The Dependence of the Magnetic Field Near the Subsolar Magnetopause on IMF in Accordance with THEMIS Data

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Abstract. Crossings of the magnetopause near the subsolar point are analyzed using data of THEMIS mission. Variations of the magnetic field near magnetopause measured by one of THEMIS satellites are studied and compared with simultaneous measurements in the solar wind by another THEMIS satellite. 30 and 90 s averaging of magnetic field in the magnetosheath is produced. The results of averaging are compared with the results of measurement just after the magnetopause crossing. It is shown, that $B_x$ component of the magnetic field near magnetopause is near to zero, which supports the possibility to consider the magnetopause as the tangentional discontinuity. Comparatively good correlation of $B_y$ component in the solar wind and near the magnetopause is observed. The correlation of $B_z$ component near the magnetopause and IMF is practically absent. It is shown, that in ≈ 30 % cases the sign of the $B_z$ component of magnetic field near the subsolar point does not coincide with the sign of IMF $B_z$ component.

Introduction

Measurements of the magnetic field (IMF) by the spacecraft in the solar wind (Wind, ACE and others) are ordinarily used analyzing the effect of the solar wind on the geomagnetic activity. However, it is a magnetosheath plasma and magnetic field that come into a contact with magnetopause. A characteristic feature of magnetosheath plasma is a high level of turbulence (see Shevryrev and Zastenker [2005], Savin et al. [2005] and references therein). The existing theories of the solar wind magnetosphere interaction are based on the assumption of laminar flow subject to conditions of frozen-in magnetic field lines, broken only at reconnection points or lines. Estimates of the global plasma properties in the magnetosheath are predominantly based on the results of the gasdynamic model predictions of Spreiter et al. [1966] and Spreiter and Stahara [1980]. Verification of the model made in the papers Němeček et al. [2000], Zastenker et al. [2002] showed that this model generally describes the nature of the flow although there may be significant deviations. Such deviations are especially noticeable in the behaviour of the magnetic field. The numerical MHD models are usually unable to reproduce the magnetic field fluctuations in the magnetosheath (see, for example, Li et al. [2009]). The correlation scale of fluctuations of module of the magnetic field in the magnetosheath in the dawn–dusk meridional plane according to CLUSTER data was determined in Gutynska et al. [2008]. It was shown that the correlation length does not exceed ≈ 1 RE in the analyzed frequency range (0.001–0.125 Hz) and does not depend significantly on the magnetic field or plasma flow direction. When the plasma flow velocity in the magnetosheath is about ≈ 200 km/s this distance is traversed by plasma during approximately ≈ 30 seconds.

The development of the solar wind-terrestrial interaction theory requires taking into account the existence of a high level of turbulence in the magnetosheath. Therefore, comparison of the magnetic field parameters directly in front of the magnetopause with the magnetic field in the solar wind (IMF) is of great interest. A large number of measurements of IMF were carried out in the libration point. The solar wind propagation time from the libration point to the Earth is about one hour. Solar wind is itself a turbulent medium (see Riazaantseva et al. [2005, 2007] and references in these papers). Therefore, its parameters may change during the propagation to the Earth’s orbit.

To assess the effect of magnetosheath turbulence on the magnetic field parameters changing during the propagation through the magnetosheath to the magnetopause these parameters should be compared directly in front of the shock wave and near the magnetopause. At the same time measuring of the solar wind should be carried out upstream the foreshock region which makes a strong
disturbance in the solar wind prior to the shock front. The opportunity of such a comparison has appeared only with the start of the five-satellite THEMIS mission (Angelopoulos, [2008]; Sibeck and Angelopoulos, [2008]). One of THEMIS satellites during summer times performed measurements in the solar wind, while the other occasionally crossed the magnetopause on the dayside.

In this study, a comparison of the magnetic field parameters near the magnetopause measured every 3 seconds (spin resolution of the probe), 30 seconds (which is ≈ the correlation time, in accordance with estimations of Gutynska et al. [2008]) and 90 seconds (≈ three times greater than characteristic correlation time) with the same parameters before the bow shock is made. Average dependences of the magnetic field parameters near the magnetopause on the corresponding parameters in the solar wind at selected averaging intervals are obtained. It is shown that the orientation of the magnetic field at the magnetopause may differ significantly from the orientation in the solar wind including even change of sign. We discuss our results and outline plans for further work in conclusions.

Method and results of data analysis

Data for analysis were taken from the website http://cdaweb.gsfc.nasa.gov/. In this paper we analyze THEMIS data for the period from June 25 to October 10, 2008. During this period the orbits of spacecrafts deployed by the precession in such a way that their apogees were located close to the Earth-Sun line, i.e. the configuration convenient for studying the interactions on the dayside of the Earth's magnetosphere takes place. The intervals when one of the spacecrafts was localized in the solar wind, and another crossed the magnetopause near the subsolar point were picked out. The events were selected when the deviation of the probe from the x-axis did not exceed 7 R_E. The moment of crossing of the magnetopause was fixed by the distinctive changes in plasma parameters and magnetic field, determined according to the Electrostatic Analyzer ESA (McFadden et al. [2008]) and the Flux Gate Magnetometer FGM (Auster et al. [2008]) on the probe. Parameters of the interplanetary magnetic field (IMF) were determined according by FGM. The events in which the solar wind did not suffer significant variations were chosen. The value of the standard deviation of the absolute value of the magnetic field from the average for the selected periods does not exceed 2 nT, the flow velocity was less than 650 km/sec.

The parameters of the magnetic field, measured by one of the spacecraft after crossing the magnetopause, were compared with the IMF parameters, observed by another spacecraft. The time resolution of the measurements was 3 seconds which is equal to the spin resolution of the probe. The following quantities were used as analyzed parameters: the magnitude and the three components of the magnetic field and the IMF clock angle. The ‘clock angle’ was considered as the angle produced in the vertical plane from the vector addition of the $B_y$ and $B_z$ components of the IMF (in GSM coordinates). Mean value and dispersion were calculated for each variable.

The magnetic field parameters near the magnetopause were averaged over periods of 30 and 90 seconds after crossing the magnetopause (what was fixed simultaneously by changes in the parameters of plasma and magnetic field). The first point of the magnetosheath was taken as the last data point before or the first after the significant change in the parameter value. Values of the magnetic field, averaged over the spin resolution of the probe, equal to 3 s, i.e. field directly close to magnetopause was also analyzed. The solar wind parameters were averaged over a maximum period of 90 s taking into account the time shift of solar wind propagation from the spacecraft performing measurements in the solar wind to the magnetopause. The shift was calculated as the time of the solar wind passing the difference between x-coordinates of the spacecrafts in the approximation of the radial propagation of the solar wind. Solar wind velocity was determined from the data of THEMIS probe located in the solar wind, or from OMNI database (http://cdaweb.gsfc.nasa.gov/) in the case of the absence of THEMIS plasma data. The solar wind velocity in the magnetosheath was considered as reduced by about two times as a result of thermalization. The magnetosheath thickness was supposed to be approximately ≈ 2 R_E. For each case the time shift was calculated individually for the specific spacecraft coordinates. Since the errors of the order of ten seconds are possible when calculating the time shift, the averaging of values in the solar wind was made for a maximum period of 90 seconds to minimize them. It was possible to analyze 26 events.
Figures 1–5 show the dependences of the magnetic field parameters near the magnetopause on the solar wind parameters. A set of three curves is given for each parameter. The first distribution is plotted for the instantaneous values (three second averaging) after crossing the magnetopause, the second—for the averaged over a 30-s interval after crossing, the third—for the averaged over a 90-s interval. The dependencies on the corresponding averaged solar wind parameters are shown. Averaging in the solar wind is realized for a maximum period of 90 s (taking into account the time shift of the solar wind propagation to the magnetopause) in order to minimize errors due to deviation of the estimated solar wind delay from the real. For each point, an error calculated as the standard deviation over the averaging periods is also shown. In Figures for the instantaneous values the errors are shown only for the averaging in the solar wind, because averaging near the magnetopause was not carried out.

The values of the magnetic field magnitude (see Figure 1) at the magnetopause noticeably trend to increase when increasing magnitude in the solar winds. The form of the distribution remains essentially unchanged when the period of averaging is increased.

In accordance with Figure 2 the x-component of the magnetic field at the magnetopause does not depend on the corresponding value in the solar wind and fluctuates around zero, which is in accordance with the assumption of magnetopause as a tangential discontinuity. As well as for the field magnitude, the increase in averaging interval does not change the form of the distribution of points on the graph.

A good linear dependence of the y-component at the magnetopause (see Figure 3) on that in the solar wind is obtained. The correlation coefficient:

$$r = \frac{\sum_{i} w_i(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i} w_i(x_i - \bar{x})^2 \sum_{i} w_i(y_i - \bar{y})^2}}$$

where $s_i^2$ is the error for $y_i$, increases when increasing averaging period and the errors of the parameters of the approximation and standard deviations are decreased. For instantaneous values after crossing the approximation with the model $B_{y, MP} = a + b \cdot B_{y, SW}$ gives the following values of parameters: $a = 1.1 \pm 2.3$ nT, $b = 6.7 \pm 1.1$, SD = 11.6 nT, correlation coefficient $r = 0.79$. For averaging over 30 seconds the values are: $a = 0.9 \pm 0.6$ nT, $b = 6.9 \pm 0.3$, SD = 2.3 nT, $r = 0.92$. For the averaging over the 90-seconds interval: $a = 0.6 \pm 0.8$ nT, $b = 6.5 \pm 0.3$, SD = 1.5 nT, $r = 0.94$. All approximations are in good agreement within calculated uncertainty.

The results obtained for the z-component of the magnetic field (see Figure 4) are of great interest. There is a vague tendency towards an increase in the value of this component with the increasing of corresponding value in the solar wind. However, in at least a quarter of cases (8 out of 26 for the instantaneous values, and 7 out of 26 for the values averaged over a period of 30 seconds and 90 seconds) the sign of the z-component at the magnetopause changes compared with the sign of $B_z$ in the solar wind from positive value (in the solar wind) to negative (at the magnetopause), and in a few cases (1 for the instantaneous and 2 averaged over 30 and 90 seconds values) from negative to positive value.

![Figure 1](image1.png)  (a)  ![Figure 1](image2.png)  (b)  ![Figure 1](image3.png)  (c)

**Figure 1.** The dependence of the magnetic field magnitude for the considered set of events (a) over 3 seconds after crossing the magnetopause, (b) averaged over a period of 30 seconds from the moment of crossing (c) averaged over a period of 90 seconds—on the magnitude in the solar wind.
Figure 2. The dependence of the x-component of the magnetic field for the considered set of events (a) over 3 seconds after crossing the magnetopause, (b) averaged over a period of 30 seconds from the moment of crossing (c) averaged over a period of 90 seconds – on the $B_x$ in the solar wind.

Figure 3. The dependence of the y-component of the magnetic field for the considered set of events (a) over 3 seconds after crossing the magnetopause, (b) averaged over a period of 30 seconds from the moment of crossing (c) averaged over a period of 90 seconds – on the $B_y$ in the solar wind.

Figure 4. The dependence of the z-component of the magnetic field for the considered set of events (a) over 3 seconds after crossing the magnetopause, (b) averaged over a period of 30 seconds from the moment of crossing (c) averaged over a period of 90 seconds – on the $B_z$ in the solar wind.

Figure 5. The dependence of the magnetic field clock angle for the considered set of events a) over 3 seconds after crossing the magnetopause, b) averaged over a period of 30 seconds from the moment of crossing c) averaged over a period of 90 seconds – on that in the solar wind. The line corresponding to equal clock angles is plotted.
The dependencies of clock angle at the magnetopause on that in the solar wind have been obtained and are presented in Figure 5. For clarity, there are a line of equal values of clock angles in solar wind and near the magnetopause in each plot. Despite the change in sign of $B_z$ in some cases, the values of clock angle at the magnetopause in general fit well to the equivalent dependence, within the errors. The number of events not conforming to the assumption of equality clock angles was no more than 27\% (7 of 26 on the first two plots, and 4 of 26 on the third, i.e. 15\%).

**Conclusions**

The produced analysis of observations obtained during realization of THEMIS mission confirmed the existence of a high level of turbulence of the magnetic field in the magnetosheath. Unlike previous studies the magnetic field parameters in this research obtained directly in front of the subsolar magnetopause were compared with the IMF parameters measured upstream of the bow shock wave. It was shown that $B_x$-component at the magnetopause varies near zero regardless of the averaging interval that fit well with the existence of the tangential discontinuity at the magnetopause. $B_x$-component at the magnetopause, as it was shown at a stage of the first studies (see Fairfield [1967]), is comparatively well correlated with IMF $B_y$. The increasing of the period of averaging leads to the increases of the correlation coefficient of IMF $B_y$ and $B_x$ at the magnetopause. The correlation of $B_z$ component near the magnetopause and IMF $B_z$ is practically absent. It was shown, that in $\approx 30\%$ for considered set of cases the sign of the $B_z$ component of magnetic field near the subsolar point does not coincide with the sign of IMF $B_z$ component. Events not conforming the assumption of equality of clock angles were observed ($\approx 20\%$ of total). Poor correlation between the magnetic field in the magnetosheath with the IMF had been noted earlier (see Coleman [2005], Safrankova et al. [2009] and references in these papers). The presented results imply that the poor correlation, even at a relatively long averaging interval of 90 s, comparable with the time of solar wind plasma propagation through the magnetosheath, is connected with the magnetosheath turbulence. In this study, due to a limited statistics (the limited number of magnetopause crossings by one of the spacecraft, when the other was located upstream the foreshock), we does not distinguish events with quasiperpendicular and quasiparallel shock waves. In accordance with the results of Shevyrrev and Zastenker [2005] one can expect that the average level of fluctuations behind quasiperpendicular and quasiparallel shock waves will differ by about a factor of 2. IMF, especially its $B_z$-component, is the major factor controlling the geomagnetic activity. It is usually assumed that this control is performed due to the processes of reconnection of the IMF and the magnetic field on the magnetopause and inside the magnetosphere. Numerous studies of turbulence in the magnetosheath, including the above analysis, give reason to reconsider such suggestion. The high level of magnetic field fluctuations in the magnetosheath, even for the relatively large averaging intervals, indicate that at different points of the magnetopause the magnetic field has different orientations, poorly correlated with the orientation of the IMF. The ideas about the role of large-scale reconnection processes at the magnetopause and formation of large-scale neutral lines were involved for explaining a relatively good correlation of IMF and large-scale magnetospheric convection. Recently a lot of experimental evidences of the support of the field-aligned current system in the magnetosphere and large-scale convection by azimuthal pressure gradients of the magnetospheric plasma were accumulated (see Antonova [2004], Xing et al., [2009] and references therein). Therefore, it is possible to reanalyze the suggestion about the penetration of the solar wind electric field inside the magnetosphere as a result of large-scale reconnection. Unresolved problems about the maintenance of the pressure balance at the magnetopause and the formation of LLBL continue to exist, which one can try to solve by analyzing a database of multisatellite experiments.

**Acknowledgments.** The authors thank the group of developers of THEMIS mission and the support group of spacecraft data website [http://www.nasa.gov/mission_pages/themis/](http://www.nasa.gov/mission_pages/themis/).

We are grateful to V. Angelopoulos and participants in NASA-grant NAS5-02099 for the THEMIS mission realization. In particular: C. W. Carlson and J. P. McFadden for the use of ESA data, K.-H. Glassmeier, U. Auster, and W. Baumjohann for the FGM data, developed under the guidance of Technical University of Braunschweig and with financial support from the German Ministry of Economics and Technology, as well as the German Air and Space Center (DLR) under contract 50 OC 0302.
We are grateful to prof. G.N. Zastenker for advice and comments during this research. The work was supported by the grants of President of Russian federation MK-1579.2010.2, Russian Foundation for Basic Research 10-05-00247-a, 10-02-01063-a.

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