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Magnetic Fields of Photosphere and Interplanetary Space: Imbalance between Positive and Negative Polarities

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Abstract—Photospheric magnetic fields are studied in this work on the basis of synoptic maps from the Kitt Peak Observatory (1976–2003) and WSO (1976–2012). The imbalance between positive and negative fluxes is considered for strong magnetic fields in the sunspot zone. The imbalance sign coincides with the polar field sign in the Northern hemisphere; it depends on both the phase of the 11-year cycle and the solar cycle parity. These features of variation in the magnetic field can be explained by a strong quadrupole moment of the photospheric magnetic field, which is also seen in a change of the polarity of the interplanetary magnetic field.

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1. INTRODUCTION

Magnetic fields on the Sun surface are symmetrically distributed to the first approximation, i.e., approximately uniformly in heliographic latitude and antisymmetric about the helioequator. However, a more detailed study shows a noticeable asymmetry of magnetic fields: longitudinal asymmetry (in the form of active longitudes), north-south asymmetry, etc. (Obridko and Shel'ting, 2007; Asgarov and Obridko, 2007). An asymmetry of magnetic fields is shown, in particular, in the imbalance of magnetic fields of different signs (Kotov et al., 2002; Kotov, 2009; Choudhary et al., 2002).

In (Mordvinov, 2007), an imbalance in the photospheric magnetic flux was considered on the basis of a time series of the solar mean magnetic field (Wilcox Solar Observatory data). The study of cumulative sums of the mean magnetic field allowed the author to reveal long-term variations in the magnetic field imbalance with the Hale cycle. An imbalance of a photospheric magnetic field varied similar to the imbalance of a magnetic field extrapolated to the source surface and was similar to time variations in the quadrupole moment. It was shown that the polarity asymmetry of the interplanetary magnetic field (IMF) also follows the Hale magnetic cycle in both the radial and azimuthal components.

The imbalance between positive and negative photospheric magnetic fields was studied earlier (Vernova et al., 2012; Vernova et al., 2013) on the basis of synoptic maps from the Kitt Peak Observatory (1976–2003). Strong magnetic fields (stronger than 100 G) in the sunspot zone (heliographic latitudes of ±40°) were used for the study. Fluxes of positive and negative magnetic fields for the Northern and Southern solar hemispheres were considered separately. Each of the four magnetic fluxes can be interpreted as a magnetic field of leading/following sunspots of one of the solar hemispheres. All the four fluxes follow the 11-year solar cycle; however, there are certain differences in their time variations during years of high solar activity. These differences are seen when considering imbalances between the magnetic fluxes. The following regularities have been revealed. The imbalance between magnetic fluxes of leading sunspots of the Northern and Southern solar hemispheres, like the imbalance between fluxes of following sunspots, varies with the 22-year solar cycle, and the sign of imbalance between leading/following sunspots coincides with the sign of the polar magnetic fields in the Northern/Southern solar hemispheres, respectively. The imbalance between positive and negative fluxes for the whole near-equatorial region (±40° heliographic latitude) is determined by the imbalance of leading sunspots. The imbalance sign does not change during an 11-year cycle from one reversal of the global magnetic field of the Sun to another and always coincides with the sign of the polar magnetic field in the Northern hemisphere.

In this work, we study the imbalance between strong magnetic fields related to active regions with the use of WSO observatory data, which allows us to extend the considered time interval and verify the validity of previous conclusions for the period of

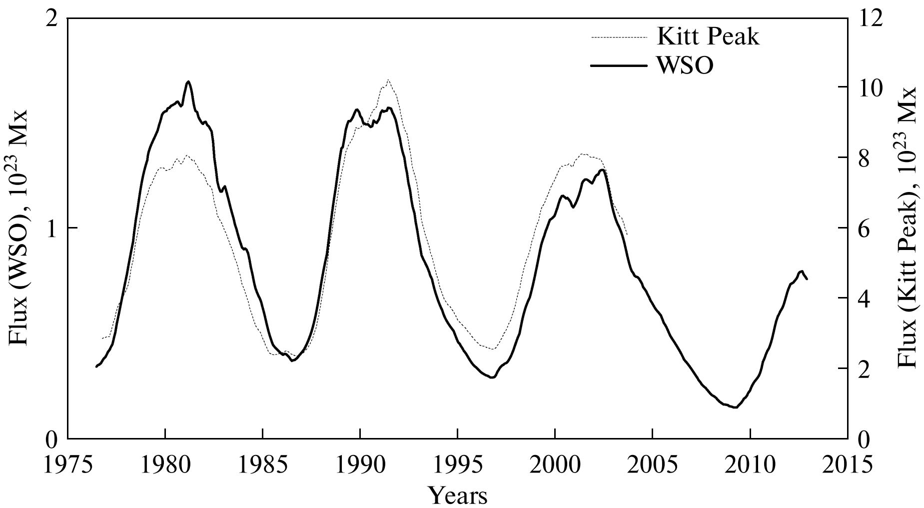

Fig. 1. Photospheric magnetic flux according to the Kitt Peak (1976–2003) and WSO (1976–2012) data for the whole solar surface. The data have been smoothed over 20 Carrington rotations.

descent of the 23rd solar cycle and the period of rising of the 24th solar cycle. In addition, we study the correlation of the imbalance between photospheric magnetic fields and the quadrupole moment with variations in the IMF polarity.

2. DATA AND METHOD

In this work, synoptic maps of the photospheric magnetic field from the National Solar Observatory (Kitt Peak, 1976–2003) and the Wilcox Solar Observatory (WSO, 1976–2012) are used. The data are available on the websites http://nsokp.nso.edu/ and http://wso.stanford.edu/. Synoptic maps of the photospheric magnetic field developed at the Kitt Peak Observatory have been obtained with a high resolution: the spatial resolution is 1° in longitude (360 steps) and 180 equal steps in sine latitude. Thus, each map contains 360 × 180 pixels of the magnetic field in gauss.

A large-scale photospheric magnetic field has been daily monitored at WSO since 1976. Daily magnetograms with a resolution of 3 arcmin were reduced to a finer grid in Carrington coordinates by means of interpolation. During synoptic mapping, the measurement results were taken into account with weights depending on the distance to the central meridian. Because of the large telescope aperture, regions from 70° latitude to the poles were fully entered into the last aperture (Scherrer et al., 1977). WSO synoptic maps of the photospheric magnetic field included the values of a magnetic field for the 30 latitude and 72 longitude ranges. Thus, each map includes 72 × 30 pixels of the magnetic field in microtesla. The area of a pixel in WSO synoptic maps is much larger; therefore, the magnetic field strength in it decreases because of the averaging of magnetic fluxes of different signs.

This is clearly seen in Fig. 1, where total magnetic fluxes measured at two observatories are compared. The fluxes have been calculated for each Carrington rotation by means of summing up the absolute values of the magnetic fields for all heliographic latitudes. Both fluxes (Kitt Peak Observatory and WSO) vary with an 11-year solar cycle. It is seen that the fluxes correlate well; however, flux values differ by about 5 times for the two observatories.

We considered features of strong magnetic fields in the sunspot zone. Magnetic field magnitudes B > 100 G (Kitt Peak) and B > 3 G (WSO) were used as thresholds for the selection of strong fields related to active solar regions. According to the stated problem, the synoptic maps were transformed as follows: (1) only pixels with values higher than the threshold were used in each synoptic map; and (2) near-equatorial zones (heliographic latitudes from +40° to –40°) were cut from each map. Synoptic maps prepared in this way were used for calculations of magnetic fluxes. Four magnetic field characteristics were calculated for each Carrington rotation: positive and negative fluxes for the Northern and Southern solar hemispheres (F_N^{pos}, F_N^{neg}, F_S^{pos}, and F_S^{neg}). The imbalance ΔF between positive and negative fluxes for the entire sunspot zone is defined as the sum of the four fluxes: $\Delta F = F_N^{pos} + F_N^{neg} + F_S^{pos} + F_S^{neg}$. The imbalance was calculated for the Kitt Peak and WSO photospheric data.

3. RESULTS AND DISCUSSION

In (Vernova et al., 2012; Vernova et al., 2013), we considered features of variations in the imbalance between positive and negative magnetic fluxes using Kitt Peak data for 1976–2003. The use of WSO data,

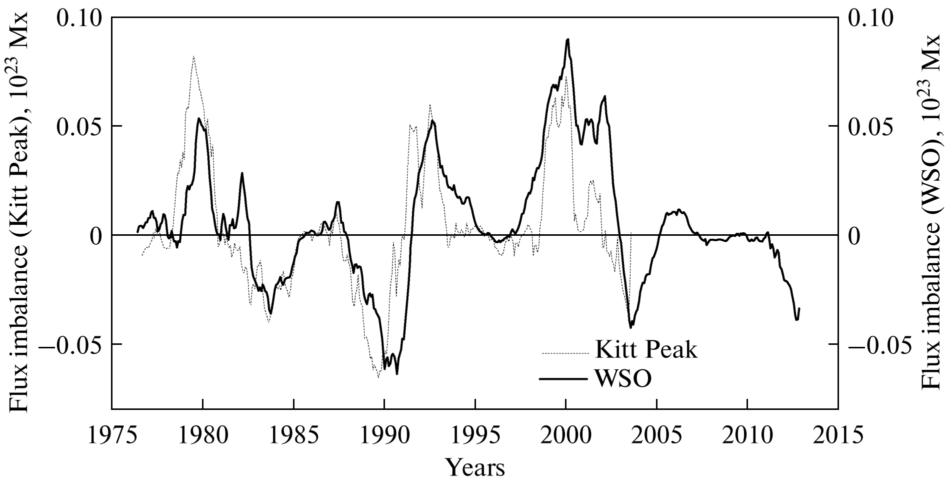

Fig. 2. Imbalance between strong positive and negative magnetic fields in the sunspot zone (heliographic latitudes from +40° to −40°) from Kitt Peak (1976–2003) and WSO (1976–2012) data.

which is less detailed compared to the Kitt Peak data, allowed us to extend the data series by 9 years. We have compared the previous results with calculations that use the WSO data (1976–2012).

Figure 2 shows imbalances between positive and negative magnetic fields (the sum of four fluxes) for strong magnetic fields in the sunspot zone (heliographic latitudes from +40° to −40°) for the Kitt Peak Observatory and WSO. The contribution of fields with a strength higher than the thresholds (B > 100 G for Kitt Peak and B > 3 G for WSO) was considered.

The results obtained from data for the two observatories correlate well for the 1976–2003 period, for which the data from both observatories are available (Fig. 2). It is noticeable that the imbalance has the same order of magnitude for both observatories, despite a strong difference in magnetic fluxes.

The main conclusions drawn earlier from the Kitt Peak data remain valid for the WSO data. The imbalance between positive and negative fluxes is close to zero during a period of low solar activity. The imbalance sign is kept during the 11 years from one reversal of the global magnetic field to another and changes like the sign of the magnetic field in the Northern hemisphere. Thus, the sign of the imbalance changes with the 22-year solar cycle and always coincides with the sign of the polar field in the Northern hemisphere.

The imbalance calculated from WSO data, up to 2012, confirms the previous conclusions, according to which the sign of the imbalance after 2012 and until the next reversal should be negative (see Fig. 2).

Let us note that the regularities of the change in the imbalance between positive and negative fluxes, which have been revealed for strong magnetic fields, are not shown in the imbalance of weak fields. Figure 3 compares the imbalance of strong (B > 3 G) and weak the imbalance of (B < 1 G) magnetic fields in the sunspot zone. It was seen that there is no correlation with the Hale cycle for weak fields. During low solar activity, the imbalance between strong fields vanishes, while the imbalance between weak fields attains its maxima. In general, the imbalance between weak fields is significantly lower than for strong fields.

In addition to the imbalance of the photospheric magnetic field, we have considered a variation in the quadrupole component of a magnetic field using WSO data. If the photospheric magnetic field is represented as multipole expansion (Hoeksema and Scherrer, 1986; Sun, 2009), then one should expect that the axisymmetric quadrupole moment mainly contributes to the imbalance between positive and negative magnetic fluxes. We have compared the change in the imbalance between positive and negative magnetic fluxes in the photosphere (Fig. 4a) with the quadrupole component of the magnetic field—the coefficient g_{20} (Fig. 4b, WSO data). The good correlation between these parameters (the coefficient of correlation $R = 0.60$) allows us to draw the conclusion that the imbalance between positive and negative fluxes is explained by the presence of the strong quadrupole component of the magnetic field.

The main result of our study of the imbalance between strong magnetic fields consists in coincidence of the imbalance sign with the sign of the polar magnetic field in the Northern hemisphere. To emphasize existence of the same feature for the quadrupole component of the magnetic field, the periods of coincidence of these signs are shown in Fig. 4b (hatching for positive polarity and solid-filled for negative one). The sign of the magnetic field in the Northern hemisphere is shown in the upper part of Fig. 4b.

Due to the mathematical properties of the model, the imbalance between photospheric magnetic fluxes

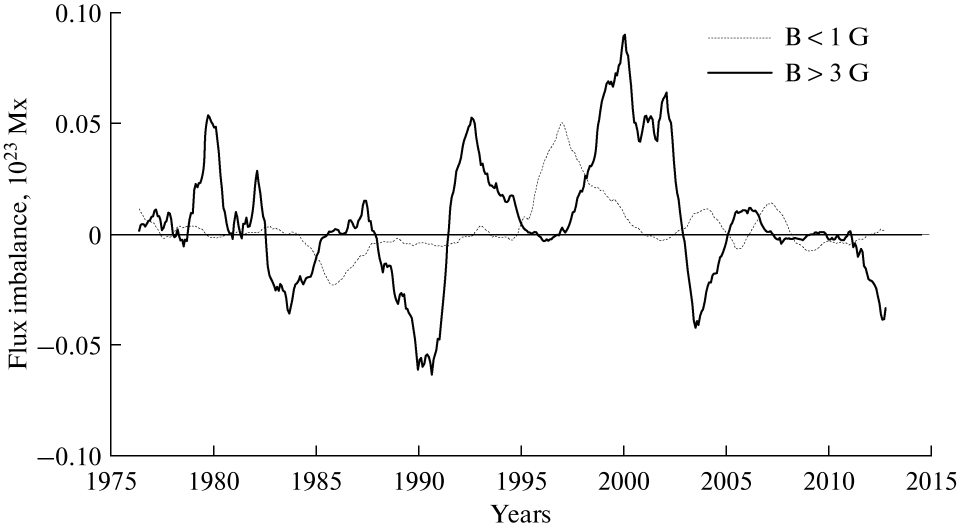

Fig. 3. Comparison of imbalances for strong (B > 3 G) and for weak (B < 1 G) photospheric magnetic fields for heliographic latitudes from +40 to −40° (WSO data).

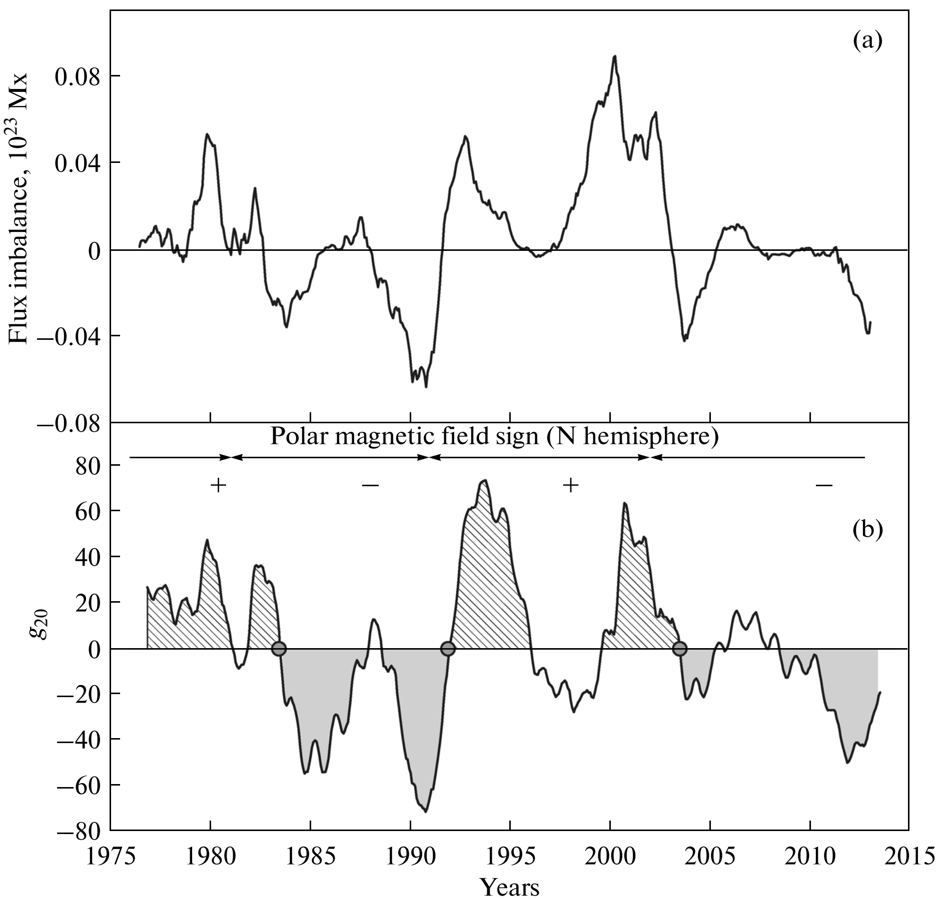

Fig. 4. Correlation between the imbalance between (a) positive and negative photospheric magnetic fields and (b) the quarupole component of the magnetic field g_{20}. The periods of coincidence of the signs of the quadrupole component and the polar field in the Northern hemisphere are hatched in the case of positive polarity and solid-filled in the case of negative polarity.

leads to the presence of an imbalance on the source surface. An imbalance between positive and negative magnetic fields is expected to be observed in the properties of the heliosphere. The solar wind in the plane of the ecliptic is ordered in the form of sectors (usually two or four), within which the IMF is directed out-

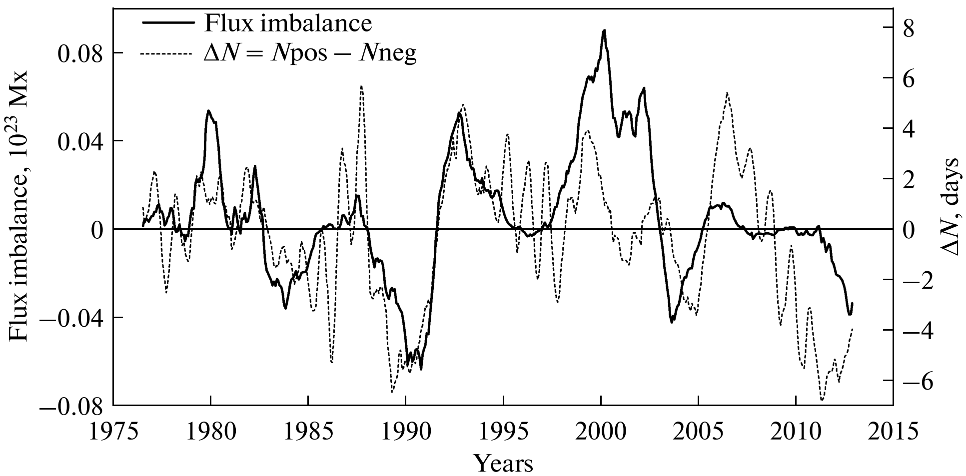

Fig. 5. Correlation between the imbalance of photospheric magnetic fields and the sector structure of IMF. The dashed curve shows the difference between the number of positive and negative days of IMF.

ward or toward the Sun. We have used data on the number of days with the positive polarity of IMF (direction is outward the Sun) and the negative polarity (toward the Sun) (Svalgaard, 2012).

The difference in the number of "positive" and "negative" days ΔN correlates well with the imbalance of photospheric magnetic field (Fig. 5). It is noticeable that the correlation is violated during the period of low solar activity. While the coefficient of this correlation is 0.57 for the whole 1976–2012 range, it increases up to 0.64 when excluding solar activity minima.

A similar correlation is observed between the quadrupole component of the photospheric magnetic field expansion g_{20} and the imbalance in IMF polarity ΔN: the coefficient of correlation is $R = -0.55$. Close results were found in (Erofeev, 2004): the correlation between the dominant IMF polarity and the amplitude of the solar magnetic quadrupole was –0.53 in 1926–1971.

This points to a correlation between IMF with the distribution of the photospheric magnetic field of the positive and negative polarities. Thus, there is a chain of interrelated phenomena: the imbalance between positive and negative photospheric fields—the imbalance of fields on the source surface—the imbalance of IMF.

The established regularity of variations in the imbalance between positive and negative fluxes (ΔF) can be represented by a simple formula. The sign of this imbalance is determined by two factors: the solar cycle parity and the phase of the 11-year cycle (before or after the reversal):

$$\mathrm{sign}\Delta F = (-1)^{n+k}, \quad (1)$$

where $n = 1, 2$ and $k = 1, 2$; $n = 1$ corresponds to odd and $n = 2$ correspsonds to even cycles; $k = 1$ corresponds to the interval from the minimum to the inversion of a 11-year cycle, and $k = 2$ corresponds to the interval from the reversal to minimum.

4. CONCLUSIONS

The results of this work allow the following conclusions.

1. The imbalance between positive and negative photospheric magnetic fluxes in the sunspot zone varies with the 22-year solar cycle.

2. The sign of this imbalance always coincides with the sign of the solar polar magnetic field in the Northern hemisphere.

3. The sighn of this imbalance is determined both by the phase of the solar cycle (before and after the reversal) and the cycle parity.

4. The IMF polarity changes with the same periodicity.

5. Asymmetry between the positive and negative magnetic fluxes on the Sun and in the heliosphere can be connected with the presence of a strong quadrupole component in the photospheric magnetic field.

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REFERENCES

Asgarov, A.B. and Obridko, V.N., Asymmetry in the inward-outward polarity in the interplanetary magnetic field, *Sun Geosphere*, 2007, vol. 2, no. 1, pp. 29–32.

Choudhary, D.P., Venkatkrishnan, P., and Gosain, S., On magnetic flux imbalance in solar active regions, *Astrophys. J.*, 2002, vol. 573, pp. 851–856.

Erofeev, D.V., Solar magnetic quadrupole and interplanetary field, *Proc. of IAU Symp. no. 223*, Stepanov, A.V., Benevolenskaya, E.E., and Kosovichev, A.G., Eds., 2004, pp. 99–100.

Hoeksema, J.T. and Scherrer, P.H., The solar magnetic field, *Rep. UAG-94*, Boulder: NOAA, 1986, p. 94.

Kotov, V.A., Khaneichuk, V.I., and Tsap, T.T., Measurements of solar magnetic imbalance, *Kinematika Fiz. Nebes. Tel*, 2002, vol. 18, no. 3, pp. 205–216.

Kotov, V.A., Forty years of measurements of the mean magnetic field of the Sun: View from today, *Bull. Crimean Astrophys. Observ.*, 2009, vol. 105, pp. 45–55.

Mordvinov, A.V., Magnetic flux imbalance of the solar and heliospheric magnetic fields, *Solar Phys.*, 2007, vol. 246, pp. 445–456.

Obridko, V.N. and Shel'ting, BD., A generalized polarity rule for solar magnetic fields, *Astron. Rep.*, 2007, vol. 51, no. 4, pp. 339–342.

Scherrer, P.H., Wilcox, J.M., Svalgaard, L., Duvall, T.L., Jr., Dittmer, P.H., and Gustafson, E.K., The mean magnetic field of the Sun: Observations at Stanford, *Solar Phys.*, 1977, vol. 54, pp. 353–361.

Sun, X. http://wso.stanford.edu/words/pfss.pdf.

Svalgaard, L., Sector structure 1926-present (IMF sector structure polarity). http://www.leif.org/research/spolar.txt.

Vernova, E.S., Tyasto, M.I., and Baranov, D.G., Photospheric magnetic field: Relationship between N-S asymmetry and flux imbalance. *Solar Phys.*, 2014, vol. 289 pp. 2845–2865.

Vernova, E.S., Tyasto, M.I., and Baranov, D.G., Relation between the photospheric magnetic field and phases of a 22-year solar cycle, *Geomag. Aeron.,* 2013, vol. 53, no. 7, pp. 857–862.

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