ROTATION CHARACTERISTICS OF LARGE-SCALE SOLAR MAGNETIC FIELDS

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Abstract. The rotation characteristics of large-scale (global) magnetic fields (GMF) and their relation to the activity of local fields (LMF) are studied over a long time interval (1915–1996). The main results are as follows. The GMF rotation rates and LMF activity vary in anticorrelation. Both variations have similar periods (11 years and a quasi-secular period of about 55–60 years), but are shifted relative to each other by half an 11-year cycle. Therefore, (1) the GMF rotation rate increases at the minimum of the 11-year cycle of LMF activity. (2) The GMF rotation rate is faster in the less active hemisphere. (3) The GMF rotation period slows down at the maximum of the secular LMF activity (cycles 18 and 19).

1. Introduction

The present contribution continues the series of work (Obridko and Shelting, 1997, 1998, 1999, 2000a, b) where the cyclic variation of large-scale solar magnetic fields was studied over a long time interval (1915–1996) using both the direct field measurements (Hoeksema, 1991; Hoeksema and Scherrer, 1986; Hoeksema, Wilcox, and Scherrer, 1982, 1983) and the field reconstructed from Hα spectroheliograms. The main problem we faced was to work out a polar correction method that would allow us to compute the source-surface field structure, thus sorting out the principal harmonics of the global field. The method was described by Obridko and Shelting (1997, 1999). In the same papers, we compared the computed polar field with the number of polar plages to show that both values varied with time in a similar way. A scrupulous comparison of the recovered structure of the source-surface global magnetic field (GMF) and the sector structure of the interplanetary magnetic field (IMF) is presented in Obridko and Shelting (1998, 1999). We used the most complete IMF data series (1926–1990) obtained by Svalgaard (1972, 1975, 1976, 1978) and Mansurov, Mansurov, and Mansurova (1976) on the base of geomagnetic measurements. The methods developed by S. M. Mansurov and L. Svalgaard allowed us to infer the sign of the IMF B_x component from the ground-based geomagnetic measurements.

These methods are similar, but not identical. The procedure proposed by Mansurov requires data from several Arctic and Antarctic geomagnetic observatories, because two types of diurnal variation of the vertical (Z) and horizontal (X) components of the geomagnetic field were pronounced in the high-latitude

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region confined to $\Phi_c = 75°$. The variations were shown to correlate well with the IMF sector polarity. The seasonal variation and the north–south asymmetry are also used for better reliability. This method ensures an 80% conformity of the reconstructed data with the spacecraft measurements (Mansurova and Mansurov, 1982). Unfortunately, the data required were not fully available until 1958. The reconstruction for earlier dates was made by Svalgaard (1972, 1975, 1976, 1978). He applied an alternative method based on variations of the H component; and, most importantly, he used the data from a single station in the northern hemisphere (Godhaven). Therefore, the results obtained by Svalgaard, particularly for the winter months, seem to be less reliable and were criticized by various authors (Campbell and Matsushita, 1973; Fougere, 1974; Berthellier and Guerin, 1975; Feldstein, 1975).

The computed values of the source-surface magnetic field at the helioprojection point of the Earth were used as the GMF data. The time resolution of all data is 1 day. On the whole, the structure inferred from Hα agrees reasonably with that obtained from direct observations and reconstructed from the geomagnetic data, especially after 1958, when both data series coincide even in detail (Obridko and Shelting, 1997, 1998, 1999). Since our data for the entire period of 1915–1996 are uniform and agree fairly well both with direct observations and with the reconstructed data after 1957, the increased number of discrepancies in the earlier periods is most likely to be due to imperfection of the data series reconstructed from geomagnetic measurements in only one terrestrial hemisphere.

It should be noted that our simulation of the source-surface field plays the role of ‘spatial filtering’ that automatically selects the field harmonics changing with height at the lowest rate. It means that our conclusions concerning the structure parameters are valid for a layer at a certain still unknown depth under the photosphere, which we shall denote as the region of generation of this particular structure of the global magnetic field.

Of course, a specific distribution of the magnetic flux with very large spatial field variations over the photosphere can also result in such a slow decrease of the field strength with height. This explanation was discussed by Sheeley, Nash, and Wang (1987) and Wang *et al.* (1988). They showed that the meridional component of magnetic-flux transport will offset the shearing effect of differential rotation and give rise to rigidly rotating patterns of large-scale magnetic field.

The rotation of the 2- and 4-sector structures was analyzed separately by Obridko and Shelting (2000a, b). The main results can be summed up as follows.

We have corroborated the conclusions of Kuklin and Obridko (1988), Obridko (1981, 1984)), and Obridko and Starkova (1981) that the 2-sector structure is generally dominating the large-scale magnetic field. Its contribution increases towards mid latitudes, while the contribution of the 4-sector structure, on the contrary, decreases. All latitude and cycle dependencies are different both for the rotation parameters and for the intensities of the 2- and 4-sector structures. It allows the authors (Obridko and Shelting, 2000a,b) to suggest that the structures develop independently.

It is shown that the global magnetic field is activated simultaneously in a broad band of latitudes and is connected with the corresponding current system, a particular one for each type of the sector structure. Since both structures execute a quasi-rigid rotation, we suppose that the current system must be confined to a narrow frequency band or must lie at the bottom of the convection zone or just under it, where the rotation becomes less differential. For other explanations see Sheeley, Nash, and Wang (1987).

At the same time, these current systems are not identical. The patterns of space-time distribution of the 2- and 4-sector structures differ significantly. The cross-correlation of their amplitudes and rotation periods is very poor.

Variations of the period over a long time interval give a far more definite pattern (Obridko and Shelting, 2000a, b). The reliably detectable general property can be formulated as follows: the rotation slows down as the local activity increases and *vice versa* – the lower the activity the faster the rotation. If it were a mere result of the latitudinal shift of activity, one should expect to observe an opposite effect: since the main contribution to the signal at the maximum of the cycle comes from the lower latitudes, the rotation periods recorded would decrease, and the rotation rates would, accordingly, increase.

This is true both for the 11-year cycle and for longer periods (Obridko and Shelting, 2000a, b). The lowest rotation rate was recorded during the powerful activity cycles 18 and 19.

In this work, we continue comparing the rotation characteristics of the Sun and the solar activity. Section 2 contains a review of literature and formulation of the problem. Section 3 is devoted to the analysis of rotation of the global magnetic field in different phases of activity of the local fields. In Section 4, we compare the rotation characteristics of the global magnetic field with the asymmetry of activity in the two hemispheres. The main conclusions are summarized and discussed in Section 5.

2. Statement of the Problem

As noted above, the rotation rates of the 2- and 4-sector structures somewhat increase in the minimum epochs of the Wolf number cycles and *vice versa*. The lowest rotation rates were recorded in the middle of the current century when the powerful cycles 18 and 19 took place. Similar results were also obtained in earlier work from the analysis of various tracers. In our review (Obridko and Shelting, 1988), we analyzed the measurements of various authors published by Schröter (1985) to show that the rotation rate at the equator, a, had increased by 1975 by 2–4%, which could be a combined result of the two effects mentioned above.

The analysis of more than 27 tracers (Obridko and Shelting, 1988) brought us to the following conclusions:

(1) As the lifetime and the characteristic size of the features under consideration grow, the rotation differentiality index, $|b|$, and the rotation rate at the equator, a, show a tendency to decrease.

(2) The differentiality index, $|b|$, is greater and the rotation rate, a, is smaller for more active features. Here, by activity we mean the activity of local fields.

It should be noted however that these conclusions suffer from two disadvantages. Firstly, they depend upon relatively short observation series. Secondly, even when several cycles could be covered, the analysis was mainly based on sunspot data, i.e., the data relevant to the local fields. Long series of data on large-scale and global fields have not been available until recently. The results of Obridko and Shelting (2000a, b) described in the Introduction are free from these disadvantages. However in those papers, the 2- and 4-sector structures were analyzed separately. Since the two structures are not identical, the obtained rotation characteristics of the global magnetic field as a whole may be different.

Therefore we have analyzed the rotation of the global magnetic field as a whole, paying special attention to the relationship between the rotation characteristics and the solar activity.

3. General Rotation of the Large-Scale Magnetic Fields

Let us consider the rotation of the large-scale solar magnetic field at the source surface as a whole, without isolating the particular sectors. We can calculate the daily values of the radial magnetic field at any latitude and, thus, to study latitudinal variations of the rotation characteristics at 10° steps in the latitude range of 50 N to 50 S. For this study, we have used the standard Fourier transform with fractional harmonics and double precision. Such an analysis, along with spatial filtering, allows us to isolate the rotation of the two-sector structure, which can be expected to be less differential than that of the photosphere magnetic fields (Hoeksema and Scherrer, 1987; Antonucci, Hoeksema, and Scherrer, 1990).

The Fourier spectra were calculated every 3-years of 8 successive cycles of solar activity. The rotation periods under consideration are equal to 26–30 days. First, one can see that the rotation is practically of the solid-body type, as was expected. The maximum of the Fourier-spectrum covers a broad range of latitudes without a significant shift. Second, the rotation periods at the maximum of the cycles are usually greater than in the following minimum epochs, i.e., the rotation rate of the global magnetic field at the source surface decreases with the growth of activity inside a cycle.

The Wolf numbers and rotation periods of the Sun for cycles 15–21 are tabulated below. Table I gives successively the number of the cycle N, date of maximum M, rotation period at the maximum of the cycle T_M, date of minimum m, rotation

TABLE I

Main periods of the global magnetic field rotation

N	M	T_M	m	T_m	T_M / T_m
15	1917	28.7	1923	26.8	1.071
16	1928	27.4	1932	27.3	1.004
17	1937	28.0	1944	27.8	1.007
18	1947	29.1	1953	28.9	1.007
19	1957	28.3	1963	28.4	0.996
20	1968	27.4	1975	27.3	1.004
21	1980	29.2	1986	28.1	1.004

period at the minimum T_m, and ratio T_M / T_m of the rotation periods at the maximum and the following minimum. By rotation period we mean the value corresponding to the maximum amplitude in the Fourier spectrum.

Figure 1 shows the global field rotation periods corresponding to the maxima of the Fourier spectrum and averaged over three-year time intervals and over the entire latitude range mentioned above. The entire interval under investigation is 80 years. The solid line is a 6-order least-squares fit calculated with the use of all data. One can readily see an increase of the rotation period in the middle of the 20th century. This maximum falls on the 1950–1960s, i.e., the years of the powerful cycles 18 and 19. We have already noted the particularities of this time interval in Obridko and Shelting (2000a, b). Besides, the ratio T_M / T_m was more than unity in six of the seven cases under consideration. The only exception was observed in cycle 19 and is possibly the result of the ‘grand’ maximum of the 1950–1960s mentioned above.

Figure 1 and Table I suggest that the rotation of the global source-surface field decelerates as the activity of the local fields grows.

4. Comparison of the Global Field Rotation Characteristics with the Asymmetry of Activity in the Hemispheres

In this section, we compare the rotation characteristics with sunspot areas separately for each hemisphere. In Figures 2 and 3 below, the sidereal angular velocities are used for convenience of determining the regions of acceleration and deceleration of the Sun as a whole and the character of torsional oscillations.

Figure 2 shows the excess of the mean angular velocities. It was determined as a result of the following procedure. Half-sums of the angular velocities in the northern and southern hemispheres were calculated as a function of latitude and

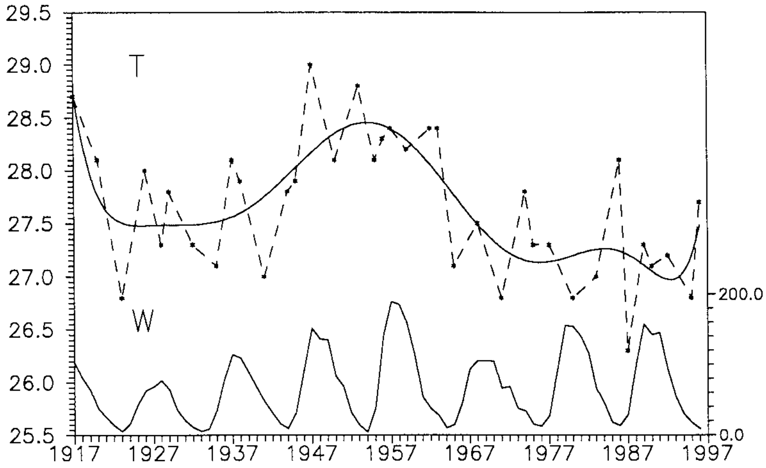

Figure 1. The magnetic field rotation periods as a function of time. The Wolf numbers are given at the bottom.

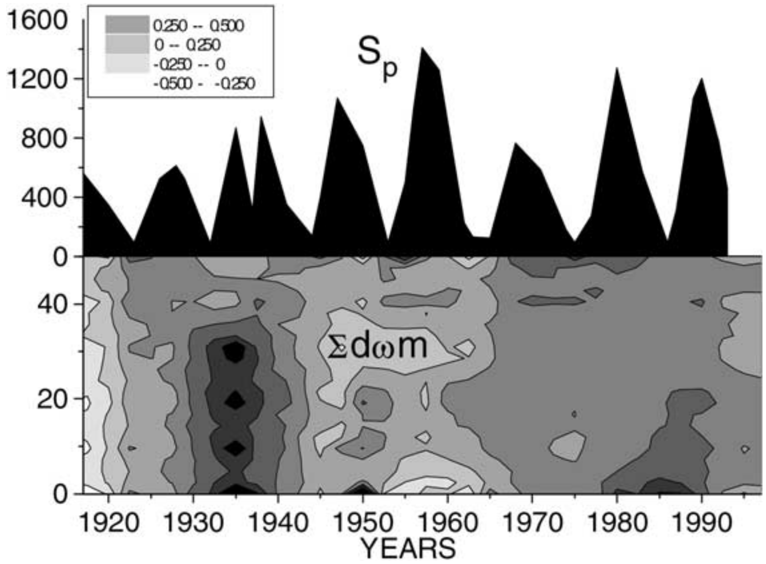

Figure 2. Mean angular velocities of magnetic fields (*bottom*) as a function of latitude and time and sunspot areas (*top*).

time. Then, the mean velocity was calculated from the fourth-order regression equation:

$$\omega = 14.1614 - 0.502792 \sin^2 \varphi + 0.107699 \sin^4 \varphi. \quad (1)$$

The excess was obtained as a difference between the half-sums for every interval and the mean rotation rate (1) for the entire time interval under consideration.

The mean sunspot area *Sp* calculated as half-sums of the areas in the northern and southern hemispheres is plotted for comparison at the top of the figure. One

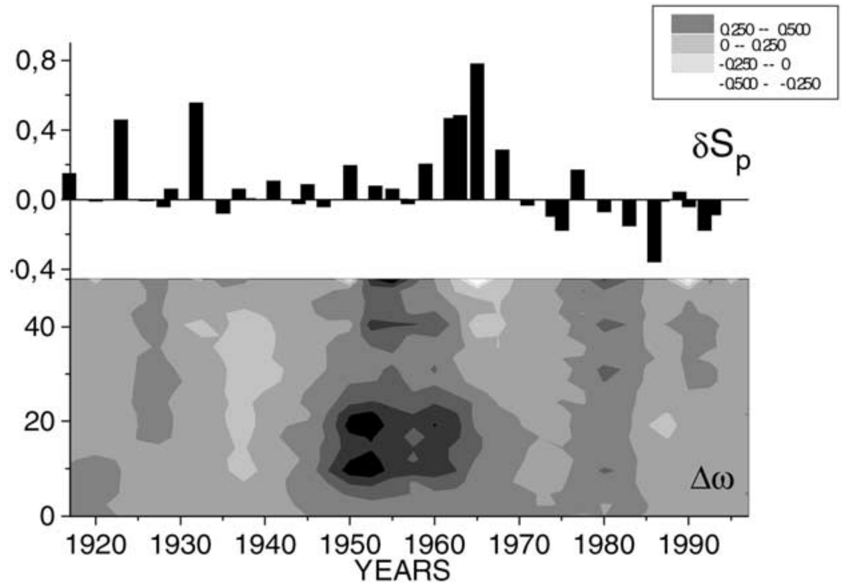

Figure 3. Asymmetry of angular velocities of magnetic fields (*bottom*) and sunspot areas (*top*) as a function of latitude and time.

can see that the maximum rotation rate of the global field corresponds to the growth phase (1934) and minimum (1985) of the 11-year cycles of local field, whereas the minimum rotation rate corresponds to a broad interval of powerful cycles 18 and 19 (1947–1962). This corroborates our conclusion (Obridko and Shelting, 2000a, b) that a certain anticorrelation exists between the rotation rate of global fields and the activity of local fields in the Sun during an 11-year and 55-year cycles.

Figure 3 illustrates half-differences of angular velocities in the northern and southern hemispheres, i.e., the asymmetry. The north–south asymmetry of sunspot areas is shown for comparison at the top of the figure. One can see that large positive asymmetry of local fields in 1923, 1933, and 1960–1970 ($S_{\delta N} > S_{\delta S}$) corresponds to small or negative asymmetry of global field rotation ($\omega_N < \omega_S$) and *vice versa*: large positive asymmetry of global field rotation ($\omega_N > \omega_S$) is recorded in the years when the asymmetry of the local field is small or zero. The same conclusion was drawn for cycle 21 by Antonucci, Hoeksema, and Scherrer (1990).

Thus, anticorrelation between the rotation and activity is proved to exist not only in time (during an activity cycle), but also in space: the more active hemisphere rotates slower.

We have calculated the cross-correlation of various pairs of local and global parameters (Figure 4). The mean sunspot areas and rotation rates of global fields proved to vary in anti-phase (long-dash line), but the correlation is very poor.

The asymmetry of sunspot areas and that of rotation rates of global fields also vary in antiphase (short-dash line): the cross-correlation is maximum (of the order

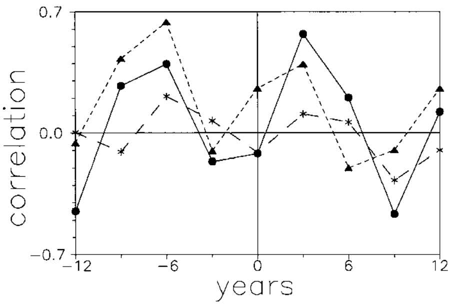

Figure 4. Correlation of local and global parameters in pairs: mean sunspot areas and rotation rates of magnetic fields (*long-dash line*), asymmetry of sunspot areas and asymmetry of rotation rates of magnetic fields (*short-dash line*), and mean sunspot areas and asymmetry of rotation rates of magnetic fields (*solid line*).

of 0.7) when the shift is 6 years. One can see that the hemisphere which rotates faster displays lower activity.

It is interesting to consider the relationship between the mean sunspot areas and the asymmetry of rotation rates of global fields (solid line). To simplify the problem we have eliminated the effect of the sign of asymmetry by choosing the absolute values. The maxima of both values had coincided until 1952, after which the maximum asymmetry of rotation rates of global fields shifted to fall on the epoch of minimum activity of local fields. Therefore the cross-correlation calculated over the entire time interval under discussion proved negative in the absence of shift and the maximum cross-correlation of the order of 0.6 was obtained at a shift of the order of 3–6 years. This suggests that a growth of amplitude of torsional oscillations is followed in about 6 years by a growth of integral activity of local fields.

5. Discussion of Results

The basic results obtained in this work can be summarized as follows:

A general tendency is likely to be revealed in the rotation of solar structures: an increased activity is accompanied by a decreased rotation rate and *vice versa*, the higher the rotation rate the lower the activity.

The tendency is best pronounced in the middle of the 20th century, when a significant increase of the rotation period coincided with the highest activity cycles. It is, probably, a manifestation of the 55-year cycle of solar rotation and solar activity, which was described by Makarov *et al.* (1997), using a larger data base, and by Yoshimura and Kambry (1993), using sunspot rotation. In addition to that, Yoshimura and Kambry (1993) propose an alternative interpretation, which suggests a 20-year shift between the variations of solar activity and rotation rate. In the presence of quasi-semisecular period, this shift must result in the observed anticorrelation. As shown by Kambry and Nishikawa (1990), the differential rotation varies from cycle to cycle in such a way that the rotation velocity in a low-activity cycle (cycle 20) is higher than in a high-activity cycle (cycle 19). Mendoza (1999) obtained a positive correlation between the solar rotation rate and the length of the cycle for cycles 12 to 20. Since the shorter cycles are usually more powerful, the result of Mendoza seems to agree with ours. The interpretation of this ‘grand’ cycle was given by Kitchatinov *et al.* (1999) based on some consequences of a nonlinear coupling between magnetic field and rotation within a solar type 2D dynamo model for a spherical convective shell.

The relationship between the local activity and rotation of global fields inside an 11-year cycle is less noticeable. As seen from Table I, the rotation period at the maximum of the cycle was greater than in the following minimum in six out of the seven cycles under discussion. It should be, however, noted that the tabulated data were obtained for intervals which were broader than the calendar duration of the epochs of maximum and minimum.

A weak correlation between the sunspot areas and rotation rates in Figure 4 suggests that we are rather dealing with variations of the rotation rate depending on the phase of the cycle than with direct relationship between the importance of local activity and rotation of the global field.

This relationship was reported by various authors. As mentioned above, the analysis of more than 27 tracers (Obridko and Shelting, 1988) brought us to the same conclusions. R. Howard (1976) analyzed the Doppler measurements for 1967–1976 and arrived at the conclusion that the equatorial velocity reached its maximum at the minimum of the cycle in 1976. On the other hand, Livingston and Duvall (1979), using similar measurements, did not obtain a decrease of the equatorial rotation rate after 1976 and could not either corroborate or disprove the change of it with the phase of the Wolf number cycle.

Later on, Gilman and Howard (1984) analyzed a great volume of data on variations in the solar rotation during a sunspot cycle. They calculated the residuals of the annual mean data on the Doppler rotation rate from Mount Wilson, formed by subtracting the grand average (1921–1982) rotation rate for each latitude bin from the annual average for that bin, and then averaging the residuals for all bins between 32 S and 32 N. One can see that the rotation rate residuals around the sunspot maximum are broader, weaker, and more poorly defined than those near the minimum for all cycles inside the time interval under consideration (16–20 cycles).

Makarov and Tlatov (1997) and Makarov, Tlatov, and Callebaut (1997) also showed that the velocity of rotation of the solar corona at the equator increased at the minimum of the cycle. Tlatov (1997) analyzed the differential rotation of the red solar corona (Fe X λ6374) from 1957–1994. The series primarily includes data from the Kislovodsk Station, supplemented with the Sacramento Peak and Pic du Midi data. The dependence of the differential rotation velocity on the phase of the solar-activity cycle is confirmed: the rotation velocity of the equatorial regions is maximum at the minimum of the cycle. Tomczyk and Hassler (1997) investigated time variations of the rotation rate of the white-light corona. They found the coronal rotation rate to vary with the solar cycle, the variation being the largest at high latitudes and being absent at the equator. The rotation of the high-latitude corona is the slowest during the rising phase of the solar cycle.

On the other hand, Rybak (1994) did not reveal any cyclic variations in the rotation of the green corona. Stenflo (1990) sought solar cycle variations in the rotation rate of photospheric magnetic fields using a 26-yr synoptic data base. The pattern of phase velocity was found to be time-invariant within the time limits set by small, apparently random fluctuations around the previously determined quasi-rigid rotation law. Hoeksema and Scherrer (1987) did not reveal reliable variations in the rotation of the source surface field in cycle 21.

The situation seems more definite as far as the rotation of sunspots is concerned. Hathaway and Wilson (1990) studied the relationship between differential rotation and solar activity and arrived at the same conclusion as we did: the fewer sunspots on the surface the faster the solar rotation. Thus, the rotation rate is the greatest in the solar minimum epochs, being greater in the low cycles with a small number and area of sunspots, than in the high ones.

Kambry and Nishikawa (1990) analyzed sunspot pictures obtained at the National Astronomical Observatory of Japan during 1954–1986 to study the differential rotation of the Sun. They showed the rotation rate at the equator to vary systematically within each cycle, decreasing from its beginning to the end.

Howard (1987) investigated the residuals of the annual mean rotation rates of all sunspots during 1921–1982, formed by subtracting the grand average, and found out that they varied in phase with the solar activity cycle, the maximum residual coinciding with the minimum of the cycle.

Our results also show that the more active hemisphere rotates somewhat slower. This is readily seen both from the diagram in Figure 3 and from the correlation curves in Figure 4. It should be noted that the rotation asymmetry was positive in cycles 19 and 21 (the northern hemisphere was rotating faster than the southern one) and negative in cycles 20 and 22. The same asymmetry of the rotation rates in cycles 19–21 was revealed by Gigolashvili and Khutsishvili (1990) from sunspot data, by Antonucci, Hoeksema, and Scherrer (1990) from large-scale magnetic fields in cycle 21, by Parker, Hansen, and Hansen (1982) and Parker (1987) from corona rotation data in cycle 20, and by Hoeksema and Scherrer (1987) from global magnetic fields in cycle 21.

Thus, the analysis of rotation of global magnetic fields for the period of 1915–1996 seems to suggest that the Sun rotates more rapidly when there are fewer sunspots. This behavior is observed in each solar cycle, with the most rapid rotation being usually recorded at sunspot minima. It is also manifested in the rotation asymmetry: the hemisphere with fewer spots rotates faster. Moreover, the Sun rotates faster in the cycles when the sunspot areas are smaller.

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