Title: Relations between variability of the photospheric and interplanetary magnetic fields, solar wind and geomagnetic characteristics.
Authors: E. A. Gavryuseva (Institute for Nuclear Research RAS)
Comments: 28 pages, 15 Postscript figures

Abstract

Large scale solar magnetic field topology has a great influence on the structure of the corona, heliosphere and geomagnetic perturbations. Data obtained over the last three solar cycles have been analysed to reveal the relationships between the photospheric field measured along the line of sight by the WSO group at 30 levels of heliolatitudes from -75 to 75 degrees and the interplanetary magnetic field.

The main aim of this first paper is to make a direct comparison between the basic structure and dynamics of the photospheric magnetic field and components and intensity of the interplanetary magnetic field without using theoretical assumptions, models, physical expectations, etc. The second paper by Gavryuseva, 2018d presents the report between different characteristics of the solar wind at the Earth orbit, and geomagnetic parameters provided by the OMNI team.

The heliospheric and geomagnetic data are found to be divided into two groups characterized by their response to variability of the solar magnetic field latitudinal structures on short and on long time scales.

Keywords: Sun; solar variability; magnetic field; interplanetary magnetic field; solar wind; geomagnetic perturbations; solar cycles

1 Introduction

Large scale magnetic field of the Sun have an important role in driving perturbations of solar, interplanetary and geomagnetic conditions.

Extensive investigations of the solar drivers was stimulated by the long-term rise of the geomagnetic activity over last century. Different explanations have been suggested, such as, for example, an increase of the strength of the interplanetary magnetic field and solar wind speed and concentration (Stamper et al., 1999). This trend is seen in the photospheric field at low latitudes, as follows from Mt. Wilson Observatory magnetic data since 1967 (Li et al., 2001). Makarov et al. (2002) found an increase of the polar cap area, which could contribute to the increase of the geomagnetic activity. Subsequently it was found that the contribution of the coronal holes is changing during the solar activity cycle (Luhmann et al., 2002). It was established that around the minimum (maximum) of solar activity the main drivers are polar (low latitude) magnetic field (Gonzalez et al., 1994, 1999; Wang et al., 2000; Wang et al., 2000) but a deeper analysis is advisable taking into account the latitudinal structure of the large scale photospheric magnetic field (SMF).

In previous papers (Gavryuseva, 2006, 2006a, Gavryuseva, E., & G. Godoli (2006), the relevance of the basic topology and dynamics of the photospheric magnetic field for the research of the solar drivers of the variability of solar wind and geomagnetic parameters has been underlined.

Direct comparison between the mean latitudinal photospheric field variability, solar wind and geomagnetic perturbations on long and short time scales was
performed to search for the relations between them. Such a direct comparison of
different parameters with solar magnetic field as a possible source of helio- and
magneto-spheric perturbations is physically meaningful as well as practically
useful, revealing the relations between them without introduction of theoretical
models, calculation of bilateral correlations, reliance on physical expectations,
etc.

This approach led to the conclusion that all solar wind data and geomagnetic
perturbations that were examined divided into two groups characterized by sensi-
tivity to the variability of the interplanetary magnetic field and photospheric
field at different latitudes.

The data used are described in section 2: solar photospheric magnetic field
(SMF) measurements from the Wilcox Solar Observatory (WSO) (section 2.1)
and interplanetary magnetic field (IMF), solar wind and geomagnetic parame-
ters taken from the Operating Missions as Nodes on the Internet (OMNI) data
base of NASA’s Goddard Space Flight Center in Greenbelt (USA) (section 2.2).
Very brief descriptions of the rotational variability of the IMF and short term
variability of the interplanetary parameters are presented in sections 3 and 4.
The delay between the IMF and SMF measurements at different latitudes
is discussed in section 5. The cross-correlation between the IMF and SMF
temporal behaviour within 2-year long subsets of data running through the last
three solar cycles is presented in section 6. Section 7 is devoted to the analysis
of the relationships between the global structures of solar magnetic field, inter-
planetary field, solar wind parameters and geomagnetic perturbations on time
scales from 1 year to 25 years for measured data (section 7.1). The summary is
presented in section 8.

2 Data

2.1 Photospheric Magnetic Field

We analyse the temporal disturbances of the interplanetary magnetic field, and
their relationships with the photospheric field of the Sun during the last three
cycles of activity from 1976 to 2004. Daily data were used to find the optimum
delay between the different parameters.

We use Wilcox Solar Observatory data for the photospheric magnetic fields
http://wso.stanford.edu/synoptic1.html, (Scherrer et al., 1977), OMNI data for
solar wind parameters at the Earth’s orbit, and indices of geomagnetic activ-
ity for the period 1976-2004, to study the relations between the solar wind,
geomagnetic disturbances and solar drivers at different solar latitudes.

In order to understand from which latitudinal zone the solar wind is ori-
ginated and how it depends on the activity cycle it is necessary to know the
latitudinal SMF structure over at least 22 years.

The latitudinal structure of the SMF has been deduced for the last 29 years
since May 27, 1976 from the Wilcox Solar Observatory (WSO) data (Scherrer
et al., 1977; Gavryuseva & Kroussanova, 2003, Gavryuseva & Gogoli, 2006,
Gavryuseva, 2005, 2006, 2006a,b, 2008a,b, 2010 and references there). The
structure in latitude and time of the 1-year running mean of the sola r magnetic
field with 1 Bartels Rotation (BR, 1 BR = 27 days) step is shown on the upper
plot in Fig. 1.
The latitudinal four zonal (4 − zonal) structure with a 22-year period with boundaries of the polarity zones located at 25 S, 0, and 25 N degrees is clearly noticeable (Gavryuseva, 2005, 2006, 2006a, 2008a, 2010). Yearly variability due to the Earth orbital rotation were removed by the 1-year smoothing.

The short-term variability of the solar filtered magnetic field (FMF) has been calculated as a residual between the SMF smoothed by one and by two years. The short-term variability of the SMF is shown on the bottom plot. The waves of the magnetic field running through latitudes and changing the polarity with a 2–3-year period (WRL-topology) are well visible on the bottom plot of Fig. 1 (for more details see Gavryuseva, 2005, 2006, 2006a, 2008a, 2010). In these plots yellow and red (blue) colors indicate positive (negative) polarity. The contours correspond to the levels of −100, −50, 0, 50, 100 µT.

The antisymmetric field, equal to the difference of the magnetic field at the same latitudes in both hemispheres, clearly reveals the magnetic field of opposite polarity of the same magnitude at certain latitudes.

Symmetric SMF structure corresponds to the mean level of the magnetic field of the same polarity at the latitudes θ and −θ in the northern and southern hemispheres.

Daily mean data were used for day-to-day comparison with solar wind and geomagnetic parameters. Fig. 2 and Fig. 3 show the original SMF distribution on the upper plot, the antisymmetric part on and the symmetric part of the solar magnetic field on the bottom plot in 1996 (before the polarity inversion in the poles in 2000) and in 2003 (after the polarity inversion during the maximum of the solar activity in The SMF in 1996 was unusual, i.e. the positive polarity spread from the northern pole to about 45-50 degrees in the southern hemisphere during the minimum of the solar activity.

The 27-day variability of the SMF seen in Fig. 2 and Fig. 3 is due to the solar rotation and its latitudinal dependence (the polar zones are rotating slower than the low latitude regions). The rotational periodicity of the SMF is more evident when the solar activity is high as 2003.

2.2 Interplanetary Magnetic Field, Solar Wind and Geomagnetic Data

The solar wind and geomagnetic data were taken from the OMNI directory [http://nssdc.gsfc.nasa.gov/omniweb] which contains the Bartels mean values of the interplanetary magnetic field (IMF) and solar wind plasma parameters measured by various space-crafts near the Earth’s orbit, as well as geomagnetic and solar activity indices). First, daily averages are deduced from OMNI’s basic hourly values, and then the 27-day Bartels averages are deduced from the daily averages. The corresponding standard deviations are related to only these averages and do not include the variances in the higher resolution data.

The IMF and solar wind parameters taken into account are the following:

- \( B_x, B_y, B_z \), and \( B = (B_x^2 + B_y^2 + B_z^2)^{1/2} \) are the components and magnitude of the interplanetary magnetic field, in nT;
- Proton density, \( N_p \), in \( N/cm^3 \);
- Proton temperature, \( T_p \), in degrees K;
- Plasma speed, \( V_p \), in \( km/s \);
- Electric field, in mV/m;
- Plasma beta, \( N_\beta = [(T * 4.16/10^5) + 5.34] * N_p/B^2 \);
Ratio $N_0/N_p$;
Flow Pressure, $P$ proportional to $N_p \cdot V^2$, in nPa;
Alfvén Mach number, $M_a = (V \cdot N_p^{0.5})/20 \cdot B$.

The geomagnetic parameters taken into account are the following:
AE-index;
Planetary Geomagnetic Activity Index, $K_p$ – index;
DST-index, in nT.

Sunspot number (SSN) was used, as well, for a further comparison.

The $X$ axis directed along the intersection line of the ecliptic and solar equatorial planes to the Sun, the $Z$ axis is directed perpendicular and northward from the solar equator, and the $Y$ axis completes the right-handed set.

The solar wind parameters analysed cover the same period as the WSO solar data with one Bartels rotation resolution. We call the set of these 16 parameters taken from the OMNI data base as “solar wind” (SW) data; they include the interplanetary magnetic field, solar wind and geomagnetic parameters and sun spot number (SSN). These data are plotted in Fig. 4, they are normalized to the maximal value and then smoothed by 13 Bartels rotations (about 1 year).

3 Rotational variability of Interplanetary Field

The daily values of the components of the interplanetary magnetic field $B$ and $B_x$, $B_y$ in 2003 with one day step are plotted in Fig. 5. The auto-correlation analysis (and FFT as well while not shown in this paper) reveals a 27-day periodicity in the $B_x$ and $B_y$ components, shown in the bottom plot of Fig. 6, a 29-day periodicity in the $B_z$ component, and a 26-day periodicity in the variability of the total value of solar wind magnetic field $B$.

These periodicities can be considered as an evidence that the $B_x$ and $B_y$ components have an origin in the solar middle latitudinal zones rotating relatively fast. 27 days correspond to the sidereal period of the solar magnetic field rotation on the latitudes of about ±40 degrees, while the sidereal period of $SMF$ rotation reaches 29 days on the heliographic latitudes of about ±60 degrees as it can be seen in Fig. 12 in Gavryuseva (2006). Perhaps $B_z$ component is mainly sensitive to the fast wind flow from the polar coronal holes.

A clear anti-correlation between the $B_x$ and $B_y$ components of the $IMF$ is illustrated in Fig. 5 for the daily data taken in 2003. On the upper plot the $B_x$ and $B_y$ components are shown by continuous and dotted lines respectively. The correlation between them with zero shift is equal to -0.85, and the period of cross-correlation is 27.00 ± 0.38 days as seen in the bottom plot in Fig. 6. This anti-correlation is due to the orientation of the coordinate system of the interplanetary magnetic field where the $X$ is directed Sun-ward.

4 Short Term Variability of Interplanetary parameters

The solar magnetic field, in addition to the 4-zonal structure with the 22-year periodicity, presents a clear topology consisting of the $SMF$ Waves Running through Latitudes (WRL-structure) with a quasi 2-year periodicity shown in the bottom plot of Fig. 1 and discussed in details by Gavryuseva, (2005, 2006,
This behaviour should be compared with the variability of the IMF, solar wind and geomagnetic data on a short term scale.

We first applied the filter of long-term periodicities to the SW sets of OMNI data, then the shortest variabilities, for example those caused by the orbital rotation, were filtered by 1-year smoothing. Such smoothed residuals of the OMNI data are called Filtered OMNI or Filtered Solar Wind (FSW) data and include the residuals of the interplanetary magnetic field, solar wind and geomagnetic parameters.

Short-term changes of the FSW are plotted in Fig. 7 for the following parameters: \( B, B_x, B_y, B_z; T_p, V_p, E, N_\alpha/N_p; P, N_p, N_\beta, M_a; \) geomagnetic indices \( AE, K_p, DST \) and Sunspot number \( SSN \) (from the top to the bottom rows). A periodicity of 2–3-year is clearly seen in the temporal behaviour of these quantities.

The SW and geomagnetic variability is discussed by different authors (see for example, Kane, (2005a, 2005b); Rivin, (1989) and references there). Fraser-Smith (1973) investigated the 27-day variation of geomagnetic activity. Clua de Gonzalez et al. (1993) found that the 6-month periodicity has a multiple origin, and 4-year in the monthly Ap power spectrum is associated to the double peak structure observed in the geomagnetic activity. It was noted by Kane, (2005b) that solar indices have a quasi-biennial oscillation in form of double peaks separated by 2-3 years during sunspot cycle.

Rivin (1989) found that the amplitude of the biennial variation of the geomagnetic field is modulated by a 10-year period. This well agrees with the presence of the WRL-topology in the photospheric magnetic field, whose strength varies with the 2-year periodicity and interferes with the 4-zonal structure that changes with the 22-year period. The detailed discussion of the periodicities of the IMF, solar wind and geomagnetic activity is not a subject of this paper, and therefore we do not present here the table of the SW periodicities. We give only an illustration of a short term variability of the OMNI data in Fig. 8. The correlation coefficients were calculated for a 4-year long subset of the FSW data running through a FSW residual calculated as a difference of an experimental data set and 4-year running means of the following parameters: \( B, B_x, B_y, B_z; T_p, V_p, E, N_\alpha/N_p; P, N_p, N_\beta, M_a; \) geomagnetic indices \( AE, K_p, DST \) and \( SSN \) (from the top to the bottom rows in Fig. 8).

The \( B_x, B_y, B_z \) values have a 378-day periodicity. This period is not equal to one year (365.25 days) (related to the orbital rotation of the Earth) due to the rotation of the Sun. The intensity of the interplanetary magnetic field \( B \) exhibits a half a year and a 1.5-year periodicities. \( B_z \) component has a 1.35-year periodicity.

A quasi biennial periodicity is seen in almost all the OMNI data sets. The plots of Fig. 8 confirm the presence of periodicities of about 2-3 years in the IMF, solar wind and geomagnetic parameters in agreement with the results of other studies Rivin, (1989).
5 Relationship Between Photospheric and Interplanetary Magnetic Fields in 2003

First we concentrate on the relationship between the photospheric magnetic field and interplanetary magnetic field. This helps to establish the channel of the Sun-Earth connection.

Daily data for 1996, 2000 and 2003 have been used to examine the delay between the phenomena on the Sun and on the Earth orbit. Here we present the result for the data sets taken in 2003.

The correlations between the SMF and IMF in 2003 provide the possibility to find their relationships during a period of high solar activity, after the polarity inversion in 2001 in the sub-polar regions and to determine the optimal delay between the SMF and IMF.

In Fig. 9 from the top to the bottom the correlations between the solar photospheric field measured in 2003 and the IMF field intensity $B$, the IMF components $B_x$, $B_y$ and $B_z$ as functions of time lag in days and of heliographic latitude are presented. Yellow and red (blue and green) colors indicate positive (negative) correlation coefficient values. The contours correspond to zero level and to the levels of $\pm 0.5$ of the maximum value of the correlation coefficient.

The solar rotational periodicity is visible on all the plots of Fig. 9 in agreement with the solar origin of the interplanetary magnetic field. These plots show that the interplanetary field is sensitive to the magnetic field of the Sun with an optimum delay of about 4 days. This delay is used to study the the correlation between the sets of the Bartels means of the SMF and OMNI data.

6 Photospheric and Interplanetary Magnetic Fields through Cycles of Solar Activity

In order to analyse the long term relationship between the photospheric and the interplanetary field over the last three cycles of the sunspot activity, the correlations between 2-year long sub-sets of the SMF and IMF data running in time with 1 Carrington Rotation (CR, 1 CR = 27.2753 days) step have been calculated. In Fig. 10 the correlation coefficients between the SMF, intensity $B$ and components $B_x$, $B_y$ and $B_z$ of the IMF are plotted from the top to the bottom. Fig. 10 gives a very interesting panorama of the relationships between the photospheric magnetic field and the IMF over the last three cycles of activity. Firstly, the correlation between the SMF and $B_x$ component, and between the SMF and $B_y$ component is of opposite sign on a long-time scale. This fact could be used to verify and to confirm conclusions related to one of them.

Secondly, as immediately follows from the top and middle plots, a strong correlation (anti-correlation) does exist between the photospheric SMF on the latitudes above the 50 degrees and $B_y$ ($B_x$) component during the minima of solar activity which took place around 1976-1977, 1985-1986 and 1995-1996. The correlation reaches the level of 0.92. Contribution of the sub-polar regions to the solar wind near the ecliptic was significant when the high latitude field was very strong during the minima of activity. In 1996 the correlation (anti-correlation)
was particularly strong between the photospheric field over all the latitudes and $B_x$ and $B_y$ components. In this period the solar magnetic field in both hemispheres was rising up. Magnetic field was positive almost everywhere from 50 degrees in the southern hemisphere to the pole of the northern hemisphere.

We could conclude that during periods of quiet Sun the generation of the interplanetary field takes place mainly in the sub-polar regions while the middle and low latitudinal zones could also contribute synchronously. These results agree with conclusions of other studies (see, for example Gonzalez et al., 1994, 1999; Wang et al., 2000; and references therein).

The $B_z$ component correlates to the pre-equatorial SMF in the northern hemisphere and middle latitude zone in the southern hemisphere during maximum of cycle No 21. It is opposite to its behaviour in cycle No 22 and similar in cycle No 23, but, additionally, at the maximum of the last cycle $B_z$ correlates to the sub-polar SMF in both the northern and southern hemispheres.

Generally speaking, the interplanetary magnetic field was well synchronized with the photospheric field variability in the broad region of latitudes in cycle No 23; this means that the low-latitude solar wind originated from isolated low-latitude and mid-latitude coronal holes could contribute significantly during the cycle. This finding contradicts the paradigm of a solar wind source consisting of two polar outflows only flanking a planar current sheet (Pizzo, 1982), but is in agreement with the results of Wang et al. (2000) demonstrating that around the solar minimum the sources of the Sun’s open magnetic field lines whose extension constitutes the IMF are the big polar coronal holes, while at solar maximum these are the small low-latitude coronal holes.

7 Relationships between the SMF and OMNI / Data on Long- and Short-Term Scales

The study of the general relationships between the Sun, solar wind and geomagnetic perturbations can be performed by comparison of the variability of the solar magnetic field at different latitudes with the temporal behaviour of the OMNI data over several activity cycles. Correlation coefficients $K_{cor}$ between full data sets from 1976 to 2004 with one Bartels rotation resolution of the photospheric field from one side and of the solar wind and geomagnetic parameters (SW-sets) on the other side have been calculated with the shift up to 22 years.

Fig. 11 shows these correlation coefficients as functions of time-shift (in years) and latitude for $K_{cor}$ between the yearly means of the SMF and of the interplanetary field intensity $B$ and $B_x$, $B_y$, $B_z$ components (upper plot), and then down to the bottom for $K_{cor}$ between the yearly means of the SMF and $T_p$, $V_p$, $E$, $N_a/N_p$ ratio; $P$, $N_p$, $N_B$, $M_a$; $AE$, $K_p$, $DST$ and $SSN$. The data used take into account the sign of the parameters. The $K_{cor}$ presented in Fig. 11 was smoothed by a 1-year running window. The "zero" shift corresponds to the SW optimum delay of 4 days discussed in section 3.

The latitudinal dependence of these correlations is a consequence of the 4-zonal SMF topology. The correlation between the SMF and $B_x$, $B_y$ and $B_z$ components has a 22-year periodical behaviour due to the 22-year variability of the solar magnetic field. The correlation coefficients $K_{cor}(SMF, B_x)$ between the SMF and $B_y$ is opposite to the correlation coefficients $K_{cor}(SMF, B_z)$ and
\(K_{\text{cor}}(\text{SMF}, B_x)\) between the SMF and \(B_x\) and \(B_z\) components. The relationship between the photospheric field and \(E\) is similar to the one between the SMF and \(B_y\), while the \(K_{\text{cor}}(\text{SMF}, T_p)\) and \(K_{\text{cor}}(\text{SMF}, V_p)\) are similar to the \(K_{\text{cor}}(\text{SMF}, B_z)\), and opposite to the \(K_{\text{cor}}(\text{SMF}, B_y)\), while \(K_p\) has the same relationship with the SMF as \(B_x\) component of the IMF and opposite to the \(K_{\text{cor}}(\text{SMF}, \text{DST})\).

The correlation between the SMF and the intensity \(B\) shows a quasi 30-year periodicity. The relationship between the photospheric field and \(P, N_p, N_\beta, M_\alpha\) is similar, while \(K_{\text{cor}}(\text{SMF}, N_\alpha/N_p)\) has an opposite sign. The correlation coefficient \(K_{\text{cor}}(\text{SMF}, \text{AE})\) is similar to the \(K_{\text{cor}}(\text{SMF}, B)\).

Figure 11 illustrates the periodic character of the relationships between the SMF and the SW data. As it was deduced the SW data can be divided into two groups having similar dependence on the time-shift with the photospheric field.

For search on the \(\text{SMF} - \text{SW}\) dependence it is important to analyse the correlation between them with the "zero" shift which corresponds to the optimum delay. Figure 12 shows the coefficients of correlation between the 1-year means of the full data sets of the photospheric field at different latitudes and the interplanetary magnetic field, solar wind and geomagnetic parameters. The latitudinal dependences of the \(K_{\text{cor}}(\text{SMF}, \text{SW})\) permit to select two groups of the SW parameters which have similar sensitivity to the SMF at different helio latitudes. The first group is composed of \(B, P, N_p, N_\beta, M_\alpha, -N_\alpha/N_p, \text{AE}\) and \(-\text{SSN}\). The second one includes \(B_x, -B_y, B_z, T_p, V_p, -E, K_p\) and \(-\text{DST}\). Figure 12 confirms the presence of two groups as deduced from Fig. 11.

The positive value of \(K_{\text{cor}}\) is an indicator of a possible connection between the SMF and a SW, but it is not enough to conclude that the SMF and a SW are physically dependent.

Since biennial variability is present in the solar magnetic field it is necessary to verify the relationship between the variability of the SMF, IMF, solar wind and geomagnetic data on a short-term scale of about 2 years. This is also useful for the study of a \(\text{SMF} - \text{SW}\) physical dependence. Such an analysis of the relationship of the short-term variability of the solar magnetic field and FSW data has been performed to complete this study. The letter \(F\) is added before the abbreviation of the title of a parameter to indicate that the residuals were calculated to filter the long-term variabilities of the corresponding parameter. The latitudinal dependences of the \(K_{\text{cor}}(\text{FMF}, \text{FSW})\) were found for the correlation between the residuals of the photospheric magnetic field (FMF) with the residuals of the different SW data (FSW) calculated as the difference between yearly and 4-year means of the SMF and SW data.

Coefficients of correlation with the optimum delay between the short-term variabilities of the photospheric field at different latitudes and the interplanetary magnetic field, solar wind and geomagnetic parameters are plotted in Fig. 13. The same two groups could be selected in the OMNI data from the point of view of their relation with the photospheric field. These relationships are better illustrated in Figs. 14 and 15 where the latitudinal dependences of the \(K_{\text{cor}}(\text{SMF}, \text{SW})\) for long-term variability (plots on the left) and of the \(K_{\text{cor}}(\text{FMF}, \text{FSW})\) for short-term variability (plots on the right) are shown for the following SW data:

- \(B, P, N_p, N_\beta, M_\alpha, \text{AE}, \text{SSN}\) (Fig. 14);
- \(B_x, B_y, B_z\) components, \(V_p, T_p, E, N_\alpha/N_p, K_p, \text{DST}\) (Fig. 15).
In this way it is established that there are two groups of the interplanetary data led by \( B \) and \( B_x \) (or \(-B_y, B_z\)) which respond to the variability of the photospheric magnetic field in a similar way (from the point of view of the periodic character and of the latitudinal dependence of the \( K_{cor}(SMF, SW) \) or the \( K_{cor}(FMF, FSW) \) and they have a similar response in the geomagnetic perturbations of \( AE, K_p \) and \(-DST \) indices).

8 Some summary remarks

Southward-directed interplanetary magnetic field is considered a primary cause of geomagnetic perturbations (Durney, 1961; Gonzales et al., 1994, 1999). As a consequence the orientation of the interplanetary magnetic field (Axford and McKenzie, 1997; Low, 1996; Parker, 1997; Smith, 1997) plays an important role.

The solar activity phenomena depend on the sunspot cycle, which can be characterized by the variability of the \( SMF \) intensity in time and along the latitudes. The topology of the solar magnetic field influences the geomagnetic perturbations through the intensity and orientation of the interplanetary magnetic field and/or through other parameters of the solar wind. In this approach we could understand the presence of two groups of the OMNI data similarly sensitive to the basic topology of the magnetic field of the Sun (from the point of view of the dependence on latitude and phase-shift of the correlation of the coefficients with the mean latitudinal magnetic field).

The formal and complete study of the problem of solar-terrestrial relations has been performed and the connections between the processes on the way from the Sun to the Earth have been revealed. A useful information was deduced from the temporal behaviour and dependence of the correlation of the photospheric magnetic field and different parameters of interplanetary space and geomagnetosphere.

It was revealed directly from the experimental data that there are two groups of \( SW \) parameter which respond in a similar way to the behaviour of solar characteristics. We found that the photospheric field influences the magnitude of the interplanetary field and, in the same way, the proton density, flow pressure, Alfvén Mach number and plasma \( \beta \) respond to the \( SMF \). Moreover the \( AE \)-index behaves in a similar way as the above mentioned solar wind parameters.

On the contrary, regarding the planetary geomagnetic activity index \( K_p \) we can deduce that solar activity events (CME, magnetic field intensity, sunspots, etc.) through perturbations of the \( B_z \) component (\( B_x, B_y \) components) of the \( IMF \), the proton temperature \( T_p \), plasma speed \( V_p \), \( N_{\alpha}/N_p \) ratio influence the \( K_p \) index. The variations of the \(-B_z \) (\( B_y \)) component produce the perturbations of the \( DST \) index, and they are of opposite sign of the \( K_p \) and \( B_z \) time dependence.

It was also revealed from the experimental data that the solar magnetic fields and solar activity processes originated below \( \pm 55 \) degrees propagate up to the Earth orbit and produce the perturbations of the magnetosphere (Gavryuseva, 2006 c.f. 2008b, Gavryuseva & Godoli, 2006).

These results are useful for understanding the origin of solar wind and geomagnetic perturbations and for long-term predictions.
Acknowledgments

I thank the WSO and OMNI teams for making available data of measurements of the solar magnetic field, solar wind and geomagnetic quantities. I am grateful to Prof. G. Godoli for his stimulating interest in these results and Profs. B. Draine, L. Paterno and E. Tikhomolov for help in polishing this paper and useful advises.

References

[1] Axford, W.L. and McKenzie J.F. (1997), The solar wind, in Cosmic winds and the heliosphere, ed. by J.R. Jokipii, C.P. Sonett & M.S. Giampapa, 31.
[2] Chua de Gonzalez, W. D. Gonzalez, S. L. G. Dutra, B. T. Tsurutani (1993), Periodic Variation in the Geomagnetic Activity: A Study Based on the Ap Index, J. Geophys. Res., 98, 9215.
[3] Durney, J.W. (1961), Interplanetary magnetic field and the auroral zones, Phys. Rev. Lett., 6, 47.
[4] Fraser-Smith, A. C. (1973), Solar cycle control in the 27-day variation of geomagnetic activity, J. Geophys. Res., 78, 5825.
[5] Gavryuseva, E. (2005), Latitudinal streams of solar magnetic field, Proc. of 11 Int. Scientific Conf. Solar-Terrestrial Influences, Nov. 2005, BAS, 229-233.
[6] Gavryuseva, E. (2006), Topology and dynamics of the magnetic field of the Sun, News of the Academy of Science, IzvRAN, ser. Physics, 70, No. 1, 102.
[7] Gavryuseva, E. (2006a), Latitudinal Structure of the Photospheric Magnetic Field through solar cycles Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 124.
[8] Gavryuseva, E. (2006b), Basic topology and dynamics of magnetic field leading activity the Sun Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 67.
[9] Gavryuseva, E. (2006c), Variability of the differential rotation of the photospheric magnetic field through solar cycles Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 65.
[10] Gavryuseva, E. (2006d), North-South asymmetry of the photospheric magnetic field Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 63.
[11] Gavryuseva, E. (2006e), Longitudinal structure of the photospheric magnetic field Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 61.
[12] Gavryuseva, E. (2006f), Relationships between photospheric magnetic field, solar wind and geomagnetic perturbations over last 30 years Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 291.

[13] Gavryuseva, E. (2008a), In search of the origin of the latitudinal structure of the photospheric magnetic field, ASP Conf. Ser., v. 383, Proc. of ”Subsurface and atmospheric influence on solar activity”, held at NSO, Sacramento Peak, Sunspot, New Mexico, USA 16-20 April 2007, Ed. R. Howe, R. W. Komm, K. S. Balasubramaniam & G. J. D. Petrie, 99.

[14] Gavryuseva, E. (2008b), Longitudinal structure originated in the tachocline zone of the Sun, ASP Conf. Ser., v. 383, Proc. of ”Subsurface and atmospheric influence on solar activity”, held at NSO, Sacramento Peak, Sunspot, New Mexico, USA 16-20 April 2007, Ed. R. Howe, R. W. Komm, K. S. Balasubramaniam & G. J. D. Petrie, 381.

[15] Gavryuseva, E. (2018), Latitudinal structure and dynamic of the photospheric magnetic field, arXiv:1802.02450.

[16] Relations between variability of solar and interplanetary characteristics

[17] To the connection between intensity of the solar and geomagnetic perturbations, arXiv:1802.02450(N)

[18] Gavryuseva, E. (2018), Latitudinal structure and dynamic of the photospheric magnetic field, arXiv:1802.02450.

[19] Gavryuseva, E. (2018b), Longitudinal structure of the photospheric magnetic field in Carrington system, arXiv:1802.02461.

[20] Gavryuseva, E.; Godoli, G. (2006), Structure and rotation of the large scale solar magnetic field observed at the Wilcox Solar Observatory Physics and Chemistry of the Earth, v. 31, issue 1-3, 68.

[21] Gavryuseva, E., Kroussanova, N. (2003), Topology and dynamics of the Sun’s magnetic field SOLAR WIND TEN: Proceedings of the Tenth International Solar Wind Conference, AIP Conference Proceedings, v. 679, 242.

[22] Gavryuseva, E., and V. Gavryusev (1994), Time variations of the $^{37}$Ar production rate in chlorine solar neutrino experiment, Astron. Astrophys, 283, 978.

[23] Gavryuseva, E., and V. Gavryusev (2000), Solar variability and its prediction, Long and short term variability in Sun’s history and global change, ed. W.Schroder, Science Edition, Bremen, Germany, p.89.

[24] Gavryuseva, E., and N. Kroussanova, (2003), Topology and dynamic of solar magnetic field, Proc. of the Tenth International Solar Wind Conference, AIP Conf. Proc., v. 679, 242.

[25] Gavryusev, V., E. Gavryuseva, Ph. Delache, and F. Laclare (1994), Periodicities in solar radius measurements, Astron. Astrophys, 286, 305.
[26] Gavryuseva, E., V. Gavryusev, and M.P. Di Mauro (2000), Internal rotation of the Sun as inferred from GONG observations, Astronomy Lett., 26, N 4, 261.

[27] Gavryuseva, E., & G. Godoli (2006), Structure and rotation of the large scale solar magnetic field observed at the Wilcox Solar Observatory, Physics and Chemistry of the Earth, Elsevier, 31, 68.

[28] Gonzalez, W.D., J.A. Joselyn, Y. Kamide, H.W. Krorhl, G. Rostoker, B.T. Tsurutani and V.M. Vasyliunas (1994), What is a geomagnetic storm?, J. Geophys. Res., 99, 5771.

[29] Gonzalez, W.D., B.T. Tsurutani and A.L. Chua de Gonzalez (1999), Interplanetary origin of geomagnetic storms, Space Science Rev., 88, 529.

[30] Kane, R.P. (2005a), Difference in the quasi-biennial oscillation and quasi-triennial oscillation characteristics of the solar, interplanetary, and terrestrial parameters, J. Geophys. Res., 110, A01108.

[31] Kane, R.P. (2005b), Short-term periodicities in solar indices, Solar Phys., 227, 155.

[32] Li, Y., Luhmann, J. G., Arge, C. N., Ulrich, R., How do solar magnetic fields influence the long term changes of some geomagnetic indexes?, American Geophysical Union, Spring Meeting 2001, abstract SH52A-02, 2001.

[33] Pizzo, V. J., A three-dimensional model of corotating streams in the solar wind. III Magnetohydrodynamic streams, J. Geophys. Res., 87, 4374, 1982.

[34] Wang, Y.-M., J. Lean, and N. R. Sheeley, The long-term variation of the Sun's open magnetic flux, Geophys. Res. Lett., 27, 505, 2000.

[35] Low, B.C. (1996), Solar activity and the corona, Solar Phys., 167, 217.

[36] Luhmann, J. G., Li, Y., Arge, C. N., Gazis, P. R., Ulrich, R., Solar cycle changes in coronal holes and space weather cycles, J. Geophys. Res., 107(A8), 1154, pp. SMP 3-1, 2002.

[37] Makarov, V. I., Tlatov, A. G., Callebaut, D. K., Obridko, V. N., Increase of the Magnetic Flux From Polar Zones of the sun in the Last 120 Years, Solar Physics, v. 206, Issue 2, p. 383-399 (2002).

[38] Parker, E.N., (1997), Mass ejection and a brief history of the solar wind concept, in Cosmic winds and the heliosphere, ed. by J.R. Jokipii, C.P. Sonett and M.S. Giampapa, p.3.

[39] Rivin, Yu.R. (1989), Cycles of the Earth and of the Sun, Nauka, IZMIRAN, p.36.

[40] Smith, E.J., (1997), Solar wind magnetic field, in Cosmic winds and the heliosphere, ed. by J.R. Jokipii, C.P. Sonett and M.S. Giampapa, p.425.

[41] Stamper E.J., (1997), Solar wind magnetic field, in Cosmic winds and the heliosphere, ed. by J.R. Jokipii, C.P. Sonett and M.S. Giampapa, p.425.
[42] Stamper, R., Lockwood, Wild, M.N., Clark, T.D.G., (1999), Solar causes of the long-term increase of the geomagnetic activity, J. Geophys. Res., 104, Issue A12, pp.28,325.

[43] Pizzo, V. J. (1982), A three-dimensional model of corotating streams in the solar wind. III Magnetohydrodynamic streams, J. Geophys. Res., 87, 4374.

[44] Scherrer, P.H., J.M. Wilcox, L.Svalgaard, T.L. Duvall, Ph.H. Dittmer and E.K. Gustafson (1977), The mean magnetic field of the Sun: observations at Stanford. Solar Phys., 54, 353.

[45] Wang, Y.-M., J. Lean, and N. R. Sheeley (2000), The long-term variation of the Sun’s open magnetic flux, Geophys. Res. Lett., 27, 505.
Figure 1: The 1-year mean photospheric field (upper plot) and its short-term variable part (bottom plot) as a function of time and latitudes. Red (dark blue) and orange (light blue) colors indicate positive (negative) intensity values. The contours correspond to the 0, +/-50, +/-100 micro Tesla.
Figure 2: Distribution in latitude and in time with 1 day step of the original WSO data (upper plot), the North-South antisymmetric part of the WSO data (middle plot) and the North-South symmetric part of the WSO data (bottom plot) of the solar magnetic field in 1996. Red (green) colors indicate positive (negative) correlation coefficient values.
Figure 3: Distribution in latitude and in time with 1 day step of the original WSO data (upper plot), the North-South antisymmetric part of WSO data (middle plot) and the North-South symmetric part of WSO data (bottom plot) of the solar magnetic field in 2003. Red (green) colors indicate positive (negative) correlation coefficient values.
Figure 4: Total intensity and components $B_x$, $B_y$, $B_z$ of the interplanetary magnetic field, solar wind and geomagnetic parameters from the OMNI data bank with 1 Bartels rotation resolution. These data are normalized to the maximal value and then smoothed by 13 Bartels rotations (about 1 year).
Figure 5: Total intensity $B$ and components $B_x$, $B_y$, $B_z$ of the interplanetary magnetic field in nT in 2003 with 1 day step.
Figure 6: On the upper plot the $B_x$ and $B_y$ components of the solar wind magnetic field in 2003 are shown by continuous and dotted lines. The coefficient of the cross-correlation between them as a function of the shift in days is presented (X axis) on the bottom plot.
Figure 7: The residuals of the interplanetary magnetic field, solar wind and geomagnetic parameters through solar cycles (the filters of periods longer than 4 years and shorter than 1 year have been applied). Short term variability of the interplanetary magnetic field, solar wind and geomagnetic parameters through solar cycles.
Figure 8: Auto-correlation coefficients demonstrate short term periodicities of about 1- and 2-year long for the interplanetary magnetic field, solar wind and geomagnetic parameters.
Figure 9: Correlation as a function of time lag in days between the original photospheric field and (from the top to the bottom) the total intensity $B$, the components $B_x$, $B_y$ and $B_z$ of the interplanetary magnetic field. Yellow and red (blue and green) colors indicate positive (negative) correlation coefficients of high and lower levels of positive (negative) values.
Figure 10: Correlation between the 2-year long sub-sets of the photospheric field at different latitudes (Y axis) with the interplanetary magnetic field intensity $B$ and the component $B_x$ (upper plot), and the components $B_x$, $B_y$ (middle plots) and $B_z$ (bottom plot) as a function of time and latitude. Yellow and red (blue and green) colors indicate positive (negative) correlation coefficient values.
Figure 11: Correlation coefficients of the 1-year mean photospheric field (taking into account its polarity) at different latitudes (Y axis) with solar wind parameters and geomagnetic perturbations as a function of delay in years (X axis) and of latitude. Orange and red (blue) colors indicate positive (negative) correlation coefficient values.
Figure 12: Coefficients of correlation between 1-year mean photospheric field at different latitudes and the interplanetary magnetic field, solar wind and geomagnetic parameters with the fixed delay of 4 days as a function of latitude (X axis).
Figure 13: Coefficient of correlation between short term variabilities of the photospheric field at different latitudes and the interplanetary magnetic field, solar wind and geomagnetic parameters with the fixed delay of 4 days as a function of latitude (X axis).
Figure 14: Coefficients of correlation between the photospheric field and the intensity of the interplanetary magnetic field, some solar wind and geomagnetic parameters (marked on the right end of the corresponding curve) for the mean values over 1 year (on the left plot) and for the short term variable part of them (on the right plot) at different latitudes with the fixed delay of 4 days.
Figure 15: Coefficients of correlation between the photospheric field and the \(B_x\), \(B_y\) and \(B_z\) components of the interplanetary magnetic field, some solar wind and geomagnetic parameters (marked on the right end of the corresponding curve) for the mean values over 1 year (on the left plot) and for the short term variable part of them (on the right plot) at different latitudes with the fixed delay of 4 days.