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Long-Term Variations of Asymmetry of the Solar Magnetic Field and Geometry of the Interplanetary Magnetic Field

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Abstract—A comparative analysis of variations of the mean solar magnetic field and the interplanetary magnetic field over all history of their measurements is performed. Asymmetry of the solar magnetic field and its manifestation in the heliosphere is investigated. Long-term variations of the solar magnetic field and the heliosphere, which manifest themselves in alternation of dominating magnetic polarities of different sign, are discovered. On the basis of the analysis of cumulative sums of the IMF components, long-term variations of the IMF geometry and of the solar wind spiral angle are found. The cumulative sum of the IMF B_z component perpendicular to the ecliptic plane also shows long-term variations. Time intervals are revealed, in which negative values of the IMF B_z component dominate, and an increased geomagnetic activity is observed.

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1. INTRODUCTION

The global asymmetry of the solar magnetic field results from nonuniform heliolongitude distribution of magnetic activity and is connected with the north–south asymmetry of the activity, quadrupole component of the solar magnetic field [1, 2]. The measurements of the mean solar magnetic field (MSMF) have shown that one or another magnetic polarity can dominate for a long time [3].

The study of long-term variations of magnetic and thermodynamic parameters of the Sun is of particular interest, since such variations influence the state of the heliosphere, geomagnetic field, and the Earth's climate. Long-term variations in the heliosphere manifest themselves in variations of energy fluxes, mass, and dynamic pressure of the solar wind [4]. Asymmetries of the solar magnetic field are imprinted in the heliosphere and manifest in systematic southward displacement of the heliospheric current sheet relative to the helioequator plane [5, 6]. An estimation of displacement of the heliospheric current sheet performed on the basis of extrapolation of the photospheric magnetic field in the potential approximation [7] is in agreement with the data of direct measurements [5].

The cause of observed unbalance of magnetic polarities is the fact that the solar magnetic field has the complex hierarchical structure containing the components of symmetries of different types, while the MSMF measurements include only longitudinal component of the field and are performed with averaging over the solar disk, the IMF measurements being performed locally. Such a limitation of performed measurements does not allow one to describe the magnetic field in the Sun–heliosphere system adequately. Nevertheless, it is possible to use the property of unbalance or asymmetry of polarities for diagnostics of magnetic fields and for studying long-term variations in the heliosphere [8–11].

In this paper, the analysis of IMF variations in an integral representation is in progress, and long-term variations of the IMF geometry and of the spiral angle of the solar wind are discovered. The analysis of behavior of the IMF B_z component in the solar–magnetospheric coordinate system has allowed one to study its long-term variations in relation to the Earth's magnetic field.

2. CYCLIC VARIATIONS OF UNBALANCE OF IMF POLARITIES

Continuous series of IMF measurements presented in the OMNI2 database [12] are investigated with the help of the method of cumulative sums [11]. Figure 1a shows plots of average hourly values of the IMF radial component and sunspot numbers. The data of IMF direct measurements enclose the activity cycles 20–23. Cumulative sums of IMF B_x, B_y, and B_z components in the solar-ecliptic coordinate system (GSE) are shown in Fig. 1b. The cumulative sum of the radial component is shown with opposite sign, which corresponds to a rule adopted for the solar magnetic fields. In this case, if values of IMF components are uncertain, they were taken to be equal to zero.

Cyclic variations are weekly expressed in the IMF radial component, but regular variations of unbalance of magnetic polarities are observed in its cumulative sum. If the positive polarity dominates, the cumulative sum increases, if the negative polarity dominates, it

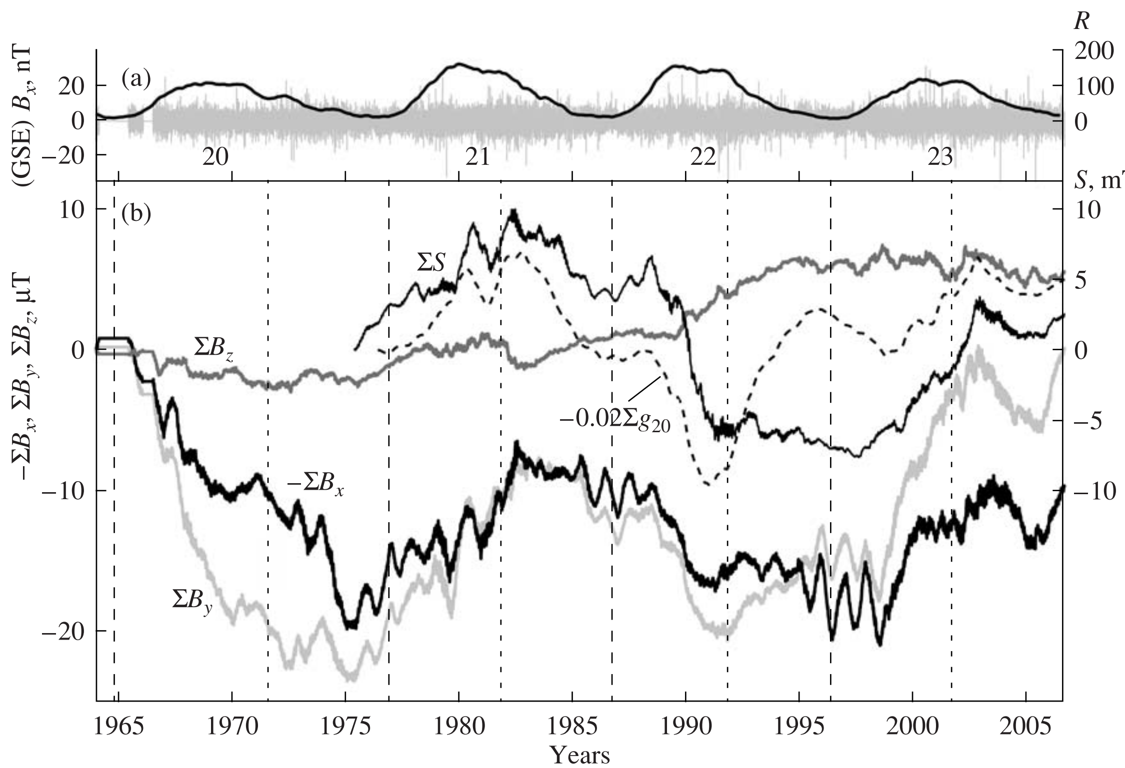

Fig. 1.

decreases. The annual wave is well pronounced, as a manifestation of the Rosenberg–Coleman effect [13]. In the cumulative sum of the radial IMF component, variations from cycle to cycle are clearly observed. In even and odd cycles dominate variations of the cumulative sum connected with its decreasing and increasing, respectively. By this means, the magnetic Hale cycle is manifested in alternation of IMF dominating polarities.

Figure 1b shows also a cumulative sum of MSMF according to the data of measurements performed in the Stanford observatory [14]. Similarly to $-\Sigma B_x$, the cumulative sum of MSMF ΣS makes a complete magnetic cycle; in this case, its level from maximum to maximum is decreased by 6.24 mT during the period May 1982 – September 2002. Such an agreement confirms the reality of cyclical and long-term variations of unbalance of IMF polarities, their solar origin. The cumulative sum of coefficients of expansion of the solar magnetic field over spherical functions g_{20} is shown in Fig. 1b by dashed curve. These coefficients describe the contribution of quadrupole mode at a distance of 2.5 solar radii, when classical boundary conditions [14] are used. The cumulative sum of coefficients g_{20} taken with a factor of –0.02 agrees with the cumulative sum of MSMF, noticeable differences between them are observed only during the period 1994–1998. The cumulative sum of coefficients g_{20} describes the most typical details and long-term variations of unbalance of polarities of the solar magnetic field, thus showing that its quadrupole component is the basic cause of initiation of the observed unbalance of MSMF and IMF polarities.

3. LONG-TERM VARIATIONS OF THE IMF GEOMETRY

Long-term variations of the cumulative sum of the IMF $-B_x$ radial component manifest themselves as systematic decrease of its level. The cumulative sum $-\Sigma B_x$ in the GSE system has decreased from the minimum to minimum by 1.16 μT for the period January 1975 – May 1998. The decrease of $-\Sigma B_x$ from the maximum to maximum was about 7.2 μT for the period April 1965 – June 1982 and 2.44 nT in June 1982 – May 2003. Such long-term variations occur as a result of systematic dominance of the magnetic polarity directed sunward.

Cyclic variations are also observed in variations of the cumulative sum of the IMF B_y azimuth component, which is connected with the IMF radial component by a relation characterizing the Parker spiral angle $\tan\psi = B_y/B_x = 2\pi r/(P \cdot V)$, where P and V are, respectively, the sidereal period of the Sun's rotation and the solar wind velocity at the distance r from the center of the Sun

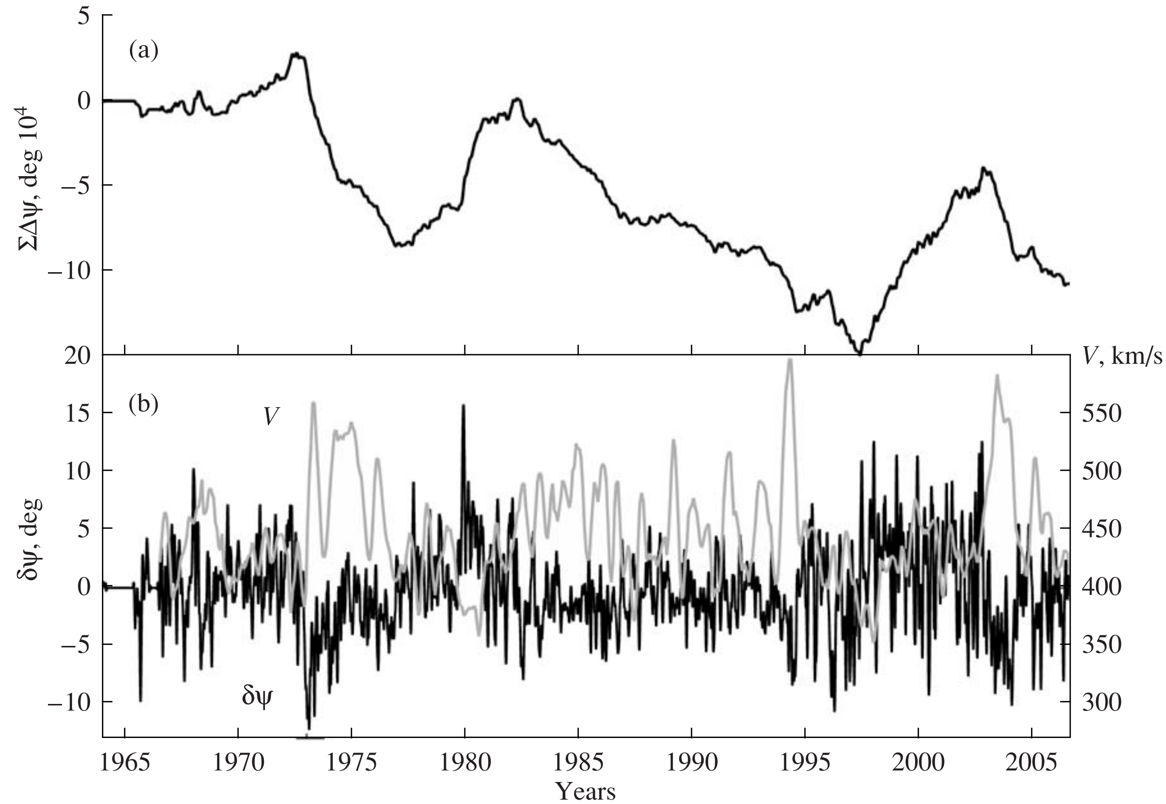

Fig. 2.

[15]. The level of the cumulative sum B_y has increased by 2.9 μT from minimum to minimum during January 1975 – August 1991 and by 7.8 μT from maximum to maximum during May 1982 – September 2002. Changing relationship between the radial and azimuth IMF components indicate to variations of the IMF geometry, its spiral angle. Indeed, if the relationship between the radial and azimuth components were strictly conserved, their cumulative sums would differ by a constant factor and would not intersect each other. Actually, cumulative sums of the radial and azimuth components intersected many times being considered in the solar-ecliptic coordinate system. Cumulative sums of the IMF components similarly behave themselves in the solar-equatorial coordinate system (QSEQ) [11].

The mean value of the spiral angle over the period 1964–2006 was $\psi_0 = 44.99°$. This angle corresponds to the direction of the principal axis of an ellipsoid, which best corresponds to the distribution of the IMF components during this period according to the minimum variance principle [16]. Let us measure azimuth angles from this mean direction passing from the azimuth angle of the IMF vector in the solar-ecliptic coordinate system to an angle between the radial direction and the direction tangent to the Parker spiral $\psi = \psi_0 + \Delta\psi$, $-90° \le \Delta\psi \le 90°$. The cumulative sum of deviations angles $\Sigma\Delta\psi$ from the mean spiral angle is shown in Fig. 2a. Cyclical and long-term variations are also seen here, and they show that the IMF geometry varies with time. Smoothed behavior of deviations of the spiral angle versus its mean value can be estimated, if one smoothes $\Sigma\Delta\psi$ and then takes differences of the smoothed cumulative sum from hour to hour. Figure 2b shows variations of the spiral angle in comparison with the solar wind velocity averaged over 27-day intervals [12]. On short time scales, there is an anticorrelation between the solar wind velocity and the Parker spiral angle: a decrease of the spiral angle arises due to high-speed streams of the solar wind.

Cyclical variations of the spiral angle are well pronounced in behavior of the cumulative sum of deviation angles of the spiral from the mean value. The Parker spiral angle is determined mainly by the solar wind velocity V. An increase of the solar wind velocity occurs on the phase of solar activity decay near its minimum. The increase of the solar wind velocity leads to a decrease of the spiral angle, which is manifested in the cumulative sum of deviations $\Sigma\Delta\psi$ in Fig. 2a. The total effect of decreasing spiral angle in the 11-year cycle is observed in a decrease of the cumulative sum, which equals about 10^5 degrees according to the mean hourly data.

Based on the relation $\partial\psi/\partial V = 2\pi r \cdot P/(P^2V^2 + 4\pi^2 r^2)$, one can estimate the total effect of variation of the solar wind velocity in the activity cycle. It is found that the observed effect can give a systematic increase of the solar wind velocity by 40 km/s for 5 years. In actually fact, variations of the solar wind velocity are not monotonic and have large amplitude, and the total effect of decreasing $\Sigma\Delta\psi$ is comparable in its value with the influence of high-speed streams in the activity cycle.

Along with the cyclical variations of the spiral angle a systematic decrease of the cumulative sum of deviation angles of the spiral from the mean value takes place. Such a decrease corresponds to growing mean velocity of the solar wind and decreasing angular velocity of the Sun's rotation. The systematic decrease of $\Sigma\Delta\psi$ for last 43 years was about $7 \cdot 10^4$ degrees. If one assumes that variation of the spirality angle is connected with the integral effect of variations of the solar wind velocity, it is possible to estimate the amplitude of long-term variations of velocity, which is about 4 km/s in the period 1964–2006.

4. LONG-TERM VARIATIONS OF THE IMF B_z COMPONENT

Of special significance is the behavior of the IMF component perpendicular to the ecliptic plane. The sign and magnitude of the IMF B_z component determine the geoefficiency of the solar wind. The existing methods of forecasting predict the IMF B_z component worst of all, because its behavior is determined by different causes. On the one hand, its sign and magnitude are determined by local magnetic fields, which are carried away by the solar wind. On the other hand, high-speed streams of the solar wind interacting with the interplanetary medium transform the IMF [17]. In addition, the global solar magnetic field makes a contribution to the B_z component [18].

Variations of the B_z component relative the helioequator [11] characterize processes in the heliosphere, which to a greater degree are controlled by the Sun. To study the geomagnetic activity taking orientation of the IMF B_z component relative the Earth's magnetic field into account the analysis of cumulative sum of B_z is performed in the solar-magnetospheric coordinate system (GSM). Figure 3a shows plots of the cumulative sum of B_z in various coordinate systems. The main peculiarity of behavior of cumulative sums is the presence of a considerable trend to the side of their increase, which testifies systematic dominance of positive values of the B_z component.

The linear trend estimated from the least-squares condition shows an increase of the cumulative sum of B_z in the solar-magnetospheric coordinate system by a value of 527 nT in recent 43 years, which is somewhat less than a similar trend in the solar-equatorial system. Such a growth could be ensured by constantly present magnetic field, which does not vary from cycle to cycle, for example, the primordial magnetic field of the Sun [11].

Subtracting the trend from the cumulative sum of the B_z component, we obtain the residual cumulative sum (Fig. 3b), in which variations from cycle to cycle are traced. The residual cumulative sum of B_z had a tendency to decrease in the 20th cycle. In the 21st cycle, its decrease stopped and the cumulative sum became increasing after considerable oscillations near to the epoch of sign reversal of the polar magnetic field. This growth continued up to 1995 and then the tendency to a decrease of the cumulative sum of the B_z component was established. This tendency goes on up to now.

Having calculated the differences of the smoothed cumulative sum from day to day, it is possible to find that constituent of the B_z component, which in pure form determines long-term variations of its cumulative sum. This constituent δB_z is shown in Fig. 3c in comparison with the *aa* index of geomagnetic activity [19]. Prolonged time intervals, in which negative values B_z dominate in the solar-magnetospheric coordinate system, are marked by black color. This was the case, for example, in 2003, when a series of superflares, powerful coronal ejections, and geomagnetic disturbances occurred. The amplitude of the δB_z component does not exceed 1 nT, but its role, apparently, consists in the fact that it creates a "seed" field, which can be significantly amplified on the front of rapidly moving magnetic clouds, when they interact with environment [17]. It is of interest to note that rather regular component on a time scale of 1.3 years is observed in behavior of the δB_z component. This component is also traced in variations of the geomagnetic activity and the solar wind velocity [20].

Comparing the behavior of the δB_z component with variations of index *aa*, one can frequently observe an increase of geomagnetic activity in the periods, when $\delta B_z < 0$. Nevertheless, the relation between them is not unambiguous and linear. Sometimes, this anticorrelation is broken which, apparently, is determined by sharp variations of dynamic pressure of the solar wind and by influence of other factors [21]. Their combined effect is characterized by ambiguity of cause-and-effect relations between solar, heliospheric, and geomagnetic disturbances, which makes essential difficulties for the forecast of the near-Earth space state [22].

CONCLUSIONS

The study of asymmetry of the solar magnetic field and unbalance of IMF magnetic polarities gives new means for diagnostics of the structure of the heliosphere and its long-term variations. In radial and azimuth IMF components, the regular alternation of dominating polarities from cycle to cycle is revealed, which

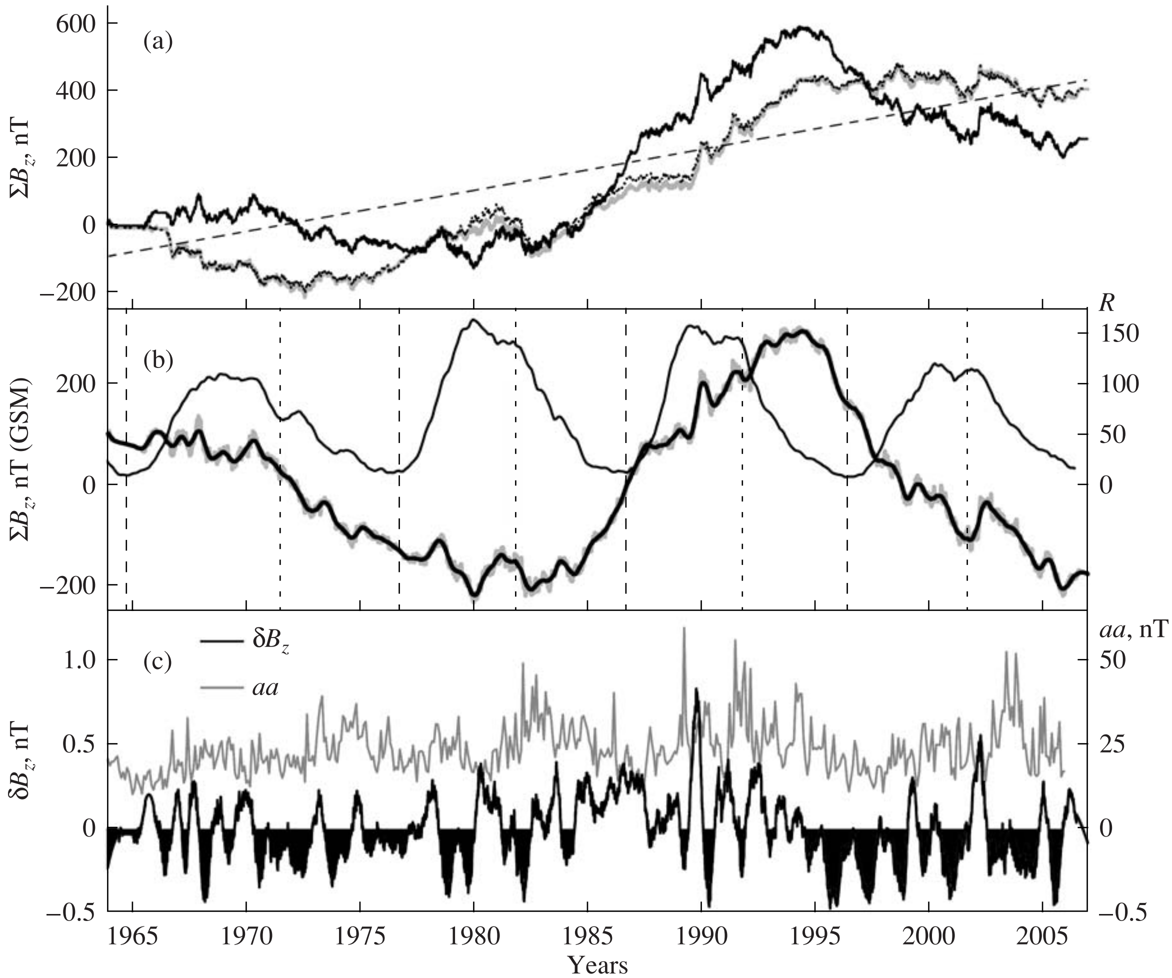

Fig. 3.

is a manifestation of the Hale magnetic cycle in the heliosphere. The performed analysis has confirmed that the main contribution to time variations of the asymmetry of dominating IMF polarities is made by the quadrupole component of the solar magnetic field.

Variations of the ratio between the radial and azimuth IMF components are discovered. They characterize short-term, cyclical, and long-term variations of the IMF geometry, spiral angle of the solar wind. The amplitude of short-term variations of the spiral angle exceeds 10°. Cyclical variations of the Parker spiral angle arise due to variations of the solar wind velocity. Long-term variations of the spiral angle become apparent in a systematic decrease of the cumulative sum of its deviations from the mean value. Such long-term variations correspond to decreasing Parker spiral angle during 20th–23rd solar activity cycles and, probably, result from slow increase of the mean velocity of the solar wind.

The contribution of the global solar magnetic field to the IMF component perpendicular to the ecliptic plane is estimated. In long-term variations of the IMF B_z component, variations from cycle to cycle are traced. On the basis of studying the behavior of the B_z component in the solar-magnetospheric coordinate system, time intervals are found, in which negative values of B_z dominate and increased geomagnetic activity is observed. The existence of long time intervals, in which negative values of the B_z component dominate, is connected with asymmetry of the solar magnetic fields, with reversal of a sign of the global solar magnetic field, and with deformations of the heliospheric current sheet.

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REFERENCES

1. Kuklin, G.V. and Obridko, V.N., Dynamic and Structural Characteristics of the Global Solar Magnetic Field and of the Interplanetary Magnetic Field, in *Fizika solnechnoi aktivnosti* (Physics of Solar Activity), Moscow: Nauka, 1988, pp. 146–167.
2. Mursula, K. and Hiltula, T., Systematically Asymmetric Heliospheric Magnetic Field: Evidence for a Quadrupole Mode and Non-Axisymmetry with Polarity Flip-Flop, *Solar Phys.*, 2004, vol. 224, pp. 133–143.
3. Grigoryev, V.M. and Demidov, M.L., The Solar Magnetic “Monopole" in Activity Cycles 19–21, in *Solar Magnetic Fields and Corona. Proc. of XIII Cons. Meeting on Solar Phys.*, Novosibirsk: Nauka, 1989, pp. 108–114.
4. Veselovskii, I.S., Dmitriev, A.V., Panasenko, O.A., and Suvorova, A.V., Solar Cycles in Fluxes of Energy and Mass of Heliospheric Plasma, *Astron. Zh.*, 1999, vol. 76, pp. 558–560.
5. Smith, E.J., Jokipii, J.R., Kota, J., Lepping, R.P., and Szabo, A., Evidence of a North-South Asymmetry in the Heliosphere Associated with a Southward Displacement of the Heliospheric Current Sheet, *Astrophys. J.*, 2000, vol. 533, pp. 1084–1089.
6. Mursula, K. and Hiltula, T., Bashful Ballerina: Southward Shifted Heliospherical Current Sheet, *Geophys. Rev. Lett.,* vol. 30, no. 22, p. SSC 2-1-4. doi: 10.1029/003GL018201.
7. Zhao, X.P., Hoeksema, J.T., and Scherrer, P.H., Prediction and Understanding of the North-South Displacement of the Heliospheric Current Sheet, *J. Geophys. Res.*, 2005, vol. 110, p. A10101. doi: 10.1029/2004JA010723.
8. King, J.H., A Survey of Long-Term Interplanetary Magnetic Field Variations, *J. Geophys. Res.*, 1976, vol. 81, p. 653.
9. Kovalenko, V.A., *Solnechnyi veter* (Solar Wind), Moscow: Nauka, 1983.
10. Mordvinov, A.V. and Plyusnina, L.A., Cyclic Changes in Solar Rotation Inferred from Temporal Changes in the Mean Magnetic Field, *Solar Phys.*, 2000, vol. 197, pp. 1–9.
11. Mordvinov, A.V., Long-Term Changes in Asymmetry of Magnetic Fields of the Sun and Heliosphere, *Astron. Zh.*, 2006, vol. 83, pp. 1042–1049.
12. King, J.H. and Papitashvili, N.E., *Interplanetary Medium Data, Suppl. 5*, Greenbelt: National Space Science Data Center, 1994.
13. Rosenberg, R.L. and Coleman, P.J., Heliographic Latitude Dependence of the Dominant Polarity of the Interplanetary Magnetic Field, *J. Geophys. Res.*, 1969, vol. 74, pp. 5611–5622.
14. Hoeksema, J.T. and Scherrer, P.H., *Solar Magnetic Fields—1976 through 1985*, UAG Report 94, Boulder, 1986 (http://sun.stanford.edu(wso)).
15. Parker, E.N., Dynamics of the Interplanetary Gas and Magnetic Fields, *Astrophys. J.*, 1958, vol. 128, pp. 664–678.
16. Song, P. and Russell, C.T., Time Series Data Analyses in Space Physics, *Space Sci. Rev.*, 1999, vol. 87, pp. 387–463.
17. Chao, J.K. and Chen, H.H., Prediction of Southward IMF B@z, in *Space Weather*, vol. 125 of *Geophysical Monographs,* Washington, D.C.: AGU, 2001, pp. 109–122.
18. Obridko, V.N., Golyshev, S.A., and Levitin, F.E., Relation of Structure of Large-Scale Magnetic Field in Cycles of Solar Activity with the Structure of IMF Exerting Influence on Geomagnetic Activity, *Geomagn. Aeron.*, 2004, vol. 44, pp. 449–452.
19. Mayaud, P.N., The aa Indices: A 100-Year Series Characterizing the Geomagnetic Activity, *J. Geophys. Res.*, 1972, vol. 77, pp. 6870–6874.
20. Paularena, K.I., Szabo, A., and Richardson, J.D., Coincident 1.3-Year Periodicities in the A_p Geomagnetic Index and the Solar Wind, *Geophys. Res. Lett.*, 1995, vol. 22, pp. 3001–3004.
21. Borodkova, N.L., Zastenker, G.N., Ryazantseva, M.O., and Richardson, J., Large and Sharp Changes of Solar Wind Dynamic Pressure and Disturbances of the Magnetospheric Magnetic Field at Geosynchronous Orbit Caused by These Variations, *Kosm. Issled.*, 2006, vol. 44, no. 1, pp. 3–11.
22. Yermolaev, Yu.I. and Yermolaev, M.Yu., Statistical Relationships between Solar, Interplanetary, and Geomagnetic Disturbances, 1976–2000, *Kosm. Issled.*, 2002, vol. 40, no. 1, pp. 3–16.