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22-Year Variations of the Solar Rotation and Solar Activity Cycles

A. G. Tlatov[*]

High-Altitude Astronomical Station, Pulkovo Astronomical Observatory, Russian Academy of Sciences, Kislovodsk, Russia

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Abstract—We have performed a comparative analysis of the results of our study of the 22-year rotation variations obtained from data on large-scale magnetic fields in the Hα line, magnetographic observations, and spectral-corona observations. All these types of data suggest that the rotation rate at low latitudes slows down at an epoch close to the maximum of odd activity cycles. The 22-year waves of rotation-rate deviation from the mean values drift from high latitudes toward the equator in a time comparable to the magnetic-cycle duration. We discuss the possibility of the generation of a solar magnetic cycle by the interaction of 22-year torsional oscillations with the slowly changing or relic magnetic field. We consider the generation mechanisms of the high-latitude magnetic field through a superposition of the magnetic fields produced by the decay and dissipation of bipolar groups and the relic or slowly changing magnetic field and a superposition of the activity wave from the next activity cycle at high latitudes.

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Key words: *Sun, differential rotation, magnetic cycle.*

INTRODUCTION

A study of the rotation variations on time scales longer than the duration of the solar magnetic cycle provides important information on the generation mechanism of solar activity. Sunspot coordinates have long been the main source of data that were used to analyze the long-term rotation variations. Studies based on sunspot data have shown that the coefficients a and b in Fay's formula for 11-year cycles nos. 12–17 (1874–1944) differ for even and odd cycles: $\omega = 14.364 - 2.60\sin^2\theta$ in even cycles and $\omega = 14.375 - 2.82\sin^2\theta$ in odd cycles (Newton and Nunn 1951). A 22-year cycle of oscillations in the north–south asymmetry of solar rotation was found: $a_{\rm N} > a_{\rm S}$ and $b_{\rm N} > b_{\rm S}$ in even cycles and $a_{\rm N} < a_{\rm S}$ and$b_{\rm N} < b_{\rm S}$ in odd cycles (Chistyakov 1982). However, after 1944, these trends broke down. Javaraiah (2003) distinguished 22-year variations in coefficient b in the formula for the expansion of the differential rate in latitude in the period 1879–1975.

There also exist other sets of observational data that can be used to investigate the rotation on long time scales. Thus, for example, data on the distribution of large-scale magnetic fields revealed a 22-year modulation of the rotation rate in the mid-latitude and equatorial regions of the Sun in the period 1890–1995; the rotation was accelerated in even cycles and decelerated in odd cycles (Tlatov and Makarov 2004; Tlatov 2005a). Analysis of the intensity of the spectral corona in the 5303 Å line revealed 22-year rotation variations at high latitudes (Tlatov 2006). It turned out that the rotation variations are high latitudes also undergo a 22-year modulation, but they are in antiphase with the rotation of low-latitude regions. A 22-year periodicity was also found from data on the rotation of the solar atmosphere observed in the CaII K line (Tlatov 2002).

In this paper, we compare the long-term rotation variations obtained from various types of observational data, such as the distributions of large-scale magnetic fields and observations of the spectral corona, and perform a comparison with the most recent results of helioseismological studies.

ANALYSIS OF OBSERVATIONAL DATA ON THE LONG-TERM ROTATION OF THE SOLAR ATMOSPHERE

22-Year Rotation Variations From Data on the Large-Scale Magnetic Field Based on Synoptic Hα Charts

One of the longest series that carries information about the topology of the large-scale magnetic field is the series of synoptic Hα charts spanning the period from 1887 until now. Using long series of data makes it possible to distinguish long-lived modes. Sliding

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[*] E-mail: `solar@narzan.com`

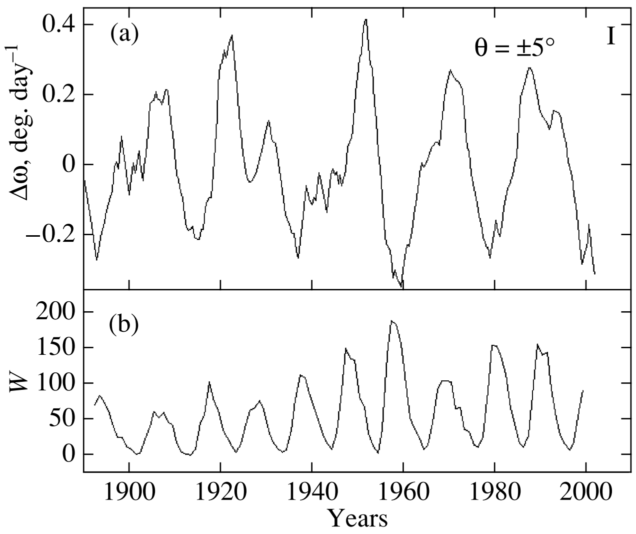

Fig. 1. (a) Amplitude of the rotation-rate deviation for the equatorial zone from synoptic charts of large-scale magnetic fields obtained with the long-term trends subtracted. (b) The activity index of yearly mean Wolf numbers from Tlatov (2005a).

sampling "windows" of sufficiently large sizes can be used for this purpose. Using sampling windows of $\sim$ 1 — —2 years allows the 11 year rotation variations to be effectively distinguished. Windows of a larger size, from 5 to 11 years, must be used to distinguish the 22-year rotation variations.

Synoptic Hα charts present information about the magnetic field polarity reversal line. To determine the time dependence of the rotation rate, we generated series of large-scale magnetic field polarity reversals at steps of 10° and 5° in heliographic longitude and latitude, respectively. Subsequently, these series were used for a spectral analysis.

The rotation rate of the solar atmosphere depends on both latitude and time. It should be noted that the equatorial and mid-latitude zones have opposite long-term trends (Tlatov and Makarov 2004). The rotation rate of the low-latitude zone increases, while the rotation rate of the mid-latitude zone decreases. Note that the variations at low and high latitudes are in antiphase after 1960.

To distinguish the 22-year oscillations, we must subtract the long-term trends of rotation rate variations for each latitude interval. Figure 1a presents the behavior of the rotation rate with time for the equatorial ±5° latitude zone as derived from synoptic Hα charts. The width of the spectral window to determine the periods here was 4.5 years. In addition, we subtracted the long-term trend. Fluctuations in the rotation rate with a duration of 20–22 years are distinguished. For comparison, Fig. 1b presents the behavior of activity based on Wolf numbers. Note that the rotation rate is at a minimum in odd activity cycles and at a maximum in even cycles.

The amplitude of the rotation-rate deviation from the mean values depends on the solar-cycle power and was at a maximum in activity cycles 18 and 19 (Tlatov 2005a). The correlation between the rotation-rate deviations from the mean values and the solar-cycle amplitude shows that there exists a correlation between rotation and solar activity (Fig. 2).

The presented results show that the rotation-rate deviations in even and odd cycles are opposite in direction. This is difficult to explain by the torsional oscillations that have an 11-year periodicity and that are probably the response of the rotation rate of the solar atmosphere to sunspot magnetic fields.

To study the drifts, we reconstructed the latitude–time diagrams for the rotation-rate deviation obtained with fairly large spectral windows. Figure 3 presents the latitude–time diagram for the rotation-rate deviation obtained for a $\sim$ 8-year-wide spectral window after the long-term trends have been removed. Note that the 22-year oscillations in the equatorial zone probably result from the organization of rotation at all latitudes. Drifts of the rotation-rate deviation with a duration up to 20 years are distinguished in Fig. 3. This gives rise to a picture where the rotation-rate deviations at low and high latitudes are in antiphase.

22-Year Rotation Variations from Coronal Observations

Out-of-eclipse observations of the solar corona with coronagraphs allow the series of coronal intensities in the 5303Å line to be reconstructed since 1939. To this end, we reduced the series from several observatories to the Kislovodsk system of observations (Tlatov 2006). The derived series allow us to analyze the rotation at various solar latitudes with a 5° step. Just as for the analysis of the series of Hα charts, changing the size of the sliding sampling window for a spectral analysis allows the variations in rotation rate related to the 11-year torsional waves and modulation of the rotation rate with long periods to be distinguished. Figure 4 presents the rotation-rate deviations as derived from solar coronal observations in the 5303Å line for the equatorial and high-latitude zones in the period 1940–2003. At low latitudes, the rotation rate was at a minimum in 1940, 1960, 1980, and 2000, i.e., near the maxima of odd solar cycles.

The rotation of high-latitude regions was in antiphase with that of low-latitude ones. Thus, analysis of the rotation of the solar atmosphere using data on the rotation of large-scale magnetic fields and coronal observations in the 5303Å line yields similar results

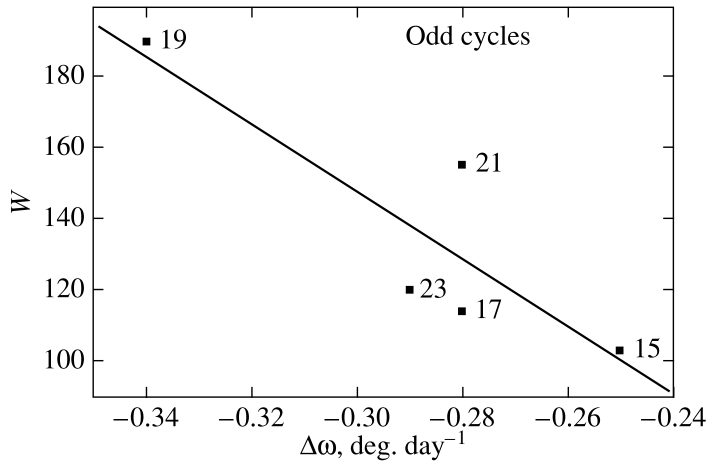

Fig. 2. Relationship between the deviations of the rotation rate of large-scale magnetic fields and the index of Wolf numbers for odd cycles.

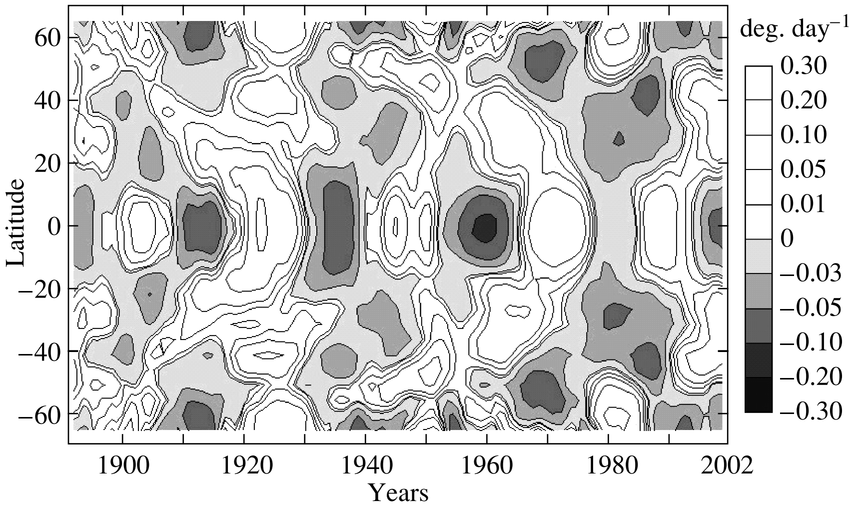

Fig. 3. Latitude–time diagram for the rotation-rate deviations from the mean values as derived from synoptic Hα charts. The long-term trends were removed.

confirming the existence of a 22-year rotation mode. The rotation rate at low latitudes slows down at an epoch close to the maximum of odd activity cycles. The rotation variations at high latitudes are in antiphase with the deviations at low latitudes.

Rotation Variations of Large-Scale Magnetic Fields from Analysis of WSO Magnetograph Observations

Magnetographic observations have been performed at the Wilcox Solar Observatory since 1975. Synoptic magnetic charts allow the magnetic field strength to be reconstructed in the ±70° latitude range and with a 5° step in longitude. To analyze the rotation variations, we chose only the magnetic field polarity on synoptic magnetic charts. This procedure allowed us to reduce the influence of active structures and to increase the role of large-scale magnetic fields. To distinguish the long-term variations, we used sliding windows 8–10 years in width. To distinguish the torsional waves, we must subtract the mean rate in each latitude interval. Figure 5 presents the distribution of rotation-rate deviations from the mean values. In the equatorial zone, slow rotation is observed at epochs close to 2000 and 1980, i.e., in odd activity cycles. In contrast, rapid rotation is observed in activity cycle 22. The waves of drift of the rotation-rate deviations from high to low latitudes are also clearly seen. On the whole, the pattern of the rotation-rate distribution is consistent with the data obtained from synoptic Hα charts and the data on solar coronal intensities and can be related to the presence of 22-year torsional waves.

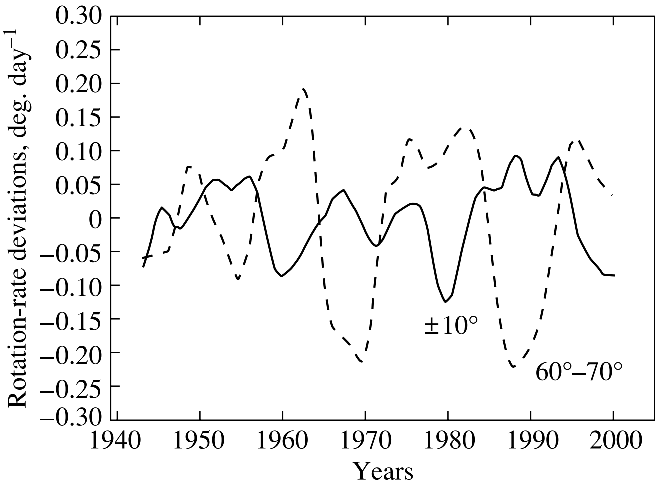

Fig. 4. Rotation variations from coronal observations in the 5303Å line at high latitudes (dashed line) and near the equator (solid line) (Tlatov 2006).

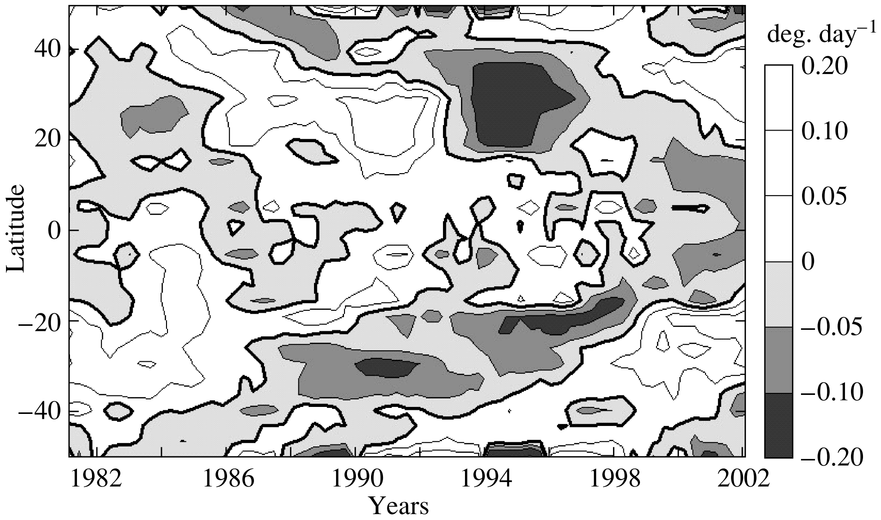

Fig. 5. Latitude–time diagram for the rotation-rate deviation from the mean values as derived from WSO magnetograph data on the magnetic field polarity distribution. The calculation was performed in 8-year-wide spectral windows. The regions of slow rotation are shaded.

A MODEL FOR THE EXCITATION OF SOLAR ACTIVITY BY 22-YEAR TORSIONAL OSCILLATIONS

The Excitation of Torsional Oscillations Beneath the Convection Zone

The 11-year torsional oscillations are a well-known observational fact (LaBonte and Howard 1982). In recent years, their properties have been effectively investigated by means of helioseismology. At present, the picture of torsional oscillations in the convection zone at depths up to $\sim 0.75R$ has been reconstructed from these data since 1996. According to these results, the 11-year modulation of the rotation rate is clearly present in the upper layers of the convection zone. At the same time, no 11-year modulation is found at depths below $\sim 0.75R$ (Howe et al. 2005). Figure 6 presents the plots of yearly mean variations in the rotation rate at a latitude of 15° at depths $r = 0.84R$ and $r = 0.75R$ obtained from SOHO/MDI observations in the period 1996–2005 (Howe et al. 2005). An extrapolation of the rotation-rate variations is presented in the right parts of the plots. At depth $r = 0.84R$, the rotation-rate modulation is close to 10 years. The maximum rotation rate is observed at an epoch close to the activity maximum. At the same time, the rotation-rate variations at depth $r = 0.75R$ have a modulation with a period of about 15–17 years. Several modes

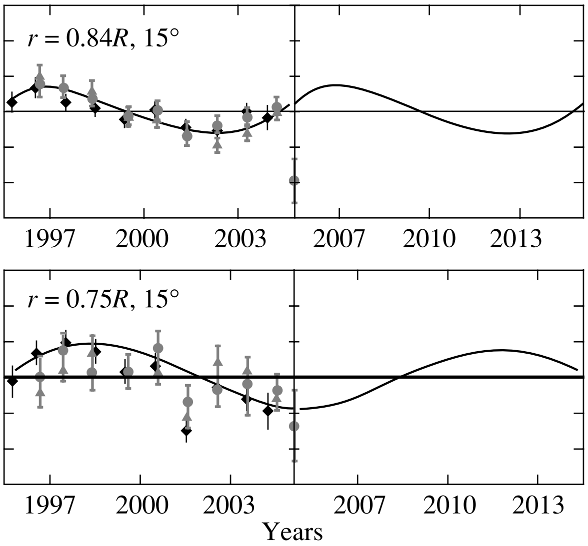

Fig. 6. Yearly mean rotation-rate variations from the mean values, nHz, at depths $r = 0.84R$ and $r = 0.75R$ as inferred by Howe et al. (2005). A possible extrapolation of the behavior of the rotation rate is shown in the right parts of the plots.

may manifest themselves in the rotation variations at these depths close to the base of the convection zone: a 22-year mode, an 11-year mode, and, possibly, a mode with a short period of 1.3 years.

The rotation of the solar atmosphere depends on latitude and relative radius. The rotation beneath the solar convection zone is believed to be close to solid-body one. At the same time, observations show that high-latitude regions at depths $(0.6–0.7)R$ can rotate more rapidly than low-latitude regions (Fig. 7) (Kosovichev et al. 1998).

The 22-year torsional oscillations of the solar atmosphere, as revealed by the investigation of large-scale magnetic fields and the solar corona, may reflect variations in the rotation rate at fairly large depths. In general, the rotation-rate variations in dynamo models are assumed to be insignificant or to be the result of a generation wave (Schüssler 1981; Kitchatinov et al. 1999). The 22-year rotation oscillations are difficult to explain as being the result of a generation wave with an 11-year periodicity. Helioseismological data show that the magnetic field can reach 300 kG at depths $\sim 0.7R$ (Antia et al. 2003). The magnetic field can affect significantly the excitation of 22-year oscillations. To compare the magnetic field energy with the torsional oscillation energy, let us introduce a parameter $t = B^2/(\rho r^2\Omega^2\mu)$. For a magnetic field strength at the base of the convection zone $B \sim$ 100–300 kG, this dimensionless parameter is close to unity, suggesting that the torsional oscillation energy can transform into the magnetic field energy and back.

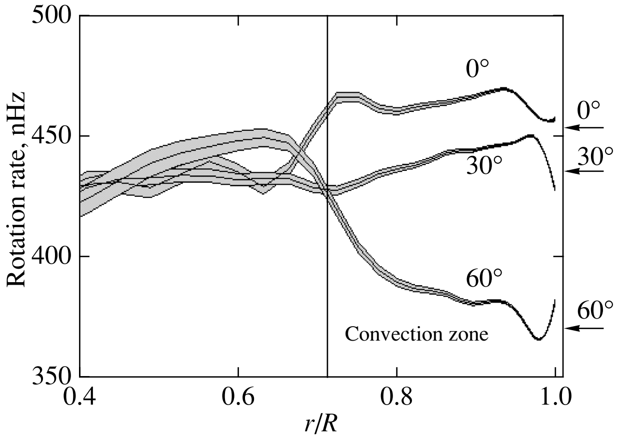

Fig. 7. Differential rotation rate versus depth from SOHO/MDI observations in 1996 (the figure was taken from http://soi.stanford.edu/results).

A critical poloidal magnetic field strength $B_{\rm M}$ sufficient for the generation of oscillations in a time interval t_{11} close to the solar-cycle duration t_{11} can be found by equating it to the travel time of an Alfvén wave near the base of the convection zone $t_{\rm A} = R/v_{\rm A} : B_{\rm M} = (4\pi\rho)^{1/2}R/t_0$. For a density near the base of the convection zone $\rho \sim 1\,{\rm g\,cm^{-3}}$, $t_0 \sim 3.5 \times 10^8$ s, and $R \sim 5 \times 10^{10}$ cm, we obtain a field strength $B_{\rm M} \sim 500$ G. It is believed that the emerging oscillations and the Lorentz force should be taken into account at large magnetic field strengths (Spruit 1999). There exist several magnetic field instabilities in a rotating solar atmosphere. These can be produced by shear perturbations at certain magnetic and kinematic diffusion parameters. Spruit (1999) considered the Taylor instabilities emerging in a stratified solar atmosphere in the presence of an azimuthal magnetic field $B\phi$. This instability arises if the Alfvén frequency $\omega_{\rm A} = \frac{B}{(4\pi\rho)^{1/2}}$ satisfies the relation

$$\omega_{\rm A} > \Omega\left(\frac{N}{\Omega}\right)^{1/2}\left(\frac{\eta}{r^2\Omega}\right)^{1/4}.$$

Here, $N = \sqrt{\frac{g}{y}\frac{d}{dz}\ln(p\rho^{-y})}$ is the buoyancy frequency andη is the magnetic diffusion coefficient. For the Sun, $r \sim 5 \times 10^{10}$ cm, $N \sim 10^{-3}$ s^{-1}, $\eta \sim 2 \times 10^3$ cm^2 s^{-1}, and $\Omega \sim 3 \times 10^6$ s^{-1}. The minimum magnetic field strength required for the instability to emerge, $B = \omega_{\rm A} r(4\pi\rho)^{1/2}$, should then be ~ 1000 G. These estimates show that the excitation of oscillations beneath the solar convection zone is possible at magnetic fields higher than 1–10 kG. Note that the emerging Taylor instabilities should propagate from the solar poles to the low latitudes (Spruit 1999).

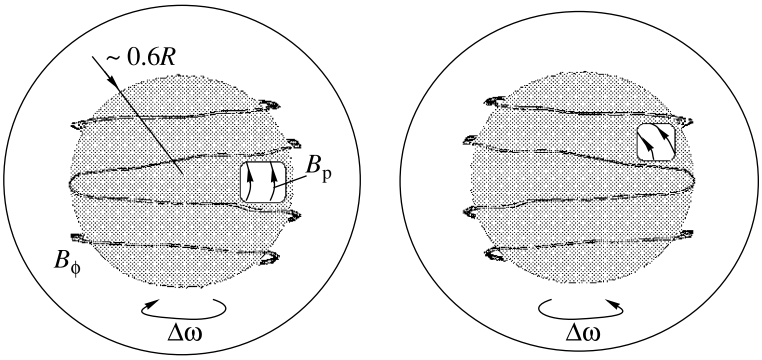

Fig. 8. Scheme for the generation of an alternating toroidal magnetic field by the 22-year torsional oscillations beneath the base of the convection zone.

The Generation of an Alternating Toroidal Magnetic Field

The discovery of 22-year torsional oscillations of the solar atmosphere can serve as a basis for developing new models for the generation of a solar magnetic cycle. Previously, Piddington (1976) pointed out this possibility. He assumed the existence of 22-year meridional oscillations that change the sign of the angular velocity gradient with respect to the relic magnetic field lines, which leads to the excitation of a magnetic cycle. Tikhomolov and Mordvinov (1996) hypothesized that the 22-year cycle is excited through a regular excitation of convective vortices that emerge at certain longitudes and drift during the cycle from high latitudes toward the equator. Note that, in this case, a significant longitudinal inhomogeneity should be observed.

We can assume that an alternating toroidal magnetic field is generated through the interaction of 22-year oscillations with the relic magnetic field in a fairly thin spherically symmetric layer beneath the base of the solar convection zone at depths $\sim 0.6R$. In this case, as we see from Fig. 8, the equatorial zone rotates at these depths more slowly than the high-latitude regions in odd activity cycles and vice versa in even cycles (Tlatov 2001).

When the magnetic diffusion is neglected, the evolution of the magnetic field $\boldsymbol{B}$ is described by the induction equation and depends on the velocity field:

$$\partial B/\partial t = \nabla \times (v \times B),$$
$$v_\phi = r\Omega(t, r, \theta) \sim r\Omega_0(r, \theta)\sin(\omega_{22}t + \psi).$$

Here, the frequency ω_{22} corresponds to the 22-year oscillation period and the latitude dependence of phase ψ describes the drift of the wave of rotation-rate deviations from high latitudes toward the equator. It can be understood that the poloidal magnetic field $B_\mathrm{p} = (B_r, B_\theta, 0)$ does not vary with time, while the azimuthal component appears due to a shear: $\partial B_r/\partial t = \partial B_\theta/\partial t = 0$, $\partial B_\phi/\partial t = r\sin\theta B_\mathrm{p}\nabla\Omega$. By choosing the latitude dependence of phase, we previously (Tlatov 2001) obtained the drift pattern of torsional oscillations with a drift time of ~ 17 years and modeled the topology of the distributions of surface magnetic fields for the 22-year torsional waves propagating from high latitudes toward the equator.

THE GENERATION OF A POLAR MAGNETIC FIELD AND THE REGENERATION OF A SLOWLY CHANGING GLOBAL SOLAR MAGNETIC FIELD

A constant or slowly changing magnetic field should play an important role in the generation of a magnetic cycle by the 22-year torsional oscillations. This field can be relic, i.e., generated at early formation stages of the Sun. The Gnevyshev–Ohl rule about the relations between the amplitudes of a pair of even and odd activity cycles provides evidence for the existence of a quasi-constant magnetic field. In the absence of a "fueling" mechanism for the relic magnetic field, such a magnetic field can decay and its role in the generation of solar magnetic cycles will decrease. If such a magnetic field is in the form of a dipole magnetic field with an axis close to the rotation axis of the Sun, then it can manifest itself in a 22-year modulation of the polar magnetic field. At the same time, magnetographic observations suggest a magnetic field reversal at the poles, which does not directly confirm the hypothesis about the presence of a relic magnetic field. The polar magnetic field may be generated when the relic field interacts with the surface magnetic field that reverses its polarity due to cyclic activity. This hypothesis is supported by our analysis (Tlatov 2005b) based on daily observations in the CaII K line (Fig. 9). This analysis revealed elements of various sizes and contrasts. The low-contrast elements can be associated with chromospheric network elements. The high-contrast elements are probably associated with ephemeral

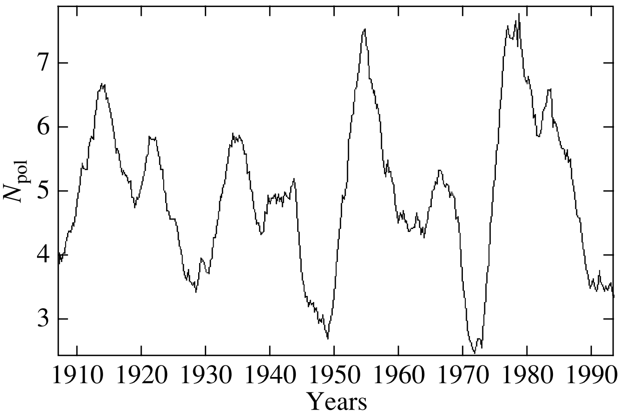

Fig. 9. Distribution of the number of chromospheric network elements in the CaII K line with an area from $S =$ 60–500 m.s.h. and a contrast no higher than 30% at latitudes above 70° from Kodaikanal data. Averaging over the northern and southern hemispheres and smoothing with a 1-year-wide sliding window were performed.

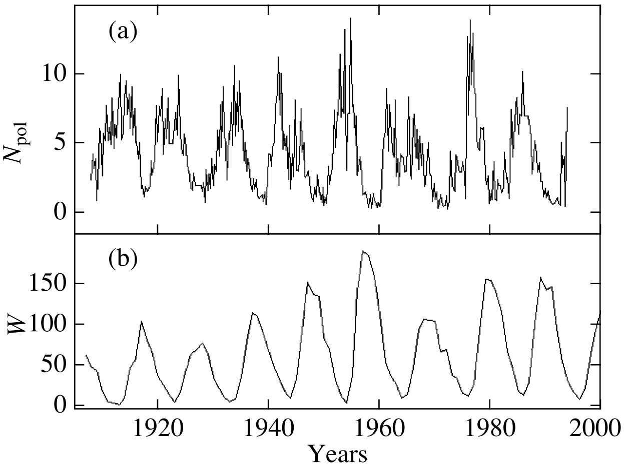

Fig. 10. (a) Number of high-latitude bright ephemeral regions N_{pol} with a contrast of at least 30% of the level of the quiet Sun. The values of the northern and southern poles were added. A correcting visibility function of the time of the year is used. (b) Yearly mean Wolf numbers.

regions (Harvey 1993). The number of low-contrast elements associated with the chromospheric network has both 11-year and 22-year modulations. The number of chromospheric network elements before odd cycles is higher than that before even sunspot cycles.

On the other hand, as we see from Figs. 10 and 11, the number of elements with a contrast higher than 30% at the activity minimum is related to the power of the next sunspot cycle (Tlatov 2005b). The largest number of such elements was observed at the minimum before solar cycle 19. This is inconsistent with the Babcock–Leighton hypothesis (Babcock 1961; Leighton 1964). Numerical simulations of the generation of a magnetic field in terms of the Babcock–Leighton hypothesis with convection effects showed that the polar magnetic field strength at the activity minimum depends on the power of the past sunspot cycle (Schrijver 2001).

Another approach to the generation of a polar magnetic field is based on the hypothesis of an extended magnetic cycle (Wilson et al. 1988). In this hypothesis, the waves of the next activity cycle that can affect the generation of a polar magnetic field are traceable at high latitudes 2–3 years before the activity minimum. Note that the waves of 22-year torsional oscillations propagating from high latitudes toward the equator (Figs. 4 and 6) are consistent with the hypothesis of an extended activity cycle.

Thus, the high-latitude magnetic field is generated through the action of several sources: the relic magnetic field, the magnetic field of the high-latitude wave of a new cycle, the transport of magnetic fields, and the decay and drift of the magnetic fields of bipolar regions.

Apart from the listed generation sources of the global magnetic field, we may consider one more alternative mechanism. The emerging magnetic fields of bipolar groups are destroyed and disappear over several months. We can assume that the magnetic field dissipates in the presence of currents flowing along the magnetic field polarity reversal boundary. In this case, field lines can reconnect near the temperature minimum above the photosphere and, as a result, matter can be expelled into the corona and filaments and prominences can be formed (Litvinenko and Somov 1994; Tlatov and Vasil'eva 1997). Based on the observational facts about the presence of an angle between the magnetic centers in a bipolar group toward the equator and taking into account the fact that several bipolar groups can exist on the Sun in its different hemispheres at a given time, we conclude that two ring currents exist in the solar atmosphere. The directions of the currents in the different hemispheres coincide and, hence, the directions of the magnetic fields generated by them coincide (Fig. 12).

The current can be estimated from models for the formation of current sheets (Syrovatskii 1975). In a quasi-steady state, the total current in the sheet is $I = c\varsigma b^2/4$, where c is the speed of light, ζ is the gradient of the external magnetic field on both sides, and $2b$ is the sheet width. If l is the sheet length, then the expression for the free magnetic energy W that accumulates and dissipates in the current sheet is

$$W = l\frac{\varsigma^2 b^4}{32}\ln\frac{4l^2}{b^2}.$$

At current sheet parameters typical of the solar plasma, $l \sim 10^{10}$ cm, $b \sim 7 \times 10^8$ cm, and $\zeta \sim$

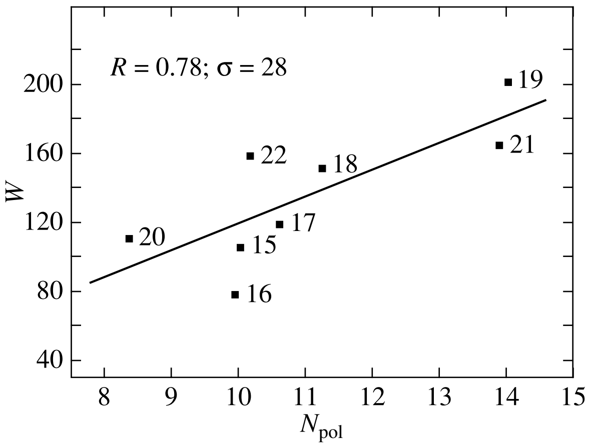

Fig. 11. Relation between the number of bright ephemeral regions in the calcium line with a contrast higher than 30% of the level of the quiet Sun at latitudes above 70° at the activity minimum and the maximum Wolf numbers of the next activitycycle.

5×10^{-7} G cm^{-1}, the current in the sheet can be estimated as $I \sim 6 \times 10^{11}$ A (Syrovatskii 1976). Substituting the current I for the solar radius $R_{\text{o}} = 6.96 \times 10^{10}$ cm yields an estimate of the generated global magnetic field: $B \sim 6$ G. This value corresponds in order of magnitude to the polar magnetic field strength and, hence, this mechanism can play a role in producing the global surface magnetic field.

The contribution from the magnetic field produced by the dissipation of bipolar groups should depend on the solar-cycle power and is different for even and odd cycles on long time scales. This suggests that the Sun can be magnetized predominantly by a field of one polarity on time scales longer than 22 years, which creates conditions for the restoration of a quasi-constant magnetic field at depths below the convection zone. Meridional circulation can serve as the mechanism of transporting the surface magnetic field to the base of the convection zone (Tlatov 1997).

DISCUSSION

The differential rotation of the Sun is of crucial importance in generating the solar magnetic cycle. The existence of 22-year rotation variations at both low and high latitudes of the solar atmosphere is difficult to explain by the 11-year sunspot activity. The magnetic field has long been assumed to be generated in the entire convection zone of the Sun. Currently available helioseismological data have revealed a region near the base of the solar convection zone where the steepest angular velocity gradients and the transition to quasi-solid-body rotation are observed. Strong magnetic fields are most likely generated precisely at these depths. For the 11-year solar cycles to be generated in dynamo theories, the direction of poloidal fields in the generation region must be changed. At the same time, the α effect, which is capable of explaining the generation of a new poloidal magnetic field, pertains to the time of flux tubes emergence at the surface. Therefore, the complex problem of transporting weak magnetic fields to the base of the convection zone for the development of a closed dynamo theory arises.

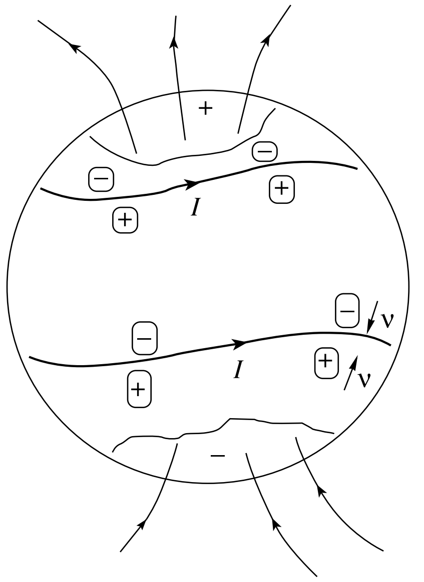

Fig. 12. Scheme for the generation of ring currents through the dissipation of bipolar regions.

The problem of a seed poloidal magnetic field can be solved by assuming the existence of a relic or quasi-constant magnetic field. At the same time, the latitude dependence of rotation beneath the convection zone differs so much from that observed near the upper layers that we may assume oscillating variations in the rotation rate near the region of quasi-solid-body rotation. In this case, the interaction of the relic magnetic field with such oscillations can lead to the generation of alternating toroidal magnetic fields.

The difference between the amplitudes of even and odd activity cycles suggests that there may exist a mechanism of accumulation of the residual magnetic field and maintenance of a slowly changing magnetic field close to the relic magnetic field.

The observed correlations between the activity indices at high latitudes at the activity minimum and the power of the next sunspot cycle are probably due to the superposition of the activity waves from neighboring cycles related to the travel time of torsional waves from high to low latitudes close to 17–20 years.

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