The Interplanetary Magnetic Field: Radial and Latitudinal Dependences

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Abstract—Results of the analysis of spacecraft measurements at 1–5.4 AU are presented within the scope of the large-scale interplanetary magnetic field (IMF) structure investigation. The work is focused on revealing the radial IMF component \( |B_r| \) variations with heliocentric distance and latitude as seen by Ulysses. It was found out that \( |B_r| \) decreases as \( \sim r^{-5/3} \) in the ecliptic plane vicinity (\( \pm 10^\circ \) of latitude), which is consistent with the previous results obtained on the basis of the analysis of in-ecliptic measurements from five spacecraft. The difference between the experimentally found \( (r^{-5/3}) \) and commonly used \( (r^{-2}) \) radial dependence of \( B_r \) may lead to mistakes in the IMF recalculations from point to point in the heliosphere. This can be one of the main sources of the “magnetic flux excess” effect, which is exceeding of the distantly measured magnetic flux over the values obtained through the measurements at the Earth orbit. It is shown that the radial IMF component can be considered as independent of heliolatitude in a rough approximation only. More detailed analysis demonstrates an expressed \( |B_r| \) (as well as the IMF strength) increase in the latitudinal vicinity of \( \pm 30^\circ \) relative to the ecliptic plane. Also, a slight increase of the both parameters is observed in the polar solar wind. The comparison of the \( B_r \) distributions confirms that, at the same radial distance, \( B_r \) values are higher at low than at high latitudes. The analysis of the latitudinal and radial dependences of the \( B_r \) distribution’s bimodality is performed. The \( B_r \) bimodality is more expressed at high than in the low-latitude solar wind, and it is observed at greater radial distances at high latitudes. The investigation has not revealed any dependence between \( B_r \) and the solar wind speed \( V \). The two-peak distribution of the solar wind speed as measured by Ulysses is a consequence of a strong latitudinal and solar cycle dependence of \( V \). It is shown that the solar wind speed in high latitudes (above \( \pm 40^\circ \)) anti-correlates with a solar activity: \( V \) is maximum during solar-cycle minima and minimum at the maximum of solar activity.

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1. INTRODUCTION

Investigations of the large-scale structure of the inner heliosphere continue to be relevant up to now. In spite of the accepted view that the interplanetary magnetic field (IMF) is “frozen-in” to the solar wind plasma, propagating along the Parker spiral, reports of disagreements between the theory and observations continue [1–3]. Numerous databases of solar wind parameters obtained from the space era beginning allow implementation of more and more detailed multi-spacecraft analysis of the heliospheric plasma properties at different solar cycle phases, heliocentric distances, longitudes and latitudes. As a result, a quantity of the accumulated material transforms into a new quality of understanding of the solar wind processes, but the number of contradictions increases too.

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It should be taken into account that Parker’s model is stationary (as well as other models using the Parker solution), and some part of deviations from the model may be explained by this fact (a history of attempts to improve the original model is presented in the review [4]). However, the use of a model or hypothesis which consistently produces significant mistakes may impact negatively the space weather prognoses quality and retard the advance of solar-terrestrial physics.

Most serious concerns about the quasi-Parker models are mainly lodged by empiricists who perform comparative analysis of predictions of the IMF parameters at the Earth’s orbit with distant spacecraft measurements and recalculate the IMF strength from one point to another. The main problem is that the solar wind speed (as well as the IMF sign) at 1 AU can be calculated by most models with pretty good accuracy, but the IMF strength and the IMF direction can not be predicted in the same way and
with the same accuracy [2, 5, 6]. For instance, the radial IMF component $B_r$ (the RTN coordinate system) is theoretically the most easily predictable IMF parameter, decreasing with distance as $r^{-2}$ in accordance with the Parker’s model, but no one of commonly accepted models does provide with adequate $B_r$ prediction at 1 AU [6]. The discrepancies are significant even at solar activity minima, and, during maxima, the correlation between the predicted and calculated $B_r$ values goes below any reasonable statistical level. At the same time, semi-empirical models exceed purely theoretical ones by the IMF behavior predictions’ quality [7].

Besides, an effect of the “magnetic flux excess” was reported in [8]. The total magnetic flux in the heliosphere $F_S$ can be calculated as:

$$F_S = 4\pi |B_r|r^2. \quad (1)$$

According to the Parker’s theory, $F_S$ should be constant everywhere in the heliosphere under at least $\sim 27$ days (one Carrington rotation period) averaging, but in fact there is a difference between $F_S$ from distant spacecraft and near-Earth measurements at 1 AU [8]. The difference was found to be increasing with distance. It becomes so large at $r > 2.5$ AU that it cannot be ignored.

Many works have been dedicated to investigations of the “flux excess” effect, and several explanations have been suggested (from the kinematic effect to incorrect averaging methods) [9–11]. In the original paper [8], the mean of the module of the radial IMF component $|\langle B_r \rangle|$ was used, but authors of some other papers prefer to use a module of the mean $|\langle B_r \rangle|$ [9–11]. It should be noted that $|\langle B_r \rangle|$ and $|\langle B_r \rangle|$ are not identical as $B_r$ ranges from negative to positive values. Sometimes it is supposed that there is no difference between $|\langle B_r \rangle|$ and $|\langle B_r \rangle|$ for a rather large temporal averaging interval, sometimes the opposite opinion prevails [8–12].

Absence of clear understanding of physical causes of the effect leads to the application of specific correction factors, special methods of data processing and other artificial techniques. At the same time, the correctness of the formula (1) has not been subject to question in the literature. Let’s consider here a hypothesis that the problem is not due to some unclear physical effects, but to the fact that $B_r$ does not depend on the heliocentric distance as $r^{-2}$. This question was raised in [13], and it will be discussed in details among other questions in the current paper.

Point-to-point IMF recalculations in the heliosphere and $F_S$ conservation are based on the Parker’s theory invariant $B_r \cdot r^2$. However, according to the recent multi-spacecraft data analysis, $B_r \cdot r^2$ is not conserved in the inner heliosphere [13]. Measurements of the Helios 2, IMP8, Pioneer Venus Orbiter, and Voyager 1 spacecraft measured IMF from 0.29 AU to 5.0 AU in the increasing phase of the solar cycle (from 1976 to 1979) allowed make such a conclusion [13]. Results of calculation for the Parker’s model (recalculations of the source surface magnetic field along the Parker spiral as $r^{-2}$) and the pure radial expansion model (when the magnetic field decreases as $r^{-2}$, but not along the spiral) are given in Fig. 1a, which represents the merged figures 1–2 from [13].

Observations show that the radial IMF component decreases with distance as $r^{-5/3}$, rather than as $r^{-2}$. At the same time, the tangential component behavior was found to be corresponding to the expected law $(r^{-1})$, and the IMF strength $B \propto r^{-1.4}$. The difference between the observed and calculated $B_r$ values is greatest at small heliocentric distances, where the observed field may several times exceed the values calculated through the models using the Parker solution. At $r > 5$ AU, the difference is not so significant.

The model’s quality can be improved through the application of some corrections, for example, by multiplying the obtained values by some constant or summarizing them with some additional field. In the result, the both model curves seen in Fig. 1a below the experimental one will be shifted up and coincide with observations better. These methods are usually used for best correspondence of calculations with 1 AU observations. The fitting methods are typically performed just for two points: “the source surface”—“the Earth’s orbit.” Unfortunately, as was mentioned above, the acceptable agreement is not reached even at 1 AU, and discrepancies inevitably become greater at other distances.

In addition, another consequence of insufficient understanding of the large-scale IMF behavior was demonstrated in [13]: there is an effect of unexpected vanishing of the $B_r$ distribution’s bimodality with distance. At the Earth’s orbit, the $B_r$ distribution has a well-known two-humped (bimodal) view because of the expressed sector structure of the IMF in the Earth’s vicinity. As a result, a $B_r$ histogram contains two quasi-normal overlapping distributions corresponding to the IMF measurements in positive and negative sectors. Earlier, it was commonly supposed that such a pattern should be observed at least up to the first turn of the Parker spiral, when the spiral gets perpendicular to the sunward direction (which occurs at distances >5 AU at any solar wind speeds). Meanwhile, the experimental data by Helios 2, IMP8, Pioneer Venus Orbiter, Voyager 1, and Ulysses do not confirm that. In fact, bimodality vanishes with distance very rapidly: it is clear at 0.7–1.0 AU, it is
seen worse at 2–3 AU, and it disappears completely at 3–4 AU.

This is most likely a consequence of a radial increase of the solar wind turbulence, which results in disappearance of the clear sector structure much closer to the Sun than was supposed earlier. Indeed, one of the IMF modeling problems is a disagreement between the predicted and observed localization and inclination of the heliospheric current sheet (HCS). Spatial and temporal parameters of this greatest structure in the heliosphere determine the entire picture of the IMF, but the HCS features are poorly known. The HCS Parker’s angle at different AU, large-scale HCS twisting as well as the south-north displacement are widely discussed questions, being of great importance for the IMF properties understanding [14–16]. Meanwhile, as shown in [17] through the comparison of observations and calcula-

Fig. 1. $B_r(r)$—the radial IMF component’s variation with heliocentric distance. (a) Comparison of the measured $B_r$ (squares) with Parker’s model (triangles) and the calculations according to a model of the radial expansion (points), which does not take into account propagation time along the spiral. See details in [13]. (b) $B_r(r)$ near the ecliptic plane ($\pm 10^\circ$ by latitude) as measured by Ulysses. The hourly data of the module $B_r$ are used for the entire period of the measurements (number of points: 33251). The approximation curve is shown by white color.
tions according to the Stanford source surface magnetic field model, predictions of the HCS position meet with serious problems. The difference between the calculated HCS azimuth angle and observational values sometimes reaches 25°. The best results can be obtained using semi-empirical models, rather than MHD-models [18, 19]. All discussed facts demonstrate insufficient understanding of processes of the solar wind expansion into the heliosphere.

Therefore, the IMF behavior in the inner heliosphere considerably differs from predictions of quasi-Parker models even under a rough approach, and demands further study. On the one hand, Parker’s model is very attractive in its simplicity and the possibility of fast point-to-point recalculation of the solar wind parameters through elementary formulas. On the other hand, there is obvious necessity to understand why those formulas work well for plasma parameters, but do not work for the IMF, and to determine the true law of the IMF radial decrease in the inner heliosphere.

The current paper continues empirical investigations of the large-scale IMF in light of the discussed problems and previously obtained results. The main idea is as follow: the revealed deviations of the observed IMF parameters from the predicted values are mainly not caused by non-stationary effects (such as coronal mass ejections), but are related to misused IMF recalculation according to \( r^{-2} \) law. Also, a-priori believing the IMF to be completely “frozen in” to the plasma may lead to the observed discrepancies.

The development of a new model is a future task. Meanwhile, there are several key dependencies which may be empirically found right now. For example: What is the law of the IMF decrease in the inner heliosphere? What is the main cause of the “flux excess” effect? Whether the IMF depends on the solar wind speed and heliolatitude? These (as well as related) questions will be discussed below.

2. PECULIARITIES OF THE INTERPLANETARY MAGNETIC FIELD RADIAL AND LATITUDINAL DEPENDENCIES

2.1. The Radial IMF Component Changes with Distance. The “Magnetic Flux Excess” Problem

Let us check the results obtained in [13] by the calculation of the \( B_r \) curve slope through the alternative spacecraft data analysis. The best candidate for this purpose is the Ulysses spacecraft, which allows consideration both radial and latitudinal dependencies due to its unique orbit, which was nearly perpendicular to the ecliptic plane. Hourly Ulysses data were used in this work for 25.10.1990–30.09.2009 (see http://cdaweb.gsfc.nasa.gov/).

For adequate comparison, let’s select the data for the near-ecliptic Ulysses passages (\( \pm 10^° \) latitudinal vicinity around the ecliptic plane). Then, the “\( |\langle B_r \rangle| \) or \( |\langle B_r \rangle| \)” problem arises (see [10]). The most reasonable and reconciling approach to the problem’s solving was demonstrated in [11]. Meanwhile, in the author’s subjective opinion, first-step averaging of a bimodally distributed parameter is unreasonable. For instance, averaging of any sinusoid gives zero. The modulus of the pre-averaged \( B_r \) (\( |\langle B_r \rangle| \)) gives an analogical result. It is not zero for short-time intervals of averaging. But the longer time interval is considered, the closer the result is to zero (which is the mean of the symmetrically distributed bimodal parameter \( B_r \)). As a result, the longer time interval, the lesser the “flux excess,” but the physical sense of the results of such averaging is as disputable as a sense of the averaged sinusoid.

To avoid the “averaging mistake,” the radial IMF component module (\( |\langle B_r \rangle| \)) without averaging used in [13] will be considered here. The result is shown in Fig. 1b, analogues to Fig. 1a. The white approximation curve has a slope of \( -1.614 \), which is close to the value \( -5/3 \) found in [13], hence \( B_r \propto r^{-1.6} \). It is interesting that the used Ulysses data covered much more long time interval in comparison with the data taken for the previous analysis in [13]. Similarity of the results means stable deviations of the IMF behavior from the theoretical expectations.

Let’s turn now to the physical meaning of the factor \( x \) multiplying \( R \) in the approximation equation \( |\langle B_r \rangle| = x \cdot R^{-y} \).

In the paper [13], \( x = 3.8 \) (see Fig. 1a), but \( x = 2.4 \) in Fig. 1b. It is known that multiplying a function by a positive number leads to an increase in the upward scale of the corresponding graph. In our case, the essential difference would be seen in rising of the graph’s part corresponding to the small distances from the Sun. According to a method of dimensions, \( x \) from \( x \cdot R^{-y} \) can be represented as \( x \cdot R^{-y} \) where \( B_0 \) is some reference field, and \( R = r/r_0 \) (\( r \) is a heliocentric distance, a variable; \( r_0 \) is a distance from the Sun to the point where \( |\langle B_r \rangle| = B_0 \)). Therefore, the radial IMF component is:

\[
|\langle B_r \rangle| = B_0 \left( \frac{r}{r_0} \right)^{-5/3}.
\]  

(2)

In [13] (see Fig. 1a), \( B_0 = B_{0AU} \) at \( r_0 = 1 \) AU as obtained on the basis of measurements, starting from the heliocentric distance of 0.29 AU. In the case of the Ulysses database (Fig. 1b), the IMF was measured at distances greater than 1 AU, and \( B_0 \) had a smaller value. It is important to note that \( B_0 \) varies with time.
and solar cycle. Its measured values are also influenced by the spacecraft magnetometer’s characteristics. As an example of the IMF temporal variations, one can see the features of the IMF changing with solar cycle at 1 AU in the first figure of the paper [20]. Accordingly to \( B_0 \) changes, the entire experimental curve correspondingly shifts up and down, but the slope very probably remains the same.

Let’s take as a basis that the \( B_r \propto r^{-2} \) statement is true only in a first approximation. Deviations of \( y \) from ‘2’ may lead to serious mistakes of \( B_r \) point-to-point recalculations. The “flux excess” effect is just a confirmation of this statement. Theoretically, \( F_S \) should be an invariant over the entire heliosphere, at any distances. As was mentioned above, a consistent increase of \( F_S \) with heliocentric distance is observed: distantly measured \( F_S \) increasingly differs from \( F_S \) calculated on the basis of measurements at the Earth’s orbit. This deviation from the theory can be neglected (as many other discrepancies) if one is interested only in order of magnitudes, but, undoubtedly, such intriguing inconsistency is worthy to be a subject of keen interest.

The assurance that \( B_r \) decreases as \( r^{-2} \) leads to the situation, when among different assumptions on the nature of the effect, a hypothesis about the inapplicability of the theory due to non-ideality of space plasma was not seriously considered. Meanwhile, one can see that the observed effect may be explained easily using this hypothesis. Let’s calculate the difference between the magnetic flux \( F_S(r) \) at some heliocentric distance \( r \) and \( F_{S\perp AU} \) at 1 AU, taking into account (2):

\[
\Delta F_S = F_S(r) - F_{S\perp AU} = 4\pi \left[ |B_r| r^2 - B_{1\,AU}(1\,AU)^2 \right] = 4\pi B_{1\,AU} \left( \frac{r}{1\,AU} \right)^{-5/3} r^2 - B_{1\,AU}(1\,AU)^2 \\
= 4\pi \frac{B_{1\,AU}}{(1\,AU)^{-5/3}} \left[ r^{2-5/3} - (1\,AU)^{2-5/3} \right].
\]

In some studies (see, for example, [11, 12, 20]) the factor of \( 2\pi \) is used instead of \( 4\pi \), as half of the flux is directed away from the Sun and half is sunward, but it does not change the matter of the effect. This dependence is graphically represented as a black curve in Fig. 2. The points are \( \Delta F_S \) values taken from [8]. In [8] \( \Delta F_S \) was calculated on the basis of several spacecraft data and averaged over 0.1 AU (the corresponding deviations can be found in Fig. 5 from [8]). The standard assumption that \( |B_r| \) varies as \( r^{-2} \) was used in [8] for the \( \Delta F_S \) calculations.

Figure 2 demonstrates rather good agreement between the data of [8] and the curve (3). For example, theoretical curves in [9] calculated in assumption of kinematic effects show the upward trend. It is remarkable that the calculations according to (3) do not require anything but heliocentric distance. Moreover, the suggested approach explains easily the mysterious “separating point” of \( \Delta F_S \) (on either side of which \( \Delta F_S \) is negative and positive). It is easy to see from (3) that this point, shown by light-grey
lines in Fig. 2, is 1 AU at the axis of abscises. This is a natural consequence of the fact that $\Delta F_S$ was calculated in [8, 9] on the basis of practically the same data as taken in [13] for derivation of the $|B_r| = B_{1\,\text{AU}} \cdot \left(\frac{r}{1\,\text{AU}}\right)^{-5/3}$ dependence. Therefore, $B_0$ in [8, 9] and in [13] coincide: $B_0 = B_{1\,\text{AU}}$. Obviously, this point may slightly shift if another database is used, as $B_0$ changes correspondingly.

Of course, the effects discussed in [9–12, 20] also exist and amplify the revealed trend. Among other things, the flux excess effect can be additionally influenced by the latitudinal dependence of $B_r$, which will be discussed below. Note that the difference between the calculated and observed flux (depending on distance as $R^{-y}$) appears for any $y \neq 2$. Hence, there is a need for further study of the $B_r$ behavior in the inner heliosphere as seen by different spacecraft at different phases of solar cycle.

### 2.2. Latitudinal and Solar Cycle Dependences of $B_r$

To answer the question about the dependency or independency of $B_r$ on latitude, look at the entire picture of the solar wind parameters’ change provided by Ulysses. Hourly data for the entire period of measurements are shown in Fig. 3. The spacecraft trajectory is presented in panel (a), where the latitude is shown in white and the heliocentric distance $r$—in black. Referring to it, three areas of the increased amplitudes and disturbances of all parameters are seen in the other panels. They correspond to relatively small distances from the Sun ($r \leq 2\,\text{AU}$) and the fast change in heliolatitude. The maximum of the parameters’ change occurs at crossings of the ecliptic plane.

Guided by morphological data analysis, investigators made conclusions that the solar wind speed decreases and density increases around $\pm 30^\circ$ of the ecliptic plane (see, for example, [20, 21], http://ulysses.jpl.nasa.gov/science/mission_primary.html and http://ulysses.jpl.nasa.gov/2005-Proposal/UlsProp05.pdf). At the same time, it is believed that the radial component of the IMF has no latitudinal dependence at any certain heliocentric distance. This statement forms the basis for many studies ([8–12, 20–23]).

The recent paper [23] gives typical views on this subject: $B_r$ does not depend on latitude, as “the magnetic flux density (referred to 1 AU) tends to be uniform, at least in the fast, polar solar wind $> \cdots >$ the magnetic flux density measured at a single point is a representative sample of the absolute value of the magnetic flux density everywhere in the heliosphere” ([23]). As was mentioned above, such an approach gives gratifying results at the first approximation, but more detailed analysis can give a key to the explanation of many inconsistencies between the theory and observations.

An unbiased look at the picture of the radial (b), tangential (c) IMF components and the IMF strength (d) in Fig. 3 may put in doubt the statement of latitudinal independence of $B_r$, because the IMF growth (as well as all its components’ increase), occurring simultaneously with the solar wind speed decrease and density increase, is rather obvious. However, taking into account the double $B_r$ dependence (on both latitude and distance), an additional statistical analysis must be performed. It is reasonable to separate variables and investigate how the radial IMF component varies with latitude and heliocentric distance. Then, a least-square 3-D surface “$B_r$—latitude—distance” can be plotted (see Fig. 4).

The radial IMF component in the subspace “$B_r$—heliolatitude” (Fig. 4a) displays two trends: $B_r$ increases toward the ecliptic plane, and there is some less-expressed $B_r$ enhancement in the polar latitudes. Fig. 4b represents $B_r$ changing with distance. The $|B_r|$ radial decrease was partially studied in the Section 2.1. The combined pattern of these two dependencies is shown in Fig. 4c as a 3-D surface.

The same kind of surface for the IMF strength $B$ is given for comparison (Fig. 4d). Both panels demonstrate very similar behavior for $B_r$ and $B$: the magnetic field decreases with distance, and it has maximum at the ecliptic plane (this increase is most clearly expressed at small distances from the Sun). The slight increase of $B_r$ and $B$ in polar regions is an interesting feature which may be related to peculiarities of the solar magnetic field generation (dynamo waves effect) as was predicted in [24].

The found effect of the IMF strength increase at the ecliptic plane may be demonstrated in another way. Let us analyze Ulysses data for three selected distance ranges from the Sun (1–2 AU, 2–3 AU, and 3–4 AU) and separate them by latitude (above and below $40^\circ$). The radial component distribution for different latitudes and heliocentric distances is shown in Fig. 5ab. One can see that at the same distance $r$ from the Sun, the high-latitude $B_r$ values are always smaller in comparison with low-latitudes values. This is a plain evidence of the found effect. Therefore, the radial IMF component can not be considered as independent of heliolatitude because of its pronounced increase it the ecliptic plane vicinity, especially at small heliocentric distances.

Continuing the analysis of the $B_r$ histogram, it is necessary to mention the $B_r$ “bimodality effect” (see Introduction), which became an object of special interest during the last years. It is known that at the Earth’s orbit, the horizontal IMF components
Fig. 3. The IMF and solar wind data, provided by the Ulysses spacecraft for the entire period of measurements (1990–2009). (a) the Ulysses’ trajectory, (b) the radial component of the IMF, (c) the tangential IMF component, (d) the IMF strength, (e) the solar wind speed, (f) the solar wind density.

The IMF and solar wind data, provided by the Ulysses spacecraft for the entire period of measurements (1990–2009). (a) the Ulysses’ trajectory, (b) the radial component of the IMF, (c) the tangential IMF component, (d) the IMF strength, (e) the solar wind speed, (f) the solar wind density.

The GSE coordinate system or radial and tangential components (RTN, in the ecliptic plane) have a two-humped form. First, variations of the histograms’ view with solar cycle was investigated in [25]. Then, the work discussing the histograms’ change with distance followed [26] (this preprint’s results were partially published in [13]). The question about the dependence of the magnetic flux density \(B_r \cdot r^2\) histogram’s shape on the solar wind flow type (high-speed, low-speed and CME) as well as on the solar cycle was discussed in [23].

Figure 5 shows that the effect of fast \(B_r\) histogram’s bimodality disappearance found in [13, 26] for the IMF in-ecliptic measurements looks significantly smoothed at high latitudes. Two peaks transformation into one peak with increasing \(r\) is clearly seen at low latitudes (Fig. 5b), but histogram’s bimodality is still apparent at 3–4 AU at high latitudes.
Fig. 4. The IMF behavior in the inner heliosphere as measured by Ulysses: (a) the latitudinal dependence of $B_r$; (b) the radial $B_r$ dependence; (c) 3-D representation of (a) and (b); (d) the same as (c), but for the IMF strength $B$.

(Fig. 5a). Obviously, at high latitudes, the bimodality disappears farther from the Sun. Possible reasons for this phenomenon are discussed below.

It would be interesting to trace changes in the $B_r$ histogram at high and low latitudes at different solar cycle phases. One can analyze histograms of the horizontal IMF (GSE) components at 1 AU in the ecliptic plane, using many spacecraft’s data collected in the OMNI long-time database (see Figs. 6a and 6b). The histograms become broader at solar activity maxima, their peaks are reduced, but the bimodality does not disappear. It is useful to note for further comparisons that the $B_x$ IMF component in GSE coordinate system equals to $-B_r$ in the RTN coordinate system.

The relation of the $B_r$ histogram shape at high latitudes to the solar activity cycle is shown in Figs. 6c and 6d, which represents parts of Fig. 5a for selected cycle phases. The Ulysses observations at the latitudes above $\pm40^\circ$ covered two minima and one maximum of sunspot numbers. At solar activity minima, the histograms’ bimodality is expressed clearer than at the solar maximum. Dominance of one or another histogram’s hump in Figs. 6c and 6d is related to statistical prevailing of positive/negative polarity active regions on the Sun. As a whole, the bimodality effect disappears neither in minimum, nor in maximum of solar activity at high latitudes.

During the solar activity maximum, the histograms’ spreading is observed at all distances from
the Sun. This effect is known in the ecliptic plane, 1 AU (see Figs. 6a, 6b), where it is usually explained by the impact of CMEs, most frequently occurring at solar activity maxima. Hence, the observed high-latitude histograms' broadening indirectly indicates that CMEs fill the significant part of the inner heliosphere.

Temporal (solar cycle) changes of the interval between the positive/negative histogram peaks seen in Figs. 6a and 6b were investigated in [25], where the IMF strength along the Parker spiral $B_L$ was calculated on the basis of OMNI data. It was found that the variations of the distance $\Delta B_L$ from one peak to another have the same tendency as was demonstrated in Fig. 6: $\Delta B_L$ reaches maximum in maxima of solar activity and minimum in solar activity minima. One can see that the distance $\Delta$ between the humps of the histogram correlates with the peaks' height. If the histogram spreads, the peaks' height decreases. This helps to fill the gap in our knowledge of the IMF behavior at high latitudes. There is no sufficient information from Ulysses on the IMF there during solar maxima, but as the solar cycle dependencies of the $B_L$ bimodality are same at any latitudes, it is possible to expect that $\Delta B_r$ varies with cycle at the latitudes above $\pm 40^\circ$ in the same way as at low latitudes.

**2.3. Whether the Radial IMF Component Depends on the Solar Wind Speed? The Solar Wind Speed Changes with Latitude and Solar Cycle**

This is remarkable that Figs. 5 and 6 are consistent with some results of [23]. The magnetic flux density ($B_r \cdot r^2$) bimodality is expressed in the “fast” solar wind rather than in the “slow” solar wind as follows from figure 1 in [23]. The solar wind speed $V$ measured by Ulysses has a two-peaked distribution, so separation of the “fast/slow” solar wind was made in [23] according to this fact. Having in mind that $V$ has only one-peak distribution at the Earth’s orbit, let’s puzzle out why the Ulysses data give these two peaks. What does the “fast” or “slow” solar wind mean when we use Ulysses measurements?

$V$ is believed to be approximately independent of latitude and longitude in [23]. The solar wind types are divided according to the Ulysses-measured $V$ distribution peaks: the “slow wind” has velocities $V < 400 \text{ km/s}$ and the “fast wind” flows faster than $600 \text{ km/s}$ independently of latitude or heliocentric distance. Meanwhile, more detailed analysis does not confirm that the $B_r$ (and, consequently, the magnetic flux density) is determined anyhow by $V$. A thesis about the latitudinal independency of $V$ is not confirmed either. As one can see below, the found in [23]
dependence of $B_r$ on the fast/slow solar wind, in fact, is a latitudinal dependence.

The solar wind speed dependencies are shown in Figs. 7–9. Fig. 7a is illustrative of a scatter of points in the “radial IMF component—solar wind speed” subspace, where two clouds of points are seen. There is no $B_r$ dependency of $V$ inside each cloud. As one can see below, these two clouds correspond to two humps of the $V$ distribution. To answer the question about the nature of the $V$ distribution’s bimodality, it is necessary to plot the Ulysses “latitude—distance” curve (Fig. 7b), as well as to reveal the “speed—latitude” and “speed—distance” dependencies (Fig. 8).

As seen in Fig. 8, the $V$ distribution’s bimodality (Fig. 8a) is a consequence of the solar wind speed
Fig. 8. The solar wind speed $V$ as seen by Ulysses: (a) the $V$ histogram; (b) the latitudinal dependence; (c) the radial dependence; (d) 3-D representation of (b) and (c).

complex latitudinal (Fig. 8b) and radial (Fig. 8c) dependencies. Fig. 8b resembles a flying eagle with two wings and two legs (one leg, corresponding to negative latitudes, is more expressed). The radial solar wind speed dependence is shown in Fig. 8c. It is also degenerate, as there are both lower and upper branches of the curve. Fig. 8d was built in the same manner as Figs. 4c and 4d. One can see there “wings” of Fig. 8b and some $V$ increase at 2–3 AU of Fig. 8c, as well as well-known strong $V$ decrease in the area of zero latitude (the ecliptic plane).

The $V$-“wings” and “legs” in Fig. 8b are related to both the Ulysses’ trajectory features and the solar cycle. “Legs” represent $V$ in high latitudes in the solar activity maximum, and “wings” correspond to $V$ measurements in high latitudes during solar activity minima. This follows from Fig. 9 where $V$ was plotted separately for the latitudes above ±40° (Fig. 9a) and latitudes of ±10° around the ecliptic plane (Fig. 9b) in comparison with the solar cycle. Fig. 9a shows that the solar wind speed has minimum in the maximum of solar activity and maximum during the solar activity minima.

Therefore, the high-latitude solar wind is fast (as it often believed) at solar activity minima only. Comparison of Fig. 9a and Fig. 9b indicates that $V$ values at high latitudes during the solar maximum are close to low-latitudes values of the solar wind speed. It is interesting that variations of the near-ecliptic solar wind speed have a ~2 years outstripping shift regard-
Fig. 9. The solar cycle dependence of the solar wind speed $V$ on the basis of the Ulysses data: (a) the annual mean of $V$ at the heliolatitudes above $\pm 40^\circ$, (b) the annual mean of $V$ near the ecliptic plane ($\pm 10^\circ$ around), (c) the sunspot numbers (27-days averaging, the OMNI database).

The solar cycle maxima/minima. There is a peak during 2002–2005, a period known for its anomalies. As it was shown in [27], the large-scale magnetic field of the Sun unexpectedly dominated during that period, and this is seen in the solar wind too. The solar wind speed relation with the solar cycle is obvious just in high latitudes. Near the ecliptic plane, it is still doubtful.

Summarizing, one can see that a bright solar cycle dependence of $V$ is the main source of the $V$ distribution bimodality. The central part of Fig. 8b (the “eagle’s body”) is $V$ in low latitudes; the high-latitude solar wind in solar activity minima forms two upper branches (“wings” of $V > 700$ km/s). Besides, the high-latitude solar wind in the maximum of solar activity is characterized by $V$ values approximately from 400 km/s to 600 km/s (see the “legs” in Fig. 8b). Weakness of this branch is explained merely by insufficiency of measurements in the solar maximum (Ulysses provided high-latitude measurements for two minima and for one maximum of solar activity only). A hypothetical continuation of the Ulysses measurements would lead to enhancement of the “legs,” and the whole picture of the solar wind speed latitudinal dependence would be completed. The “wings” in Fig. 8b form the 650–850 km/s peak of the $V$ distribution (Fig. 8a). The “legs” and the
“eagle’s body” give the second peak of the \( V \) distribution with values of 250–550 km/s. Thus, the \( V \) distribution bimodality is determined by changing of the Ulysses’ latitude and solar cycle.

This effect may lead to some misunderstandings. For example, the authors of [23], in fact, did not study the magnetic field of the “fast” solar wind, but revealed the high-latitude solar wind properties at solar activity minima. This fact does not diminish the results [23], but demands a correct approach to their interpretation. It is obvious from Fig. 8b that the lower threshold of the “fast” solar wind (600 km/s), as selected in [23], corresponds to a super-fast stream at low latitudes, but at high latitudes such a stream is super-slow. This also should be taken into account in further investigations. Most reasonable “fast/slow wind” separation has been already performed in [28], where the threshold of 450 km/s was used, and its physical causality was confirmed.

Regarding the radial dependence of \( V \), the lower branch in Fig. 8c, rising with distance according to theoretical expectations, mainly belongs to the Ulysses measurements in low latitudes, and the branch, decreasing after 3 AU, primarily corresponds to the measurements in high latitudes. The “primarily” word is used here because there is also the solar cycle \( V \) dependence. Furthermore, Ulysses registered fast streams in high latitudes even during the solar activity maximum (mainly in 2001–2002). Meanwhile, overall, the solar wind speed radially decreases in high latitudes at solar activity minima, and \( V \) radially growth in low latitudes independently of solar activity cycle (see Fig. 10). Two solar activity minima data were selected for high latitudes (Fig. 10a), and all available data for near-ecliptic measurements (±10° of heliolatitude) were used (Fig. 10b).

A “noisy” part of the data in Fig. 10b is a consequence of the Ulysses orbital rotation, as a spacecraft has a minimal velocity in its apogee, so the \( r \) interval of > 5 AU contains more points and the curve is noised by non-stationary effects such as CME. The same effect is seen in Figs. 1b and 4b.

According to Figs. 7–10, the solar wind speed depends on heliolatitude and solar cycle phase in a high degree. At the same time, the radial IMF component does not depend on the solar wind speed.

3. CONCLUSIONS AND DISCUSSION

Several problems important for understanding of the large-scale picture of the magnetic field in the inner heliosphere were discussed in the paper:

1. What is the law of the radial IMF component \( (B_r) \) decrease with heliocentric distance?
2. What is the cause of the “magnetic flux excess”—the enhancement of the open solar flux calculated from distant spacecraft measurements over the flux measured 1 AU?

3. Whether \( B_r \) depends on heliolatitude?

4. How does the \( B_r \) distribution’s bimodality vary with latitude and solar cycle?

5. Is there the \( B_r \) dependence of the solar wind speed \( V \)?

6. How does \( V \) depend on heliolatitude, heliocentric distance and solar activity?

The results of the analysis of the Ulysses and OMNI data show that listed above problems are related. For example, the deviation of the \( B_r(r) \) law from the classical dependence used in Parker-like models is one of the main causes of the “magnetic flux excess.” The latitudinal \( B_r \) dependence also contributes to this effect. At the same time, the dependence of the magnetic flux density on the solar wind speed reported in [23], in fact, is the \( B_r \) dependence on latitude and solar cycle.

Correspondingly to the listed above questions 1–6, it was found out that:

1. The radial IMF component \( B_r \) decreases as \( r^{-5/3} \), but not as \( r^{-2} \).

This conclusion was based on the Ulysses data analysis for the entire period of measurements. The \( B_r \) module approximation was used to avoid the “module of the mean or mean of the module” problem (see Section 2.1). The same result was obtained in [13] from the five spacecraft data analysis.

The phenomenon’s nature may be not only in the fact that Parker’s model is stationary, but also in poor applicability of the “frozen-in” magnetic field assumption to the non-ideal space plasma conditions. Indeed, the “frozen-in” IMF conditions’ break occurs in the solar wind very often, for example, in some vicinity of current sheets. As was shown [13], zero IMF lines, corresponding to current sheets, are observed in the solar wind inside the IMF sectors more frequently than it was supposed earlier (zero lines were expected to be mainly an attribute of the heliospheric current sheet).

A magnetic reconnection recurrently occurs at the large-scale heliospheric current sheet as well as at smaller-scale current sheets during the solar wind expansion. As a result, current sheets are subjects of a multiplication (bifurcation) process. A significant part of the heliosphere is filled with secondary current sheets and other products of the magnetic reconnection. Under averaging, it looks as a radial increase of turbulence and intermittency of the solar wind plasma (especially in low latitudes), and, finally, as a break of the expected IMF radial dependence law. It is worthy to remark that the solar wind plasma obeys the Parker’s theory much better than the IMF does. This is also a confirmation that the IMF is not fully frozen into the solar wind plasma.

2. The “magnetic flux \( (F_S) \) excess” is mainly a consequence of the previous conclusion.

Accepting that the \( B_r \) decreases as \( r^{-5/3} \), it is easy to explain the calculated values of the excess \( \Delta F_S \) — i.e. the difference between \( F_S \) obtained through distant spacecraft data and the measurements at the Earth’s orbit. Obviously, any deviation of the real law of the \( B_r \) radial decrease from the theoretically expected leads to unavoidable dissimilarities at the point-to-point recalculations using \( B_r \cdot r^2 \) formula. Thus, experimental studies of the radial IMF dependence observed by different spacecraft seems to be a perspective way of future investigations. The latitudinal IMF dependence as well as effects discussed in [11, 12, 20] contribute to the “flux excess” effect.

3. The radial IMF component depends on the heliolatitude. \( B_r \) as well as the magnetic flux can be considered as independent of heliolatitude just in a rough approximation. More detailed analysis shows that the radial IMF component and the IMF strength increase toward the ecliptic plane. Additionally, some IMF enhancement is observed in the polar solar wind. The result is checked by different methods, including the analysis of the \( B_r \) histograms at different heliocentric distances.

Most probably, the discussed underestimated of the IMF latitudinal dependence comes from historical development of views on the large-scale solar magnetic field. Before the Ulysses mission, the dominant opinion was that the magnetic field of the Sun should be similar to the Earth’s magnetic field, which is very close to a classical magnetic dipole. The polar magnetic field strength was expected to be twice of the equatorial value. The Ulysses data did not confirm that. Against the background of the expected difference between the solar and low-latitude IMF, the picture observed by Ulysses looked as any absence of the latitudinal dependence of the IMF.

It is necessary to remark that the statement of the \( B_r \) latitudinal independence seems very strange from the point of view of specialists who investigate solar processes, since the zonality and difference of the solar magnetic field properties at low and high latitudes are obvious and proved by long-term observations. It seems very unlikely that all observed differences take place only at distances of less than ten solar radii and then disappear (the open magnetic flux uniformity demands such an assumption).

Discarding of the \( B_r \) and \( B \) increase in low heliolatitudes inevitably reduces a quality of even very competent models (such as [29] and [30]), since they
are based on slightly simplified views on the large-scale IMF picture in the inner heliosphere, assuming a constant $B_r$ at any latitude with a sharp [29] or more gradual [30] change of the $B_r$ sign at the ecliptic plane.

4. (a) The $B_r$ histogram's bimodality is expressed at high heliolatitudes (above $\pm 40^\circ$) rather than in low latitudes. It is observed at high latitudes at the heliocentric distances, where it has already vanished near the ecliptic plane.

This fact may bear evidence of radial increasing of turbulence and intermittency in the solar wind due to mentioned above processes in current sheets (most notably, in the heliospheric current sheet). Indeed, unimodality of the $B_r$ histogram means an absence of any clear sector structure. Most possibly, mixing of structures occurs in low latitudes at 3–4 AU, but in high latitudes the solar wind remains well-structured at the same distances.

(b) At high heliolatitudes, the $B_r$ histogram's view has the same solar cycle dependence as at low latitudes: the distribution spreads and its peaks are reduced at the solar maximum.

This means that both $B_r$ and the $B_r$ internal scatter increase at solar activity maximum. Most possibly, this is a consequence of the CME impact on the high-latitude solar wind. Therefore, this result confirms the observers' conclusion that CMEs fill a significant part of the inner heliosphere [31].

5. $B_r$ is independent of the solar wind speed.

6. (a) The solar wind speed significantly depends on heliolatitude. In high latitudes, it strongly depends on solar activity.

The solar wind speed increase at high latitudes (in comparison with its values near the ecliptic plane) has been known since the first Ulysses flyby. After that, the solar wind above $\pm 40^\circ$ has been mostly believed to be fast.

The current investigation revealed that aforesaid is true only for solar activity minima. During a solar activity maximum, the high-latitude solar wind speed decreases to values, typical for low heliolatitudes. The difference between the yearly mean high-latitude $V$ in maximum and minimum is $200–300$ km/s.

The latitudinal dependence of $V$ has four branches resembling “an eagle with outspread wings.” The solar wind flows above $\pm 40^\circ$ form the high-speed “wings” during solar activity minima. At the solar activity maximum, lower high-latitude branches are formed (the “legs” with $V \sim 270–500$ km/s). The low-latitude solar wind speed is characterized by values of $300–550$ km/s well-known through the data by in-ecliptic spacecraft.

(b) The solar wind speed depends on distance differently at high and low latitudes.

There are two branches of the radial $V$ dependence. The lower one is mainly formed by $V$ measurements in low latitudes, when $V$ expectedly grows with distance. This branch also contains a significant part of data obtained at high latitudes during the solar activity maximum.

The upper branch mainly corresponds to high-latitude $V$ measurements at solar activity minima. It looks like an arch having maximum at $\sim 2–3$ AU. Overall, $V$ in high latitudes decreases with heliocentric distance. Further investigations should be carried out to find why the coronal hole's plasma propagates with decreasing speed.

Therefore, using the solar wind speed data by Ulysses, it is necessary to take into account the following:

— the high-latitude solar wind is not permanently fast;

— the $V$ histogram’s bimodality is a consequence of the latitude and solar cycle dependencies of the solar wind speed;

— the solar wind speed increases with distance at low latitudes as well as at high latitudes during solar activity maximum, but the high-latitude $V$ radially decreases in solar activity minima.

All found peculiarities of the solar wind plasma propagation may be used in advanced models such as [32].

All the discussed effects together demonstrate that the observed solar magnetic field and plasma properties are clearly seen in the solar wind at rather far distances from the Sun, beyond the Earth’s orbit. The Ulysses measurements have revealed both solar wind zoning and distinctions of the solar wind propagation at different phases of the solar cycle.

Keeping in mind all above said, one can see a substantial input of high-latitude missions into our understanding of the magnetic field properties in the heliosphere. The Ulysses mission provides nutriment for long-time investigations, although statistical data insufficiency does not allow detailed analysis of the solar cycle dependencies on IMF and plasma propagation. In some measure, there is no enough information on the radial IMF variation in heliosphere. Many hopes are anchored now on the future Russian Interheliosond mission. Meantime, the obtained here results will be verified and supplemented through the analysis of available data of past missions.

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OMNI data were obtained from the Goddard Space Flight Center OMNIweb plus web-site: http://omniweb.gsfc.nasa.gov/.

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REFERENCES
1. R. L. Rosenberg, J. Geophys. Res.: Space Phys. 75, 5310 (1970).
2. A. V. Belov, V. N. Obridko, and B. D. Shelting, Geomagn. Aeron. 46, 430 (2006).
3. E. J. Smith, J. Geophys. Res.: Space Phys. 118, 58 (2013); doi:10.1002/jgra.50098.
4. M. M. Echim, J. Lemaire, and Ø. Lie-Svendsen, Surv. Geophys. 32, 1 (2011).
5. V. N. Obridko, A. F. Kharshiladze, and B. D. Shelting, Astron. Astrophys. Trans. 11, 65 (1996).
6. P. Riley, Astrophys. J. Lett. 667, L97 (2007); doi:10.1086/522001.
7. M. J. Owens, H. E. Spence, S. McGregor, et al., Space Weather 6, S08001 (2008); doi:10.1029/2007SW000380.
8. M. J. Owens, C. N. Arge, N. U. Crooker, et al., J. Geophys. Res. 113, A12103 (2008); doi:10.1029/2008JA013677.
9. M. Lockwood, M. Owens, and A. P. Rouillard, J. Geophys. Res. 114, A11104 (2009); doi:10.1029/2009JA014450.
10. E. J. Smith, J. Geophys. Res.: Space Phys. 116, A12 (2011); doi:10.1029/2011JA016521.
11. M. Lockwood and M. Owens, J. Geophys. Res.: Space Phys. 118, 5 (2013); doi:10.1002/jgra.50223 (2013).
12. M. Lockwood and M. Owens, Astrophys. J. 701, 964 (2009); doi:10.1088/0004-637X/701/2/964.
13. O. Khabarova and V. Obridko, Astrophys. J. 761, 82 (2012); doi:10.1088/0004-637X/761/2/82.
14. P. Riley, J. A. Linker, and Z. Mikic, J. Geophys. Res. 107, A7 (2002); doi:10.1029/2001JA000299.
15. N. A. Schwadron and D. J. McComas, Geophys. Res. Lett. 32, L03112 (2005); doi:10.1029/2004GL021579.
16. K. Mursula and I. I. Virtanen, J. Geophys. Res. (2013, in press); doi:10.1029/2011JA017197.
17. C. M. Ho, B. T. Tsurutani, J. K. Arballo, et al., Geophys. Res. Lett. 24, 915 (1997); doi:10.1029/97GL00806.
18. M. Neugebauer, R. J. Forsyth, A. B. Galvin, et al., J. Geophys. Res. 103, 14587 (1998); doi:10.1029/98JA00798.
19. X. P. Zhao, J. T. Hoeksema, Y. Liu, and P. H. Scherrer, J. Geophys. Res. 111, A10108 (2006); doi:10.1029/2005JA01576.
20. M. Lockwood, R. B. Forsyth, A. Balogh, and D. J. McComas, Ann. Geophys. 22, 1395 (2004).
21. E. J. Smith, A. Balogh, R. F. Forsyth, et al., Adv. Space Res. 26, 823 (2000); doi:10.1016/S0273-1177(00)00144-4.
22. A. Balogh, E. J. Smith, B. T. Tsurutani, et al., Science 268, 1007 (1995); doi:10.1126/science.268.5213.1007.
23. G. Erdős and A. Balogh, Astrophys. J. 753, 130 (2012); doi:10.1088/0004-637X/753/2/130.
24. K. M. Kuzanyan and D. D. Sokoloff, Geophys. Astrophys. Fluid Dyn. 81, 113 (1995); doi:10.1080/03091929508229073.
25. A. B. Asgarov and V. N. Obridko, Sun Geosphere 2, 29 (2007).
26. O. Khabarova and V. Obridko, Preprint Inst. Terrestr. Magn. (IZMIRAN, Troitsk, Moscow, 2011). http://arxiv.org/ftp/arxiv/papers/1102/1102.1176.pdf
27. V. N. Obridko, E. V. Ivanov, A. Özgüç, et al., Solar Phys. 281, 779 (2013).
28. Yu. I. Ermolaev, N. S. Nikolaeva, I. G. Lodkina, and M. Yu. Ermolaev, Kosmich. Issled. 47, 1 (2009).
29. I. S. Veselovskii and A. T. Lukashenko, Solar Syst. Res. 46, 149 (2012).
30. A. V. Usmanov, W. H. Matthaeus, B. A. Breech, and M. L. Goldstein, Astrophys. J. 727, 84 (2011); doi:10.1088/0004-637X/727/2/84.
31. D. F. Webb, T. A. Howard, C. D. Fry, et al., Solar Phys. 256, 239 (2009); doi: 10.1007/s11307-009-9351-8.
32. A. V. Usmanov, M. L. Goldstein, and W. H. Matthaeus, Astrophys. J. 754, 40 (2013); doi:10.1088/0004-637X/754/1/40.

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