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The Large-Scale Solar Magnetic Field and 11-Year Activity Cycles

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Abstract—Magnetic Hα synoptic maps of the Sun for 1915–1999 are analyzed and the intensities of spherical harmonics of the large-scale solar magnetic field computed. The possibility of using these Hα maps as a database for investigations of long-term variations of solar activity is demonstrated. As an example, the magnetic-field polarity distribution for the Hα maps and the analogous polarity distribution for the magnetographic maps of the Stanford observatory for 1975–1999 are compared. An activity index $A(t)$ is introduced for the large-scale magnetic field, which is the sum of the magnetic-moment intensities for the dipole and octupole components. The 11-year cycle of the large-scale solar magnetic field leads the 11-year sunspot cycle by, on average, 5.5 years. It is concluded that the observed weak large-scale solar magnetic field is not the product of the decay of strong active-region fields. Based on the new data, the level of the current (23rd) solar-activity cycle and some aspects of solar-cycle theory are discussed. *© 2000 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

The origin of the large-scale solar magnetic field, its role in the organization of the overall magnetic field of the Sun, and its relation to sunspot activity are likely key points for our understanding of the 22-year magnetic cycle. One remarkable feature of solar activity is the 11-year cycle for the appearance of local magnetic fields in the solar atmosphere, with induction values of up to 5 kG, which have different polarities in the northern and southern hemispheres of the Sun and change their sign at the activity minimum. The large-scale solar field also changes its polarity, but at the activity maximum of each 11-year cycle. The characteristics of polarity reversals of the solar magnetic field have been studied in detail for more than 120 years [1]. At latitudes higher than 50°, the polar-activity cycle begins after the polarity reversal of the polar magnetic field; it also lasts about 11 years, but proceeds in antiphase with the sunspot cycle. These cycles are related, and manifest a single process of global solar activity at all latitudes, from the poles to the equator [2]. This structure of the global magnetic cycle of the Sun has been discussed on the basis of both observations [3, 4] and theory [5, 6].

Over the past two decades, Makarov and Sivaraman [7] constructed magnetic Hα maps of the polarity distribution for the large-scale solar magnetic field from observations carried out at the Kodaikanal Observatory (India) from 1910 to 1975. These data were later augmented with Hα maps from the Kislovodsk Mountain Astronomical Station of the Main Astronomical Observatory of the Russian Academy of Sciences. Based on the magnetic Hα maps for 1910–1999, the topology of the large-scale solar magnetic field and its role in the development of solar activity were studied in [8–13]. Makarenko *et al.* [14] found qualitative evidence that the weak large-scale solar magnetic field may be primary with respect to the strong local magnetic fields of sunspots. However, no quantitative characterization of this relationship was found. On the other hand, early theories of the solar cycle took the weak large-scale magnetic field to result from the decay of strong active-region fields and their poleward drift [15, 16]; i.e., to be a secondary product of the activity of local magnetic fields. In some studies, meridional circulation was invoked to account for the poleward drift [17–20]; however, the question of the durations of the solar cycle and the field polarity reversals remains open.

On the other hand, studies of long-term, poleward magnetic-field drifts [1, 3, 4], equatorward field drifts or torsional oscillations [11–13, 21], high-latitude and polar-facula magnetic activity [2, 3, 22], and coronal intensity variations over the course of the global activity cycle [11, 12] have shown that the magnetic activity of the Sun is not manifest only in local magnetic fields. According to global solar-cycle models, a new activity cycle starts at high latitudes several years before the emergence of the earliest new active regions of the new cycle, whereas its pattern-forming activity appears only later [8].

Here, we discuss the quantitative relationship between the 11-year cycle of the large-scale magnetic field and the 11-year cycle of local magnetic fields for the past eight solar-activity cycles, from 1915 to 1999. We use new data to discuss the activity level of the current (23rd) cycle, as well as some aspects of solar-cycle theory.

2. OBSERVATIONAL DATA AND PROCESSING TECHNIQUES

Information about the intensities of modes for the large-scale magnetic field and poleward and equatorward drifts of the fields were derived from Hα synoptic magnetic maps for 1915–1999 constructed using the technique described in [7]. Data on Wolf numbers, numbers of groups, and sunspot areas for this period were obtained in accordance with [2, 23, 24]. To compare the magnetic Hα maps with the magnetographic observations of the Stanford observatory, we expanded synoptic maps taken to have magnetic-field polarities of +1 or –1 G in spherical harmonics.

The surface magnetic field of the Sun can be represented as a function of latitude θ and longitude ϕ using the spherical-harmonic expansions

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

where P_l^m are the associated Legendre functions. The expansion coefficients g_l^m and h_l^m can be found via a surface integration:

$$g_l^m = \frac{(2l+1)}{2\pi}\frac{(l-m)!}{(l+m)!}\int_0^{2\pi} d\phi \cos(m\phi)$$

$$\times \int_0^{\pi} B_r(\theta, \phi) P_l^m(\cos(\theta)) \sin(\theta) d\theta,$$

$$h_l^m = \frac{(2l+1)}{2\pi}\frac{(l-m)!}{(l+m)!}\int_0^{2\pi} d\phi \sin(m\phi)$$

$$\times \int_0^{\pi} B_r(\theta, \phi) P_l^m(\cos(\theta)) \sin(\theta) d\theta.$$

Here, $B_r(\theta, \phi)$ is the surface magnetic field. In our case, we used only the sign of the magnetic field for the Hα synoptic maps: +1 or –1 G for positive and negative magnetic fields, respectively. If the expansion coefficients g_l^m and h_l^m are known, the synoptic map of the magnetic field can be reconstructed and its distribution analyzed.

When performing the expansion, we assumed that the number of harmonics was $l = 9$. We carried out comparisons for the period of the observations at the Stanford Observatory, for Carrington rotations 1642–1950 (i.e., for the years 1975–1999).

3. RESULTS

Figure 1 displays latitude–time diagrams for the magnetic-field polarity distribution obtained from the Kislovodsk Hα synoptic maps and the Stanford magnetographic observations. A comparison reveals fairly good agreement in these distributions for the period under study. The observed small differences may be due to inaccuracy in constructing the Hα maps and/or possible displacements of the zero point in the magnetographic observations. The similarity of the patterns of the magnetic-field poleward drift for 1975–1999 obtained using the two different sources testifies to the uniformity and reliability of the Hα-map series for the Kislovodsk Mountain Astronomical Station data. The general pattern of the poleward drift and sign reversals of the magnetic field for 1915–1999 derived from the spherical-function expansions is shown in Fig. 1.

The time variations in the coefficients of the spherical-function expansion for the magnetic field reflect changes in the topology of the large-scale magnetic field. Obviously, the presence of bipolar active sunspot regions during the period of activity maximum increases the contribution of high-l harmonics. Conversely, the simplification of the distribution of large-scale fields during the period of activity decline and minimum increases the contribution of lower harmonics. Thus, in general, periods of intensity maxima for the harmonics should be displaced with respect to maxima in the sunspot distribution; i.e., they should have a phase shift that depends on l.

Let us consider the time behavior of low-l harmonics. We represent the magnetic dipole ($l = 1$) and octupole ($l = 3$) moments in the form

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

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

where g_l^m and h_l^m are the coefficients of the spherical-function expansion. We introduce a parameter characterizing the intensity of the dipole and octupole magnetic moments:

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

The top panel of Fig. 2 shows the distribution of $A(t)$ for 1915–1999. The 11-year cycle of the large-scale solar magnetic field can clearly be seen. We applied a sliding-averaging procedure with a 2-year window to reduce the noise. The bottom panel of Fig. 2 presents the 11-year solar-activity cycle in the Wolf number W. Both $A(t)$ and $W(t)$ exhibit cyclic behavior with a period of about 11 years, with the phase shift of $A(t)$ relative to the Wolf number being about 5.5 years (Fig. 3). The cycle of the large-scale magnetic field leads the sunspot cycle. The relative variations in the amplitudes of $A(t)$ are similar to the cycle-to-cycle variations in the amplitudes of $W(t)$, but are phase shifted. As for the Wolf numbers, $A(t)$ increases from 1920 to 1956, then

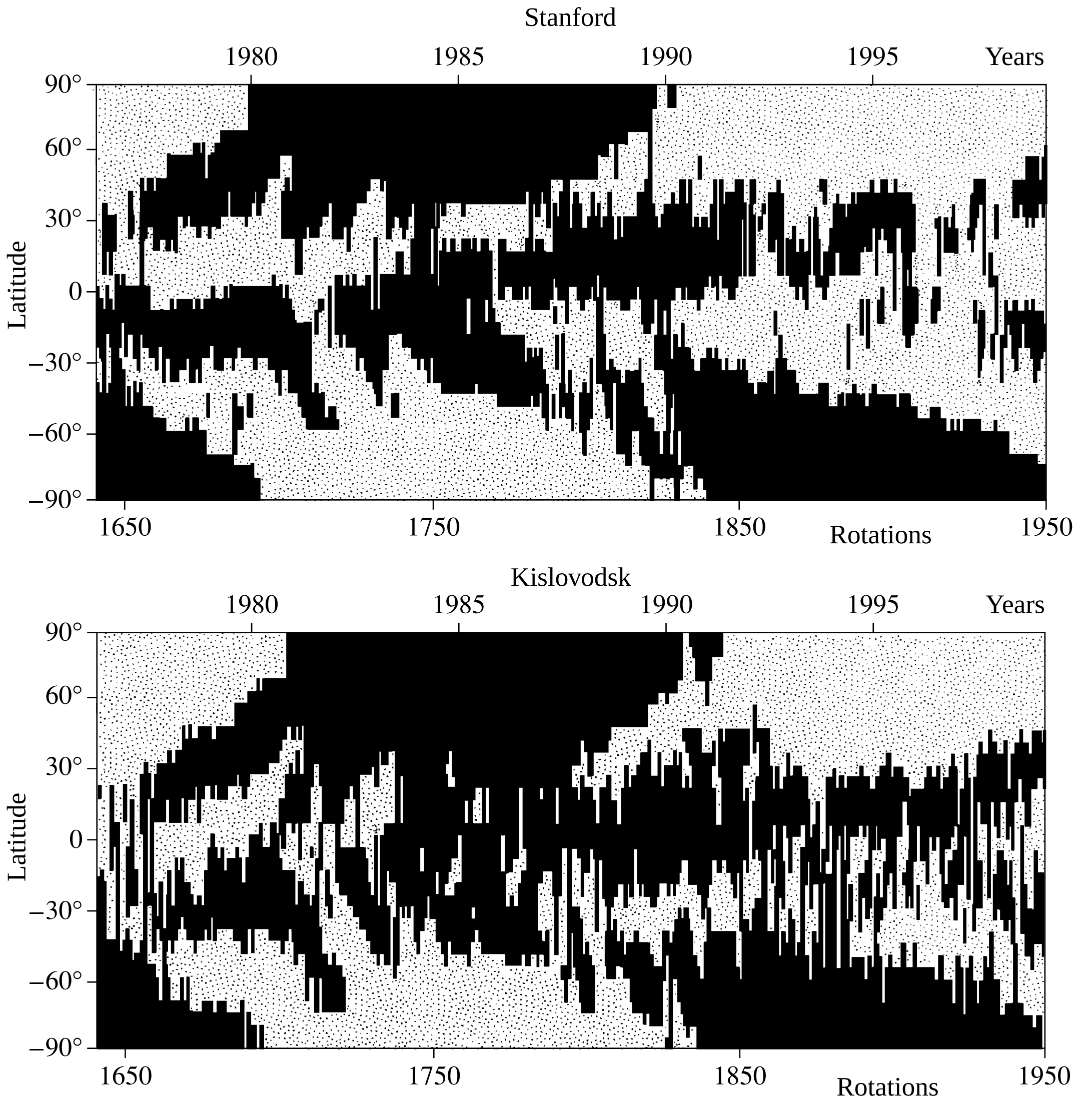

Fig. 1. Latitude–time distribution of polarities of the large-scale solar magnetic field derived from Stanford magnetographic observations (top) and Hα synoptic magnetic maps obtained at the Mountain Astronomical Station of the Main Astronomical Observatory (bottom) for 1975–1999. The light and dark regions correspond to + and – magnetic-field polarities, respectively. The zonal structure of the solar magnetic field, latitude drift, and reversal of the polar magnetic field can be seen.

sharply falls during the period of the minimum preceding cycle 20. Later, the values at the minima before cycles 21 and 22 are roughly equal, and relatively low values are observed at the minimum preceding activity cycle 23.

The parameter $A(t)$ describing cyclic variations in the large-scale magnetic field includes the intensities of the magnetic moments of only the dipole and octupole components. Higher odd harmonics, e.g., $l = 5, 7, 9, \ldots$, can also be taken into account; however, as can be seen from the calculations, they enhance only the noise component. The intensity of the even modes $l = 2, 4, 6, \ldots$ is low, and their contribution is significant only in analysis of the quasi-biennial cycle (Fig. 4).

Our results confirm that the large-scale magnetic field plays a leading role in the organization and dynamics of the solar cycle. The amplitude of the total power of the dipole and octupole components ($l = 1, 3$) depends on the field topology at middle and high latitudes. Therefore, the field of a new cycle, which has the sign of the leading spots of the next activity cycle, determines the polarity topology—primarily for middle and high latitudes at the phases of activity decline and minimum of the current cycle. Obviously, the stronger the high-latitude field, the less likely the penetration of the opposite-polarity field to the poles (associated with meridional circulation), and the higher the smoothed value of the index $A(t)$. Comparisons between $A(t)$ and the Wolf-number index $W(t)$ demonstrate possibilities for solar-activity forecasting. For instance, the current (23rd) activity cycle is expected to be weaker than cycle 22, since $A(23)$ is about 11.4,

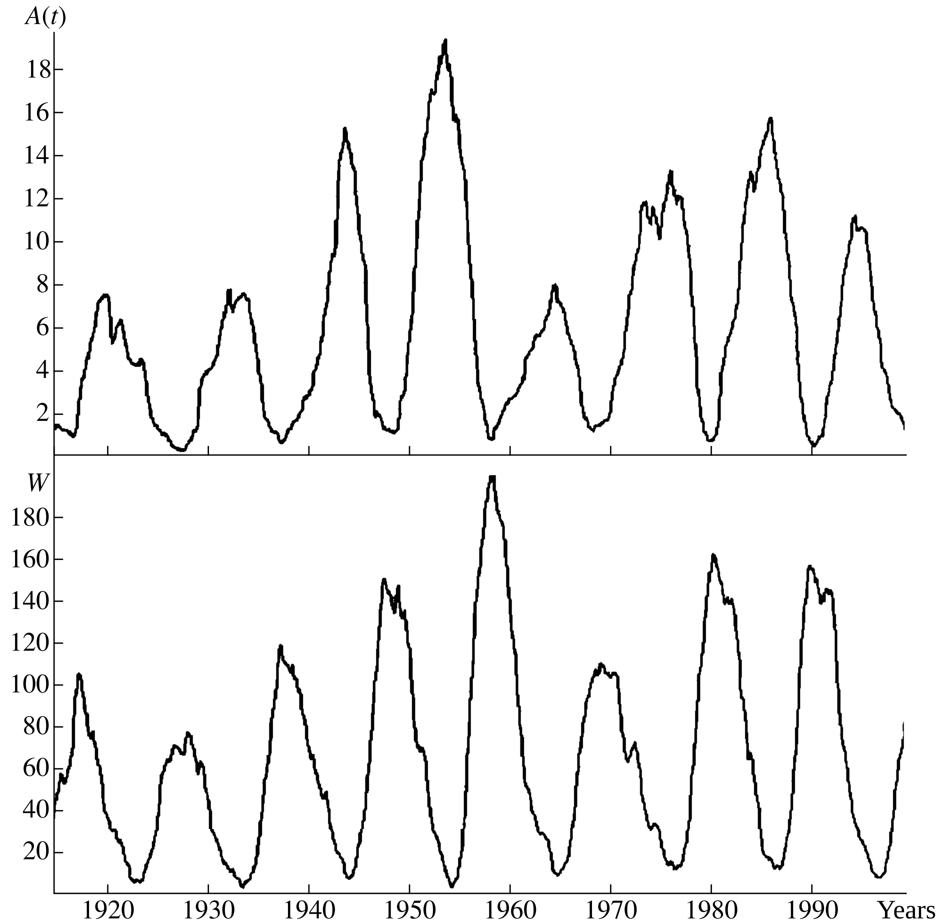

Fig. 2. Top: 11-year cycle of the large-scale solar magnetic field represented by the parameter $A(t)$. $A(t)$ is calculated from Hα synoptic magnetic maps, for 1915–1999, where the magnitude and polarity of the field are taken to be either +1 or –1 G. Bottom: 11-year solar-activity cycle represented by the Wolf number, for 1915–1999. The activity cycles of the large-scale solar magnetic field lead the corresponding cycles of sunspot activity by 5.5 years, and are in antiphase with the latter.

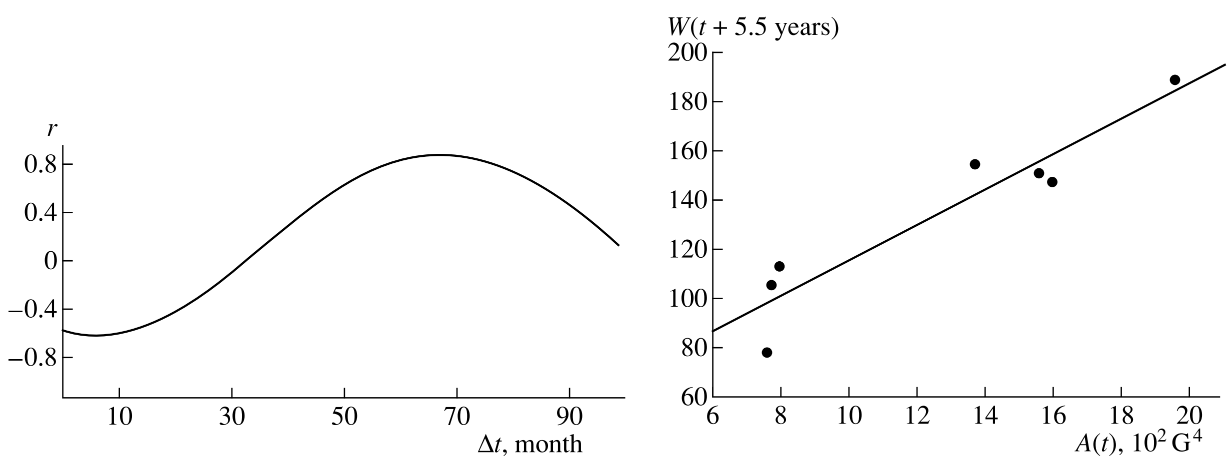

Fig. 3. Top: mutual-correlation coefficient as a function of the shift Δt between $A(t)$ and $W(t)$ for 1915–1999. The mutual-correlation coefficient is maximum for a shift of 65 months (i.e., 5.5 years), with $A(t)$ leading $W(t)$. Bottom: relationship between the maximum magnitude $A(t)$ of the large-scale magnetic field and the maximum Wolf number in a cycle, taken 5.5 years later. For cycle 23, $A(t)$ is 11.4; equivalently, $W(23) = 130 \pm 10$.

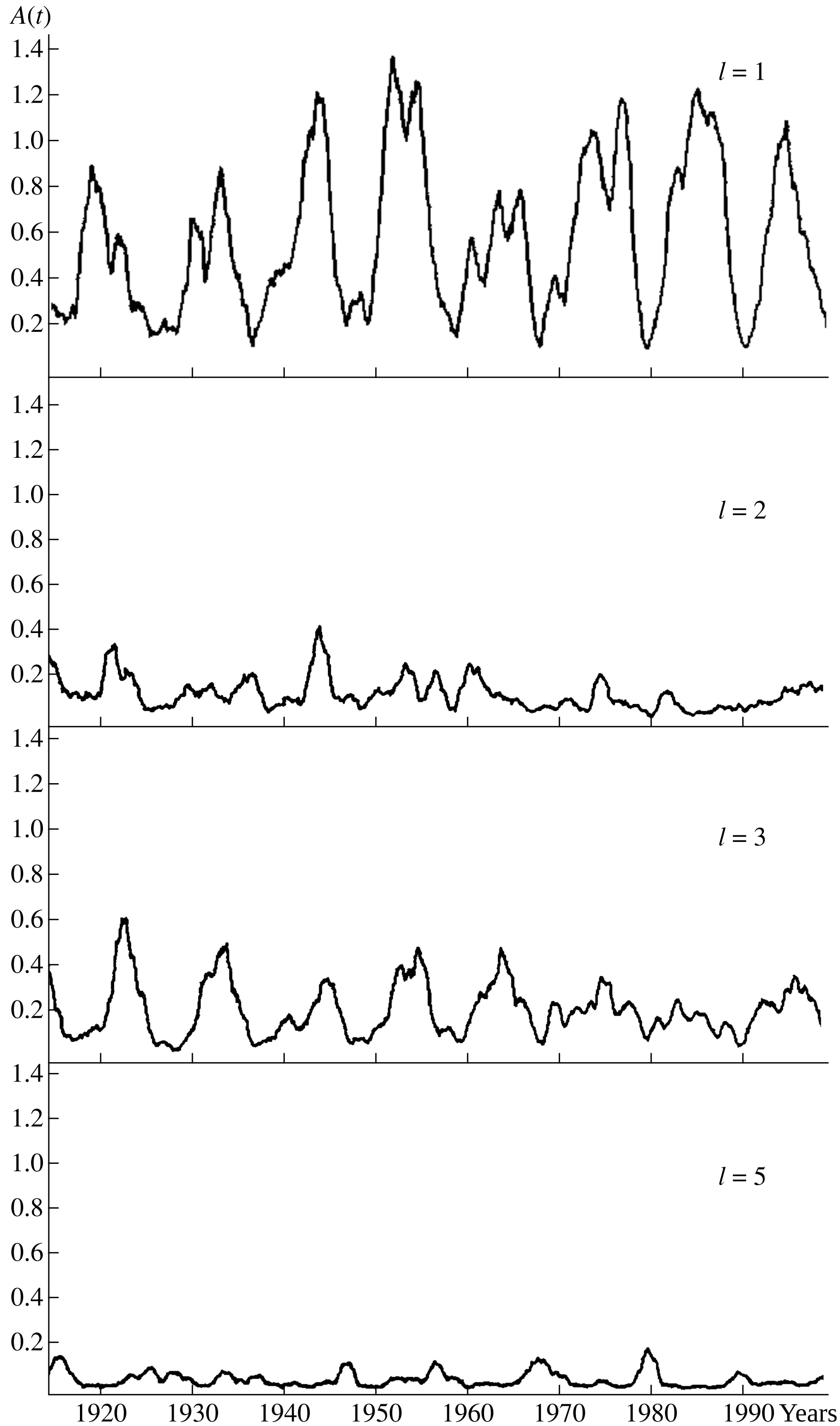

Fig. 4. Relative intensity of the harmonics $A^*(t)$ calculated from the Hα maps according to the formula $A^*(t) = \sum_{m,\,l}(g_l^m g_l^m + h_l^m h_l^m)$, for $l = 1, 2, 3, 5$.

whereas $A(22)$ was equal to 15.9 for cycle 22 (Fig. 2). In view of this, the maximum value of $W(23)$ should reach about 130.

The solar magnetic cycle can be schematically represented as periodic waves of propagation of a new magnetic field excited at high latitudes [11]. The new magnetic field is probably excited close to the lower boundary of the convection zone. The wave of field generation travels with the meridional flow from the poles to the equator over 15–18 years. This wave is traced by a slow wave of torsional oscillations. The reason for the observed reversal of the polar magnetic field of the Sun remains unclear. In the context of our data, we can consider the transfer of the magnetic field from the surface to the base of the convection zone, which accompanies the sinking of material near the poles [11]. Sources of the large-scale magnetic field emerge at all latitudes, from the poles to the equator. As this takes place, sources belonging to two successive cycles can be superposed and form a zonal polarity distribution, with a neutral line at middle latitudes, between the sources of opposite polarities, which can persist for several years [13]. The sunspot cycle is the final dynamical stage of the magnetic cycle.

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