Large-scale Structures and their Role in Solar Activity
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22-Year Variations of the Solar Rotation

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Abstract. We have studied the rotation of the solar atmosphere on the basis of H_α synoptic charts for 117 years (1887 - 2003) and derived the latitude-time diagrams for variation of the rotation periods in the interval of latitude $\pm 45^o$. We determined the periods within 8 to 12 year "windows", subsequently shifting the "window" along the data set, which makes it possible to reveal long-term variations in the solar rotation. It has been shown, that within the interval of latitude $\pm 20^o$, the basic rotation period of the background magnetic field of the Sun is 22 years. During odd cycles of solar activity, the rotation rate decelerates, while during even cycles, more rapid rotation is observed. When the sampling "window" increases to around 17 years, the 55 to 60 year quasi - period of rotation can be recognized. In this case, the maximum rotation velocity falls roughly on years 1930 and 1990. We consider possible generation of the solar cycle by 22-year period torsion waves interacting with relic magnetic field.

1. Introduction

Surface layers of the Sun undergo cyclical variations of their rotation; the most thoroughly studied are those with 11-year period, probably related to torsion waves. Presently, however, no systematic interrelated data on long-term variations of the solar rotation are available. Sunspots are most frequently used as tracers in the analysis of the rotation. Numerous studies based on this technique indicate that the Sun rotated most rapidly during 12th-13th (Ikhsanov & Vitinsky 1980; Balthasar & Wöhl 1980), 15th (Newton & Nunn 1956; Balthasar & Wöhl 1980), 17th -18th (Ward 1966; Balthasar & Wöhl 1980), and 20th (Balthasar & Wöhl 1980; Yoshimura & Kambry 1993) cycles of its activity. Several authors were able to recognize long-term variations of the rotation with the duration of 55 years (Ikhsanov & Vitinsky 1980; Yoshimura & Kambry 1993), and also with a 22-year period Chistyakov (1982). The technique based on sunspots, however, has its drawbacks, related to difficulties in taking into account their proper motions and the absence of data for years of minimum activity.

H_α synoptic charts of large-scale background magnetic field based on observations in H_α line provide another source of data to restore parameters of the solar rotation for a long period of time. H_α charts display 22-year variations of the sector structure rotation (Vasil'eva, Makarov & Tlatov 2002) as well as roughly 55-year variations in torsion oscillations (Makarov & Tlatov 1997) and in the rotation of the Sun (Obridko & Shelting 2000).

2. Initial Data and their Processing

The structure of the global magnetic field of the Sun is specified by the distribution of unipolar magnetic regions, which are distinctly seen on magnetograms. These regions are delineated by boundaries with zero radial component of the magnetic field (neutral magnetic lines), which are traced by prominences and dark filaments in the center of the H_α line (Duvall et al. 1977). For one rotation of the Sun, a set of the neutral magnetic lines forms a topological pattern of polarity distribution for the global magnetic field. Although these data do not contain the field strength, the time-latitude distribution of neutral magnetic lines displays the topology of the field with higher accuracy than that derived from magnetograms, particularly for regions of weak field and in polar zones of the Sun Duvall et al. (1977).

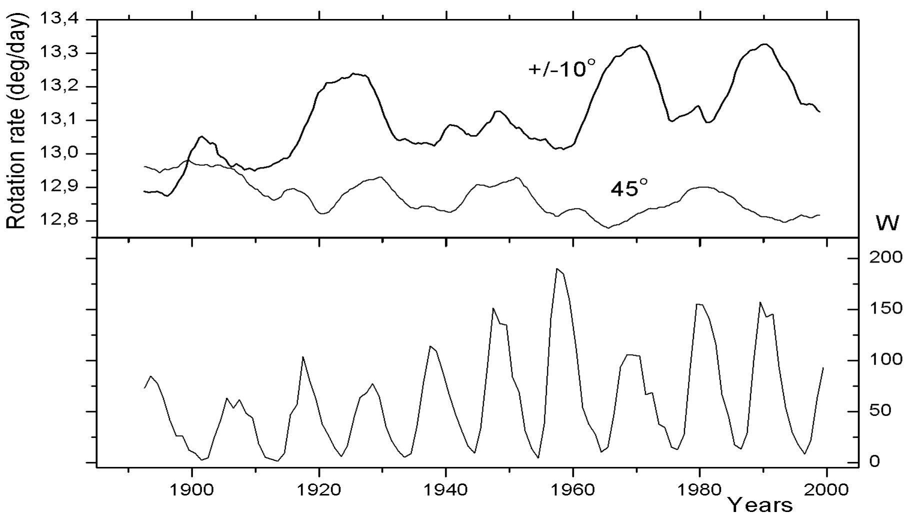

Figure 1. The average rotation velocity at the latitudes $\pm10^o$ and $40^o - 50^o$ in the northern and southern hemispheres (upper graph). The average annual Wolf numbers (lower graph).

Here, we used the composite set of data, from 1887 to 1915, provided by H_α charts based on the data from Wolfer (1897, 1899, 1902,1909) and Kodaikanal Observatory (Vasilyeva 1998). H_α charts from 1915 to 1964 were made on the basis of Kodaikanal observations presented in the study by Makarov & Sivaraman (1989). For 1964 to 1978, H_α charts were reproduced from Solar Geophysical Data (McIntosh 1979; SGD 1964-1978). From 1978 to 2003, we used regular synoptic H_α charts obtained at Kislovodsk Solar Station and published in Solnechnye Dannye Bulletin (Solnechnye Dannye 1978-2003).

The topology of the field is essential for the study of global activity in the large-scale background magnetic field (without taking the fields of active regions into account). Therefore, to study the structure of the field on the H_α charts, regions with positive and negative polarity (for example, with the size $5^o \times 5^o$)

may be ascribed the field strength +1 or -1 Gauss, respectively. Thereby, sets of values for the magnetic field strength may be derived at all latitudes.

Here, we studied the rotation of the Sun within the latitude zone $\pm 45^o$ from the equator. For each 5^o latitude interval and 10^o longitude interval, we determined the magnetic field $\alpha(t)$. The total 1887 to 2003 set of $\alpha(t)$ contains around 56,000 values for each latitude interval. The power spectrum of the set was obtained with the use of the fast Fourier transformation. To study the rotation rate, we used "windows" with the size 4000 to 9000 values. Since a 10^o longitude interval corresponds to the interval of time dt = 0.757647 days, the "window" in this case correspond to 8 to 17 years. Then the maximum period of rotation lies within the interval 26 to 9 days. The basic periods were searched repeatedly with the shift of the "window" along the data set. As a result, a matrix describing the rotation velocity of the Sun as the function of time and latitude was derived.

The validity of the suggested technique is justified by its consistency with other methods, such as auto-regression and co-variation spectral analysis, and comparison with the results for other sampling "windows". Previously, a similar technique was used in the study (Vasil'eva et al. 2002) to determine the rotation velocity of the sector structure, where smaller "windows" were used in the spectral analysis.

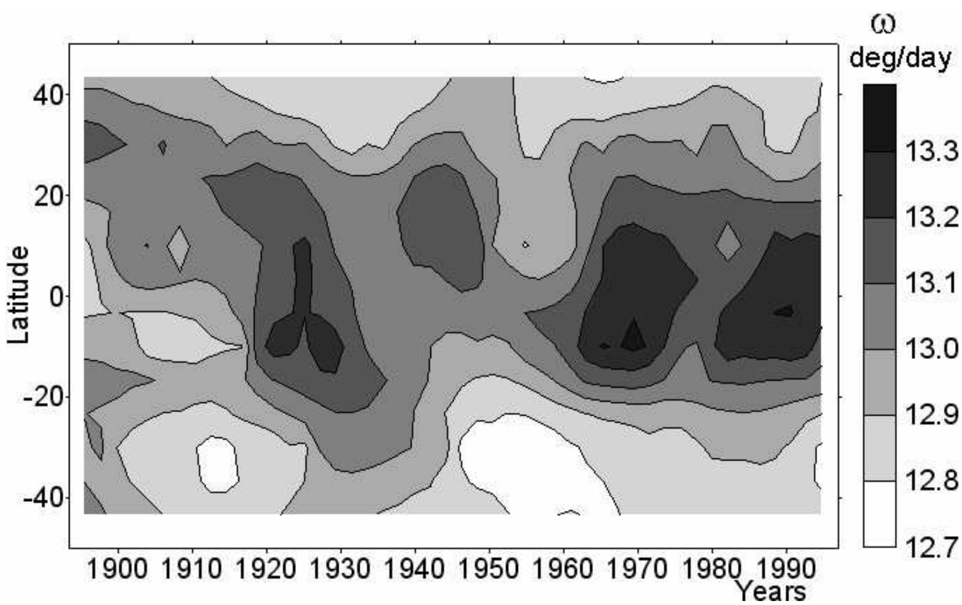

Figure 2. The rotation velocity as a function of latitude, with the 12-year "window", obtained from the spectral analysis. The velocity units: degrees per day.

3. Results

The rotation velocity of the Sun depends both on the latitude and time. Figure 1 (upper graph) presents the rotation velocity as a function of time for the $\pm 10^o$ equatorial zone for the $40^o - 50^o$ latitude zone. The periods of rotation for the northern and southern hemispheres were averaged. The periods were determined with the "window" of 6100 values; 20-to-22-year fluctuations of the rotation velocity were recognized. Note that equatorial and middle-latitude zones display long-term trends with different gradients of inclination, so that the rotation velocity for the low-latitude zone increases, while for the middle-latitude zone decreases. For comparison, the lower graph of Figure 1 presents the solar activity as a function of Wolf numbers. It can be noticed that the minimum of the rotation velocity corresponds to odd cycles of activity.

Figure 2 presents the overall period distribution obtained in latitude-time coordinates for the "window" with the width of 6100 values, or in the time-scale commensurable with a cycle of the solar activity. The most rapid rotation was observed in the periods of 1920 - 1930, 1940 - 1950, 1960 - 1970 and 1980 - 2000. The rotation velocity reached its maximum in the vicinity of the equator and varied within 13.0 - 13.3 degrees per day, depending on the epoch.

To reduce the noise, the rotation velocity was averaged over the hemispheres in the corresponding intervals of latitude. Then in each 5^o latitude interval the trend was subtracted. Figure 3 presents the resulting time-latitude diagram of the rotation velocity, which displays regular structure. The 22-year rotation mode is seen in the $\pm 20^o$ latitude interval. After the removal of the trend, the slowest rotation was observed before the activity cycle 19, 1955 - 1965. The middle-latitude and low-latitude zones display different phases of the variations of velocity. Note that, according to Figure 1, before the cycle 19, the rotation velocities near the equator and at the latitudes around $\sim 45^o$ were of the same phase, while after the cycle 19 it becomes anti-phase. Figure 3, the time-latitude diagram, displays the variation of the velocity and the direction of the deceleration and acceleration waves of the rotation from middle to low latitudes. This fact confirms the conclusions made in the study by Makarov & Tlatov (1997) concerning long-term variations of torsion oscillations. Figure 4 shows solar rotation rate at a "window" by a width 17 years. One can see that the greatest rotation rate was observed during an epoch close to 1930 and in 1990. During an epoch 1900 and 1955, the minima of rotation rate was observed. It confirms earlier established facts on an existence of 55 - 60 year waves in rotation rate of the large-scale magnetic fields, (Makarov & Tlatov 1997; Obridko & Shelting 2000).

4. Discussion

The detection of 22-year modulation of the rotation velocity may be a prerequisite for more accurate modeling of the solar cycle. By now, dynamo models suggested for the solar magnetic cycle still contain essentially unsolved problems (Stix 1981); therefore, using non-dynamo mechanisms for the solution of the problem of solar cycle may be very promising. One of the approaches in which the field is generated without the dynamo is related to the transformation of the powerful relic field of the Sun into magnetic fields observed on its surface. It is suggested that by the moment when the Sun reaches the main sequence, the strong field is confined in its core. When the restrictions by the effects of turbulent diffusion and magnetic field buoyancy are taken into account, the residual fields are estimated to be of the order of $10^6 - 10^7$ Gs (Stix 1981; Dol-

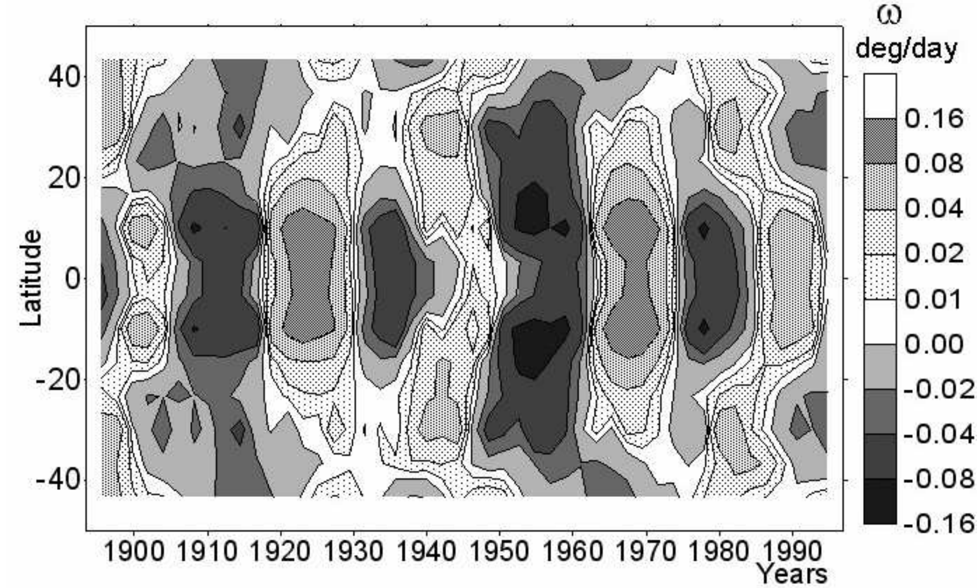

Figure 3. The deviation of the rotation velocity from its average value at corresponding latitudes. The "window" for the spectral analysis was 12 years. The regions where rotation decelerates painted dark. The velocity was averaged over the northern and southern hemispheres.

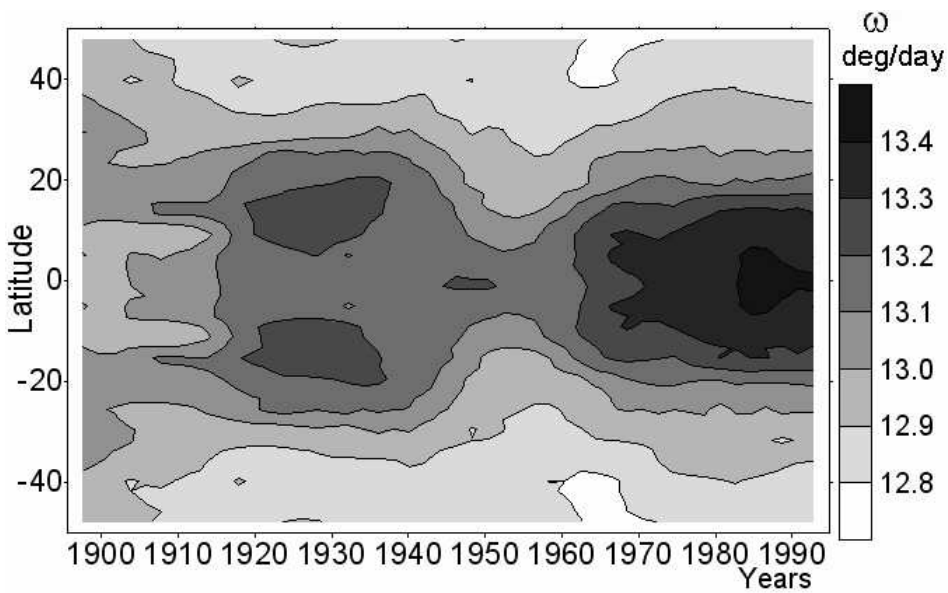

Figure 4. The rotation velocity of the Sun as a function of latitude, with the size of the "window" for the spectral analysis 17 years. The values were averaged over the northern and southern hemispheres.

ginov 1976). Based on the hypothesis of strong torsion oscillations, Piddington (1975) described oscillations in the resulted magnetic fields. In his study, it was suggested that poloidal magnetic field periodically alters its position relative to cylindrical iso-rotational surfaces within a convective envelope. Presently, due to helio-seismological studies, the concepts of the solar rotation have substantially changed. It is unlikely, in particular, that the 22-year magnetic cycle is formed within the convective zone. At the same time, the hypothesis of torsion oscillations as the source of the magnetic solar cycle is still applicable. It may be suggested that solid-state rotation is possible under the convective envelope at the levels below $\approx$0.6 of the solar radius. It may be also assumed that the relic magnetic field exists at these depths. Let us suppose that the base of the convective zone is susceptible to torsion oscillations, and at these depths the equator may rotate both faster and slower than polar zones. In this case, under the action of ω- effect, the azimuthal component of the magnetic field will be formed. A topological model and the estimate for the amplitude of the torsion oscillations under the convective zone were given in the study Tlatov (2001). In this model, the most controversial was the hypothesis of torsion oscillations with the period of the order of $T \sim 22$ years. Our present study provides the evidence for a distinct manifestation of the 22-year mode in the rotation of the background magnetic field. Thereby, in our opinion, the solar magnetic cycle may be generated due to the interaction between torsion waves and the relic field inside the Sun, rather than to the dynamo mechanism.

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