ON THE ROTATION OF LARGE-SCALE BACKGROUND FIELDS IN THE 21st CYCLE OF SOLAR ACTIVITY

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(Received 8 February, 1991; in revised form 16 July, 1991)

Abstract. We study some peculiarities of the time variation of dipole components in the longitudinal field distribution in individual low-latitude belts of the Sun. For analyzing the horizontal dipole rotation and variations of amplitudes we used magnetic and Hα data.

From 1979 to 1981 the rotation of the dipoles of the northern and southern low-latitude belts (0°–30° N and 10°–40° S) occurs with periods of about 26.8 days (N) and 28.2 days (S), in agreement with the results reported by Antonucci, Hoeksema, and Scherrer (1990) and Hoeksema and Scherrer (1987). A uniform rotation of the low-latitude dipoles of these belts continued until the end of 1981. Following the next coincidence of the magnetic poles in longitude the dipoles change in their rotation character. During about 15–20 rotations the low-latitude dipoles co-rotate with a new period close to the Carrington period. This is followed by a rapid (in 3–5 rotations) transition of the poles to a new stable state, also with the Carrington rotation period. The change in rotation and dynamics of the low-latitude dipoles at the end of 1981–beginning of 1982 can be explained either by a mutual penetration of the fields of different hemispheres to the opposite hemisphere or by the onset of the formation of relatively shortlived (15–20 rotations) structures which cover the entire low-latitude belt.

Unlike the trajectories of the poles, the dipole amplitudes of the low-latitude belts showed a significant variability. However, simultaneous increases of the amplitudes in both hemispheres correlated with times at which the dipole poles coincide in longitude, and the greatest increase corresponded to the moment of 'merging' of the dipole poles early in 1982. This suggests that sources of large-scale structures of the background field in the low-latitude belts of the Sun or the related fields interacted when the dipole poles coincided.

1. Introduction

One of the properties of the background magnetic field (BMF) of the Sun is the discrete character of power spectra of time-sequences. Part of the peaks in the spectrum appear to be attributable to the existence of large-scale sources of field having different periods of rotation. In another time interval or phase cycle, the peaks are often shifted. Variations in field rotation are, possibly, associated with some global processes of energy redistribution on the Sun (Kotov, 1987). As an example, Kotov gives the events of the year 1972 when changes in rotation periods of the general magnetic field of the Sun and the interplanetary magnetic field coincided in time with a sequence of powerful flares. Physical mechanisms for such relationships are not accurately known yet; therefore, more detailed investigations of the rotation of fields are needed. This requires studying the dynamics of the background field from one rotation to another.

However, strong local fields which are, to some extent or other, present on all magnetic maps, hamper the identification of structures of weak large-scale field which would be suited for use as tracers. It appears that the methods of preliminary mathemati-

Solar Physics **138:** 23–33, 1992.

cal filtering, enabling the large-scale component of field to be filtered out, are useful.

The dipole component of the magnetic field is the component of largest scale. An arbitrarily oriented dipole can be represented as the sum of two vectors, namely in the direction of the rotation axis (the polar dipole) and in the equatorial plane (the equatorial dipole). The rotation of the background fields influences only the equatorial dipole.

Obviously, the temporal variation of the equatorial dipole depends on the longitudinal distribution of the BMF and on peculiarities of their differential rotation. Since field structures in different latitude belts appear to be relatively independent and rotate with a different velocity, the equatorial dipole rotation has a complicated, obscure character.

For analyzing the rotation of the equatorial dipole, its components in the equatorial plane (g and h) can be represented as the sum of the coefficients g_i and h_i which depend on the field distribution in individual latitude belts:

$$\begin{Bmatrix} g \\ h \end{Bmatrix} = A \int_0^{2\pi} \mathrm{d}\varphi \int_0^{\pi} \mathrm{d}\theta B_r(\theta, \varphi) \sin^2\theta \begin{Bmatrix} \cos\varphi \\ \sin\varphi \end{Bmatrix} =$$

$$= A \sum \int_0^{2\pi} \mathrm{d}\varphi \int_{\theta_i}^{\theta_{i+1}} \mathrm{d}\theta B_r(\theta, \varphi) \sin^2\theta \begin{Bmatrix} \cos\varphi \\ \sin\varphi \end{Bmatrix} = \sum_i \begin{Bmatrix} g_i \\ h_i \end{Bmatrix},$$

where B_r – radial component of the photospheric magnetic field, θ, φ – colatitude and heliolongitude, A – constant. It is possible to introduce the notion of the dipoles of individual latitude belts determined by the components g_i and h_i. The ratio of the components determines the orientation of the dipoles in the equatorial plane $\varphi_i = \arctan g_i/h_i$ or, equivalently, the sinusoidal wave phase in the longitudinal distribution of the field of the i-th belts, and the sum of the squares determines the wave amplitude or the amplitude of the dipoles $M_i = \sqrt{g_i^2 + h_i^2}$. The variation of φ_i from one revolution to another characterizes the rotation of the field of the i-th latitude belts and has a relatively simple form, if one large-scale region predominates in the belt. Otherwise, in the analysis of the rotation, it is necessary to use higher-order harmonics.

2. Rotation of the Background Field of the Low-Latitude Belts of the N- and S-Hemispheres in the 21st Cycle of Solar Activity

For analyzing the BMF dynamics, we have used synoptic maps of the photospheric magnetic field for 10 years of the 21st cycle which were preliminarily reconstructed from the data reported by Hoeksema and Scherrer (1986) as well as synoptic Hα maps for the photospheric field polarity distribution from *Solar Geophysical Data*, Part 1. The Hα maps were digitized under the assumption of the constancy of the radial component of the magnetic field on the solar surface. Each value represented the ratio of the difference of areas occupied by the + and − polarities in a 10° × 10° square to the area of the square. Values obtained in this way varied in the range from +1 to −1. During the activity growth phase the polarity inversion lines showed numerous discontinuities attributable, perhaps, to the small magnitude of the background field; therefore, the Hα maps were processed only starting from Carrington rotation 1674 onwards. Obviously the Hα data reflect a scale, geometrical factor in the background field distribution. Using them together with data of magnetographic measurements makes it possible to separate effects associated with variations in amplitude and background field polarity distribution.

Antonucci, Hoeksema, and Scherrer (1990) made a spectral analysis of the background field in the 21st cycle of solar activity with good spatial resolution. According to results obtained, the magnetic field of the Sun for the entire cycle, on the average, had two well-defined rotation periods (26.9 days and 28.2 days), and these periods were predominant in the low-latitude belts but in different hemispheres: the period of 26.9 days had a maximum power at latitude 15° N and occupied a latitude range of about 0°–30° N, and a period of 28.2 days dominating the latitude range of about 10°–40° S, and had a power maximum at 26° S. The boundaries of the latitude belts indicated here are quite approximate because in different time windows the spectra differed rather substantially.

Similar results were obtained by Hoeksema and Scherrer (1987) using data on extrapolating the photospheric field to the corona. At the distance of 2.5 $R_\odot$ ($R_\odot$ – radius of the Sun), background fields had two well-defined periods, and at the end of the cycle both periods were dominant in both the northern and southern hemispheres.

For analyzing the rotation of the background field from one revolution to another, we calculated, in each of the latitude belts 0°–30° N and 10°–40° S, the dipole components g_i and h_i. The longitude φ_i of the positive poles of these low-latitude dipoles (LLD) determined for each Carrington rotation, was then used as a tracer characterizing the rotation of the BMF of different latitude belts.

Trajectories of the LLD poles of the latitude belts 0°–30° N and 10°–40° S are constructed in Figure 1(a–b) using, respectively, magnetic and Hα data. The plots resemble each other very much, which indicates that the main contribution to the observed rotational dynamics of the fields is made by the variation of the polarity distribution rather than of the magnitude of the BMF.

During the growth phase of solar activity, the dipole poles of the low-latitude belts often change their position and rotation period. In Carrington rotations 1686–1689 (the year 1979) at maximum solar activity the rotation of the dipole poles becomes time-coincident, and a common dipole structure is formed in the N- and S-hemispheres. At the end of 1979 the common structure breaks down, and the northern and southern dipoles start rotating with periods of 26.8 and 28.2 days, respectively.

Prior to rotation 1718 (the year 1982) the dipoles rotate independently and with different periods. This is followed by 'merging' of the poles of the LLDs, resulting in the formation, in the longitudinal distribution, of a common dipole structure in the N- and S-hemispheres of the Sun that rotates with a period close to the Carrington one. In about one year and a half, during rotations 1736–1738 (mid-1983) the structure breaks down, and the dipole poles move apart. In Carrington rotations 1748–1758 (the year 1984) a common dipole structure forms again. The trajectories in the figure take on a typical 'step-like' form, i.e., to each new large-scale structure of field there corresponds a plateau on which the dipole poles have the same position and rotate with the Carrington period.

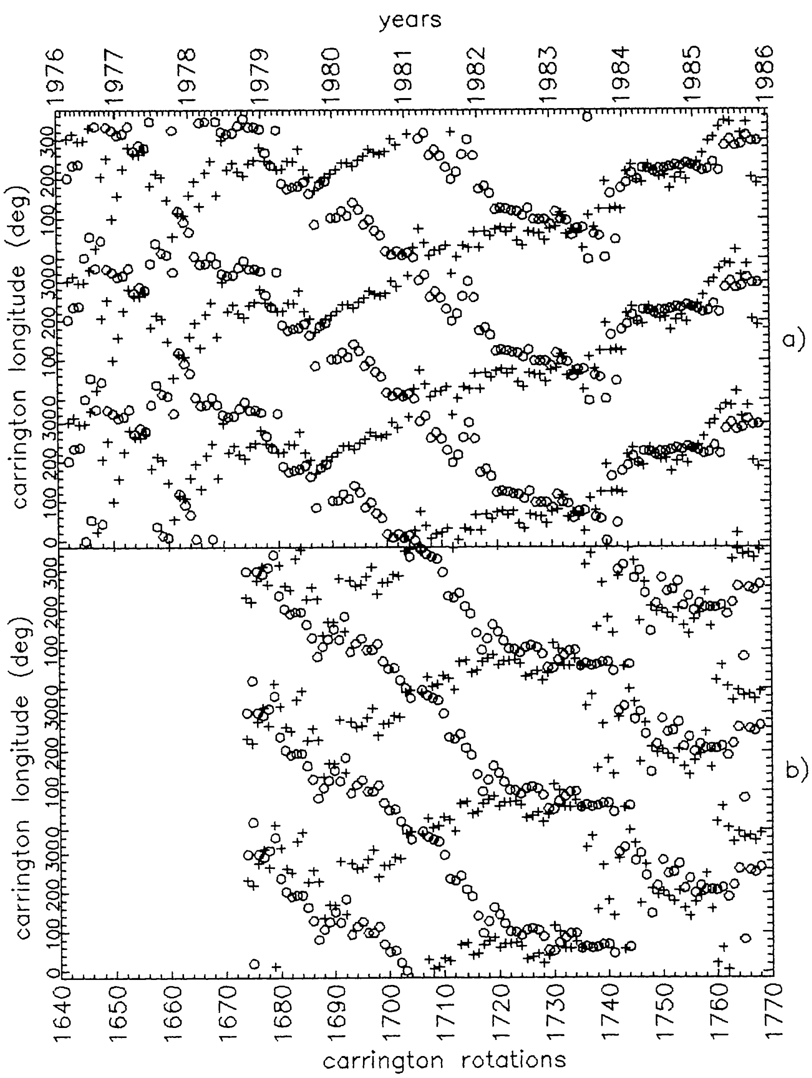

Fig. 1. The variations in heliolatitude of the LLD poles over the 21st cycle of solar activity. (a) The trajectories of the poles of dipoles in the latitude belts 0°–30° N (+) and 10°–40° S (○) obtained from the data reported by Hoeksema and Scherrer (1986). (b) The trajectories of the poles of dipoles of the latitude belts 0°–30° N (+) and 10°–40° S (○) obtained from Hα data.

It is interesting to note the regularity of formation of new stable states ('steps') in time and space. The new states that arise in about a year and a half–two years, have an opposite (displaced by about 180°) orientation of the dipole component axis and form near places at which the periods of 26.8 and 28.2 days intersect.

It might be anticipated that the background field sources having a different rotation period persist also in the declining phase; however, related fields penetrated the neighbouring hemisphere after 1982. As a result, in each latitude belt the dipole component became equal to the sum of the dipole components of fields of different hemispheres, and this did, indeed, lead to the appearance of the typical 'steps' in the trajectory of the dipole poles.

The transfer of the field across the equator is a rather unusual, but not so inbelievable phenomenon. Signs of such a phenomenon are traceable, for example, in averaged data (Howard and LaBonte, 1981), in the fields extrapolating to the corona (Hoeksema *et al.*, 1983), and, possibly, even in peculiarities of the butterfly diagram of sunspots (Vitinsky, Kopecký, and Kuklin, 1986). It seems likely that the mutual penetration of fields does not ultimately imply their simple superposition but is accompanied by certain interaction effects, whose morphology and physics are still unknown.

Unfortunately, because of the small length of the time-sequence and a rather large spread of points, one cannot say with sufficient certainty that the 'steps' are regular and, hence, that field sources with different rotation periods remain in the declining phase. It seems likely that in order to more reliably reveal these sources and signs of mutual penetration of fields, it is necessary to make a more detailed analysis of the synoptic maps themselves.

Certain difficulties are also encountered when interpreting the rotational dynamics of the dipole components if it is assumed that after 1982 the low-latitude belts starts to form relatively shortlived ($\sim$15 rotations), large-scale transequatorial structures, and the regularity in the appearance of 'steps' is a random one. In this case it is necessary to explain why the rotation velocity and the scale of the forming structures (which after 1982 occupied the entire low-latitude range of the Sun) change rather rapidly.

The relatively simple behaviour of the trajectories of the LLD poles during the cycle seems rather unexpected. Indeed, large-scale dipole-type distributions of the BMF in individual latitude belts are not identified visually on the synoptic maps themselves. According to results reported by Antonucci, Hoeksema, and Scherrer (1990), the 27-day period has a quadrupole structure. However, the character of the plots in Figure 1 and the dependence of the moments of BMF restructurings on the relative orientation of the dipoles indicate that the dipole components in each of the belts, possibly, have a real physical nature, i.e., a long-lived, large-scale region (or two regions of opposite polarity displaced by about 180°) or some organization center of the background fields. These features can be localized elementary structures or stable conglomerates of smaller-scale structures. The appearance of such features is rather characteristic for open dissipative systems such as, in particular, the convection zone of the Sun.

3. Time Coincidence of the Rotation of the Low-Latitude Dipoles and the Variations of Their Amplitudes

The orientation of LLDs depends on the localization of background field sources. The intensity of these sources determines the dipole amplitude. The temporal variation of the LLD amplitude depends on peculiarities of the formation and decay process of the large-scale structure of background fields in a given latitude belt.

The temporal dependence of the LLD amplitudes of the belts 0°–30° N and

10°–40° S as deduced from magnetic and Hα data is depicted in Figures 2(a) and 2(b). The behaviour of the amplitudes is in sharp contrast with the plots of the LLD poles' trajectories in Figure 1. During the entire time period there occur significant variations in dipole amplitudes, whose value can change several times during 1–2 rotations. So

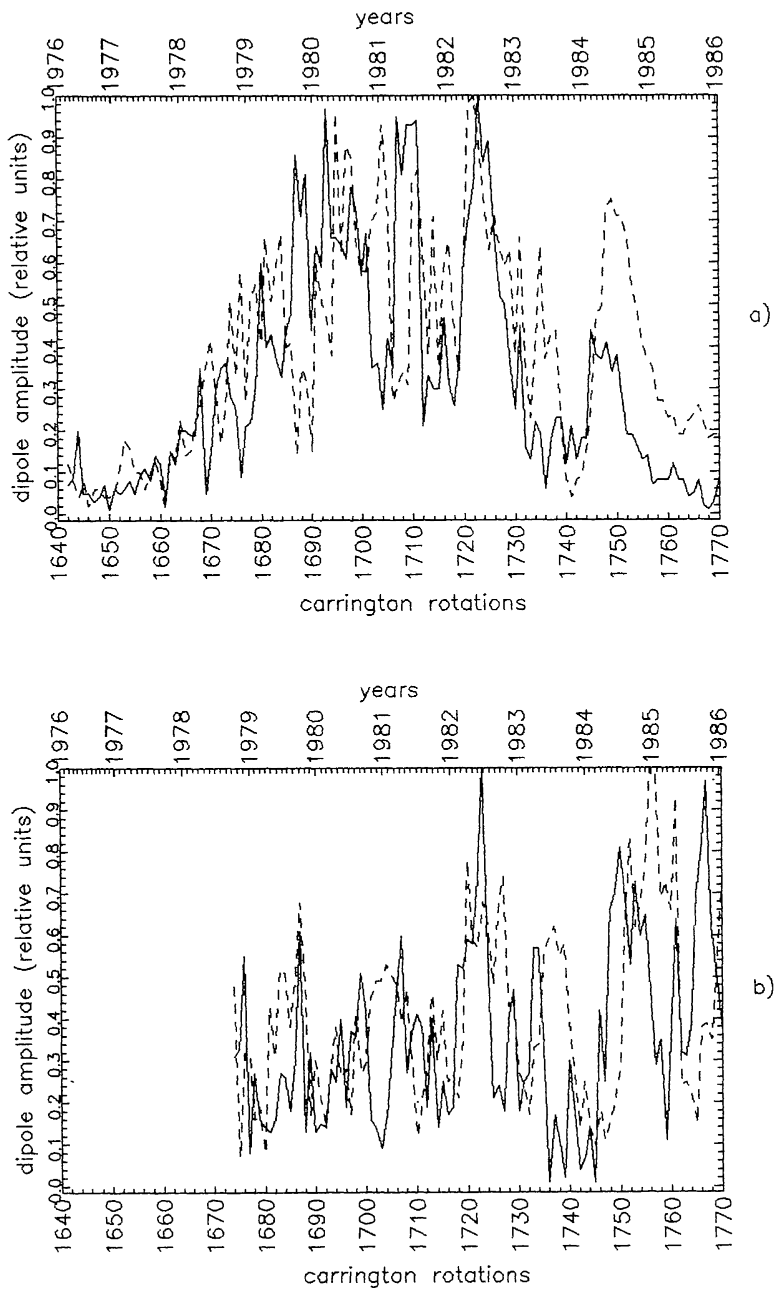

Fig. 2. The variation in LLD amplitudes in the 21st cycle of solar activity. (a) The temporal variation of dipole amplitudes of the latitude belts 0°–30° N (solid line) and 10°–40° S (dashed line) obtained from the data reported by Hoeksema and Scherrer (1986). (b) The temporal variation of dipole amplitudes obtained from Hα data.

different a behaviour of the orientation and amplitudes of the LLDs is extremely significant and seems to be an important feature of the formation processes of a large-scale structure of the field.

Of special interest are the variations coincident in time in both hemispheres of the Sun. The 'merging' of the trajectories of the low-latitude dipoles in 1981–1982 and the appearance of time-coincidence in variations of the dipoles' rotation was the main distinctive feature of Figure 1, which was used to draw the conclusion about the variation of the character of the BMF dynamics. It was also suggested that such variations must be accompanied by interaction effects, whose manifestations should also be expected in time-coincident changes in dipole amplitudes. In order to identify variations of the amplitudes time coincident in both hemispheres of the Sun, the

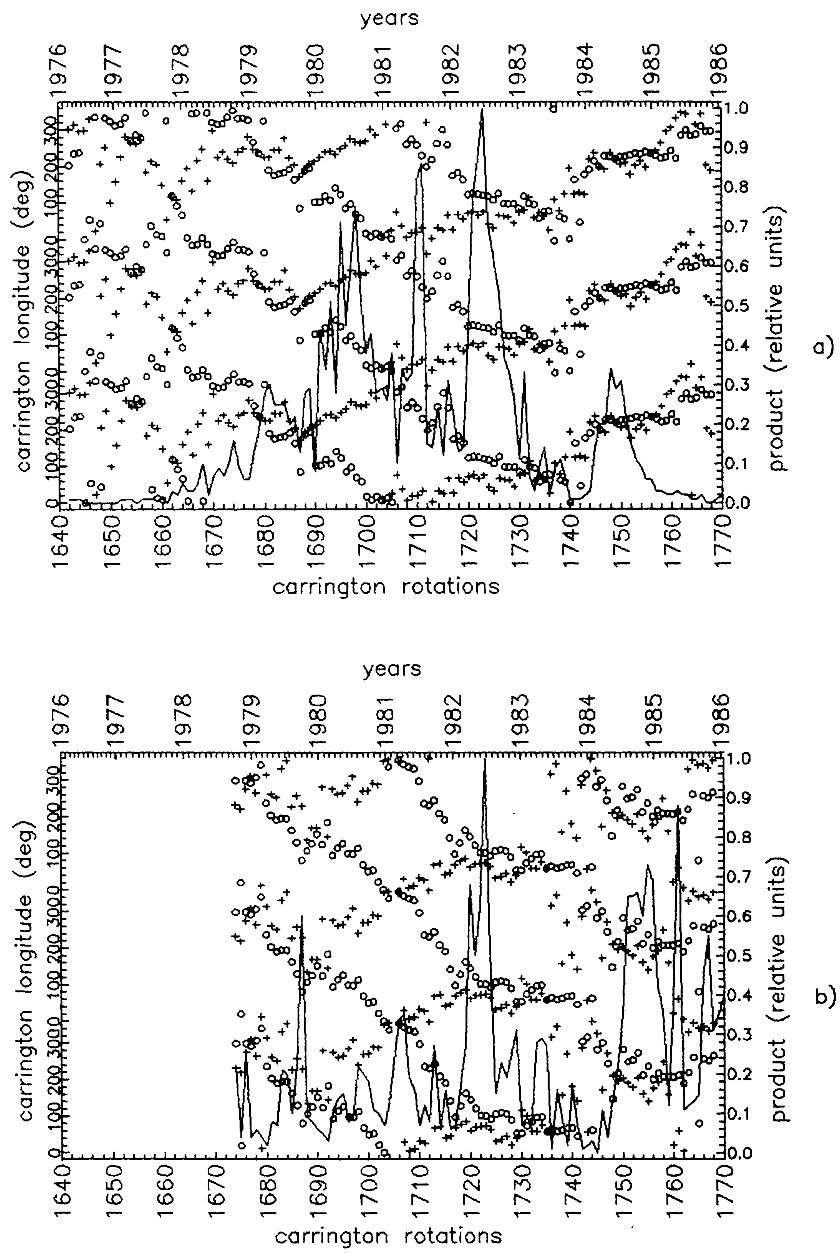

Fig. 3. The product of the LLD amplitudes of the northern and southern hemispheres (solid line) and the LLD pole trajectories. (a) The product of the LLD amplitudes obtained from the data reported by Hoeksema and Scherrer (1986). (b) The product of the LLD amplitudes obtained from synoptic Hα maps of polarity distribution.

products of the amplitudes of the LLDs were calculated (Figures 3(a) and 3(b)). For comparison purposes, trajectories of the dipole amplitudes are also drawn in these figures.

Time variations of the products of the amplitudes of the LLDs as deduced from magnetic and Hα data were found to be alike, though not coinciding in time. Onsets of most of the major time-coincident disturbances according to Hα data precede magnetic disturbances and correspond to times, at which the poles of the LLDs coincide in longitude. If the time-coincident variations of the LLD amplitudes are not the result of a superposition of random events, then one can conclude that the interaction of the BMF of different hemispheres starts to manifest itself not in 1982, as might be anticipated by analyzing the trajectories, but much earlier; however, it was until 1982 that it covers rotation periods of large-scale structures of the field. Following the 'synchronization' of the trajectories, simultaneous disturbances in the north and south occurred after each reconstruction of the large-scale structure of the BMF in the low-latitude belt.

The most powerful time-coincident increase in dipole amplitudes in both hemispheres accompanied the 'merging' of the dipole poles at the end of 1981–beginning of 1982. An increase of the dipole component can result from both an increase of the number and sizes of regions of one sign and an increase in field amplitude. By comparing plots of variations in LLD amplitudes as deduced from magnetic data with those determined from Hα maps (Figures 2(a–b) and 3(a–b)), one is led to suggest that the scale factor of the increase of the dipole component is the most significant in 1982.

Since time-coincident variations of the LLDs correlate with the moments of longitudinal coincidence of the dipole poles, it seems natural to relate these variations with manifestations of interaction processes of large-scale BMF sources of different hemispheres, which have a different rotation period. In such a case one can suppose that the interaction of fields of different hemispheres starts following activity maximum and attains its culmination in 1981–1982. At this time the interaction manifests itself as an increase of the dipole amplitudes and the appearance of a new field rotation period common for both hemispheres.

4. Can the Rotation and Dynamics of a Total Field be Deduced from the Dipole Component?

In order to compare the results of field rotation investigations obtained by analyzing the trajectories of the dipole components and by spectral methods, we have calculated, using the technique reported by Kopecký and Kuklin (1971), rotation spectra of a reconstructed background field and of the dipole components of the individual belts for sections 20° N and 30° S. The spectra obtained from magnetic maps are given in Figure 4(a–b). The spectra are found to be identical to those reported by Antonucci, Hoeksema, and Scherrer (1990), and the significance of these separated periods of the dipole components is considerably higher than that of a total field. This indicates that the main features of the solar magnetic field rotations are attributable to the largest-scale components, whose dynamics may be treaceable from the dipole component behaviour.

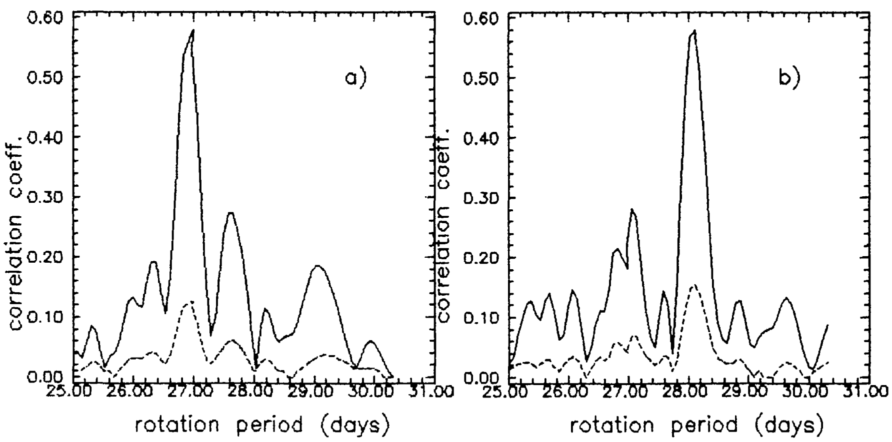

Fig. 4. Rotation spectra of a total background field (dashed line) and of the dipole component of the individual belts (solid line) for sections 20° N (a) and 30° S (b).

5. The Main Results

(1) Rotational features of solar background fields can be ascertained by using the simplest, dipole components of field in individual latitude belts. For analyzing rotations, one can use synoptic Hα maps which reflect the polarity distribution of the background field.

(2) In the 21st cycle of solar activity, from 1979 to the beginning of 1982, the dipole components of the magnetic field of the low-latitude belts of the Sun had rotation periods of about 26.8 and 28.2 days.

(3) After 1982, the rotation of the dipoles acquired an identical 'step-like' character. The dipoles resided in each of the stable states during about 1.5–2 years and rotated with the Carrington period. The transition from one state to another lasted 3–5 rotations. The change in the character of the dynamics of the LLD components of fields after 1982 can be explained by either the penetration of fields of different sources into the neighbouring hemisphere or the decay of these fields and the beginning of the formation of new, relatively shortlived structures, occupying the entire low-latitude belt of the Sun and having a rotation period close to the Carrington one.

(4) It seems likely that sources of large-scale structures or related fields interacted throughout the cycle. This manifested itself in time-coincident changes of LLD amplitudes. The most significant changes of the dipole amplitudes occurred in the period of 'merging' of the trajectories of the dipole poles at the beginning of 1982.

6. Discussion

A clear understanding of sources of solar background fields and of the nature of their large-scale organization is lacking at present. According to models reported by Leighton

(1969), Bumba (1979), and Wang, Nash, and Sheeley (1989), background fields are the product of decay and diffusion of strong fields. Stepanian (1985), Bumba (1987), and Antonucci, Hoeksema, and Scherrer (1990) have suggested the existence of BMF sources which are unassociated with active features and are located at the base of the convection zone.

In this paper we studied the peculiarities of the large-scale organization of BMFs and of its variations over the solar activity cycle. Lifetimes of the stable structures of background field were found comparable with the cycle duration. It seems likely that processes with such large typical space-time scales are a global phenomenon and cover the entire convection zone of the Sun.

Sources of the large-scale organization of BMFs (or of active regions) can be giant convective cells or large-scale vortices having a scale comparable with the solar radius and located in the convection zone. Theoretical and experimental investigations of the various hydrodynamic objects and observations of the dynamics of planetary atmospheres and oceanic currents have shown that, in the presence of a sufficiently rapid rotation, angular velocity gradients and nonuniform heating, there can, indeed, exist (in open dissipative systems such as, in particular, the convective shell of the Sun) longlived and self-sustained localized hydrodynamic structures (auto-structures) such as tropical cyclones, Taylor vortices and Rossby solitons. It is unclear, however, that the convective shell is in the stationary, statistically stationary or nonstationary states. A long lifetime of the structures is characteristic for quasi-stationary states; however, signs of 'interaction' of sources or related fields indicates the possibility that the system moves to the new, more stable state, which can be associated with a change in the regime of convection.

Possibly, large-scale organization of BMF sources lie on the boundary of or even below the convection zone. If sufficiently large latitudinal and radial gradients of angular rotation velocity exist at the base of the convection zone, longlived vortices can be excited in the zone of radiative equilibrium. An analog of such features are oceanic vortices.

The investigations made here have demonstrated that when constructing an adequate model of the dynamics of large-scale background field sources, it is necessary to take into account 'interaction' effects of sources or related surface fields which are, perhaps, brought about by an oppositely travelling meridional drift in the direction toward the helio-equator.

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