the limb to the red as compared with the spectrum of the centre, the rotation displacements at the west limb are in general apparently greater than those at the east. If the spectra represent points at opposite ends of a solar diameter, and therefore in the same latitude, it may be assumed that half the difference of shifts (west-east) represents the limb displacement, and half the sum of the shifts the rotation displacement.

In the series of plates obtained it was intended to measure first the displacements in a few of the best-defined lines of each plate and get out the rotation velocity, merely as a check on the reliability of a plate, before proceeding to determine as accurately as possible the very minute limb displacements; for it was found that in a few cases, owing perhaps to unequal heating of the jaws of the slit, or to temperature changes in the grating during the successive exposures, the values of the rotation speed, after the usual corrections, differed considerably from the accepted values.

In most cases, however, fairly consistent values were obtained, and if a plate gave a result within about 10 per cent of Adams' values, it was considered suitable for estimating the limb shifts. This rather wide allowance was made because it was found that all the plates gave consistently smaller values than Adams of the order of 5 per cent.

At first this was considered to be due to some instrumental cause, and the spectrograph was improved in various ways in the direction of increasing the stability of the different parts. After this some high-dispersion spectra were obtained and measured of the a group of lines in the red, including the lines used by Dunér and Halm in their measures of the solar rotation. In these spectra the stability of the apparatus is proved by the telluric lines, which remain unshifted in the successive exposures. In the measures, however, the solar lines were referred to the telluric lines instead of measuring the direct displacements, so that there could be no question of a temperature effect.

The results from these plates (years 1911 and 1912) again showed smaller values of the rotation than those obtained by Adams in 1908.

The plates were not, however, as consistent amongst themselves as could be wished, the values ranging from 90 to 99 per cent. of Adams' values, and doubts still remained as to the possibility of errors arising from diffusion at the surfaces of the mirrors, there being four reflexions from silvered surfaces before the light reached the slit. The effect of these might be supposed to be the same as that of a diffusive sky in causing light from the whole disc of the Sun to enter the slit together with light from the limb.

The hypothesis that the Sun had actually slowed down in rotation speed, or that strong easterly winds prevailed in the region of the reversing layer, appeared to be less probable than that some error affected our results.

In the autumn of 1912 it was decided to make preparations for a new campaign in the approaching dry season, and to arrange for *simultaneous* exposures for east limb, west limb, and centre of disc. An 8-inch objective acquired from the Poona Observatory was substituted for the concave mirror previously used to form the solar image, and a large reflexion prism directs the light on to the slit, with a concave lens interposed to enlarge the image to 60 mm. diameter.

The diffusion of light with this arrangement is noticeably less than with the concave mirror and convex enlarging mirror previously used, and is probably less than is produced by the two cœlostat mirrors and concave mirror of the Snow telescope at Mount Wilson.

A special piece of apparatus was constructed for reflecting the light from two opposite points on the Sun's limb and from the exact centre of the disc on to the spectrograph slit, so that the spectra from the three sources may be photographed simultaneously, special adjustments being provided for securing perfectly equal and uniform illumination of the grating from the different sources.

The main purpose in view was the measurement of the limb displacements, but it was felt that reliable values of the solar rotation ought to result also from the measures.

It was at this stage that we learned of the interesting results obtained by Dr. Hubrecht at the Cambridge Observatory. His results agree with ours in two ways, first in the lower equatorial speed found as compared with the usual values,* and secondly in the unexpectedly large variations between plates obtained at different dates.†

In view of the possibility of a real change of velocity between times of maximum and minimum sun-spots, and of real variations due perhaps to easterly or westerly currents in the reversing layer, it was resolved to take a series of plates during the early months of 1913, with the special object of measuring the equatorial speed with the greatest attainable accuracy, and it is the purpose of this communication to give a preliminary statement of the results obtained, and to draw attention to the apparent inconstancy of the rotation velocity when determined spectrographically.

A more complete statement of our results and a full description of the spectrograph employed must be deferred until all the observations for the year have been worked out, when they will be published in an Observatory Bulletin.

Observations in 1913.

Three series of spectra have been obtained covering the period January–April 1913.

Series I. were obtained with a special reflecting device, placed in front of the slit of the spectrograph, to enable simultaneous exposures to be made on the electric arc and the Sun.

The large concave mirror was used to form the image, which was enlarged to 120 mm. diameter by means of a convex mirror. The arc lines appear on either side of a narrow strip of spectrum representing a point on the Sun about $\frac{1}{24}$ of the radius inside the limb. Two spectra are photographed on each plate, one representing the east and the other the west limbs at latitudes not exceeding 8 degrees from the equator.

Series II. were obtained with the 8-inch object-glass to form the image and the reflecting device for simultaneous exposures on east limb, centre of disc, and west limb. The solar image is enlarged to 60 mm. diameter on the slit plate, and the limb spectra represent points usually $\frac{1}{30}$ of the radius inside the limb and at latitudes from 0° to 15°. The arc spectrum of iron is impressed on either side of the solar spectra.

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* Observatory, December 1912, p. 421.

† *Monthly Notices*, vol. lxxiii, p. 15.

Series III. are similar in every respect to Series II., excepting that there is no central strip of spectrum representing the centre of the disc, the two limb spectra being contiguous.

In Series II. and III. the arc spectra are not photographed simultaneously with the solar spectra; they are used for the purpose of determining the correction to be applied for inclination of the micrometer thread to the spectrum lines.

As micrometer makers do not supply a ready means for rotating the thread, its adjustment exactly parallel with the spectrum lines is practically impossible, and serious errors may result if the exact inclination is not carefully measured and allowed for. The Fe arc lines afford an excellent means for doing this.

In Series I. the spectra on either side of the central strip being similar, no corrections for inclination of the wire are needed, settings being made on the arc line at equal distance above and below the solar spectrum.

It is evident that in Series I., in which each limb is separately compared with a terrestrial spectrum, the probable error of a velocity determination will in general be larger than in a measurement made when the opposite limbs are directly confronted, and the displacement is the result of twice the rotation speed. We considered, however, that it was of great importance to secure this series of plates and compare the results with Series II., taken on the same days but under somewhat different instrumental conditions. The method is analogous to that adopted by Dunér and others, who used the lines of terrestrial oxygen as intermediaries or standards of reference, but it has the advantage that the much sharper solar lines in the violet region can be used, and a higher order of spectrum utilised than is convenient for the red end.

It was hoped that by a comparison of the two methods adopted systematic errors affecting either might be detected, and it might also be possible to determine whether the large variations of velocity at different dates, previously found by the alternate method of exposure, were real or due to systematic errors.

The spectra were all taken with a Rowland grating of 3¼-inch ruling and 14438 lines to the inch, the 3rd order being used throughout. The scale of the plates varies considerably in different regions; 1 mm. is equal to 0·82 Å near K, and 0·55 Å near D.

Each plate includes a length of spectrum equal to about 100 Å.U. As it was desired to utilise Series II. for determining limb displacements over a great range of spectrum, it was found convenient to photograph the entire region from λ 3900 to λ 4800 in all three series, and after this had been done a number of plates of Series II. and III. were taken in the region λ 5300 to λ 5600. It was hoped that the different lines might give more consistent values of the rotation speed in this less refrangible region, since the linear dispersion and also $\Delta\lambda$ increase towards the larger wave-lengths. It was found, however, that the probable error of a velocity determination is about the same in the green region as in the violet near "K," notwithstanding the smaller displacements in the latter region. This may be accounted for by the extremely good definition and narrowness of the lines in the violet.

The plates were measured and reduced by four observers, using two photo-micrometers by Hilger. Some of the plates of the green region were measured very successfully by sliding a positive copy on the negative, by means of a special piece of apparatus which can be attached to one of the micrometers. By this method, a full description of which will be published shortly, the intervals measured are double those between the displaced lines, or, for Series II. and III., four times the displacement due to the rotation speed of the Sun.

In the reduction of the measures a dispersion curve has been drawn for each plate and separate dispersion factors determined for each individual line. This is necessary, because the spectra are far from being normal and the change in 100 units is considerable.

In Table I. the results are given for the plates of Series I. and II., and in Table II. those for Series III. and II. In columns 4 and 5 of these tables *v* represents the observed velocity in kilometers per second corrected to the limb and for inclination of the Sun's axis to the line of sight.

TABLE I.

Deduced Sidereal Velocity at Equator (V) *for Series I. and II.*

Date.	Region.	ϕ.	Series.	*v*.	V.	Measurer.
1913.						
Jan. 13	4760 – 4660	7°·5	I	1·804	1·973	R
13	,,	4·1	I	1·812	1·964	R
16	,,	3·6	I	1·876	2·026	R
21	,,	3·0	I	1·843	1·991	R
21	,,	2·0	I	1·800	1·945	R
22	,,	0·1	I	1·882	2·024	R
28	4640 – 4530	0·6	I	1·762	1·904	R
30	,,	0·4	I	1·848	1·990	R
31	,,	2·6	I	1·952	2·098	R, E, N, and F
Feb. 4	,,	2·6	I	1·799	1·945	R
4	,,	2·2	II	1·858	2·003	E
5	4530 – 4420	6·5	I	1·860	2·022	R
5	,,	1·7	II	1·773	1·917	R
6	4410 – 4310	4·7	I	1·810	1·963	R
6	,,	0·5	II	1·818	1·960	R
6	4522 – 4427	5·4	II	1·800	1·956	F
7	4410 – 4310	2·0	I	1·873	2·017	R
7	,,	8·9	II	1·754	1·932	F
8	4290 – 4190	4·6	I	1·758	1·910	R
8	,,	0·6	II	1·794	1·936	R
10	4200 – 4070	2·1	I	1·746	1·890	R
10	,,	3·2	II	1·822	1·969	R
13	4080 – 3970	5·2	I	1·710	1·864	R
13	,,	0·6	II	1·764	1·906	R
13	4200 – 4070	5·6	II	1·855	2·011	R

TABLE II.

Deduced Sidereal Velocity at Equator (V) *for Series III. and II.*

Date.	Region.	ϕ.	Series.	v.	V.	Measurer.
1913. Mar. 11	3906 – 3971	10°·6	III	1·767	1·958	F
14	3990 – 4107	6·3	III	1·795	1·953	E, F
14	3998 – 4009	0·2	II.	1·867	2·007	F
15	4118 – 4232	0·0	III	1·819	1·959	E, F
15	4232 – 4294	6·7	III	1·759	1·919	F
19	4376 – 4466	2·5	III	1·826	1·969	F
19	,,	0·1	III	1·835	1·975	F
19	4494 – 4590	13·0	III	1·709	1·924	F
20	,,	0·0	III	1·833	1·972	F
20	4603 – 4700	5·1	III	1·757	1·908	F
21	3906 – 3971	5·3	III	1·842	1·995	F
22	,,	1·4	III	1·863	2·003	F
26	,,	3·0	III	1·818	1·961	F
27	,,	14·4	III	1·736	1·968	F
28	5500 – 5000	0·1	III	1·730	1·868	E, F
Apr. 1	5346 – 5410	6·8	III	1·722	1·882	E
4	5569 – 5624	10·3	III	1·728	1·915	E, F
5	5562 – 5624	3·5	III	1·782	1·926	E
6	5569 – 5624	1·4	II	1·807	1·945	E, F
10	5543 – 5615	5·2	II	1·750	1·901	F
12	,,	15·6	II	1·591	1·838	E
12	,,	0·9	II	1·759	1·896	F

In the column V these values have been converted to sidereal velocities with the aid of Dunér's tables, and reduced to the equator on the assumption that the formula $(1{\cdot}507 + {\cdot}546 \cos^2\phi) \times \cos\phi$ derived by Adams from his observations in 1908 represents the change of velocity with latitude with sufficient accuracy.

The last column in the tables gives the measurer's initial, E, F, N, R, designating Evershed, Miss Feline, Nagaraja, and Royds.

No large systematic differences between the observers have been found, and in five plates of Series II. and III. measured in duplicate by E and F, four agree within 0·005 km./sec. and one gives a difference of 0·031 km./sec. All the plates have been measured in both directions, viz. with the end towards the red to the right hand, and to the left on the micrometer.

As regards the lines used, in Series I. we were limited to the lines of Fe and Ni produced in the arc. In Series II. and III. the best-defined lines were selected, and include the following elements: Fe, Ni, Ti, Sc, Cr, Ca, V, Mg, Zr. We have not so far detected any systematic differences between different elements, and the variations from line to line seem largely due to accidental errors of measurement, although in some cases we have strong reasons for suspecting errors peculiar to certain plates, due possibly to irregular shrinking of the film in drying.

The agreement between the plates of Series I. and II. obtained during February is not very good, although the mean results agree within 0·01 km./sec. It may be remarked, however, that there is always a difference of many degrees in the heliographic positions of the points photographed, more difference in fact than appears from the latitude column in Table I., because the points photographed on the same day by the two methods will usually be on opposite sides of the solar equator. It is conceivable, therefore, that a local current in the reversing layer may affect one plate and not the other, obtained on the same day but perhaps half an hour later, when the image will have rotated through several degrees.

We believe that there can be no serious errors in the latitudes determined for each plate. These are computed in the same way as is done daily for the prominence plates photographed with the spectroheliograph, and these are checked by visual observations with an equatorial telescope and position circle. The spectroheliograph is fed by the same siderostat which supplies light to the spectrograph, and the hour angle of the Sun at the time a photograph is obtained affords the datum for computing the position angle of the vertical point on the solar image. This is done with the aid of convenient tables giving the position angles corresponding with different hour angles and dates. The tables have been prepared from the formulæ of Cornu.*

Probable Errors.—The probable error of a plate for Series I. is approximately ±0·03 km./sec., where about seven lines are measured. For Series II. and III., in which ten to fifteen lines were measured on each plate, it is of the order of ±0·015 km./sec. More accordant values for the different lines are obtained by the method of sliding a positive copy on a negative, and the average p.e. of six such measures is ±0·009 km./sec., the best plate giving ±0·0045 km./sec. for twelve lines, and the worst (underexposed) ±0·015 km./sec. for eleven lines.

The probable error for a single line for Series I. is about ±0·08 km./sec.; for Series II. and III. the average of nine determinations is ±·052 km./sec., and the average of six determinations by the positive on negative method is ±·032 km./sec. The discordance between the different plates is of about the same order as that between the different lines on a plate for Series II. and III.

Results for the Different Months.—The statement in the last paragraph shows that the variations from plate to plate are not due to errors of measurement. As we can discover no instrumental cause, we conclude provisionally that real variations occur.

For convenience of comparison with results which may have been obtained at some of the co-operating observatories of the Solar Union, we group the results for the four months January to

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* *Astrophysical Journal*, xi. 148.

April 1913 as follows, giving probable errors derived from the accordance of the different plates in a group.

Mean of	9 plates,	Jan. 13 to 31,	Series I.	V = 1·990	km/sec.	± ·0124
,,	7 ,,	Feb. 4 to 13,	,, I.	V = 1·944	,,	± ·0155
,,	9 ,,	,, 4 to 13,	,, II.	V = 1·953	,,	± ·0077
,,	15 ,,	Mar. 13 to 28,	,, III.	V = 1·956	,,	± ·0065
,,	7 ,,	Apr. 1 to 12,	,, II. and III.	V = 1·900	,,	± ·0087

It may be noted that all these values are considerably lower than Adams' results for 1908 (V = 2·053 km./sec.) :—

Series I.	January	being	3	per cent. lower.
,, I. and II. . . .	February	,,	5	,, ,,
,, III.	March	,,	5	,, ,,
,, II. and III. . .	April	,,	7½	,, ,,

There seems strong evidence here of a progressive change, which, however, cannot be followed up effectively at this Observatory, owing to diffusive skies which are commonly prevalent after April and continue with very few days of sufficient clearness until December.

The large reduction of velocity in April coincides with a change from the violet to the green region of the spectrum. While admitting that we should have had greater confidence in the April results had we continued photographing in the violet, we can yet discover no reason why the less refrangible region should give systematically low values. The plates are excellent in definition and contrast, and are not difficult to measure. On April 4, without moving the grating, a plate was obtained of the fourth order violet overlapping the third order green. This was measured, and eleven lines in the region 4182–4126 gave the value V = 1·904 km./sec. ± ·0075, which is in agreement with the average results obtained from the green region.

Conclusions.—The possibility that large proper motions in the reversing layer may affect rotation measures has been discussed by Adams, who found differences of the order 0·13 km./sec. at the equator in the neighbourhood of sun-spot disturbances.*

Our results, so far as they go, would appear to indicate that variations amounting to 2 or 3 per cent. are of frequent occurrence at a time when there are very few spot disturbances. Larger progressive changes are also indicated, so that it is not possible to derive reliable values of the equatorial velocity from observations extending over a few months.

A possible connection between rotation speed and sun-spot disturbances may be worth mentioning. A small sun-spot was on the east limb at latitude + 15° on January 14, another on the west limb at lat. − 14° on January 16, and a third on the east limb at

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* *An Investigation of the Rotation Period of the Sun*, p. 122. Mount Wilson Solar Observatory Papers, vol. 1. part 1.

lat. − 11° on January 22. No more low latitude spots occurred until April 5, and this one disappeared before reaching the limb. The rotation results give high values for January, and the highest of all on January 16 and 22, when spots were very near the limb and not far from the region photographed.

It is suggested here that there may be a relation between higher rotation speeds and the development of spots; and that times of maximum spot development correspond with high values of the rotation, or rather, it should be said, large proper motion of the reversing layer in the direction of the Sun's rotation.

The interesting results of Mr. Hubrecht's latitude observatio made in June 1911 seem favourable to this suggestion. By h method of observation he was able to discriminate between the tw hemispheres of the Sun, and he obtains a larger rotation velocit in the southern hemisphere than in the northern.* During 19 the southern hemisphere was far more active in spot productio than the northern.

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