THE SOLAR ROTATION AND SHIFT TOWARDS THE RED DERIVED FROM THE *H* AND *K* LINES IN PROMINENCES.
(THIRD PAPER.)

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The solar rotation derived from measures of the displacements of absorption lines at the east and west limbs of the Sun appears to increase in angular speed with the height above the photosphere. In the reversing layer I have found the stronger iron lines, and the sodium and magnesium lines tend to give rotation values 1 or 2 per cent. in excess of that given by the weaker low-level lines.

In the chromosphere Adams found that the hydrogen line $H\alpha$ yielded an angular velocity 0°·6 in excess of the reversing layer near the equator.* Similarly, measures of 19 spectra of the $H\alpha$ line obtained in 1918 at Kodaikanal gave an excess of 1° over low-level lines in the reversing layer, according to my own measures. Extending the enquiry to higher levels outside the chromosphere, the displacements of the *H* and *K* lines in prominences appear to yield much greater angular speeds.

I have summarized the results from 92 prominence spectra photographed between 1926 August and the end of 1927 in *Monthly Notices*, **88**, 130, 1927, and from 289 spectra photographed during the year 1928 in *M.N.*, 89, 252, 1929. These were years of great prominence activity: according to the Kodaikanal records mean areas and mean numbers of prominences attained their highest values during those years, which was also the case with sunspots. From 1929 to 1934 there was a progressive reduction of activity, prominences becoming less frequent and also less dense, so that many of them failed to indicate their presence on the disc of the Sun as absorption markings. Consequently it became progressively more difficult to photograph their spectra.

During the two years 1929, 1930 I photographed and measured 174 spectra, and in the four subsequent years 227 spectra. In the present paper

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* *Astrophysical Journal*, 29, 145, 1909.

I analyse and compare the results obtained during the entire period from 1926 August to 1934 December.

The autocollimating spectrograph is substantially as described in *M.N.*, 88, 127, with the addition of a 30° reflecting prism of 6 inches aperture lent by the Royal Society, which is used to return the light through the two 6-inch 45° prisms in place of a plane mirror previously used.

A carbon arc giving narrow sharply defined *H* and *K* lines is used to impress a comparison spectrum on the plates, and the small displacements of the prominence lines with reference to the arc lines are measured. The scale of the plates does not vary appreciably except when the temperature of the prism chamber changes, which it does very slowly in the course of a season. As already stated in my previous papers, the scale bears a linear relation to the wave-length over an interval of about 50 angstroms, that is to say, the most accurate measures of standard iron lines in the region fail to indicate any deviation from this relation, and the factors required at *H* and at *K* for converting the measured displacements into fractions of an angstrom are easily derived from the distance separating *H* and *K*. This interval is usually about 35 mm., or approximately 1 mm. = 1 A. midway between *H* and *K*. A higher dispersion up to 40 mm. can be obtained without any loss of definition by setting the prisms out of minimum deviation, and this dispersion has been used for some of the brighter prominences.

As the east and west spectra are not obtained at the same time or date, each individual measure is corrected for the annual and diurnal motions of the Earth in the direction of the Sun, and the resulting shifts, expressed in km./sec., are then corrected for the revolution of the Earth and inclination of the Sun's axis. These corrections were, in the earlier series, obtained from Duner's tables, and later from the more accurate tables of Zagar published in the *Memorie della Società Astronomica Italiana*, vii, 3.

It is assumed that all prominences observed were at the Sun's limb, or 90° from the central meridian. As the distance from the limb cannot be exactly determined, no correction can be applied to the observed velocities, which must be slightly underestimated. On the other hand, the values of the angular rotation will be very slightly overestimated, since they decrease with the height, which also is underestimated when a prominence is not actually at the limb. These small errors in ξ therefore have opposite signs and tend to be annulled.

In any given zone of latitude on the Sun the western prominences give larger apparent rotation shifts than the eastern, owing to the general shift of the lines towards red, the rotation being given by half the sum of the shifts $W+E$ and the general shift by half the difference $W-E$, reckoning the shift as a positive quantity in each case.

The prominences are found mainly between the equator and latitude 55°, and I have grouped them in different zones without distinction between north and south, viz. an equatorial zone with a mean latitude between 7° and 9°, and zones around 18°, 26° and 40°. The limits of these zones are somewhat arbitrarily determined, according to the number of prominences found in the different regions.

TABLE I

Group 1.—1926 *August to* 1928 *September*

No. of Spectra	ϕ	V	H	ξ	$(W-E)/2$
	°	km./sec.	"	°	A.
132	9	2·65	42	18·3	+·0131
76	18	2·34	31	16·9	+·0148
104	25	2·64	35	20·0	+·0128
69	40	1·85	36	16·5	+·0143

Group 2.—1929 *February to* 1934 *December*

No. of Spectra	ϕ	V	H	ξ	$(W-E)/2$
124	8	2·24	26	15·6	+·0128
52	18	1·90	24	13·8	+·0103
108	26	2·08	31	15·9	+·0128
117	40	1·77	31	15·9	+·0055

I give in Table I the results for the entire period 1926 August to 1934 December, divided into two groups in which nearly the same number of spectra were measured. The first group represents a period of great prominence activity in which 381 spectra were measured in two years; the second group, of six years, in which I measured 401 spectra, includes the time of minimum activity.

Confining attention to the values of ξ, it is seen that there is no systematic variation with latitude. There are differences which probably have no real significance. In Group 2 the zone of 18° yields the mimimum value, the other regions in this group giving remarkably constant values.

Assuming that in the long run the angular rotation does not change with latitude, we may take a mean value of the angular speed from a series of observations in all latitudes. Thus, in Table II such means are given, and for the purpose of comparison with the solar activity the entire series is divided into three groups representing different phases in the cycle of prominence activity.

TABLE II

	No. of Spectra	Mean Height	ξ	Mean Daily Number (Kodaikanal)
		"	°	
Group 1, including maximum activity	381	37	18·1	18·9
Group 2, intermediate	174	26	16·0	13·6
Group 3, including minimum activity	227	30	15·2	10·9

The first group includes all the measures from 1926 August to 1928 September, the second includes the years 1929 and 1930, and the third 1931 to 1934 inclusive. From the last two columns it appears that ξ decreases as the prominence activity decreases. It will be of interest to continue the work during the next period of activity, to see if the daily rotation continues at 15° or increases again to 18°.

It is possible that my method of selection of prominences with small individual motions and narrow undistorted lines does not give values of ξ which would apply to prominences in general. This appears to be the case when comparing my results with those of E. Perepelkin. This observer, working with the 3-prism spectrograph attached to the 30-inch Poulkovo refractor has published his results for the years 1928, 1929 and 1930.* Measuring 821 radial velocities in the lines Ca^+ and 689 in the line $H\epsilon$, in which the random motions did not exceed 3 km./sec., he gives the angular motion $\xi = 14^\circ{\cdot}2 - 1^\circ{\cdot}6 \sin^2 \phi$, almost in agreement with the solar rotation from spots and differing entirely from my results. For random motions not exceeding 6 km./sec. he gives the result $\xi = 13^\circ{\cdot}7 - 0^\circ{\cdot}9 \sin^2 \phi$, which suggests that smaller angular speeds are found with prominences having larger proper motions, and this is confirmed by his measures of the same lines in the chromosphere, which is not subject to such large movements as the prominences. For this he gets the value $\xi = 15^\circ{\cdot}7 - 0^\circ{\cdot}5 \sin^2 \phi$, practically in agreement with my results for the prominences during the same period and showing a reduction of 0°·2 only between the equator and latitude 40°.

It may be mentioned that the dispersion of the Poulkovo spectrograph is quite small, only 7 mm. between H and K, or 1/5th of the dispersion of my spectrograph. It is perhaps difficult to believe that reliable mean values can be obtained with such small scale spectra in which the greatest observed shift of the lines at the Sun's equator due to rotation would not exceed ·006 mm., and a difference of 1° in ξ would amount to a difference of ·00036 mm. in the measures. Experience in the measurement of spectra leads me to distrust any figure that depends on differences smaller than 1/1000 mm., even when it is derived from a very large number of measures. Actually the difference in ξ near the equator, Evershed-Perepelkin, is 1°·5 approximately, or on the scale of the Poulkovo plates about half a micron. It appears nevertheless from the results obtained from lines in the reversing layer with the same instrument that the prominence measures may not be affected with a considerable systematic error.

The high speed of rotation obtained by me is apparently not confirmed when the movement of prominences traversing the Sun's disc as absorption markings is measured by successive meridian transits. In the year 1910 I deduced the times of meridian transits of a prominence very favourably situated near the equator, and photographed in calcium light during three successive apparitions. From this I obtained the values $\xi = 14^\circ{\cdot}37$ and 14°·40 from the two complete rotations. This agrees with the values obtained at Kodaikanal from a large number of $H\alpha$ markings between lat. 5° and 10° during the years 1918 to 1929.† I also measured the apparent daily motion of the marking when near the central meridian in 1910 February and again after a rotation in March, and obtained angular motions of 15° and 16°, but this is subject to uncertainty regarding the height above the photosphere at which the absorption takes place.‡

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* *Poulkovo Observatory Circular*, No. 1, 1932.

† *Kodaikanal Observatory Bulletin*, No. 93, 1931.

‡ *Astrophysical Journal*, 33, 1, 1911.

The lack of agreement between my spectrographic measures and the angular motion derived from the times of successive meridian passages of prominences could be explained by supposing that it is the place of origin that rotates with the speed of the photosphere, whilst the prominence gases are driven forward in the direction of rotation and dissipated on emerging from the chromosphere. There is little doubt that the stable prominences are continually being renewed from below, and those of a temporary eruptive type show that the luminosity of a mass of gas cannot be maintained for more perhaps than an hour, or in some cases only a few minutes after it has been projected above the chromosphere.

A possible explanation may now be suggested of the increasing angular speed with height above the photosphere, and of the decreasing speed with decreasing solar activity. This depends upon the fact, I believe fairly well established, that the gases above the photosphere do not form a true atmosphere to the Sun, but consist of innumerable jets of luminous gas projected radially outwards from beneath the photospheric level. If the interior of the Sun is rotating faster than the photosphere, and with a uniform angular speed in all latitudes, then these jets will tend to retain the velocity of the interior regions, and the deeper the origin of a jet the more closely will its motion conform to the angular speed of the interior. The prominences coming from the deepest layers will give the greatest rotation speeds, and the most uniform angular motion. At times of intense solar activity the great prominences, streaming out at definite points in the photosphere, are probably ejected from greater depths than the smaller prominences seen at times of minimum activity. Hence their rotation speeds will be greater, as I have observed in 1927 and 1928.

The observed increase of angular speed with height above the photosphere appears therefore to indicate the opposite condition, namely, an increase of speed with depth below the photosphere.

Shift of the H and K Lines towards Red.—The last column on Table I gives the observed values of the shift (West–East)/2 in the different zones of the two groups. Group 1 includes 92 spectra photographed in 1926–27, and in this series the values of $(W-E)/2$ have been corrected for the error in the assumed wave-lengths of H and K referred to in *Monthly Notices*, **90**, 189. The variation in the different regions probably has no significance excepting possibly in the highest latitudes around 40°, which give consistently low values in all the spectra of Group 2. The mean results of the whole series of 782 spectra are given in Table III, adding the shift due to the

Table III

No. of Spectra	ϕ	$(W-E)/2$	Mean Pressure Shift for 1 atm.	Sun–Vacuum Arc
	°	A.		A.
256	9	+·0129	+·0017	+·0146
128	18	+·0130	,,	+·0147
212	25	+·0128	,,	+·0145
186	40	+·0088	,,	+·0105

pressure of one atmosphere in the arc. These are the mean values of *H* and *K* and the mean pressure shifts of the lines according to the measures of Humphreys.* Actually *K* is shifted more than *H* in the prominences by a small amount, and it is less shifted by pressure in the arc. If the best series of measures is selected, excluding spectra having broad or ill-defined lines, the difference of shift between *K* and *H* is found to approximate very closely to the difference of pressure shift for one atmosphere according to Humphreys. In measuring the spectra I estimate the quality of the line images. Those of Class A are narrow and well defined, whilst Class B are broad and less satisfactory to measure but still considered good enough for estimates of the rotation.

If the two series of measures in all latitudes of *K* and of *H* are compared, rejecting those of Class B, the following mean results are found from 579 spectra :—

	K	*H*
(W−E)/2	+·0115 A.	+·0109 A.
Correction for 1 atmosphere	+·0015 A.	+·0020 A.
Sun—Vacuum Arc	+·0130 A.	+·0129 A.

The year 1928, which proved the most prolific in Class A spectra, gives the following results from 183 spectra :—

	K	*H*
(W−E)/2	+·0130 A.	+·0126 A.
Correction for 1 atmosphere	+·0015 A.	+·0020 A.
Sun—Vacuum Arc	+·0145 A.	+·0146 A.

This seems to confirm the relative accuracy of Humphreys' measures, if the fourth decimal in my results is to be trusted, it implies the fourth place also in millimeters.

The value +·0146 appears from Table III to be a very close approach to the truth for the lower latitudes, but by rejecting Class B measures it would be reduced to +·0140. The mean for all the A spectra including the high latitudes is as given above, +·0130. I do not give probable errors in these figures, as they would have little meaning and might give undue weight to some of the results.

As regards the high-latitude prominences, namely, those exceeding 30°, the high value at $\phi = 40°$ in Group 1 of Table I is very much influenced by prominences of Class B. Excluding these the mean would be reduced by ·003 A., and the mean for the whole series, including 147 spectra at mean latitude 40°, would then be +·0075, or excluding Class B in Group 2 also, 119 spectra give +·0070 A. This may be subject to considerable revision when more high-latitude spectra have been measured. The difference compared with low-latitude results may even turn out to be illusory, but it may be of some interest to note that outside the regions of sunspot disturbance the shift is close to the theoretical relativity shift, which is +·0081 at 30″ above the photosphere.

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* *Astrophysical Journal*, **26**, 21, 1907.

In the reversing layer I have found no evidence of any difference of shift in spectra from low latitudes and from the Sun's poles. In the *H* and *K* region I have measured 15 iron lines in 8 polar spectra, 4 at the north pole and 4 at the south, and the result, limb – arc, corrected for 1 atmosphere is again +·0146. This result, which includes 7 strong and 8 weak lines, agrees with the mean of the strong and weak lines in this region previously measured in low latitudes, and recorded in *Monthly Notices*, 91, 268. The prominence result +·0151 from the earlier measures is probably too large by ·0015 A. Taking the lowest estimate from 579 spectra of Class A in all latitudes, it is still ·005 A. in excess of the relativity shift.

The results of this research may be stated briefly as follows :—

1. The angular speed of rotation for prominences having very small random motions is found to exceed that of sunspots at the equator by at least 1° per day.

2. The speed appears to vary with the general activity of the Sun, being greatest at times of maximum activity.

3. The angular speed is probably constant for all latitudes.

4. An explanation of these results is suggested.

5. The general shift of the *H* and *K* lines in the prominences towards red is approximately +·0146 between the equator and latitude 30°, and +·0075 in higher latitudes. In the reversing layer the *Fe* lines in the same region of the spectrum give +·0146 both at the poles and in low latitudes.

6. The shift of *H* and *K* may be said to exceed the relativity shift by not less than ·005 and not more than ·0065 A.