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Relation between the Structure of the Large-Scale Solar Magnetic Field in the Activity Cycles and IMF Governing Geomagnetic Activity

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Abstract—It has been corroborated that the sign and amplitude of the annual mean IMF B_z component agree with the structure of the large-scale magnetic field of the Sun in its polar zones. Therefore, recurrent geomagnetic activity is best pronounced in the cycles when the solar field at the north pole is positive.

INTRODUCTION

The vertical (B_z) component of the IMF vector is the most important geoeffective parameter of the solar wind, which is used to describe the level of disturbance in the Earth's magnetosphere [Feynman and Gabriel, 2000]. Therefore, the mechanism of generation of the southward component ($B_z < 0$) is of particular interest. The fast changes of sign and amplitude of B_z are directly controlled by the processes in the interplanetary medium along the solar wind stream, whereas the cause of the longer-term structure of the IMF vector is still unknown. Based on more than a secular history of the *aa* index of geomagnetic activity, some conclusions are drawn concerning the role of the large-scale solar magnetic field (LSMF) in forming a definite temporal pattern of geomagnetic activity, which is characterized by the time series of the *aa*(*t*) index. Moreover, the observed increase in the annual mean values of the *aa* index caused Stamper *et al.* [1999] to assume that the LSMF enhancement in the last century was twofold. A relationship between geomagnetic activity and LSMF was also revealed earlier by various authors, including the first author of this paper [Legrand and Simon, 1991; Ohl, 1996; Obridko, 1995; Obridko and Shelting, 1992, 1999a, 1999b].

If the time variation in the *aa* index to a certain extent depends on the IMF B_z component, then the relationship should exist between the sign and amplitude of this component and the LSMF temporal structure (see the papers cited above). This assumption is developed in the present study.

2. ANALYSIS OF MONTHLY AND ANNUAL MEAN IMF B_z VALUES IN ORDER TO SEARCH FOR THEIR RELATIONSHIP WITH LSMF

The study of the relationship between the IMF B_z component and LSMF is based on interplanetary data for the period 1965–1996 (http://nssdc.gsfc.nasa.gov). The hourly mean B_z amplitudes were used to calculate the monthly and, then, the annual mean values of this component, which were compared with the LSMF time variation at the north pole of the Sun.

Figure 1 illustrates the calculated polar magnetic field of the Sun ($-B_{pol}$), reversed in sign and decreased by a factor of 80, and the annual mean values of IMF B_z (with their dispersions) for the time interval under examination. The field B_{pol} was calculated in a potential approximation at a distance of 2.5 solar radii, using the Mt-Wilson, Kitt-Peak, and WSO observations. It is clear that both magnitudes behave rather conformably: IMF B_z changes sign as the direction of polar LSMF is reversed from cycle to cycle (the change occurs at a cycle maximum). This implies that the long-lived large-scale magnetic field in the heliosphere is an extension of the high-latitude solar magnetic field, and its field lines converge to the plane of the heliographic equator. Such a field is rather weak and cannot affect the partic-

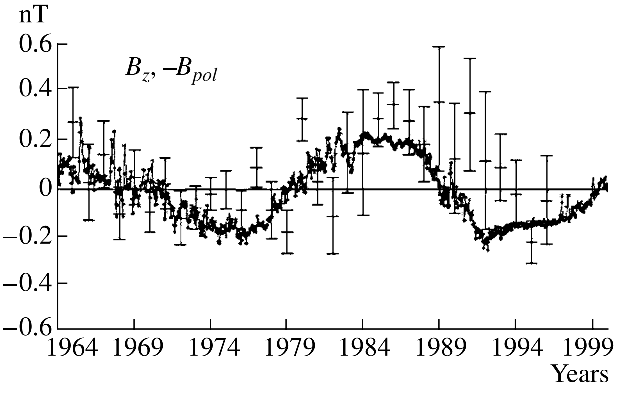

Fig. 1. Variation in LSMF ($-B_{pol}$) and the IMF B_z annual mean values (together with their variance) for the period 1965–1996.

ular geomagnetic disturbances generated by IMF. However, it can create a certain secular trend in the level of recurrent geomagnetic activity in different solar cycles.

Since geomagnetic activity increases at $B_z < 0$, one can expect from Fig. 1 that the *aa* index should be, on the average, greater in the periods between the reversals of the solar magnetic dipole, when the magnetic field at the north pole is positive. However, this conclusion is applicable to only recurrent geomagnetic events because it is based on the concept of quasi-stationary solar magnetic field and ignores disturbances associated with the coronal mass elections.

We have analyzed the daily values of the *aa* index for the period from January 1, 1868, to December 31, 1998 (47847 days). The entire database was divided into moving intervals of 1018 days with a shift of 339 days. For each interval, we calculated the mean index and the variance σ. The mean index over the interval was subtracted from all index values in that interval, and the result was normalized to σ. Then, the data obtained were expanded into the Fourier series, and the sum of the squares of the expansion harmonic amplitudes was determined in the range of periods from 24 to 35 days (139 values). This quantity (S_{27}) is the fraction of the power of the recurrent geomagnetic disturbances among all disturbances for 1018 days. We will call this quantity the normalized spectral power of recurrent geomagnetic disturbances.

The curve in Fig. 2 illustrates the dynamics of S_{27} for 1968–2000. The shaded areas show the periods when the solar magnetic field at the north pole was positive and, hence, one could expect the IMF B_z at the Earth's orbit to be smaller than zero. One can see that the amplitude of S_{27} is always somewhat higher near the cycle minimum, as follows from our analysis. It is also evident that the S_{27} maximums associated with the positive magnetic field at the solar north pole have as a rule larger amplitudes, which corresponds to the results illustrated in Fig. 1.

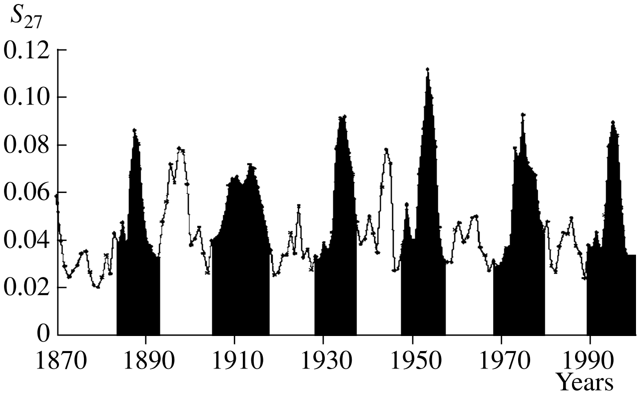

Fig. 2. Variation in the normalized spectral power of the 27-day component (S_{27}) in the *aa* index spectrum for 1968–2000.

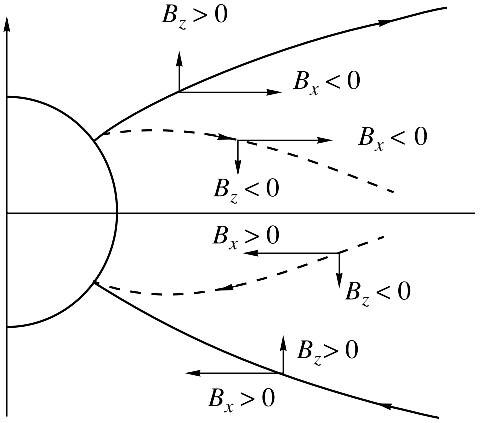

Fig. 3. Schematic relationship between the IMF B_z and B_x components for the convergent and divergent field lines (the solar–equatorial coordinate system).

3. RELATIONSHIP BETWEEN THE B_z AND B_x COMPONENTS AND CONFIGURATION OF THE IMF LINES

The IMF sector structure manifests itself in the presence of spatial features in the interplanetary medium characterized by a stable relationship of signs of the IMF vector components: $B_x > 0$, $B_y < 0$ for the positive sector and $B_x < 0$, $B_y > 0$ for the negative one. It is shown (e.g., see [Hoeksema and Scherrer, 1986]) that the sign and, largely, the amplitude of IMF B_x depend on the sign and amplitude of the radial LSMF component (B_r) on the sphere of 2.5 solar radii at its intersection with the interplanetary field line passing through the Earth (a time shift of about 4.5 days). In turn, the magnitude and sign of B_r are controlled by the global magnetic field of the Sun. In the epochs of solar minimum, when the Earth in spring is under the equatorial plane of the Sun, the sign of B_r (and, hence, of the IMF B_x component) coincides with the LSMF sign at the south pole. In autumn, the situation is opposite.

To analyze the IMF–LSMF coupling based on the potential configuration of the LSMF lines, it is convenient to introduce the parameter $A = (N_+ - N_-)/(N_+ + N_-)$. Here, N_+ is the number of days in the time interval under examination when the IMF B_x and B_z coincide in sign, and N_- is the number of days when these components have opposite signs [Kuklin and Obridko, 1982; 1988]. At $A > 0$, the situation when both components have the same sign prevails in the time interval under discussion; at $A < 0$, the signs are mainly opposite. We have calculated the monthly mean values of A. The cases when one of the IMF vector components was zero were included in N_+ and N_- with the weight 1/2 and, hence, affected only the denominator in the above calculation formula.

Figure 3 demonstrates the scheme of the IMF lines for the solar magnetic dipole directed northward and

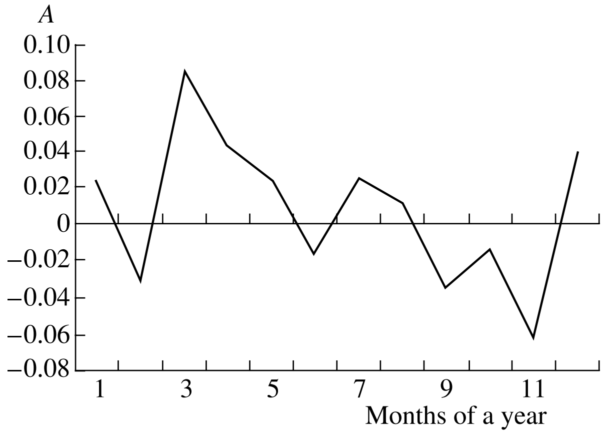

Fig. 4. Annual variation in parameter A based on the B_z and B_x data in the solar–equatorial reference frame, averaged for 1966–1998.

the field lines going either away from or towards the solar equator. In the first case, $A > 0$ in the interplanetary space below the solar equator and $A < 0$ above the equator. In the second case, the situation is opposite.

Using the same IMF data for 1966–1998 in the solar equatorial reference frame, we have plotted the annual variation in parameter A averaged over the entire 23-year interval (see Fig. 4). As follows from the Fig. 4, the IMF lines near the Earth slightly diverge from the solar equatorial plane. Earlier, Rosenberg and Coleman [1969] and Ponyavin and Usmanov [1985] arrived at the same conclusion.

4. CONCLUSIONS

An analysis of the hourly mean vector components of IMF for 1965–1996 has shown that the sign and amplitude of IMF B_z averaged over a year agree with the LSMF structure in the polar zones. Hence, recurrent geomagnetic activity is particularly strongly pronounced in the solar cycles when LSMF at the north pole is positive. On the other hand, an analysis of parameter $A = (N_+ - N_-)/(N_+ + N_-)$, where N_+ is the number of days in the time interval under discussion when B_x and B_z had the same sign, and N_- is the number of days when they had opposite signs, has revealed that the IMF lines near the Earth slightly diverge from the solar equatorial plane.

There seems to be a conflict between these conclusions. The first conclusion implies that the field lines converge towards the solar equator, while the second conclusion displays their divergence (though rather weak and observed only near the equatorial plane). However, the contradiction is explained in the following way. The heliospheric magnetic field is composed of two field systems with the "quasi-stationary" and "variable" structure. In the first case, we have analyzed annual mean IMF B_z, i.e., the slowly changing "quasi-stationary" LSMF structure. In the second one, an analysis is based on the daily mean B_x and B_z values, which reflect the "variable" LSMF structure. The second conclusion means that the IMF lines go along the Archimedean spiral and slightly diverge from the solar equatorial plane owing to the super-radial expansion associated with continuous activity in the solar equatorial zone. So, when analyzing geomagnetic variations over long time intervals, we have to consider the "quasi-stationary" LSMF system, while an analysis and forecast of geomagnetic disturbances must take into account the more intense "variable" system with the typically divergent IMF lines.

Note that a weak systematic growth of S_{27} in the periods when $B_z < 0$ is observed in Fig. 2, precisely which probably results in the systematic trend in the *aa* index (see [Stamper *et al.*, 1999]. This can also be associated with a gradual increase in the magnetic moment of the solar dipole described by Makarov *et al.* [2001].

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