ISSN 1063-7737, Astronomy Letters, 2009, Vol. 35, No. 4, pp. 247–252. © Pleiades Publishing, Inc., 2009.
Original Russian Text © V.N. Obridko, B.D. Shelting, 2009, published in Pis'ma v Astronomicheskiĭ Zhurnal, 2009, Vol. 35, No. 4, pp. 279–285.

Anomalies in the Evolution of Global and Large-Scale Solar Magnetic Fields as the Precursors of Several Upcoming Low Solar Cycles

V. N. Obridko* and **B. D. Shelting**

Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences, Troitsk, Moscow oblast' 142190, Russia

Received August 18, 2008

Abstract—Anomalies in the solar magnetic fields of various scales are studied. The polar magnetic field strength is shown to have decreased steadily during the last three solar cycles. This is because the increase in the dipole magnetic moment observed from 1915 to 1976 has changed into a decrease in the last three cycles. At the same time, the intermediate-scale magnetic fields (like those of isolated coronal holes) have been unusually strong in the last cycle. As a result, the tilt of the heliospheric current sheet is still about 30°. The large effective contribution from the intermediate-scale fields to the total energy of the large-scale fields is also confirmed by our calculations of the effective multipolarity index. The aa-index at the cycle minima is correlated with the height of the succeeding maxima. The set of data considered may be indicative of the possible approach of a sequence of low solar cycles.

PACS numbers : `96.60.Hv`

DOI: `10.1134/S1063773709040045`

Key words: *solar cyclicity, large-scale magnetic field.*

INTRODUCTION

The present solar cycle (23 according to the adopted numbering) is widely known to be anomalous in several respects, breaking many of the previously established typical characteristics of solar cycles. This primarily applies to the data on local magnetic fields. Below, we list the best-known characteristics.

Violation of the Gnevyshev–Ohl Rule

As is well known, according to this rule, an odd cycle should be higher than the preceding even one for the adopted cycle numbering. This rule was formulated in 1948 by Gnevyshev and Ohl for the sums of monthly Wolf numbers and it had only one exception over 26 cycles in the pair (4, 5) until the present pair of cycles (22, 23). This rule was updated by Kopecký (1950), who generalized it for the maximum (in the cycle) Wolf numbers. Unfortunately, this rule (which, for definiteness, should have been called the Gnevyshev–Ohl–Kopecký rule) already has three violations in the pairs (−2, −1), (4, 5), and (8, 9). The current pair of cycles (22, 23) violates this rule in both formulations.

A Very Long Cycle

By August 2008, there had been no reliable data on the termination of cycle 23, but now it is clear that its duration approaches 12 years and it is one of the longest cycles or just the longest one in the recording history of solar activity since 1848.

A more detailed list of anomalies in solar activity related to the behavior of sunspots and nonstationary processes can be found in Ishkov (2005). In this paper, we would like to draw attention to some peculiar features in the behavior of global and large-scale magnetic fields in the present cycle, which, in our opinion, suggest a transition to the period of low solar activity.

First of all, let us define what we mean by the large-scale and global magnetic fields. Looking at modern high-resolution magnetograms, for example, SOHO/MDI magnetograms, it is immediately apparent that the magnetic fields have a small-scale patchy pattern. However, we see at once that these small-scale elements are distributed over the surface not randomly but form extended regions in which one of the polarities dominates, i.e., they form quasi-unipolar regions of various scales. Undoubtedly, this is due to the existence of weak large-scale (or global) magnetic fields.

---

*E-mail: `obridko@izmiran.ru`

In what follows, we will call the fields with a characteristic spatial scale comparable to the solar radius global ones and the fields with a slightly smaller scale (0.3–0.7 of the solar radius) large-scale ones. Naturally, separating these relatively weak fields requires a complex filtering procedure. Such filtering is usually performed by decomposing the observed magnetograms into spherical harmonics followed by the summation in the selected range of spatial frequencies.

Obviously, the largest-scale, global magnetic field is related to the first harmonic of the decomposition and is called a dipole field. The usually discussed polarity reversal of the global field primarily means the polarity reversal of the global dipole. Direct observations of the polar magnetic field give an idea of this polarity reversal. However, it should be kept in mind that these two times, the polarity reversals of the global and polar fields, may not coincide. Moreover, times when the fields had the same sign at the two poles of the Sun were repeatedly observed in the past, which, naturally, cannot be for a dipole.

CHARACTERISTICS OF THE GLOBAL AND LARGE-SCALE FIELDS ESTABLISHED FROM THE PAST CYCLES

First, recall the universally accepted characteristics of the behavior of the global fields in a solar cycle.

— The global (in particular, polar) magnetic fields develop in antiphase with the local fields, which are commonly characterized by Wolf numbers.

— The global fields change their sign at the maximum of the Wolf numbers and reach their maximum at the minimum of the Wolf numbers.

— If the most global fields are related to a dipole, then it is reversed at the cycle maximum.

— Occasionally, the total magnetic moment of the dipole decreases greatly but it never becomes zero. During one or two years at the decay phase of the solar cycle, the vertical (i.e., coaxial with the Sun's rotation axis) and horizontal (whose axis lies in the solar equatorial plane) dipoles are comparable. This situation is known in astrophysics as an oblique rotator (Livshits and Obridko 2006).

— The polar (and, in general, large-scale) field can serve as a prognostic index of the upcoming cycle (Makarov et al. 2001a).

— Observations of the sector structure (Wilcox and Ness 1965) revealed the existence of a heliospheric current sheet (HCS) as the surface that separates the heliosphere into two magnetic hemispheres with opposite magnetic polarities (Schulz 1973; Hundhausen 1977). This surface is also commonly called a heliospheric equator. The HCS structure is determined by the field structure on the source surface.

— The corrugated surface formed by the HCS is often compared with the flaring skirt of a ballerina. At the cycle minimum, the HCS lies in the solar equatorial plane; at the cycle maximum, it is tilted and its tilt becomes very large, up to 90°. Mursula and Hiltula (2003) analyzed the direct observations of the interplanetary magnetic field polarity for 1965–2001 and showed that the frequency of the polarity corresponding to the northern solar hemisphere during solar minima is higher than that of the polarity corresponding to the southern hemisphere. They concluded that the HCS is shifted southward during solar minima. They called this effect "bashful ballerina", comparing the Sun at the decay of activity to a ballerina pushing her high flaring skirt downward.

— Thus, the HCS undergoes two types of changes in the course of time. Depending on the cycle phase, the main component of the global magnetic field, the global dipole, is tilted and passes from the position coaxial with the Sun's rotation axis to the position in the equatorial plane and then passes into the other hemisphere (Livshits and Obridko 2006). The HCS becomes corrugated and the size of this corrugation or the tilt is denoted by T. Mathematically, this quantity can be found by calculating the maximum latitude of the neutral line of the large-scale field on the source surface. Subsequently, the southern (negative) latitude T_S is subtracted from the northern latitude T_N and the mean value is found. Basically, the heliospheric equator is found in this way. The definition of the tilt T includes only the odd antisymmetric harmonics of the global field multipoles. (The term "tilt" is not quite appropriate. In fact, not the HCS but the axis of the corresponding equivalent dipole is tilted.)

The even harmonics (the quadrupole and higher), which do not change their sign when the equator is crossed, lead to an HCS asymmetry. This means an HCS shift ΔT relative to the solar equator. Mathematically, this shift is defined as the half-sum of T_N and T_S. The southward shift described by Mursula and Hiltula (2003) must give T_S larger in magnitude than T_N and, hence, $\Delta T < 0$. Previously (Obridko and Shelting 2008), we calculated the yearly mean T_N, T_S, and ΔT for 1915–2000. The center of gravity of the HCS undergoes quasi-periodic oscillations with a period close to 11 yr. The minima of the curve usually lie in the negative half-plane and are often close to the solar minima. This confirms the conclusions by Mursula and Hiltula (2003). However, in addition to this fact, another effect is observed: near the cycle maxima, positive values of ΔT are encountered more frequently, which is indicative of a northward HCS shift. Occasionally, the curve near

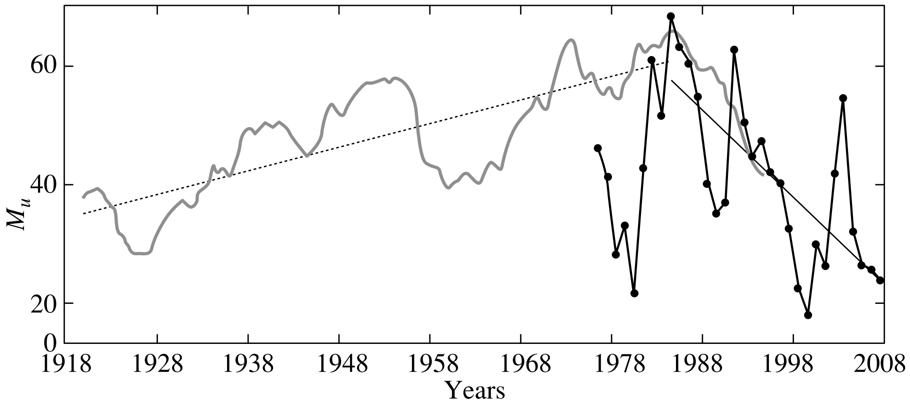

Fig. 1. Magnetic moment of the solar dipole versus time.

the maximum does not pass through zero but the value of ΔT at maximum is always higher than that at minimum.

Thus, the intensity and structure of the global and large-scale magnetic fields can be characterized by the following indices:

— the field strengths at the solar poles B_N and B_S;

— the magnetic moment of the effective solar dipole M_u;

— the HCS tilt T;

— the HCS shift ΔT, the negative sign of ΔT points to a southward shift.

A more sophisticated analysis of the variation in the ratio of the fields of various scales is provided by calculations of the mean square of the magnetic field strength on a selected spherical surface. These indices were introduced by Obridko and Ermakov (1989), Shelting et al. (1989), and Obridko and Shelting (1992). Two indices are used most commonly: the mean square of the magnetic field strength on the photospheric surface IBr(ph) and the mean square of the magnetic field strength on the source surface at a height of 2.5 solar radii from the center IBr(ss).

In addition, the effective multipolarity index introduced by Ivanov et al. (1997) is commonly used. Its definition is related to the fact that the multipole magnetic field strength decreases with height as $2l+1$, where l is the multipole number. Thus, comparing the mean squares of the fields at two levels, we can find the effective index of multipole n using the formula

$$n = \ln \frac{\mathrm{IBr(ph)}}{\mathrm{IBr(ss)}} \frac{1}{2\ln(2.5)}.$$

An increase in this parameter at the decay phase points to a decrease in the effective field scale. During the minima when mainly the dipole component remains on the Sun, the parameter n approaches three; at the cycle maxima, it reaches five, six, or higher.

PECULIARITIES IN THE THE BEHAVIOR OF THE GLOBAL AND LARGE-SCALE FIELDS IN CYCLE 23

According to the data of the John Wilcox Solar Observatory (WSO) in Stanford, a decrease in the polar field has been observed over the last three cycles. Here, we will not present the full plot of the polar field against time; it can be seen at the WSO site http://wso.stanford.edu/gifs/Polar.gif. Although we cannot confidently talk about the polar field strength in 1976 (at that time, the observations had just begun), it is higher than 2 G in absolute value. In 1985, it was higher than 2.5 G in absolute value. The field strength did not exceed 2 G in 1995 and was about 1 G in 2007. This means that the polar field strength decreased by a factor of 2–2.5 over three cycles.

This strongly suggests that the global magnetic fields gradually decrease. This conclusion is confirmed by an analysis of the magnetic moment of the effective global solar dipole. Makarov et al. (2001b, 2002) showed that the magnetic moment increased until 1984–1985 and then decreased sharply (but the data at that time were sufficient only until 1991). These calculations are indicated in Fig. 1 by the thick curve; a linear fit is drawn. At present, we have calculated the magnetic moment for another three cycles. These calculations are indicated by the thin dotted curve. It turned out that after 1980, the magnetic moment showed a tendency to gradually decrease and, at present, it has already reached values lower than those at the beginning of the 20th century.

This points to a tendency for the largest-scale fields to decrease. However, this cannot be said about the intermediate-scale fields, as confirmed by our calculations of the effective multipolarity index n. The variation of this parameter for 1976–2008 is shown in Fig. 2.

Note that this parameter behaved in a standard way in cycles 21 and 22. It reached values of the order

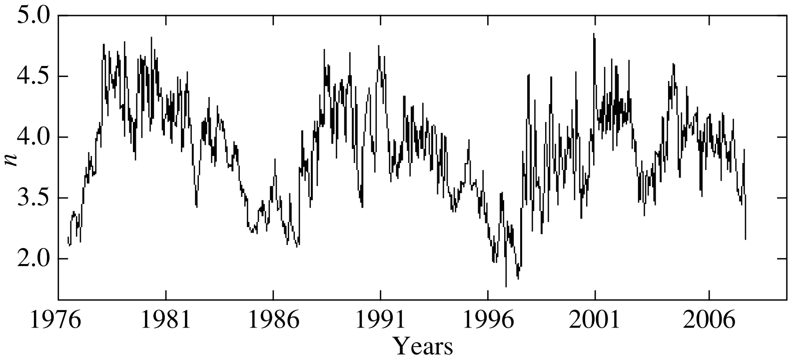

Fig. 2. Effective multipolarity index versus time.

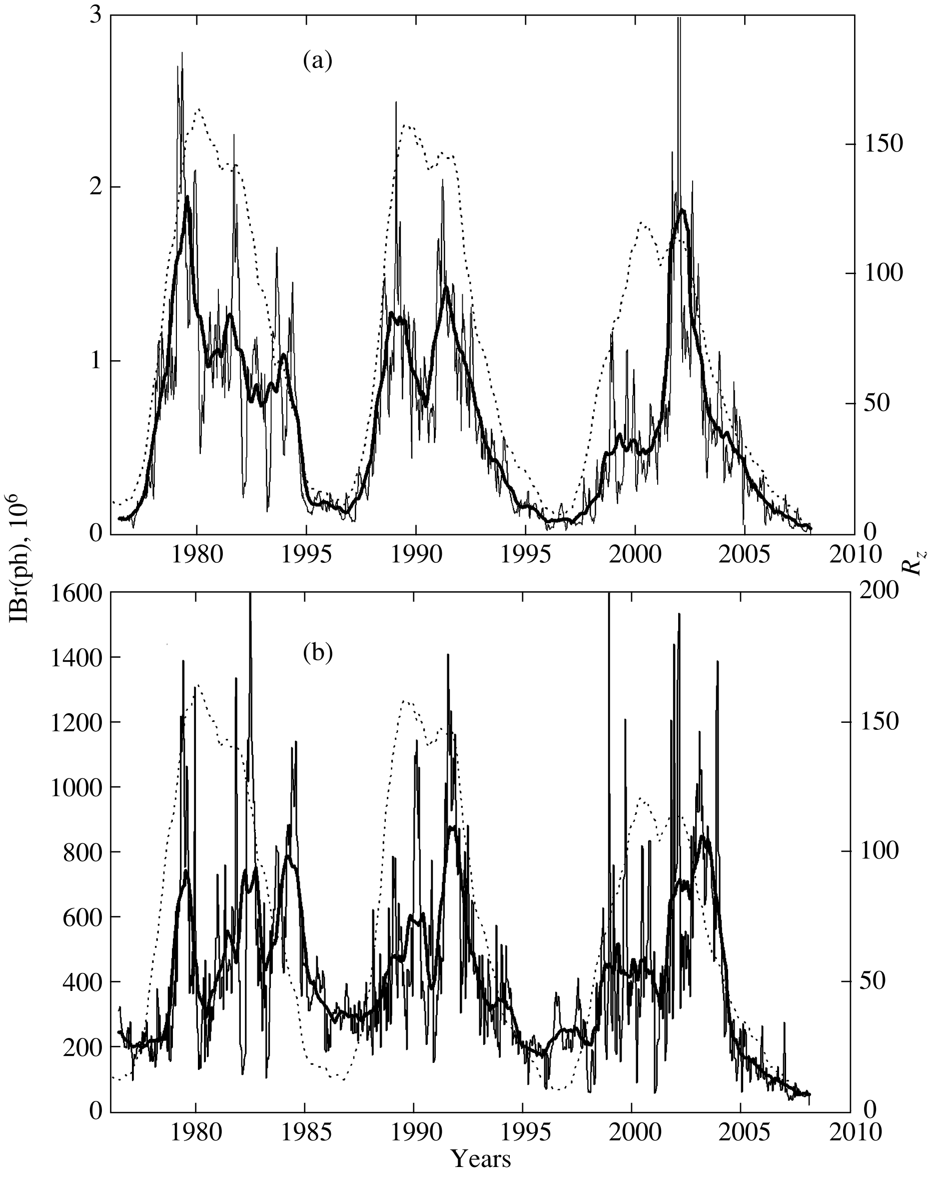

Fig. 3. Indices of the large-scale magnetic field versus time: (a) the index on the photosphere and (b) the index on the source surface. The thin curve indicates the indices for each half Carrington rotation; the thick curve indicates the smoothed values. The dotted line indicates the relative sunspot numbers.

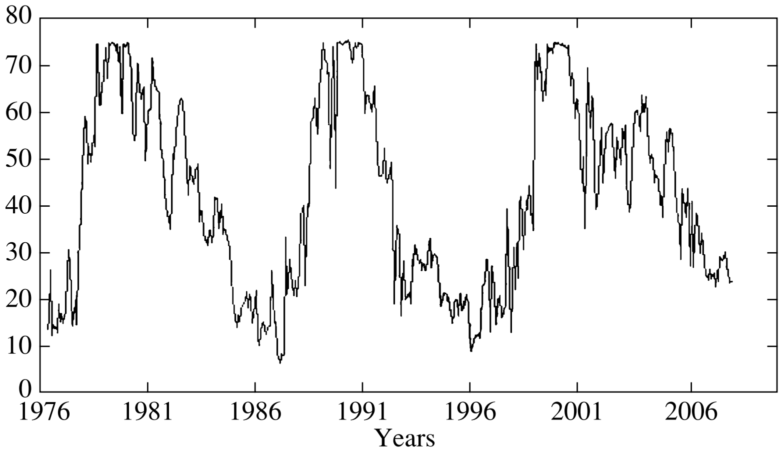

Fig. 4. HCS tilt versus time.

of 5 at the cycle maxima, which was determined by the contribution from the local fields, and fell to ~3 at the minima, which is completely determined by the behavior of the global quasi-dipole field. However, its behavior has changed sharply in the current cycle. After the short-term decrease in 2003–2004, this index has again increased to values comparable to those at the cycle maximum. The decrease in 2003 per se agrees well with the behavior of the large-scale field shown in Fig. 3.

It stems from the fact that in 2003–2004, the indices shown in Fig. 3, the mean square of the magnetic field strength on the photospheric surface IBr(ph) and the mean square of the magnetic field strength on the source surface Ibr(ss), reach their maxima. However, the further rise in n is not quite clear. The increase in this parameter at the decay phase points to a decrease in the effective scale of the fields compared to the global field. However, these cannot be the sunspot fields, because only the open fields remain on the source surface by definition. Moreover, the number of sunspots decreased greatly by 2006–2008. The effective size of the elements with $n \sim 4.5$ can reach 40 heliographic degrees. These may be the large-scale unipolar regions with which equatorial coronal holes are often associated. Note that equatorial coronal holes have been continuously observed on the Sun since 2003. It is these coronal holes that probably cause the HCS tilt to be above 30°. Indeed, whereas part of the flux on the photospheric surface can occasionally be closed back through low-lying loops, a coronal hole on the source surface is almost always a unipolar region. The neutral line cannot pass through a coronal hole. In this case, it is shifted away from the equator, causing the HCS tilt to increase.

Turning again to Fig. 3, which shows the Wolf numbers together with IBr(ph) on the upper panel and with IBr(ss) on the lower panel, note that the maximum of the large-scale field is increasingly receded from the maximum of the Wolf numbers. The meaning of this effect is not yet clear.

The behavior of the HCS tilt is also anomalous. By the minimum, the HCS is smoothed out and sinks to the equator. As we see from Fig. 4, the typical values of the tilt at minimum are less than 10°. In this cycle, it exceeded 25° by June 2008. This phenomenon is not completely clear either and may be related to the unusually wide distribution of intermediate-scale fields.

ON THE HEIGHT OF THE UPCOMING SOLAR CYCLE 24

Since the behavior of the magnetic fields in the present cycle is anomalous, the prediction of the height of the upcoming cycle is additionally complicated. Previously (Obridko and Shelting 2008), we analyzed a large number of predictions of cycle 24. Today, forecasters cannot reach any firm conclusion. The debate conducted in June 2008 at the NOAA Space Weather Prediction Center (SWPC) http://www.swpc.noaa.gov/SolarCycle/SC24/ showed that two alternative viewpoints exist: the cycle will be either high (140 units) or below the average one (90 units). The choice between these two possibilities cannot yet be made. Previously (Obridko and Shelting 2008), we also suggested several possible scenarios for the development of cycle 24. The data on the polar field are more likely indicative of a low cycle (the maximum value is of the order 80). This is confirmed by Fig. 1. We see from this figure that the magnetic moment of the global solar dipole in 2008 decreased to values typical of those at the beginning of the 20th century, when three low cycles were observed (the maximum in 1907.0 was 64.2 in cycle

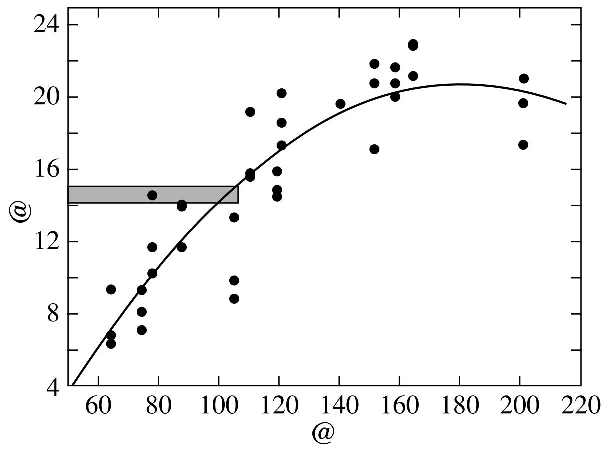

Fig. 5. Correlation between the geomagnetic aa-index in the years of minimum solar activity (vertical axis) and the relative sunspot number at the upcoming solar maximum (horizontal axis). The solid curve represents a quadratic fit.

14, the maximum in 1917.6 was 105.4 in cycle 15, and the maximum in 1928.4 was 78.1 in cycle 16). On the other hand, in this paper, using the characteristics of the large-scale field and geomagnetic activity, we obtained moderate values for the maximum of cycle 24, 128 and 113 units, respectively. Using the data on the geomagnetic field seems most reliable. Some increase in the intermediate-scale fields associated with the fields of extended unipolar regions must lead to an increase in the geomagnetic disturbances.

The height of the upcoming maximum can be correlated with the geomagnetic disturbance level at the minimum. In Fig. 5, the yearly mean monthly geomagnetic aa-indices for the year of minimum, one year before, and one year after it are shown along the vertical axis. This index can be determined from the data of several geomagnetic observatories and has been tabulated from 1968 until the present time. The height of the upcoming maximum is shown along the horizontal axis. A satisfactory quadratic dependence with a correlation coefficient of 0.89 ± 0.03 is observed. Unfortunately, we do not yet know the exact date of the current minimum, not to mention the aa-index in the next year. If we use the data for 2007 and 2008, then we will obtain 14–15 (these values are indicated in the figure by the shaded rectangle) and this corresponds to a height of the next maximum of about 110. Analyzing the shift between the maximum of the Wolf numbers and the maximum of the aa-index, Georgieva (2008) obtained the same value. The shift obtained in this work may be somehow related to the shift of the maximum of the large-scale field relative to the maximum of the sunspot number shown in Fig. 3.

Thus, in general, one may expect the beginning of the 21st century to be characterized by one or two cycles with a fairly low or just low intensity. A more serious, Maunder-type decline of activity or at least the decline that was observed at the beginning of the 20th century cannot be ruled out either.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 08-02-00070).

REFERENCES

1. K. Georgieva, in *Proc. of the All-Russian Conf. on Solar and Solar-Terrestrial Physics, 7–12 July, 2008, St.-Petersburg, GAO RAN* (2008), p. 25.
2. M. N. Gnevyshev and A. I. Ol', Astron. Zh. **38**, 15 (1948).
3. A. J. Hundhausen, in *An Interplanetary View of Coronal Holes, in Coronal Holes and High Speed Solar Wind Streams* Ed. by J. B. Zirker (Colorado Univ. Press, Boulder, 1977), p. 298.
4. V. N. Ishkov, Astron. Vestnik. **39**, 507 (2005) [Solar Syst. Res. **39**, 453 (2005)].
5. E. V. Ivanov, V. N. Obridko, B. D. Shelting, et al., Astron. Zh. **74**, 273 (1997) [Astron. Rep. **41**, 236 (1997)].
6. M. Kopecky, Bull. Astron. Instit. Czechoslovakia **2**, 14 (1950).
7. I. M. Livshits and V. N. Obridko, Astron. Zh. **83**, 1031 (2006) [Astron. Rep. **50**, 926 (2006)].
8. V. I. Makarov, V. N. Obridko, and A. G. Tlatov, Astron. Zh. **78**, 859 (2001b).
9. V. I. Makarov, A. G. Tlatov, D. K. Callebaut, et al., Solar Phys. **198**, 409 (2001a).
10. V. I. Makarov, A. G. Tlatov, D. K. Callebaut, et al., Solar. Phys. **206**, 383 (2002).
11. K. Mursula and T. Hiltula, Geophys. Res. Lett. **30**, 21 (2003).
12. V. N. Obridko and F. A. Ermakov, Astron. Tsirk., No. 1539, 24 (1989).
13. V. N. Obridko and B. D. Shelting, Solar Phys. **137**, 167 (1992).
14. V. N. Obridko and B. D. Shelting, Astron. Zh. **85**, 750 (2008a) [Astron. Rep. **52**, 676 (2008a)].
15. V. N. Obridko and B. D. Shelting, Solar Phys. **248**, 191 (2008b).
16. M. Schulz, Astrophys. Space Sci. **24**, 371 (1973).
17. B. D. Shelting, V. N. Obridko, and F. A. Ermakov, Astron. Tsirk., No. 1540, 23 (1989).
18. J. M. Wilcox and N. F. Ness, J. Geophys. Res. **70**, 5793 (1965).

Translated by G. Rudnitskii