THE SUN'S ROTATION DERIVED FROM SUNSPOTS 1934–1944 AND ADDITIONAL RESULTS

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Summary

Results are given for the Sun's daily sidereal motion (ξ) derived from 136 single recurrent sunspots for the cycle 1934–1944. The expression relating ξ to solar latitude (ϕ) so derived, $\xi = 14°\cdot38 - 2°\cdot96 \sin^2 \phi$, is in satisfactory accordance with values from similar data for the five previous 11-year cycles. A good internal accordance of measures is found by comparing ξ values derived from a full rotation period interval (27 days) with the mean (ξ_1), given by the two separate disk-passages of the same spot.

From the combined data of six sunspot cycles there appears no measurable variation in the Sun's rotation period (1) with alternate 11-year cycles, (2) within the (mean) cycle itself. Neither do the two hemispheres, north and south, behave differently.

Although not included in the discussion, the derived expression for the daily sidereal motion from non-recurrent spots, 1934–1944, is stated as a point of interest in the Addendum.

Introduction.—The problem of the Sun's rotation still deserves more observational data. Considerable differences in spectroscopic values cannot wholly be ascribed to differences of level in the chromosphere for the particular line or lines used. Moreover, St. John pointed out in 1932* that collective spectroscopic results "show a progressive change in the equatorial rotation determined from the reversing layer during the past thirty years greater than can be attributed to errors of observation". The overall range in the (smoothed) observational values from 1906 to about 1925 is equivalent to no less than two days in the respective rotation periods for the Sun's equator.

Values derived from sunspots are more accordant *inter se*. The range in the equatorial value (a) for the daily sidereal rotation (ξ) at the equator from the expression $\xi = a - b \sin^2 \phi$ given by some half-dozen investigations† is 0°·22, equivalent to about 0·4 day in the rotation period.

Very consistent values over five sunspot cycles (1878–1933) have been given by the Greenwich measures of individual spots of long duration.‡ The range in the value of a does not exceed 0°·04 per day. The dispersions of ξ values in the 5° zones of latitude, into which the data are divided, is also much less than in determinations based on spot *groups* (as in the investigation by Mr and Mrs Maunder §), especially those that are shorter-lived.

In the present paper, the results from recurrent spots for a sixth sunspot cycle (1934–1944) are presented. Over the whole period since 1878 there are now sufficient homogeneous data from at least two of the 5° latitude zones to

* C. E. St. John, *Trans. I.A.U.*, **4**, 43, 1933; see also *P.A.S.P.*, **47**, 295, 1935.

† The smallest value of a is 14°·35 (Spoerer) and the largest 14°·57 (O. A. Akesson).

‡ Royal Observatory, Greenwich, *M.N.*, **85**, 548, 1925. H. W. Newton, *M.N.*, **95**, 62, 1934.

§ E. W. and A. S. D. Maunder, *M.N.*, **65**, 813, 1905. O. A. Akesson, *Medd. Lunds Astronomiska Observatorium*, Serie II, Nr. 11, 1913.

show whether ξ varies within measurable limits (1) alternately from one cycle to the next, as do the magnetic polarities of sunspots, and (2) with the phase of the (mean) 11-year sunspot cycle. Results of this enquiry are stated herein.

Data.—The basic data comprise individual recurrent sunspots tabulated in Ledger I of the *Greenwich Photoheliographic Results* for the years 1934 to 1944. The volumes for 1937 and 1939 are in course of publication, those for 1940 to 1944 being still in MS.

Although the advantages in using stable recurrent spots appear far to outweigh the disadvantages, it is true nevertheless that the non-uniform characteristic motions*, especially of the leader spots of groups, are imposed on the true values of ξ. The present data include a large proportion of leader spots first seen as such or later as the sole survivor of the group, when they would be classified as "unipolar" spots.

Counting each appearance separately, the spots used in this paper were as follows:—

Leader spots (89): Followers (8): Other components (1):
Single spots, i.e. "unipolar" (174).

Any systematic effect from non-uniform proper motion on values of ξ is much reduced by (1) the data including spots in all stages of development, and (2) the use of the long time-interval of a solar rotation for deriving the values of ξ.

Regarding the stage of spot development, the distribution in three broad divisions for the present data is as follows:—

		Number	Mean area†
Phase I	Origin or early development to maximum	63	394
II	Middle life	139	298
III	Late decline (and extinction)	70	71

The time spent in each of the three phases is very approximately in the ratio 1 : 2 : 1. Phase II is sometimes markedly prolonged with a spot of area 200 or 300 millionths.

Derivation of ξ.—The method of reduction as used in earlier Greenwich papers is simply as follows:—

The mean longitude of the spot during its first complete (or part) disk-passage is compared with the corresponding mean longitude at its second appearance. Days on which any spot was $>80°$ from the central meridian are excluded.

If the change in longitude be $x°$ in the interval y mean solar days, then the diurnal angular motion is $x°/y$ relative to a meridian on the Sun having a sidereal rotation of 25·38 days‡ or $14°{\cdot}18_4$ per day, this being the datum adopted in the *Nautical Almanac* for computing the daily values of the longitude of the central meridian. Thus the daily angular sidereal motion, ξ, per mean solar day is $14°{\cdot}18 + x°/y$. In rounding off mean values of ξ to two decimal places of a degree (as in Table I), the correction of $+0°{\cdot}004$, being the excess over $14°{\cdot}18$, has been taken into account.

Observational checks.—The comparison of the mean position of the same sunspot 27 or 28 days apart implies a (close) symmetrical distribution of the measures of longitude with respect to the central meridian. In the case of

* Royal Observatory, Greenwich, *M.N.*, **85**, 553, 1925.

† Areas, corrected for foreshortening, are expressed in millionths of the Sun's hemisphere.

‡ It is perhaps worth recording that this was the period adopted by Carrington because of "its admitting conveniently of much subdivision without remainders". He found later that this value applied to latitude 14°.

incomplete disk-passages of spots, the daily longitudes for comparison at the two epochs were selected so as to make the mean distances from the central meridian (and on the same side of it) correspond as nearly as possible. In this way, any small systematic displacements that may be present in the measures and which are a function of the distance from the centre of the disk will be eliminated. A small systematic error of this nature—zero at the centre of the Sun's disk and a maximum at the limb—could arise from differential foreshortening (not allowed for by the measurer) of the area subtended by the larger spots approaching the limb. This will tend to make the measured distance, r, of the spot from the disk centre smaller than its true value.

Other displacements have been suggested * as arising from (*a*) refraction above the photosphere producing an augmentation of the Sun's radius measured as R (irradiation will also produce an augmentation), and (*b*) a possible "depth-parallax" arising from a difference of level between spots and the effective limb. The combined effect of these possible displacements would tend to decrease the ratio r/R which enters directly into the computation of longitude and latitude of the spot, and thus decreases the derived daily angular motion. Although the use of recurrent spots avoids these systematic errors inherent in single disk-passage determinations, there is occasional uncertainty in the continuity of the longer-lived spots from one rotation to another. A general check is therefore desirable by comparing ξ values given by the same spot from the 27-day interval and the mean value (ξ_1) given by the separate disk-passages. Cases of complete or nearly complete disk-passages only have been included for this purpose. For each of the two disk-passages the mean longitude from the first five days is compared with that from the last five days. Days on which the spot position exceeded 80° from the central meridian are excluded, so that the reduced effect of the small possible displacements considered above would be unlikely to invalidate the check, as such, on the continuity of any particular sunspot.

The distribution of values, $\xi - \xi_1$, from 86 pairs of disk-passages is shown in Fig. 1, which also incorporates the development phases of the spots concerned. With respect to the centre grouping of values, say from $-0°{\cdot}10$ to $+0°{\cdot}10$ (comprising 63 of the 86 values), it may be said that the distribution, when slightly smoothed, is essentially that of a normal error distribution for a probable error of $\pm 0°{\cdot}03$ (single value) and displaced $+0°{\cdot}02$ from the origin.

This small positive asymmetry of $0°{\cdot}02$, which is five times the p.e. of the mean of the above 63 observations, may be real and represent the combined effects of the small systematic errors entering into a single disk-passage determination of the solar rotation.

It may be added that differential foreshortening alone would amount, on purely geometrical grounds, to about $0°{\cdot}01$ in the above derivation of ξ_1 values from circular spots of the average order of 3° in diameter or 350 millionths of the Sun's hemisphere in area.† A systematic error of this order could well arise from the optical distortion of the lens system of a photoheliograph, as instanced by the small corrections used since 1926 on this account for the Greenwich photographs.

* Papers of the International Union of Solar Research, Computing Bureau: R. S. Capon, *M.N.*, **73**, 361 and 732, 1913, in which various references are included.

† We are indebted to Mr H. F. Finch for the evaluation of this effect after an informal discussion on possible systematic errors.

The large negative values in Fig. 1 are found to be all* associated with Phase I of leader spots, when their forward motion in longitude would entirely obscure the other very small displacements.

A few other high values of $\xi-\xi_1$ indicated doubtful continuity of the spots on the Sun's invisible hemisphere, and this uncertainty was confirmed by a re-examination of their daily positions and areas. Such cases are not included in Fig. 1 nor in the data from which ξ was derived.

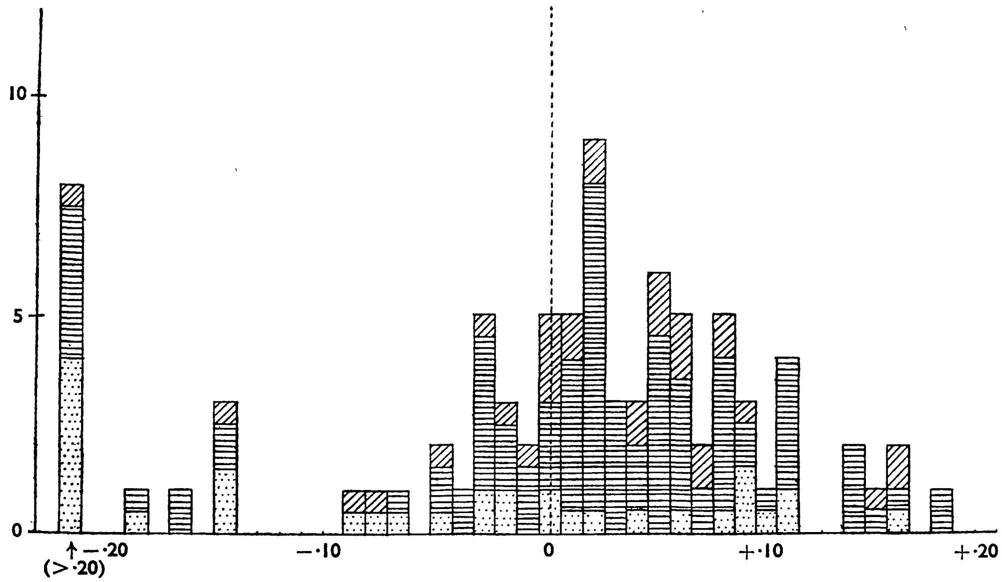

FIG. 1.—*Frequency distribution of $\xi-\xi_1$ values and phase development of the associated recurrent sunspots at both disk-passages.*

Ordinates: *Frequency.*

Abscissae: *Values of $\xi-\xi_1$.*

Phase I.

Phase II.

Phase III.

The overall mean, $\xi-\xi_1$, is less than $0^\circ{\cdot}01$ $(-0^\circ{\cdot}007)$. This small statistical difference not only substantiates the continuity of the spots provided by Ledger I, but suggests that non-recurrent spots from Ledger II can serve at least as a useful independent check for Table I.

The 282 non-recurrent spots selected include some from Ledger I which do not meet the requirements of a 27-day interval comparison. The derived values of the solar diurnal motion from these single disk-passages (designated ξ_0) are tabulated in the Addendum.

Results.—In Fig. 2 the separate values of ξ from 136 recurrent sunspots are plotted against their respective solar latitudes (ϕ). The same values averaged for 5° zones of latitude ($0^\circ{\cdot}0$ to $4^\circ{\cdot}9$; $5^\circ{\cdot}0$ to $9^\circ{\cdot}9$, etc.) are given in Table I with northern and southern hemispheres shown separately in satisfactory accordance.

* Each recurrent spot is of course assigned two indices of phase development. Phase I scarcely ever extends to the second passage. Hence in Fig. 1, a 50 per cent occurrence of Phase I indicates a complete association of these spots with Phase I at their first disk-passage.

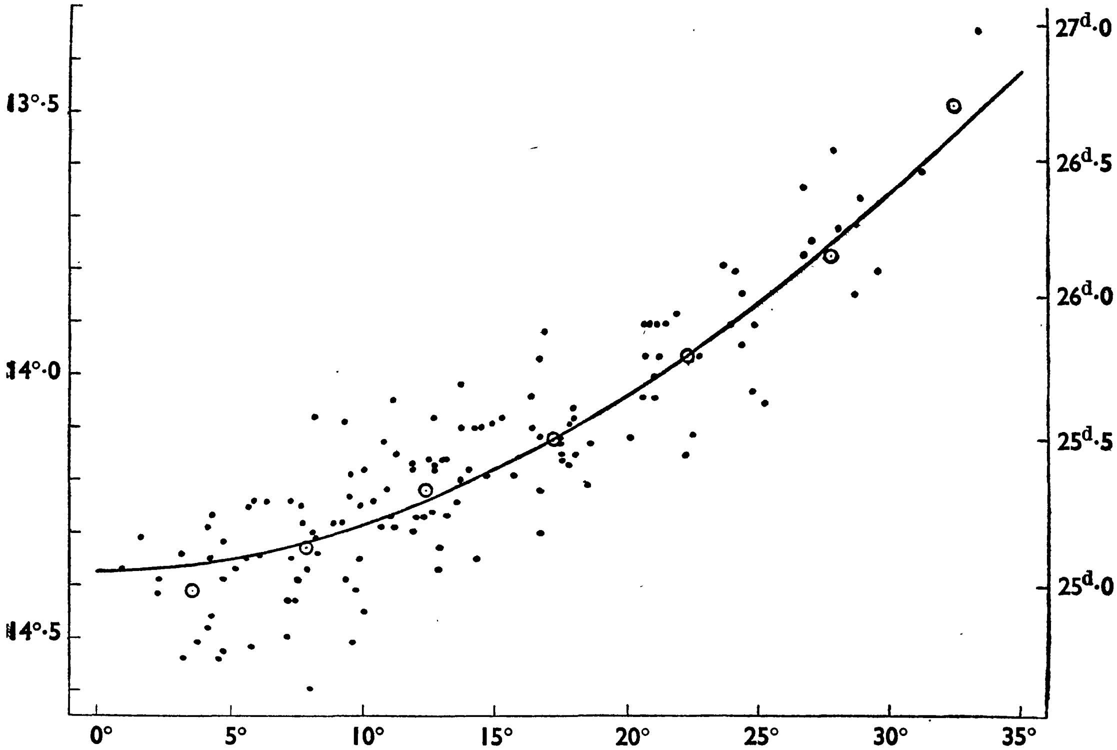

FIG. 2.—*Observed values of ξ from recurrent sunspots,* 1934–1944. *Means for each* 5° *zone of latitude are represented by open circles. The curve is computed from the expression*

$$\xi = 14^\circ{\cdot}38 - 2^\circ{\cdot}96 \sin^2 \phi.$$

Ordinates (left-hand side) : Daily sidereal motion.
Ordinates (right-hand side) : Sidereal rotation period in days.
Abscissae : Solar latitude.

TABLE I

Mean daily sidereal motions of sunspots, 1934–1944

		N. spots	S. spots	Mean	Mean dispersion	O–C
0°–5°	ϕ	3°·4	4°·0	3°·6		
	ξ	*14°·40*	*14°·43*	*14°·41* ± *0°·02*	±0°·08	+0°·04
	n	10	6	16		
5°–10°	ϕ	7°·7	7°·8	7°·8		
	ξ	*14°·32*	*14°·34*	*14°·33* ± *0°·01*	±0°·09	0°·00
	n	15	14	29		
10°–15°	ϕ	12°·9	11°·9	12°·4		
	ξ	*14°·20*	*14°·23*	*14°·22* ± *0°·01*	±0°·08	$-0^\circ{\cdot}02_5$
	n	18	18	36		
15°–20°	ϕ	17°·2	17°·2	17°·2		
	ξ	*14°·13*	*14°·12*	*14°·12* ± *0°·01*	±0°·06	0°·00
	n	7	15	22		
20°–25°	ϕ	22°·0	22°·7	22°·3		
	ξ	*14°·01*	*13°·90*	*13°·96* ± *0°·02*	±0°·08	+0°·01
	n	11	9	20		
25°–30°	ϕ	28°·4	27°·3	27°·6		
	ξ	*13°·76*	*13°·77*	*13°·77* ± *0°·03*	±0°·10	+0°·02
	n	3	8	11		
30°–35°	ϕ	32°·4		32°·4		
	ξ	*13°·48*	...	*13°·48*	±0°·14	−0°·05
	n	2		2		

In column 5 the mean dispersion (or scatter of observed points in Fig. 1) is given, from which the respective probable errors in the preceding column have been computed.

Taking the observed mean values of ξ in each 5° belt of latitude and weighting the values according to the respective number of observations (the mean dispersion in each 5° belt being comparable), a solution by least squares was obtained, giving

$$\xi = 14^\circ{\cdot}38_2 \pm 0^\circ{\cdot}009 - (2^\circ{\cdot}96 \pm 0^\circ{\cdot}09)\sin^2\phi.$$

Residuals (observed *minus* computed) are given in the last column of the table. This evaluation of ξ is in good accordance with those for the five earlier sunspot cycles as shown in Table II.

In Table II this result is compared with those yielded by the preceding five cycles.*

TABLE II

Solutions for ξ (recurrent sunspot data) over six cycles

Cycle	Years	Number of sunspots	Diurnal motion (ξ)
I	1878–1888	89	$14^\circ{\cdot}34 \pm 0^\circ{\cdot}01 - (2^\circ{\cdot}35 \pm 0^\circ{\cdot}08)\sin^2\phi$
II	1889–1899	122	$14^\circ{\cdot}36 \pm 0^\circ{\cdot}01 - (2^\circ{\cdot}58 \pm 0^\circ{\cdot}18)\sin^2\phi$
III	1900–1913	99	$14^\circ{\cdot}38 \pm 0^\circ{\cdot}01 - (2^\circ{\cdot}69 \pm 0^\circ{\cdot}13)\sin^2\phi$
IV	1914–1923	139	$14^\circ{\cdot}38 \pm 0^\circ{\cdot}01 - (2^\circ{\cdot}50 \pm 0^\circ{\cdot}18)\sin^2\phi$
V	1924–1933	130	$14^\circ{\cdot}37 \pm 0^\circ{\cdot}01 - (3^\circ{\cdot}01 \pm 0^\circ{\cdot}11)\sin^2\phi$
VI	1934–1944	136	$14^\circ{\cdot}38 \pm 0^\circ{\cdot}01 - (2^\circ{\cdot}96 \pm 0^\circ{\cdot}09)\sin^2\phi$

Using the present solution (6th cycle), values of ξ at 5° steps of latitude are given in Table III, together with the equivalent rotation periods. These values will be found to compare best with those derived by Carrington from his visual measures of sunspots 1853 to 1861.

TABLE III

Computed values of ξ and equivalent rotation periods from $\xi = 14^\circ{\cdot}38_2 - 2^\circ{\cdot}96 \sin^2\phi$

Solar latitude	Daily sidereal motion, ξ (°)	Sidereal period (d)	Mean synodic period (d)
0°	14·38	25·03	26·87
5°	14·36	25·07	26·92
10°	14·29	25·19	27·06
15°	14·18	25·38	27·28
20°	14·04	25·65	27·59
25°	13·85	25·99	27·98
30°	13·64	26·39	28·45
35°	13·41	26·85	28·98

Test for periodic variation of ξ.—(1) Alternation with cycle; (2) during mean cycle.

(1) *Alternation with cycle.*—The mean values of ξ for the odd and even cycles have been taken from Table II and weighted according to the respective relative

* These solutions differ slightly from those given in *M.N.*, **95**, 62, 1934 (Table II) for which a less rigorous solution was used. In that table, lines 1 and 2, *read* 14°·35 and 14°·38 respectively for 14°·36 and 14°·39.

weights of *a* and *b* in each of the six solutions. The derived expressions, in close accordance, are as follows:—

Cycles I, III, V. $\xi = 14^\circ{\cdot}36_4 \pm 0^\circ{\cdot}005 - (2^\circ{\cdot}60 \pm 0^\circ{\cdot}06)\sin^2\phi$,

Cycles II, IV, VI. $\xi = 14^\circ{\cdot}37_5 \pm 0^\circ{\cdot}007 - (2^\circ{\cdot}82 \pm 0^\circ{\cdot}07)\sin^2\phi$.

However, the derivation of the equatorial value from an expression which best fits the whole range of latitude values (with considerable weight because of numbers in the middle latitudes) might obscure some small significant differences near the equator itself. We therefore give the observed values of ξ for the equatorial zone, 0°–5°, and also these values reduced to the equator by the present solution for ξ.

	Observed ξ	ϕ	ξ at 0°
Odd cycles	$14^\circ{\cdot}36_0 \pm 0^\circ{\cdot}01_5$	$3^\circ{\cdot}1$	*$14^\circ{\cdot}36_9$*
Even cycles	$14^\circ{\cdot}40_9 \pm 0^\circ{\cdot}01_1$	$2^\circ{\cdot}9$	*$14^\circ{\cdot}41_7$*

The difference of 0°·05, being less than three times its probable error, is therefore of very doubtful significance.

The two most prolific 5° zones of latitude (10°–15°; 15°–20°) provide the following observed mean values over the same extended period, 1878–1944. Values of ξ in italics indicate the slightly adjusted values to a common mean latitude of 12°·5 for the lower zone and to 17°·2 for the higher. *n* is the number of spots.

TABLE IV

Cycles	Zone 10°–15°			Zone 15°–20°		
	ξ	ϕ	n	ξ	ϕ	n
Odd	$14^\circ{\cdot}23_6$	$12^\circ{\cdot}7$	86	$14^\circ{\cdot}13_1$	$17^\circ{\cdot}0$	73
	$14^\circ{\cdot}24_0$			*$14^\circ{\cdot}12_6$*		
Even	$14^\circ{\cdot}23_0$	$12^\circ{\cdot}3$	115	$14^\circ{\cdot}12_8$	$17^\circ{\cdot}5$	73
	$14^\circ{\cdot}22_7$			*$14^\circ{\cdot}13_0$*		

From these values we see that there is no observational evidence of any cyclical variation of ξ in these latitude ranges as great as 1 part in 1000 in a 22-year period.

(2) *Variation of ξ within the* 11-*year cycle*.—To test whether there is any periodic variation of ξ during the (mean) sunspot cycle, the data for the above two zones were divided into four epochs according to time-interval from solar maximum. The epochs of the six maxima were adopted from the Zürich data of sunspot "numbers", and the limits of each of the four epochs within the mean 11-year cycle were adjusted so as to include as nearly as possible the same number of observations in the same 5° zone. The results are set forth in Table V. For more exact comparison, values of ξ in italics include the small correction necessary to bring the values appropriate to the mean latitude of 12°·5 in the case of the first zone and of 17°·2 for the other zone. Although the greatest difference between one epoch and the next is 0°·08 (i.e. about four times the probable error), the overall run of values suggests no real variation with phase of the cycle.

This result from sunspots (with the reservation that the solar minimum itself is barely represented) contrasts sharply with those typical of the upper chromosphere for which Evershed*, for instance, obtained from measures of the H and K lines in prominence spectra, a difference of 2° *per day* as between solar minimum and times of greatest activity.

* J. Evershed, *M.N.*, **105**, 205, 1945.

TABLE V

ξ values during the (mean) sunspot cycle

Zone		Epoch from sunspot maximum ($=0^{y}\cdot0$)			
		1	2	3	4
10°–15°	e	$-1^{y}\cdot7$	$-0^{y}\cdot1$	$+1^{y}\cdot3$	$+3^{y}\cdot6$
	ϕ	$12^{\circ}\cdot6$	$12^{\circ}\cdot5$	$12^{\circ}\cdot5$	$12^{\circ}\cdot3$
	ξ	$14^{\circ}\cdot22$	$14^{\circ}\cdot26$	$14^{\circ}\cdot22$	$14^{\circ}\cdot23$
		14°·22	*14°·26*	*14°·22*	*14°·23*
	n	52	51	50	48
15°–20°	e	$-2^{y}\cdot3$	$-1^{y}\cdot0$	$+0^{y}\cdot5$	$+2^{y}\cdot5$
	ϕ	$17^{\circ}\cdot7$	$17^{\circ}\cdot8$	$16^{\circ}\cdot8$	$16^{\circ}\cdot6$
	ξ	$14^{\circ}\cdot17$	$14^{\circ}\cdot11$	$14^{\circ}\cdot11$	$14^{\circ}\cdot12$
		14°·18	*14°·13*	*14°·10*	*14°·10*
	n	34	37	37	38

Mean ξ, 1878–1944 { (10°–15°) 14°·233 at latitude 12°·5 (201 spots).
(15°–20°) 14°·126 at latitude 17°·2 (146 spots).

Northern and southern hemispheres compared (1878–1944).—Finally from the combined data, a solution for ξ has been made for the separate hemispheres * to see whether there is any measurable difference in behaviour. It will be seen that there is no difference within the range of present accuracy.

North: $\xi=14^{\circ}\cdot37_2\pm0^{\circ}\cdot010-(2^{\circ}\cdot68\pm0^{\circ}\cdot12)\sin^2\phi$ (357 spots),
South: $\xi=14^{\circ}\cdot38_5\pm0^{\circ}\cdot005-(2^{\circ}\cdot91\pm0^{\circ}\cdot07)\sin^2\phi$ (358 spots).

Combining data for six cycles by 5° latitude zones and re-solving, we obtain

$$\xi=14^{\circ}\cdot37_7\pm0^{\circ}\cdot006-(2^{\circ}\cdot77\pm0^{\circ}\cdot08)\sin^2\phi.$$

It is of interest to compare the above solution with that obtained from the six individual solutions in Table II combined according to the weights of a and b, as follows:—

$$\xi=14^{\circ}\cdot36_8\pm0^{\circ}\cdot004-(2^{\circ}\cdot69\pm0^{\circ}\cdot04)\sin^2\phi.$$

Acknowledgment is gratefully made to the Astronomer Royal for the opportunity given to prepare this paper; for advice concerning the weighted solution adopted, and also for his suggestion that the data might be arranged to show any existing periodic variation of ξ.

With the kind cooperation of the Superintendent, H.M. Nautical Almanac Office, the various data on the original working cards were transferred to punched cards and so passed through the Hollerith machine to give the collected values in Table I and in the Addendum, together with other information.

Addendum

Using data from the non-recurrent sunspots for the period 1934–1944, values (designated ξ_0) of the daily sidereal motion have been derived from 5-day means of longitude as for ξ_1 values (i. e. separate disk-passages of recurrent spots).

Of the 282 spots available, mainly from Ledger II of the *Greenwich Photoheliographic Results* but including a few components of groups in Ledger I that were not suitable for the basic discussion, 89 spots were seen as leaders of groups,

* As for the first four cycles in *M.N.*, **85**, 552, 1925.

41 as followers, three as other components and 149 as single or "unipolar" spots. The distribution of their development-phases is as follows, the mean areas being added in brackets:—

Phase I—20 (309); Phase II—170 (236); Phase III—92 (122).

The above phase assessment is necessarily more approximate than for the long-lived spots. Sometimes, the whole life-history of the spot was completed during its disk-passage, and in such cases the index II was assigned.

Mean values of ξ_0 in 5° belts of latitude were derived as for ξ values in Table I, and a solution made as before, which gave:—

$$\xi = 14^\circ{\cdot}41_4 \pm 0^\circ{\cdot}004 - (3^\circ{\cdot}36 \pm 0^\circ{\cdot}04) \sin^2 \phi.$$

The residuals (O–C) for the respective 5° latitude belts are satisfactorily small and read as follows from the equatorial belt to that for 30°–35°, the respective numbers of spots being added in brackets:—

$+0^\circ{\cdot}02$ (9); $+0^\circ{\cdot}01$ (58); $-0^\circ{\cdot}01$ (87); $0^\circ{\cdot}00$ (54); $-0^\circ{\cdot}01$ (41); $+0^\circ{\cdot}02$ (20); and $0^\circ{\cdot}00$ (13).

It seems worth recording the above subsidiary result without stressing the possible significance of the larger values of the *a* and *b* coefficients as compared with those derived from long-lived spots. Although a small physical difference (e. g. level difference) between these two classifications of spots may be indicated, it is nevertheless true that the values derived for the solar rotation depend to some extent on the selection of spots used and their phase and rate of development. A more rapid development of the shorter-lived spots may contribute larger values of ξ_0 (contrary to the effect of small systematic errors previously mentioned on p. 415), since the forward movements in longitude of leaders during growth will be effectively averaged over a 9 or 10 day interval instead of 27 days, as for the recurrent spots.

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