The Solar Rotation and the Einstein Displacement derived from Measures of the H and K Lines in Prominences. By J. Evershed, F.R.S.

In *Monthly Notices*, **85**, 608, values of the solar rotation are given derived from spectrographic measures in the reversing layer, the chromosphere, and the prominences. These show a general increase of angular speed with height above the photosphere; the prominences with a mean height of 46″ yielding a daily angular motion of 16°·8 at the equator, corresponding to a complete rotation in about twenty-one days.

The prominence results were derived from measures of the H and K lines in 61 prominences photographed in the years 1908–11 at Kodaikanal. The result was considered to be somewhat doubtful, owing to the large individual motions of the prominences, even when those of a quiet type were selected for the measures.

During the past year about 200 spectra of prominences have been photographed at Ewhurst, and the results of measures of a selected series of these plates give a striking confirmation of the previous results, and they are of interest also in giving a value of the general displacement towards red (Einstein effect), free from the disturbing effects which may alter the wave-lengths of lines in the reversing layer. On the other hand, the results are subject to a larger uncertainty than is the case with measures of lines in the reversing layer, owing to the very considerable random motions of the prominences, movements which disturb all regions of the Sun's atmosphere, and, as recorded in my paper referred to above, appear to increase in amplitude with height above the photosphere. It is on the assumption that these motions may be treated as accidental, and are not systematic with reference to the direction of the Earth, that the results of this paper are based.

Before giving a *résumé* of the measures, I will briefly describe the instrumental equipment and the methods employed in photographing the spectra and in measuring the plates.

The spectroheliograph of the Pitch Hill Observatory is designed primarily for photographs of the Sun's disc and limb in monochromatic $H\alpha$ light. It is constructed of parts which I made for use in Kashmir in 1916, and the two prisms of 6-inch aperture and 45° angle, which served in Kashmir for photographs in calcium light with a relatively short camera and single transmission, are now again employed, after having been re-annealed by the Parsons Optical Company and refigured by Messrs. Hilger. These prisms are now probably the finest that have ever been produced of this size, and give excellent definition if kept under perfectly uniform temperature conditions. The spectroheliograph is auto-collimating; a plane mirror placed behind the two prisms returns the light through them, doubling the dispersion. The collimator is a simple lens of meniscus form and 16 feet focal length. The concave rear surface has the convenient property of returning the reflected white light to a focus at the first slit, and in fact returning it to the Sun through the slit if the squaring-on adjustment is made accurately, but in any case eliminating it from the spectrum. A plane mirror placed near the first slit, and to one side of the incoming beam of light, reflects a short section of spectrum to the second slit of the spectroheliograph, and a second movable mirror is used to intercept a portion of the spectrum and reflect it to a photographic plate. Small secondary reflectors are also used, by means of which the $H\alpha$ line and the prominences can be observed with an eyepiece, and when used as a spectrograph a part of the spectrum on the redward side of the region to be photographed can also be seen and adjusted to the correct position.

The instrument is mounted in a room the floor of which is about 10 feet below ground-level. It is fed by a 15-inch Cooke cœlostat mounted 4 feet above ground, or 10 feet above the spectroheliograph. A second mirror placed a few feet to the south of the cœlostat reflects the sunlight to a 6-inch achromatic lens, also by Cooke, of 20 feet

9 inches focus. After a third reflection, the image of the Sun formed by this lens is projected on the slit-plate of the spectroheliograph; it is about 60 mm. in diameter, with the north point always at the top, and the vertical slit always touches the east or west points of the Sun when tangent to the limb.

The instrument is provided with three primary slits of fixed widths, which can be used alternatively: first, a circular slit 0·6 mm. wide, for observing the prominences over a large arc of the limb; secondly, a slit of the correct curvature and 0·1 mm. wide for spectroheliograph work; and thirdly, a slit of lesser curvature and 0·03 mm. width for photographing spectra. The curvature is arranged to give perfectly straight spectrum lines, which is a convenience in measuring displacements. Used as a spectrograph, the instrument is very well adapted for solar and terrestrial comparison spectra, owing to the stability of the parts, and especially to the fact that the prisms, mirror, and lens are mounted together in a partly enclosed recess in the end-wall of the room, forming what is virtually a constant-temperature chamber situated about 5 feet underground. Under these conditions, long exposures can be made without fear of shifts due to temperature changes.

The routine work on a clear morning is first to survey the east and west limbs in Hα light with the circular slit, if possible within an hour of sunrise. The positions of prominences observed determine the subsequent proceedings. Photographs in Hα light are then taken, showing the prominences at the limb and on the disc. As soon as these have been developed, the Sun will have risen to a more favourable altitude for work in the H and K region. The narrow slit is substituted for the spectroheliograph slit, and observations are made of the character of the Hα line in any prominence that may be in a favourable position. The height of the prominence above the limb is estimated by means of lines ruled on the slit-plate, spaced at intervals from the slit corresponding with 30″ of arc. The spectroheliograph is then converted into a spectrograph, which involves four simple operations, occupying in all about a minute of time. The image of the Sun on the slit is then observed in a small telescope by reflection from an unsilvered mirror; it is adjusted so that the slit will bisect the prominence at a known height, the exposure is then begun. After from two to four minutes the light from the Sun is intercepted, and an image of the iron arc is projected on the slit. A tongue of metal is made to cover the central part of the slit where the prominence was. This is necessary, as the calcium lines are usually present in the iron arc spectrum and would be superposed upon the prominence lines. After a two-minute exposure on the arc, using a ground-glass diffusing screen in front of the slit, exposure on the prominence is resumed, and continued for the same number of minutes as before. Guiding is necessary in all exposures exceeding a minute in duration, and this is easily effected by means of a large screw, which operates the moving parts of the spectroheliograph against a 50-lb. weight: this simultaneously moves the 6-inch object-glass, which is mounted on a carriage running on rails. In this way a very delicate and satisfactory guiding is effected.

For prominences found at some position-angle other than about 90° or 270° the slit has to intersect a portion of the Sun's disc, and a more or less inclined or radial section of the prominence is obtained. In this case the height at any point in the spectral image can be ascertained from its distance from the edge of the solar spectrum, and the angle at which the slit and limb intersect.

The heliographic latitudes are obtained from measures of the spectroheliograph images photographed earlier in the day.

The spectra have a dispersion at H of 1·3 mm. to the angstrom, and in these high-dispersion prism spectra the dispersion may be assumed to vary linearly with the wave-length over a length of about 50 angstroms: the reduction of the measures is therefore as simple as with grating spectra.

Numerous iron arc lines are shown on the plates, but it is only necessary to measure four of these to determine the scale and the factors necessary in computing the apparent wave-lengths of H and K. The following lines, which are not subject to appreciable pole-effect, have been used throughout:—

3920·261,
3930·300,
3969·262,
4005·248.

In some plates the line 3969 is over-exposed, and when this occurs the line 3967·424 is substituted. These lines are from the list of Tertiary Standards published in the *Transactions of the Astronomical Union*, **1**, 43.

The normal wave-lengths in air of H and K are assumed to be as determined by St. John,* viz.:

K 3933·667,
B 3968·476.

These depend on interferometer measures by Fabry and Buisson of iron lines in the neighbourhood, but no correction seems necessary to reduce them to the tertiary standards quoted above.

The measures have been made on a remodelled Hilger micrometer, in which the screw moves a carriage to which the plate is clamped and the microscope of special design is fixed.

In measuring the plates, I have found it necessary to classify the spectra according to the general character of the H and K emission lines. In Class A the lines are narrow, well-defined, and straight; in Class B they are either broad or diffuse, or irregularly bent and displaced, so that measures cannot be made with satisfactory precision. In Class C the displacements and irregularities are so great that only rough estimates can be made of the limiting velocities of the flying masses of gas. These plates are useless for the purpose of this research, and those of Class B have very little weight unless an enormous number is averaged.

The displacements of the prominence lines compared with the above values of H and K are tabulated separately for eastern and

* *Astrophysical Journal*, **81**, 152.

western prominences. It is then found that the western shifts almost invariably exceed the eastern by a considerable amount, half the difference W−E giving the general shift of these lines towards red, whilst half the sum of the shifts W+E gives a value of the solar rotation.

Rotation Results.—Of the whole number of spectra photographed, 92 are of Class A, 45 representing the east limb and 47 the west. The latitudes range from the equator to latitude 44°. In Table I. the mean shifts are given in angstroms of all the western and all the eastern prominences of Class A. The resulting rotation velocity in km./sec. is also given, with the correction to reduce it to sidereal velocity.

TABLE I.

Mean Shifts from all Measures of Class A Prominences.

	K.		H.	
West . . .	+·0420 A		+·0424 A	
East . . .	−·0242 A		−·0251 A	
Half sum . .	·0331		·0337	
Mean		·0334 A		
Equivalent to				2·67 km./sec.
Corrections for revolution of Earth and inclination of Sun's axis				+ ·14 ,,
Sidereal velocity				V=2·81 km./sec.

Mean latitude 18°.

Mean height 29″.

The sidereal velocity here shown is about 1 km./sec. in excess of the normal velocity in the reversing layer at latitude 18°, and, allowing for the mean height of 29″, it corresponds with a daily angular speed of 20°.

A subdivision of the results into four zones of latitude brings out irregularities, due to the random motions of the prominences: it also reveals a tendency to a polar retardation of angular speed, although a considerable modification in the figures would probably result from a larger number of measures. Omitting the separate values of H and K in angstroms, and tabulating only the corrected values, V, of the observed velocities, and the daily angular motion, ξ, results are obtained as in Table II.

TABLE II.

Rotation in different Latitudes at a Mean Height of about 28″ in each case.

No. of Spectra	ϕ.	V.	ξ Prominences.	Spots.
33	8°	3·17 km./sec.	22°·1±1°·1	14°·4
25	18	2·29 ,,	16·6±0·8	14·1
26	25	2·59 ,,	19·7±1·4	13·9
8	35	1·99 ,,	16·8±1·8	13·5

It is seen that each zone gives an angular speed greatly in excess of that observed for sunspots, and spectrographic measures of the reversing layer give still smaller results, that is about 5 per cent. less than the sunspot values. The relatively high value of ξ at 8° and the low value at 18° is mainly due to the eastern prominences, which have been more erratic in their movements than the western. Taking the western alone, and subtracting the average shift to red given by all the measures, the results are more uniform ; but whether we take the western or the eastern prominences separately, or together, each zone in every case gives a rotation value in excess of the corresponding values derived from spots or the reversing layer, and it seems clear from these different groupings that the accidental movements tend to cancel out even in a quite small number of measures of spectra of Class A.

The probable errors in ξ are derived from the residuals of individual measures in each group, taking the mean results given by H and K. The measuring errors are therefore relatively small, and the departures from the mean values are mainly the accidental motions of the prominences.

The rapid angular rotation is apparently not confirmed by direct observation of prominences at the limb, for in the case of those that outlast one or more rotations they may be observed to recur on opposite limbs after intervals of approximately 13 or 14 days, in agreement with spots, and this is sometimes clearly shown when a prominence appears as an absorption marking that can be identified when near the meridian in successive rotations. Such a marking was photographed at Kodaikanal in the year 1910, and observations during three successive apparitions gave a mean daily speed of 14°·4, in close agreement with spots. Yet measures of the same marking from day to day indicated a considerably larger angular speed. The marking was also intermittent in visibility, disappearing completely after some days and then reappearing in a more easterly position.* This seems to indicate that it is the point of origin of a prominence that rotates with the speed of the photosphere, while the prominence material is driven westward over the Sun, like smoke from a chimney.

An interesting case of a prominence detached from the Sun and floating entirely free at a height of 45,000 miles above the photosphere was observed on the 23rd and 24th of August 1927, on the north-west limb. The densest part of the cloud gave sharp undistorted lines (Class A), whilst in the highest portion the lines were much widened and diffused. Measures of the sharp lines gave the following results, after subtracting the general shift towards red, and adding the usual corrections :—

ϕ.	H.	V.	ξ.
+18°	100″	+3·06 km./sec.	21°

So far as could be judged on both days, it had no appreciable ascending motion, but increased in apparent altitude between the 23rd and 24th by reason of the rotation. The line-of-sight motion was somewhat greater on the 23rd. This object therefore appeared to be moving in

* *Astrophysical Journal*, **33**, 1. See also D'Azambuja, *Comptes rendus*, **176**, 950.

an orbit outside the Sun, with an angular speed considerably greater than that of the Sun, yet not nearly fast enough to maintain it in a circular orbit under gravity. The cloud could only maintain its position by radiation-pressure or other outward force. It is to be noted that in such cases, and indeed in all prominences, the atoms of hydrogen, helium, and calcium appear to be without distinction balanced against gravity: there is no segregation of these elements.

General Shift of H and K Lines in the Prominences.—The shift of the lines towards red may be shown, as a first approximation, by taking all prominences of Class A, irrespective of latitude, and subtracting the mean eastern from the mean western shift, as given in Table I. Thus we get:

	K.	H.
Half difference W − E	+·0089 A	+·0087 A
Mean . . .	+·0088 A	

This assumes that the eastern and western prominences have the same distributions in latitude, which is only approximately true. It is perhaps more instructive to group them in the four zones of Table II. Taking the differences W − E and averaging H and K, we get the following results for each zone:—

TABLE III.

Shift of Prominence Lines towards Red.

ϕ.	Mean of H and K. A.	No. of Spectra.
8°	+·0073 ± ·0021	33
18	+·0126 ± ·0015	25
25	+·0090 ± ·0024	26
35	+·0068 ± ·0027	8
Weighted mean	+·0092 ± ·0009	

The irregularities here shown are the counterpart of those in Table II., that is, they are mainly due to the eastern prominences, which give abnormally large total displacements in the 8°-zone, and abnormally small displacements in the 18°-zone. Hence the rotation shift is large and the general shift small in the first zone, and the reverse in the second. The probable errors are derived as in Table II.

This result appears to agree, within the limits of observational uncertainty, with the relativity shift, which is about +0·008 A, but it depends upon the assumed wave-lengths of the terrestrial H and K lines, which were measured at atmospheric pressure. We can only suppose the prominence lines to be emitted at zero pressure, consequently a small correction is necessary in the direction of increasing the displacement. According to the measures of W. J. Humphreys at 42, 69, and 101 atmospheres,* the mean shift of H and K is +·0017 A per atmosphere. Adopting this, we get:

Mean shift of H and K in prominences = + 0·0109 A.

* *Astrophysical Journal*, 26, 21.

The predicted relativity shift is +0·00835 A at the Sun's surface. At 28″ above the surface it reduces to +0·0081 A. There is an outstanding difference, therefore, of 0·0028 A, which seems larger than can be accounted for by errors in the observations.

In the year 1921, a number of limb spectra of the H and K region was obtained in the third and fourth orders of the large Anderson grating at Kodaikanal, and measures of these plates gave results for the chromosphere which are almost in agreement with the above value of the shift in prominences. Thus, for H and K in the chromosphere I obtained the following :—

	K.	H.	Mean of K and H.
10 plates Sun—arc, May 1921	+0·0105	+0·0090	+0·0097 A
Add for ⅔ atmosphere at Kodaikanal			+0·0013
			+0·0110 A

This value depends on the direct measurement of the shifts with reference to the calcium arc, but the measuring errors are likely to be greater than in the prominence measures, because of the width of the chromosphere lines.

For the iron lines in the reversing layer at the limb the shifts are slightly larger. The following mean shifts were obtained from the same series of plates :—

	Limb—Arc
20 Fe lines, 3885 to 3977 inclusive .	+·0102 A
Add for ⅔ atmosphere	+·0014
	+·0116 A

There is very little variation in these 20 lines, only 4 giving values appreciably different from the mean.

It would seem from these results that prominences, chromosphere, and reversing layer, in this spectral region, all conspire in giving values of the shift in excess of the Einstein effect. It is evident, however, that another year's work is called for to reduce the uncertainties due to the irregular movements of the prominences. There is a possibility also of a small error, not exceeding 0·001A, in the assumed relative wave-lengths of H and K and the Fe lines to which they are referred. For this reason it would be better to measure the shift directly, between the prominence lines and the terrestrial calcium lines, and this would simplify the work. In the Fe arc the calcium lines are present, but weak, and there is an iron line so near to K that in most spectra it is blended with it. The carbon arc gives a more satisfactory calcium spectrum, and this will be used in the next series of prominence spectra.

Prominence Spectra of Class B.—Of the total number of spectra photographed, 93 are of Class B, and more than two-thirds of these are of eastern prominences. As in the case of Class A, the eastern spectra show a greater range of displacement than the western, the total range of velocity being 29 km./sec. for the eastern, and

13 km./sec. for the western spectra. The small shifts due to rotation and the Einstein effect are almost entirely swamped by these large velocities, and so no useful results can be obtained by an analysis of the measures. There are, however, some very interesting features in many of these spectra which will be discussed when a sufficient number of plates has been secured.

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