LARGE-SCALE MAGNETIC FIELD AND SUNSPOT CYCLES

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Abstract. Hα magnetic synoptic charts of the Sun are processed for 1915–1999 and the spherical harmonics are calculated. It is shown that the polarity distribution of the magnetic field on Hα charts is similar to the polarity distribution of the Stanford magnetic field observations during 1975–1999. The index of activity of the large-scale magnetic field $A(t)$, representing the sum of the intensities of dipole and octupole components, is introduced. It is shown that the cycle of the large-scale magnetic field of the Sun precedes on the average by 5.5 years the sunspot activity cycle, $W(t)$. This means that the weak large-scale magnetic fields of the Sun do not result from decay and diffusion of strong fields from active regions as it is supposed in all modern theories of the solar cycle. On the basis of the new data the intensity of the current solar cycle 23 is predicted and some aspects of the theory of the solar cycle are discussed.

1. Introduction

The origin and role of the large-scale magnetic field in the organization of the general solar magnetism and its connection with sunspot activity is a key question for understanding the 22-yr cycle of magnetic activity. Conspicuous features of solar activity are the cyclic occurrences in the solar atmosphere of pairs (or groups) of sunspots with different polarity and with strong fields up to 5 kG. The polarity of these pairs has different orientation in both hemispheres and after a *minimum* of activity they reverse polarity. The large-scale magnetic field regions of the Sun are another remarkable magnetic manifestation. It changes polarity too, but at a *maximum* of sunspot activity.

Many modern theories of a solar cycle consider the weak large-scale magnetic field as the result of breakup of strong fields of active regions and their drift to poles, i.e., as a secondary product of the activity of strong magnetic fields. The underlying idea is that the supergranular motions, differential rotation, and meridional flow transform the magnetic fields of active regions to form the large-scale field patterns (Babcock, 1961; Leighton, 1964; DeVore, Sheeley, and Boris, 1984; Wang, Nash, and Sheeley, 1989). However, many questions, e.g., concerning the duration of the solar cycle and magnetic field reversals of the Sun, remain open.

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Moreover, there are no indexes of the large-scale solar activity which allow one to correctly predict the strength and evolution of the sunspot cycle.

On the other hand, studies of long-term processes of solar activity such as torsional oscillations (LaBonte and Howard, 1982; Makarov, Tlatov, and Callebaut, 1997), magnetic activity at high latitudes (Makarov and Makarova, 1996; Homann, Kneer, and Makarov, 1998) and behaviour of the solar corona (Wilson *et al.*, 1988; Tlatov, 1997) have shown that the solar activity appears not only in sunspots. The features of polar magnetic field reversals of the Sun during the last 120 years were investigated in detail (Makarov and Sivaraman, 1989; Makarov, 1994). It was shown that the cycle of polar activity of the Sun at latitudes higher than 40° begins after polar magnetic field reversal and proceeds during about 11 years, but in anti-phase with the sunspot cycle. High-latitude and low-latitude cycles are connected and show up as branches of a united process, the global solar activity manifesting itself at all latitudes from poles to equator (Makarov, Ruzmaikin, and Starchenko, 1987; Makarov, 1994; Makarov and Makarova, 1996; Obridko and Shelting, 1999). An approximate prediction of the sunspot cycle 23 using the preceding polar faculae cycle was made by Makarov and Makarova (1999).

In the last decade the topology of the large-scale magnetic field of the Sun and its role in the development of the magnetic activities was investigated on the basis of Hα charts of the Sun in the period 1915–1999. However, quantitative characteristics of these connections are unknown till now.

In the present paper some quantitative connections between large-scale magnetic field and sunspot cycles are discussed during the last 9 cycles of activity of the Sun from 1915 to 1999. The level of the current cycle 23 is predicted and some aspects of the theory are discussed.

2. Observational Data

Observational data for the magnetic fields on the Sun were obtained on the basis of Hα synoptic charts from 1915 to 1999 (Makarov and Fatianov, 1982; Makarov and Sivaraman, 1986; *Soln. Dann.*, 1978–1999). They reflect the distribution of the polarity of the magnetic field in this period (McIntosh, 1979; Makarov and Fatianov, 1980; Makarov and Sivaraman, 1989). Wolf numbers and sunspot areas for this period were taken from Hoyt and Schatten, 1998; Makarov and Makarova, 1996; *Soln. Dann.*, 1978–1999.

The photospheric large-scale magnetic field of the Sun can be represented as a function of latitude θ and longitude ϕ, using decomposition in spherical harmonics:

$$B_r = \sum_l \sum_m P_l^m g_l^m \ \cos(m\phi) + h_l^m \ \sin(m\phi)),$$

where P_l^m are Legendre polynomials. The coefficients of decomposition, g_l^m and h_l^m, are surface integrals:

$$g_l^m = \frac{(2l+1)}{2\pi}\frac{(l-m)!}{(l+m)!}\int_0^{2\pi} \mathrm{d}\phi \cos(m\phi) \int_0^{\pi} B_r(\theta,\phi) P_l^m(\cos(\theta)) \ \sin(\theta)\ \mathrm{d}\theta,$$

$$h_l^m = \frac{(2l+1)}{2\pi}\frac{(l-m)!}{(l+m)!}\int_0^{2\pi} \mathrm{d}\phi \ \sin(m\phi) \int_0^{\pi} B_r(\theta,\phi) P_l^m(\cos(\theta)) \ \sin(\theta)\ \mathrm{d}\theta.$$

Here $B_r(\theta, \phi)$ is the value of the surface magnetic field. In the case of Hα charts we took only the sign of the magnetic field, keeping the absolute value constant: $+1$ G or -1 G, according to whether the field was positive or negative. Nine harmonics were taken into account. It is possible to restore Hα charts of a magnetic field using the factors of decomposition g_l^m and h_l^m.

The calculations of the decomposition factors g_l^m and h_l^m were executed independently by two groups: one at the Kislovodsk Solar Station and one at IZMIRAN. It was supposed that the magnetic field is a potential field from the photosphere to the source surface, which was assumed to be situated at 2.5 $R_\odot$, where $R_\odot$ is the radius of the Sun. The results agreed very well. More details of the technique used are given by Obridko and Shelting (1999) and Makarov and Tlatov (1999). The factors of g_l^m and h_l^m are accessible through the INTERNET at the address: www.izmiran.ru.

3. Results

Let us consider the temporal behaviour of harmonics with low numbers $l = 1$ and $l = 3$. The magnetic moments of dipole and octupole are, respectively,

$$\mu_1 = \left(\sum_{m,l=1} (g_l^m g_l^m + h_l^m h_l^m)\right)^{1/2},$$

$$\mu_3 = \left(\sum_{m,l=3} (g_l^m g_l^m + h_l^m h_l^m)\right)^{1/2}.$$

Let us introduce a quantity describing the intensity of the large-scale field:

$$A(t) = (\mu_1^2 + \mu_2^2/3)^2.$$

$A(t)$ represents the sum of the squares of the magnetic octupole and dipole moments. In Figure 1 (top) the distribution of $A(t)$ is given for 1915–1999. The 11-yr cycle of a large-scale magnetic field of the Sun leaps to the eye. The procedure of smooth sliding by a window of 2 years was applied to eliminate noise. In Figure 1 (bottom) the solar activity in Wolf numbers, $W(t)$, is given for comparison. It is

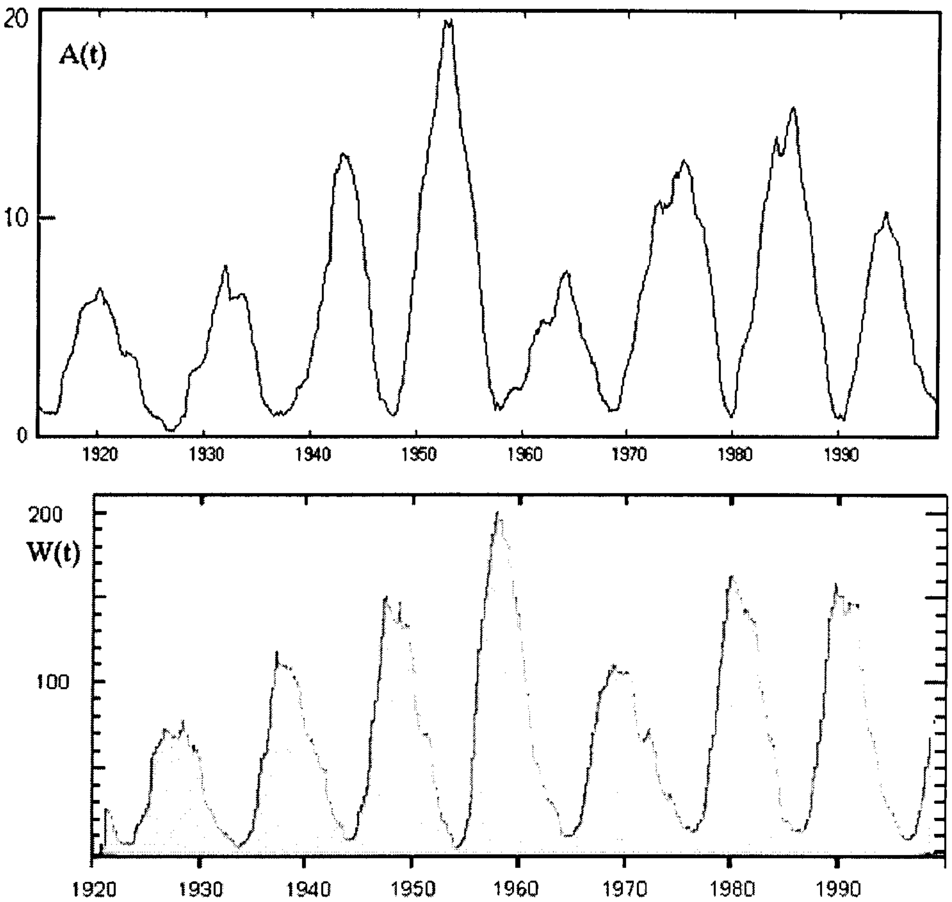


Figure 1. Top: the 11-yr cycle of the large-scale magnetic field of the Sun expressed by the parameter $A(t)$. The value $A(t)$ is calculated on a basis of Hα synoptic charts for 1915–1999. Parameter $A(t)$ is calculated using only the polarity of the field on the charts: taking either $+1$ G or -1 G. *Bottom:* the 11-yr solar cycle expressed by Wolf number for 1915–1999. The cycle of the large-scale magnetic fields of the Sun precede by 5.5 years the sunspot cycles and are with them in anti-phase.

remarkable that the cycle of the large-scale magnetic field *precedes* the sunspot cycle according to the Stanford magnetographic observations for 1975–1999 (Figure 2). The relative variations in the amplitudes of $A(t)$ are similar to those of $W(t)$ from cycle to cycle, but they are shifted in phase. Both the maxima of the Wolf numbers and the quantity $A(t)$ increased from 1920 to 1956 and then showed a sharp decrease for solar cycle 20.

The phase shift between $A(t)$ and $W(t)$ is about 5.5 years (Figure 3, top). Figure 3 (bottom) shows the connection between the maximum of a large-scale magnetic field $A(t)$ and the maximum Wolf number $W(t)$ shifted over 5.5 years. For the present cycle 23 the parameter $A(t)$ turns out to be 11.4, which allows us to predict $W(23) = 130 \pm 10$. The parameter $A(t)$ representing the large-scale

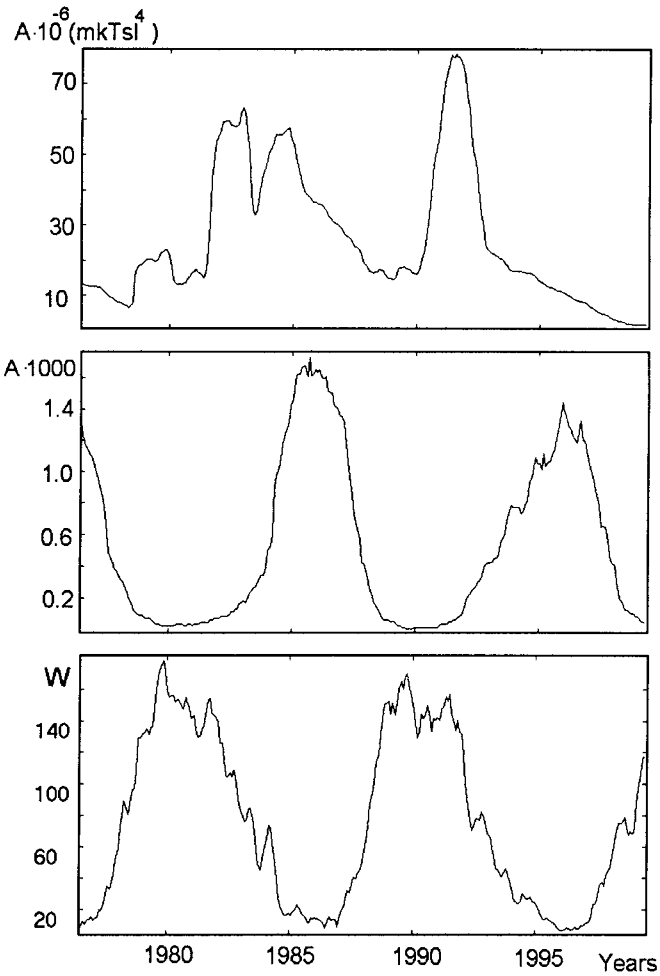


Figure 2. Top: the 11-yr cycle of the solar magnetic fields according to the Stanford magnetographic observations for 1975–1999. *Middle*: the 11-yr cycles of the large-scale magnetic fields according to the Stanford magnetographic observations expressed by the parameter $A(t)$. Parameter $A(t)$ is calculated using only the polarity of the field. *Bottom:* the 11-yr solar cycle expressed by Wolf number for 1975–1999. The cycles of the large-scale magnetic fields of the Sun precede by 5.5 years the sunspot cycles and are with them in anti-phase.

magnetic field cycle includes only dipole and octupole components. We considered higher harmonics as well (Figure 4). The even modes $l = 2, 4$ have small intensity and their contribution is essential only to the analysis of a biennial cycle (Stenflo and Vogel, 1986).

Figure 5 shows the correlation functions between the magnetic moments of odd modes with $l = 1, 3, 5, 7, 9$ and Wolf numbers. For the dipole and octupole components the shift of half of an 11-yr cycle is very manifest. High modes $l = 7, 9$ practically are completely due to local fields and do not show a temporal shift

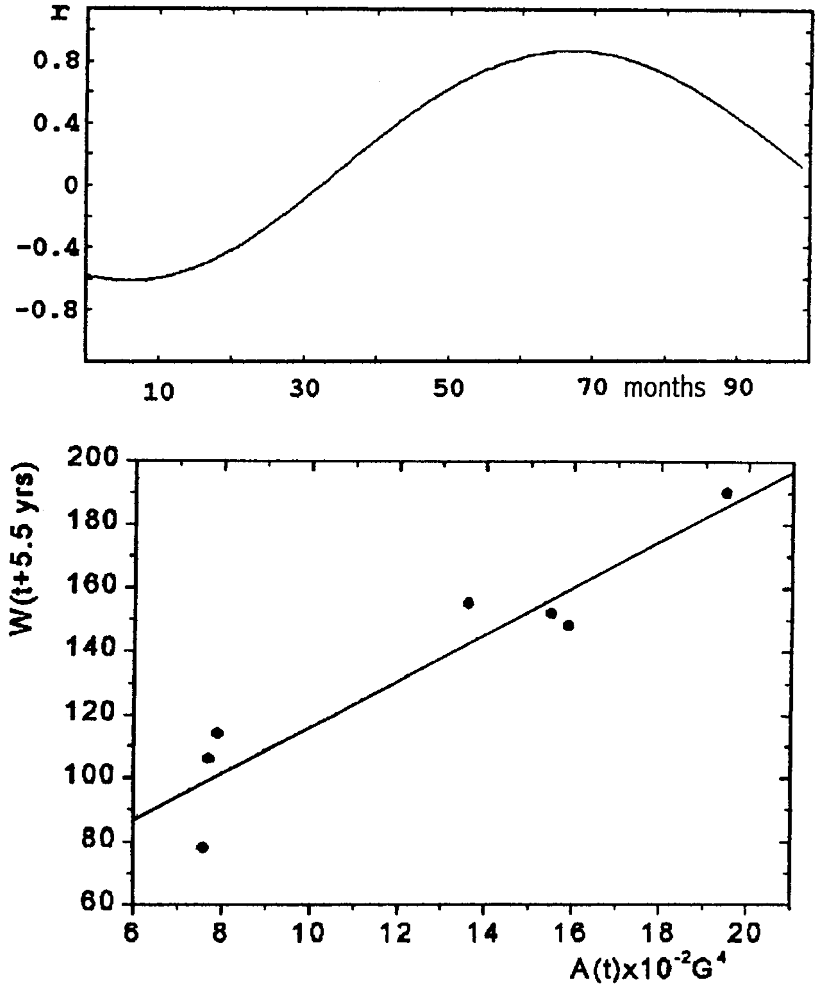


Figure 3. Top: the correlation r between $A(t)$ and $W(t)$ for 1915–1999. Maximum correlation occurs for a shift between $A(t)$and $W(t)$ of 65 months, i.e., 5.5 years. Thus $A(t)$ precedes $W(t)$. *Bottom:* connection between the maximum of a large-scale magnetic field $A(t)$ and the maximum Wolf number $W(t)$ shifted over 5.5 years. For the present cycle 23 the parameter $A(t)$ turns out to be 11.4, which is equivalent to $W(23) = 130 \pm 10$.

in comparison with Wolf numbers. The harmonic with $l = 5$ has intermediate properties between those of $l = 1, 3$ and $l = 7, 9$.

4. Power Indexes of a Global Magnetic Field

According to Obridko and Yermakov (1989) and Obridko and Shelting (1992) the power index of a global magnetic field $i(B_r)|_R$ as a square of the radial components of a magnetic field average on some spherical surface of the radius R of the Sun is

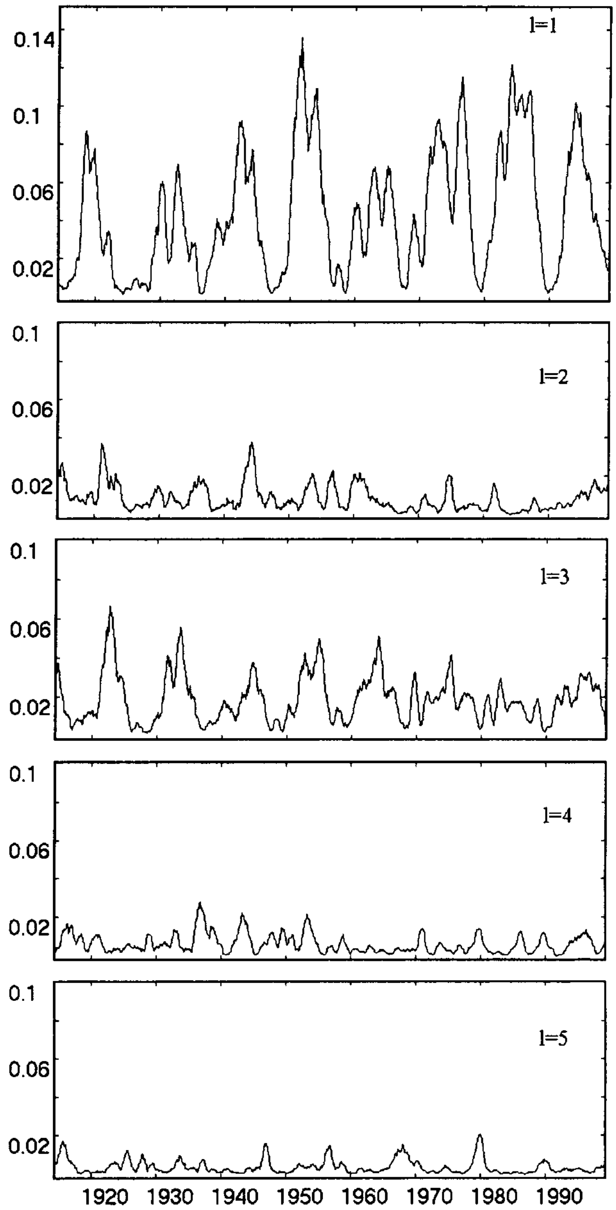


Figure 4. Relative intensity of harmonics calculated on a basis of Hα synoptic charts for $l = 1, 2, 3, 4, 5$.

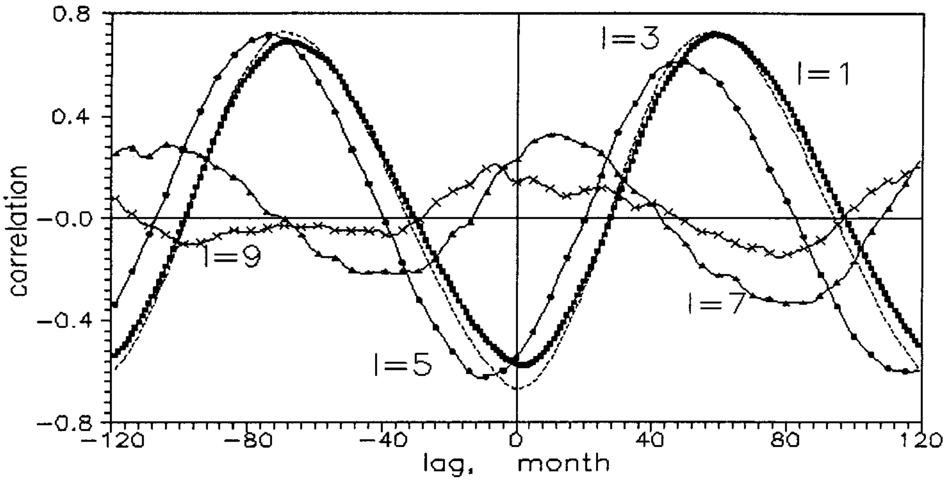


Figure 5. Correlation function between the magnetic moments of odd modes with $l = 1, 3, 5, 7, 9$ and Wolf numbers.

$$i(B_r)|_R = \left(\sum_{lm} (2l + 1)\zeta^{2l+4}(g_{lm}^2 + h_{lm}^2 \right),$$

where $\zeta = 0.4$.

Partial indexes, namely the pure zonal-even, ZE ($m = 0, l = 2k$), pure zonal-odd, ZO ($m = 0, l = 2k + 1$), full sectorial-even, SE ($m = l = 2k$), and full sectorial-odd, SO ($m = l = 2k + 1$) may be calculated too. These indexes are introduced to give insight in the direct measurements of a magnetic field and have direct power meaning, that is to say they represent an average energy of the total magnetic field, respectively of some of its components on the surface. In fact the Hα charts show the distribution of the polarity of magnetic field only. On the other hand, the indexes characterize the relative contribution and phase variation of a cycle in zonal and sectorial structures. The sectorial-odd indexes characterize the contribution of 2 and 4 sectorial structures, and the sectorial-even indexes characterize a contribution of 3 and 5 sectorial structures. Moreover, with the help of these indexes it is possible to better understand some differences between the Stanford system, where the direct measurements of a magnetic field are carried out and consequently the contribution of strong fields is especially emphasized and the Hα system, where the polarity of the magnetic field is used only. In the last case all indexes are defined by the *topological* structure of the field only.

Figures 6(a,b) show the index $i(B_r)|_R$ (solid line) that was calculated from the Stanford and Hα data for 1976–1991 (solar rotation 1640–1840). The sectorial component in Figure 6(a) and zonal component in Figure 6(b) are shown by a dotted line. The difference between both systems becomes clear. Hα charts show the basic contribution by the zonal structures and the Stanford observations show the basic contribution by the sectorial structures. Thus Hα magnetic charts (with-

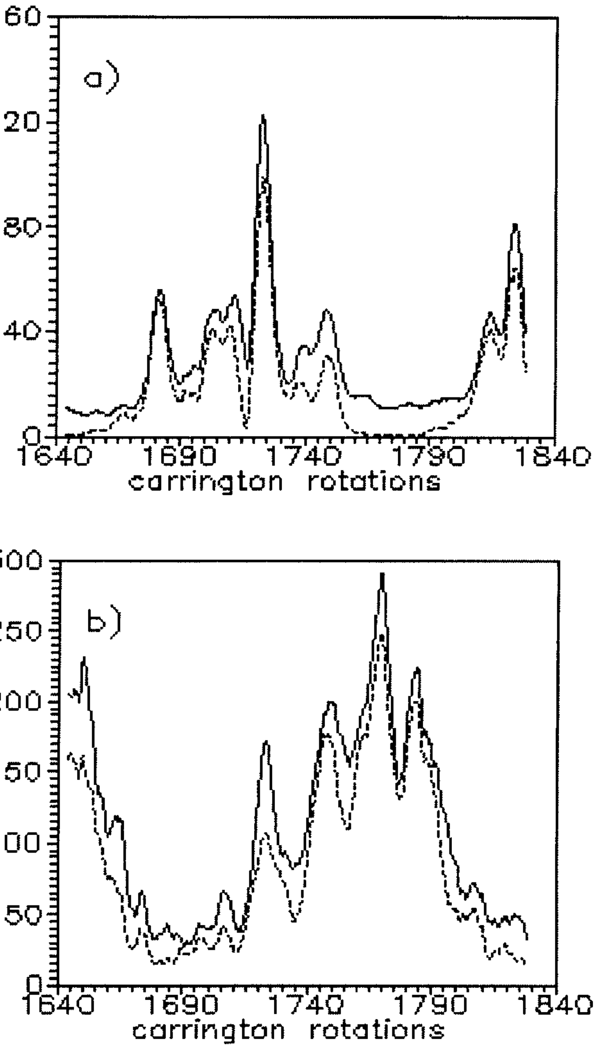


Figure 6. Comparisons of the total 'power' index and its components. (a) The value of $i(B_r)|_R$ is shown by a *solid line* according to the Stanford data. The *dotted line* shows the sum of all NOT ZONE components. (b) shows the value of $i(B_r)|_R$, (*solid line*), according to Hα charts. The *dotted line* shows the sum all ZONE components.

out fields from active regions) reflect the global magnetic structure better than the magnetographic observations.

This advantage with respect to the zonal structures is again clearly illustrated in Figure 7, where a dotted line indicates the zonal-odd component from Hα charts and Stanford data. For the purpose of comparison the Hα data were multiplied by 0.09. The coincidence of the cyclic curves has a correlation factor of 0.825.

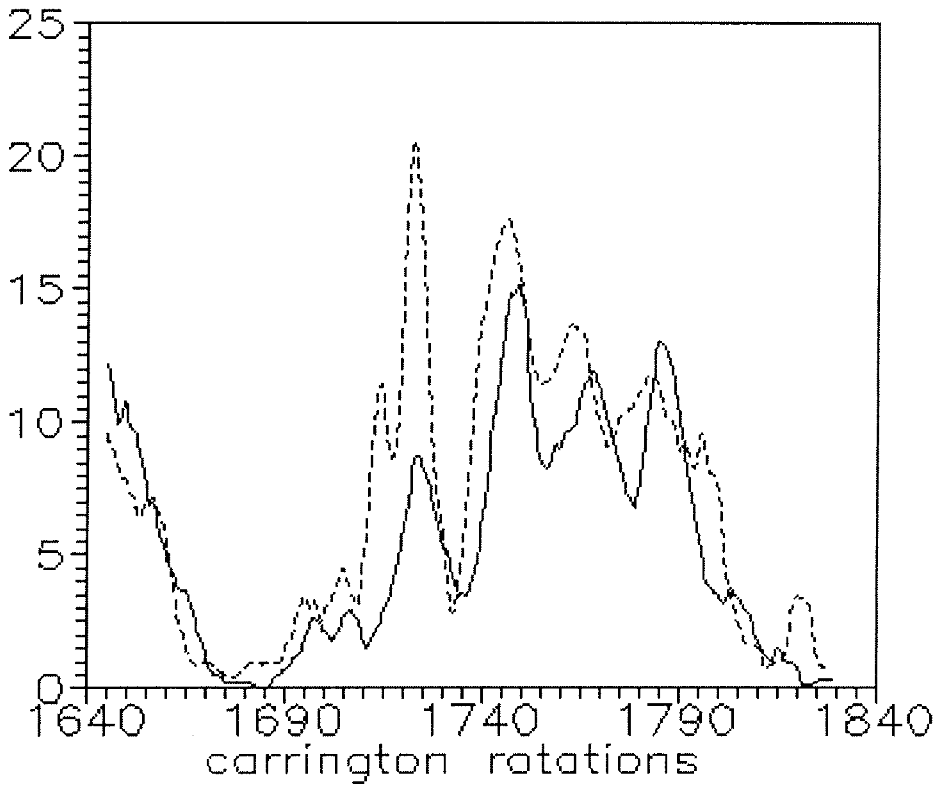
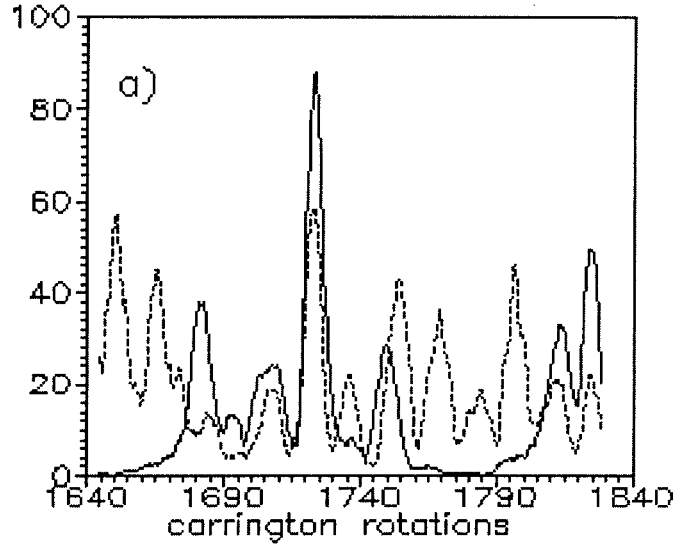


Figure 7. Behaviour of an index ZO according to Hα charts (*dotted line*) and according to the Stanford magnetograph data (*solid line*).

However, the zone structures in the Stanford case are strongly underestimated by one order of magnitude.

Figure 6(b) shows the value of $i(B_r)|_R$ (solid line), according to Hα magnetic charts. The dotted line shows the sum of all ZONE components. Figure 8(a) shows the sectorial-odd component from Stanford data (solid line) and Hα charts (dash line). Figure 8(b) shows similarly the index $i(B_r)|_R$ for the sectorial-even component. It is seen that the sectorial structure (index SO) is satisfactorily described in both systems everywhere, except for the minima of 11-yr cycles (rotations 1640 –1670 and 1760–1800). In fact the Stanford magnetographic system is mostly used to work with strong magnetic field signals and near the minima of activity it tends to indicate the apparent disappearance of the sector structure. However, this sector structure is still present, despite the drop in intensity of the magnetic field, as is made clear by the Hα charts, and these reveal even quasi-biennial fluctuations (Makarov and Tlatov, 1999).



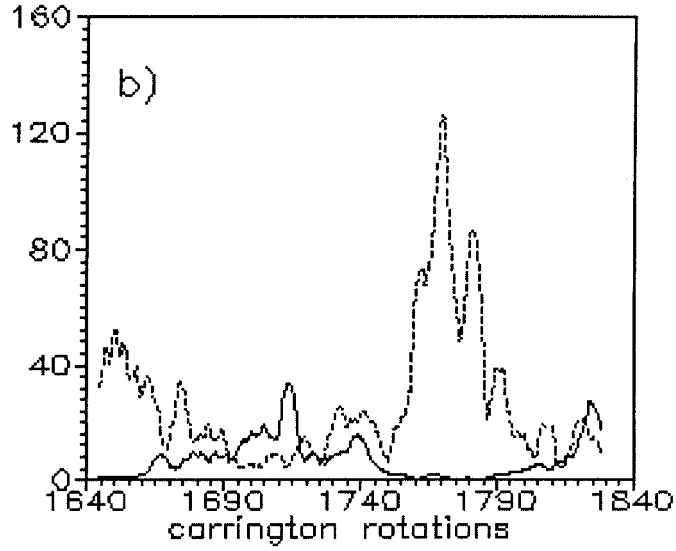


Figure 8. (a) Behaviour of an index SO for Stanford data (*solid line*) and according to Hα charts (*dotted line*). (b) Behaviour of an index SE for Stanford data (*solid line*) and according to Hα charts (*dotted line*).

5. Discussion of Results

The obtained results confirm the leading and prominent role of the large-scale magnetic field in the organization and dynamics of a sunspot cycle. The amplitudes of the dipole and octupole contributions, $l = 1, 3$, which determine the parameter $A(t)$ depend on the topology of the fields. The sunspot cycle is a finishing stage of dynamics of a magnetic cycle. The comparison of the index $A(t)$ with the index of Wolf numbers $W(t)$ shows the possibility to forecast solar activity. Thus the current cycle 23 is expected to be less than cycle 22, as $A(23)$ makes about 11.4, whereas for previous cycle 22 the value of $A(22)$was about 15.9 (Figure 3). Thus our prediction is that the maximum $W(23)$ is expected to be about 130.

The solar magnetic cycle can possibly be represented as a periodic wave of a new magnetic field raised at high latitudes (Makarov, Tlatov, and Callebaut, 1997). The probable depth of excitation of new field is close to the bottom of a convection zone. The generating wave may move together with the meridional flow at the bottom of the convection zone from poles to equator during 15–18 years. A generating wave is perhaps routed by a slow wave of torsional oscillations, (Makarov and Tlatov, 1997). What exactly happens during the observed polar magnetic field reversals of the Sun remains unclear. In view of the received data it is possible to consider a process of transport of magnetic field by matter immersing near the poles from the solar surface to the bottom of the convection zone. Anyway this can be only a fraction of the large-scale field as a large part of it is dissipated by eruptions of the filament belts. Emergence of large-scale magnetic field occurs at all latitudes from poles up to the equator.

It may be noted, that in some respects the system of the magnetic fields constructed on the basis of Hα charts has appeared a little more convenient, than existing direct magnetographic observations. There is an obvious advantage of Hα charts in view of the long time span of data. We note two less obvious aspects:

(1) In the Hα system all intensities of the magnetic fields are equal, hence the contribution of local magnetic fields is essentially underestimated. It means, that the Hα system describes large-scale and global magnetic fields more adequately for global purposes.

(2) For the same reason the Hα system better describes the variations of the topological structure of the magnetic field.

Acknowledgements

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