18

Turbulence in the Magnetosheath and the Problem of Plasma Penetration Inside the Magnetosphere

Elizaveta E. Antonova[1,2], Maria S. Pulinets[1], Maria O. Riazantseva[1,2], Svetlana S. Znatkova[1], Igor P. Kirpichev[1,2] and Marina V. Stepanova[3]
[1]*Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow*
[2]*Space Research Institute RAS, Moscow*
[3]*Physics Department, Universidad de Santiago de Chile*
[1,2]*Russia*
[3]*Chile*

1. Introduction

Chapman & Ferraro (1931) introduced the concept of confinement of the Earth's magnetic field in a cavity carved in the solar plasma flow. The balance between the Earth's magnetic field (more accurately between the magnetic pressure at the boundary of the cavity) and the solar wind dynamic pressure was considered as the condition of the formation of the boundary of the cavity. Chapman-Ferraro model is called a closed magnetosphere. Low energy particles can not penetrate through the boundary of the cavity. Dungey (1961) made the most drastic revision of Chapman-Ferraro's original theory. Dungey envisaged that the connection process, called reconnection, takes place on the dayside magnetopause and that the connected field lines are then transported in the antisolar direction by the solar wind, resulting in the magnetotail. Subsequently, the field lines are reconnected there and then transported back to the dayside magnetosphere. Such process takes place when interplanetary magnetic field (IMF) has the southward direction. The large scale reconnection takes place at high latitudes when IMF has the northward direction. The scheme shown on Fig. 1 demonstrates Dungey's concept of reconnection at the dayside magnetopause when IMF has southword (a) and northward (b) directions. The model of Dungey qualitatively accounts for such phenomena as the inward motion of the dayside magnetopause, equatorward motion of the cusp, expansion of the auroral oval, increase in magnetotail magnetic field strength, and expansion of the magnetotail radius which occur when the IMF turns southward. It can also easily explain the penetration of the plasma of solar wind origin inside the magnetosphere. That is why this concept for a long period was the dominant concept in the physics of the magnetosphere and was widely used for the description of different phenomena including the formation of boundary layers (see, for example, the review Lavraud et al. (2011)). However step by step a number of observations ant theoretical arguments have appeared which give the possibility to throw doubts on the applicability of the scheme shown on Fig. 1 for the real situation.

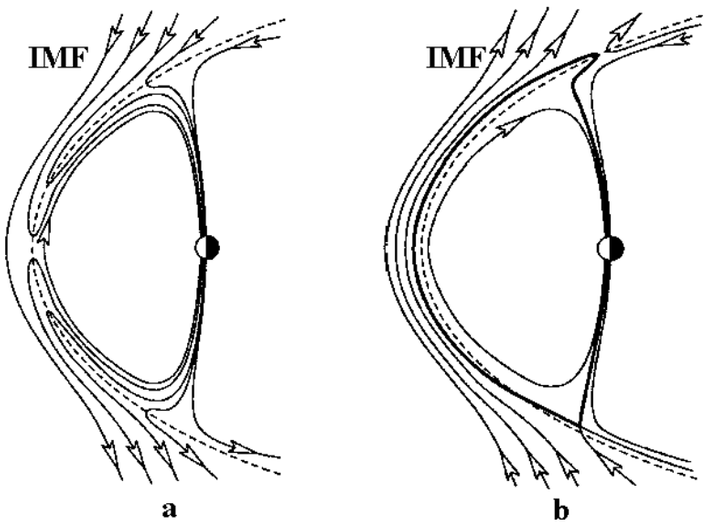


Fig. 1. Sketch illustrating the process of reconnection at the dayside magnetopause when IMF has southward (a) and northward (b) directions

In this paper, we try to summarize arguments demonstrating principal differences of the scheme shown on Fig.1 and the picture, which corresponds to the results of experimental observations. We discuss the process of particle penetration through the magnetopause and try to select arguments demonstrating the formation of the changes of the form of the magnetopause and particle penetration inside the magnetosphere as the results of the change of conditions of pressure balance at the magnetopause. THEMIS mission multisatellite observations available at (http://www.nasa.gov/ mission_pages/themis/) were used for illustration of the main features of magnetic field and plasma observations near the magnetopause. The paper is organized as follows. Section 2 contains the analysis of the properties of turbulence in the magnetosheath. Section 3 is dedicated to the condition of pressure balance at the magnetopause. We discuss the applicability of the frozen in condition for the description of plasma flow in the magnetosheath in Section 4. Section 5 contains conclusions and discussions.

2. Turbulent magnetosheath and magnetic field near the subsolar magnetopause

The magnetopause is formed not as the boundary between the solar wind and the geomagnetic cavity. Magnetosheath plasma and magnetic field come into a contact with magnetopause. The magnetosheath is a region through which mass, energy and momentum are transported from the solar wind into the Earth's magnetosphere. There is a significant number of experimental results showing the high level of plasma turbulence in the magnetosheath (see Luhmann et al. (1986), Sibeck et al. (2000), Zastenker et al. (1999, 2002), Lucek et al. (2001), Němeček et al. (2000a,b; 2002a,b), Shevyrev & Zastenker (2005), Shevyrev et al. (2007), Gutynska et al. (2008), Savin et al. (2008), Rossolenko et al. (2008), Šafránková et al. (2009), Znatkova et al. (2011) and references therein). Fig. 2 shows an example of plasma and magnetic field fluctuations in the magnetosheath measured by Geotail satellite March 2, 1996. It is possible to see that the amplitude of magnetic field fluctuations is much larger than the averaged field and constitutes ~10-20 nTl.

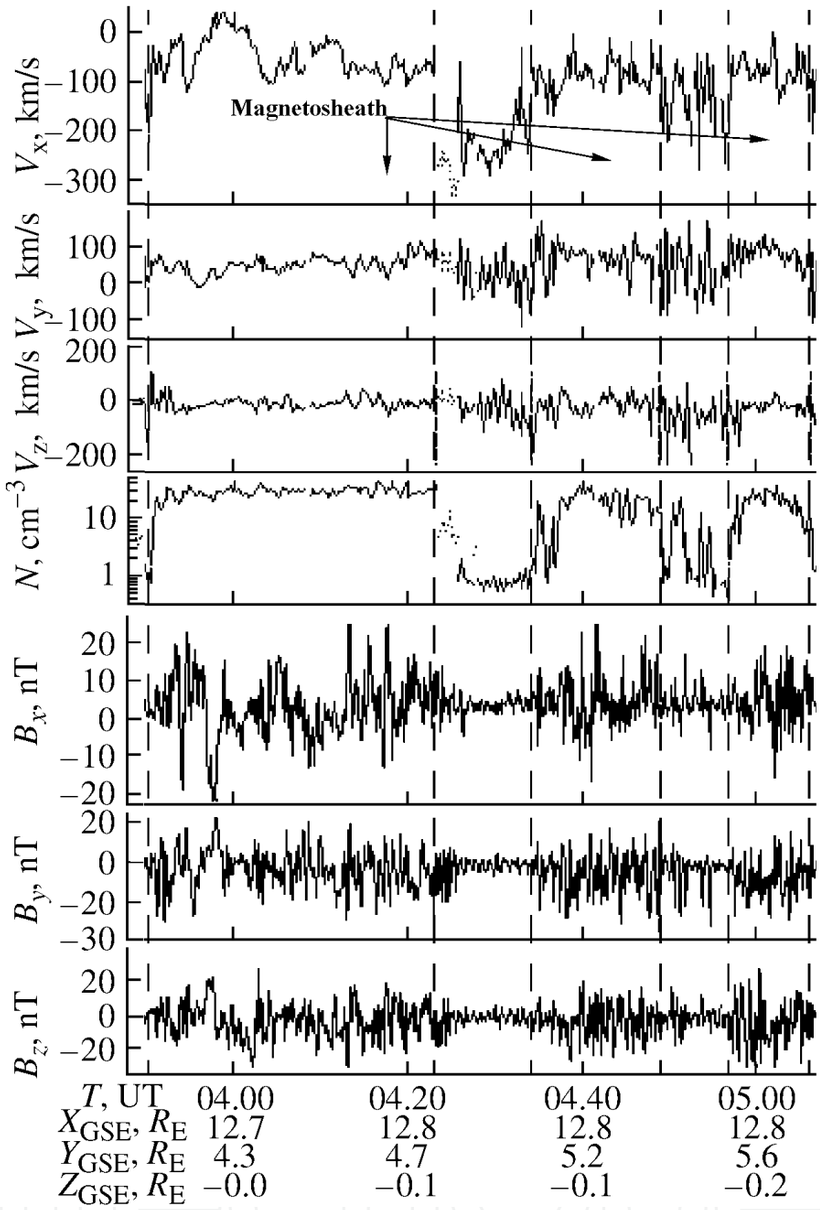


Fig. 2. Results of measurements on the Geotail satellite on March 2, 1996

Zastenker et al. (2002) discussed the origin of magnetosheath variations and showed that a part of these variations is from propagation and/or amplification of solar wind or interplanetary magnetic field (IMF) disturbances, which pass through the bow shock, and a part of these variations originates inside the magnetosheath. Gutynska et al. (2008) present the results of a statistical survey of the magnetosheath magnetic field fluctuations and other parameters using two years of Cluster observations. They have found that the correlation length of the turbulence in the magnetosheath is approximately ~1R_E in the 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 the distance ~1R_E is traversed by plasma during approximately ~ 30 seconds.

The existence of high level of turbulence in the magnetosheath suggests that the direction of magnetic field near magnetpause can not coincide with the direction of IMF. Ŝafránková et al. (2009) determine a probability of simultaneous observations of the same sign of the magnetic field B_Z component in the solar wind and magnetosheath. They conclude that the probability of observations of the same B_Z sign in the solar wind and in the magnetosheath is surprisingly very low from a general point of view. It was shown that regardless of the solar cycle phase, the probability to observe the same B_Z sign in the solar wind and in the magnetosheath is close to 0.5 (random coincidence) for IMF $|B_z| < 1$ nT, and it is a rising function of the B_Z value.

Solar wind is the turbulent medium (see Riazantseva et al. (2005, 2007) and references in these works). Therefore, solar wind parameters may change during the propagation to the Earth's orbit from the position of such satellite in the solar wind as ACE and Wind till the orbit of the Earth. That is why 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 before the shock front. The opportunity of such a comparison has appeared only with the start of the five-satellite THEMIS mission (Angelopoulos, 2008; Sibeck & Angelopoulos, 2008). One of THEMIS satellites during summer in the north hemisphere performed measurements in the solar wind, while the other occasionally crossed the magnetopause on the dayside.

To obtain the dependences of the component of magnetic field before the magnetopause with magnetic field before the bow shock we used results of THEMIS mission (http://cdaweb.gsfc.nasa.gov/) 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 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 following quantities were used as analyzed parameters: the magnitude and the three components of the magnetic field. 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). 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. 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. 26 events were analyzed.

Fig. 3–6 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 (panels a), the second – for the averaged over a 30-seconds interval after crossing (panels b), the third – for the averaged over a 90-seconds interval (panels c). The dependencies on the corresponding averaged solar wind parameters are shown. Averaging in the solar wind is realized for a maximum period of 90 seconds (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. On the charts 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.

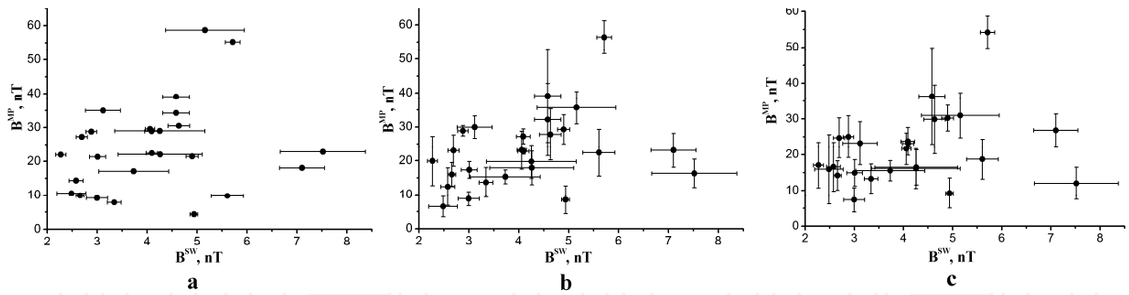


Fig. 3. The dependence of the magnetic field magnitude for the considered set of events a) over 3 seconds after crossing the magnetopause, b) averaged over a period of 30 seconds from the moment of crossing c) averaged over a period of 90 seconds – on the magnitude in the solar wind

The values of the magnetic field magnitude at the magnetopause (see Fig. 3) 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 Fig. 4, 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

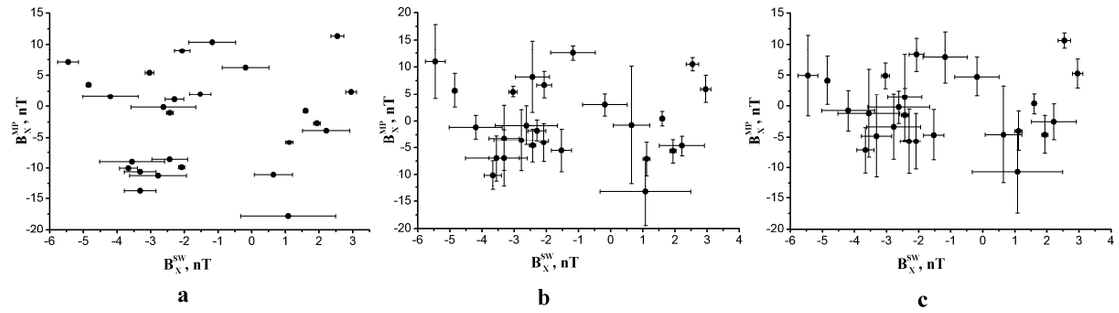


Fig. 4. The dependence of the x-component of the magnetic field for the considered set of events a) over 3 seconds after crossing the magnetopause, b) averaged over a period of 30 seconds from the moment of crossing c) averaged over a period of 90 seconds – on the B_x in the solar wind

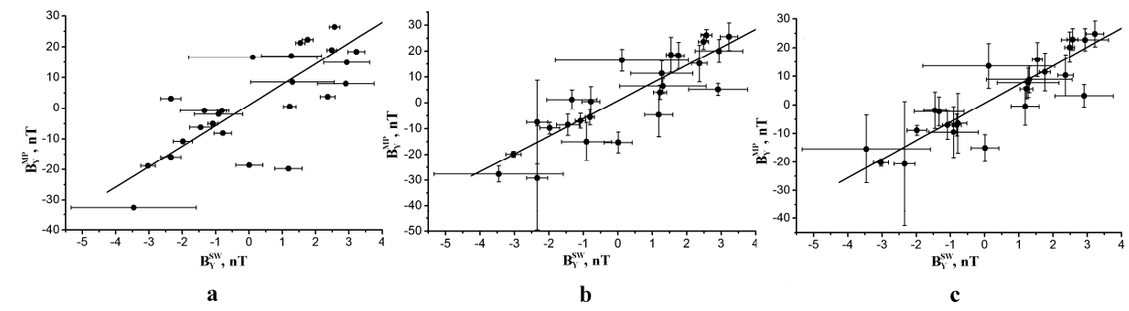


Fig. 5. The dependence of the y-component of the magnetic field for the considered set of events a) over 3 seconds after crossing the magnetopause, b) averaged over a period of 30 seconds from the moment of crossing c) averaged over a period of 90 seconds – on the B_y in the solar wind

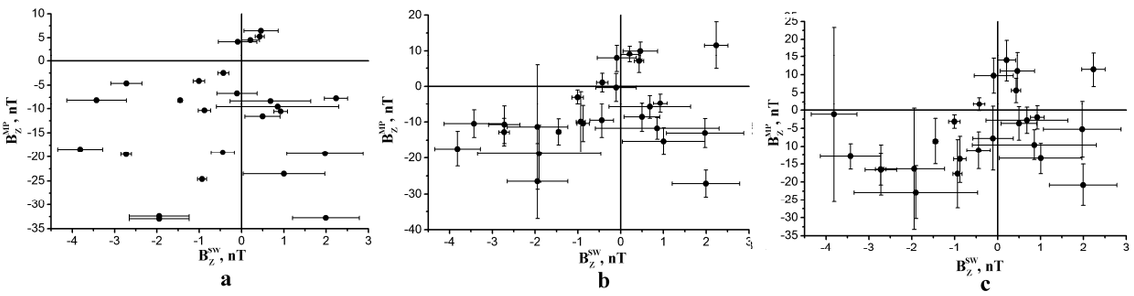


Fig. 6. The dependence of the z-component of the magnetic field for the considered set of events a) over 3 seconds after crossing the magnetopause, b) averaged over a period of 30 seconds from the moment of crossing c) averaged over a period of 90 seconds – on the B_z in the solar wind

distribution of points on the graph. A good linear dependence of the Y-component of the magnetic field at the magnetopause (see Fig. 5) on that in the solar wind is obtained. Therefore B_Y-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 correlation coefficient increases when increasing averaging period and the errors of the parameters of

the approximation and standard deviation is decreased. The results obtained for the Z-component of the magnetic field (see Fig. 6) 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. Therefore, the correlation of B_Z component near the magnetopause and IMF B_Z is practically absent.

3. Pressure balance at the magnetopause

The problem of pressure balance at the magnetopause continues to be one of the most actual problems of the physics of the magnetosphere as the solution of this problem is deeply connected with the solution of the problem of particle, momentum and energy penetration inside the magnetosphere and the formation of boundary layers. It is necessary to mention that the condition of pressure balance at the magnetopause was not analyzed in connection with Dungey's picture. Sibeck et al. (1991) named Dungey's model the "onion peel" model of magnetic merging. They stressed that "onion peel" model violates pressure balance at the magnetopause and therefore does not lead to a quantitative prediction of the magnetopause location as a function of IMF orientation. Sibeck et al. (1991), Sibeck (1994) verify the pressure balance relationship between the solar wind dynamic pressure and the location of the subsolar magnetopause. It was shown, that the pressure balance between the incident solar wind and the magnetospheric magnetic field determines the location of the dayside magnetopause.

The analysis of the validity of pressure balance at the magnetopause was produced using data of AMPTE/IRM by Phan et al. (1994), Phan & Paschman (1996). Plasma moments are obtained every 4.35 s. The total pressures P_{tot} are obtained by Phan et al. (1994), Phan & Paschman (1996) for cases of small and large magnetic shear across the magnetopause. The perpendicular thermal pressure $P_{\perp}$ and the magnetic pressure are used to calculate the total pressure. In the low-shear case, both perpendicular plasma pressure and magnetic pressure change significantly across the magnetopause and magnetosheath regions but their sum P_{tot} remains rather constant throughout these regions. In the high-shear case, the magnetosheath magnetic and plasma pressures both remain rather uniform in the entire region within 20 min preceding the magnetopause crossing, so that P_{tot} is also constant. Across the magnetopause, the plasma and magnetic pressures vary significantly, and their sum generally has a small jump across this boundary: a deficiency of P_{tot} on the magnetosheath side and an excess on the low latitude boundary layer (LLBL) side of the magnetopause are often observed. On average, the change of P_{tot} is less than 10%.

Panov et al. (1998) study the pressure balance at high latitude magnetopause using data of CLUSTER mission. Suggestion about thermal pressure isotropy was used during calculation of P_{tot}. It was shown that for most of the analyzed 154 magnetosheath-magnetosphere transitions the pressure balance between the two sides of the transitions was fulfilled within the error bars, the magnetosheath-to-magnetosphere pressure ratio was close to unity, within the range of 0.5 to 2.

THEMIS mission multisatellite observations give the opportunity to clarify the conditions of pressure balance near the subsolar point at the magnetopause having simultaneous observations inside and outside the magnetopause by two satellites quite near to its surface with 3 s resolution. THEMIS Flux Gate Magnetometer (FGM) and the Ion and Electron Electrostatic Analyzer (ESA) data from the THEMIS satellite mission can be used to determine the total plasma pressure with 3 s resolution (McFadden et al., 2008). The magnetometer measures the background magnetic field and its low frequency fluctuations (up to 64 Hz) with amplitudes of 0.01 nT in a range extending over six orders of magnitude (Auster et al., 2008). The electrostatic analyzers measure plasma over the energy range from a few eV up to 30 keV for electrons and 25 keV for ions (McFadden et al., 2008).

An analysis of the pressure balance on the magnetopause near the subsolar point was made for 18 crossings of the magnetopause by the THEMIS project satellites under magneto-quiet conditions by Znatkova et al. (2011). Dynamic and static pressures of plasma are determined, as well as magnetic pressure in the magnetosheath, and magnetic and plasma static pressure inside the magnetosphere. Variations of the total pressure have been studied in the case when one satellite is located inside the magnetosphere and another one stays in the magnetosheath near the magnetopause. It is demonstrated, that for 18 investigated events the condition of pressure balance at the subsolar point is valid on average with an accuracy of 7%, within measurement errors and under applicability of the approximation of anisotropic magnetic hydrodynamics to collisionless plasma of the magnetosheath and magnetosphere.

For this study the event July 22, 2007 of the magnetopause crossing have been selected, using the following criteria: the interplanetary magnetic field has a stable northward orientation and magnetosphere was very quite to exclude the contribution of changes of magnetic fields inside the magnetosphere as a source of magnetopause stress balance destruction. Fig. 7 shows the positions of satellite orbits in GSM coordinate system. Fig. 8a shows interplanetary magnetic field and solar wind dynamic pressure for analyzed event in accordance with Wind data shifted on the time delay of solar wind flow from Wind to the magnetopause (http://cdaweb.gsfc.nasa.gov/). Wind data were used as all THEMIS satellites were near to the magnetopause for the analyzed event. Arrow shows the selected moments of magnetopause crossings. It is possible to see analyzing Fig. 8a that IMF has stably northward orientation. Variations of geomagnetic parameters

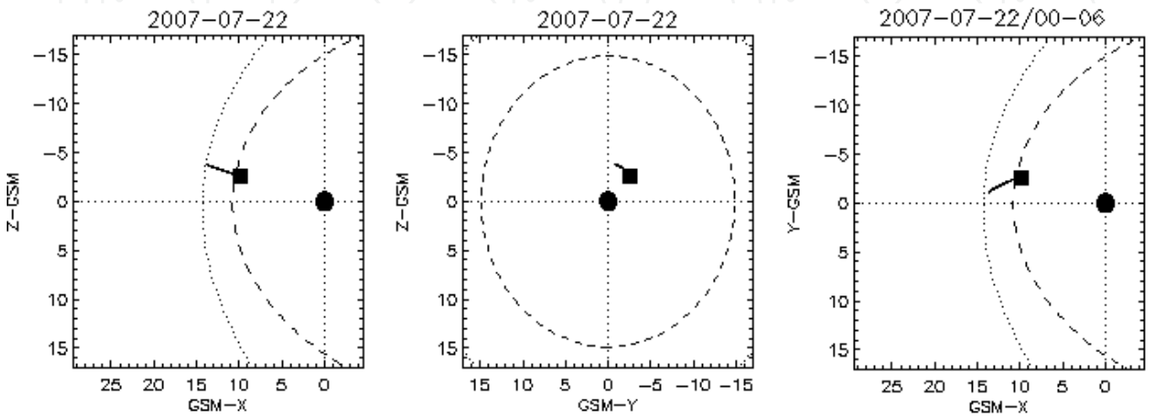


Fig. 7. Positions of THEMIS-C, -D,-E orbits for the event July 22, 2007

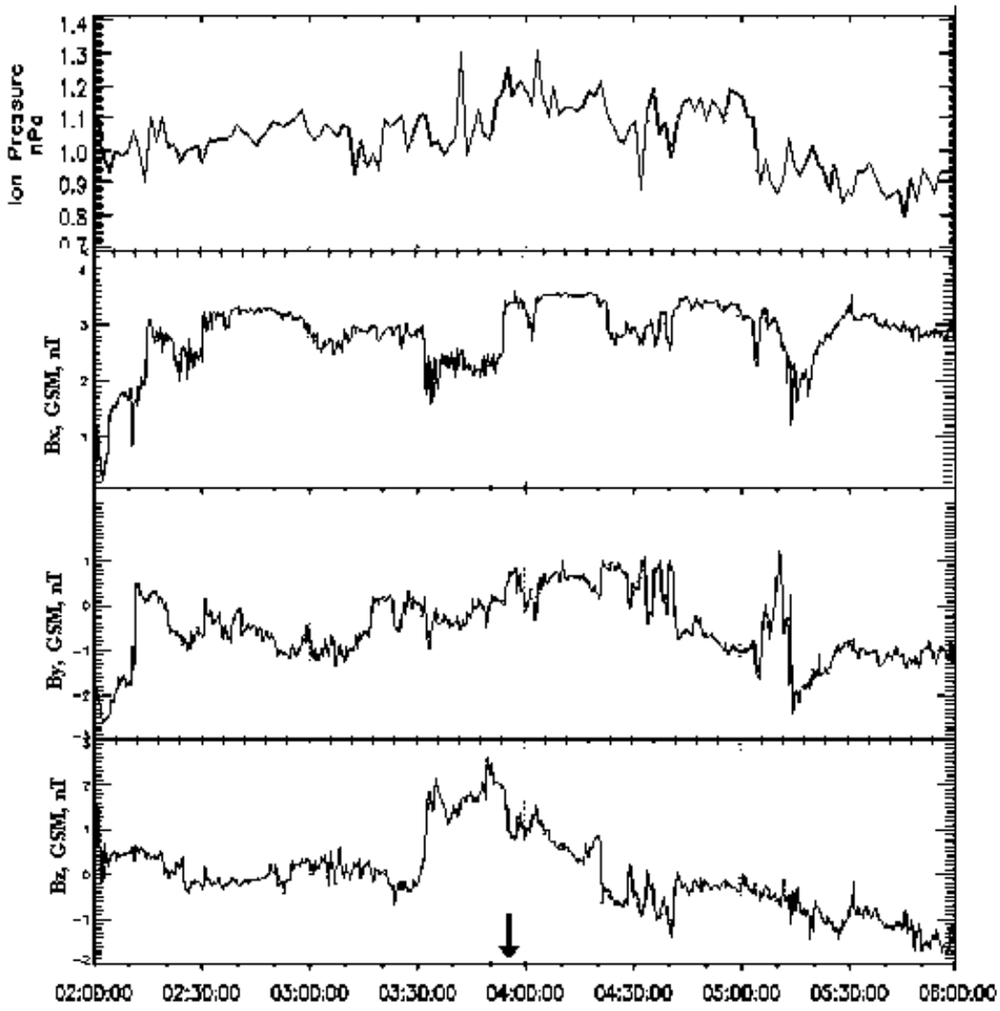


Fig. 8a. Solar wind dynamic pressure and IMF parameters for the event July 22, 2007

(http://swdcdb.kugi.kyoto-u/ac/jp) for the event July 22, 2007 are shown in Fig. 8b. Arrow shows the time for the discussed magnetopause crossings. Dst=-15 hT for the event July 22, 2007. It is possible to see analyzing Fig. 8b that magnetosphere was rather quite having the AE index below 100 nT.

Fig. 9 shows the results of the calculation of dayside magnetic field lines using Tsyganenko-2001 magnetic field model (Tsyganenko, 2002a,b). Stars show the positions of the regions at the magnetic field line where the magnetic field has the minimal value. The values of magnetic field in these regions are also shown. Magnetic field has minimal values at the equator in the inner magnetosphere. These minima are shifted from the equator near the magnetopause. Squares show the position of the equator. Figures near squares show the values of the magnetic field at the equator. It is necessary to mention that Tsyganenko model predicts the existence of closed field lines (dashed lines on Fig. 9) which correspond to the values of the magnetic field at the subsolar point, which can not produce the necessary magnetic pressure for the compensation of the pressure in the magnetosheath.

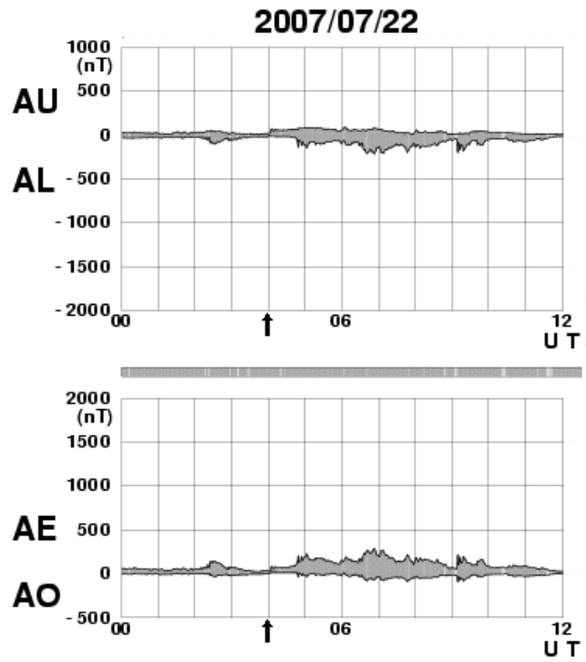


Fig. 8b. AU, AL, AE, AO indexes for the selected time interval in accordance with (http://swdcdb.kugi.kyoto-u/ac/jp)

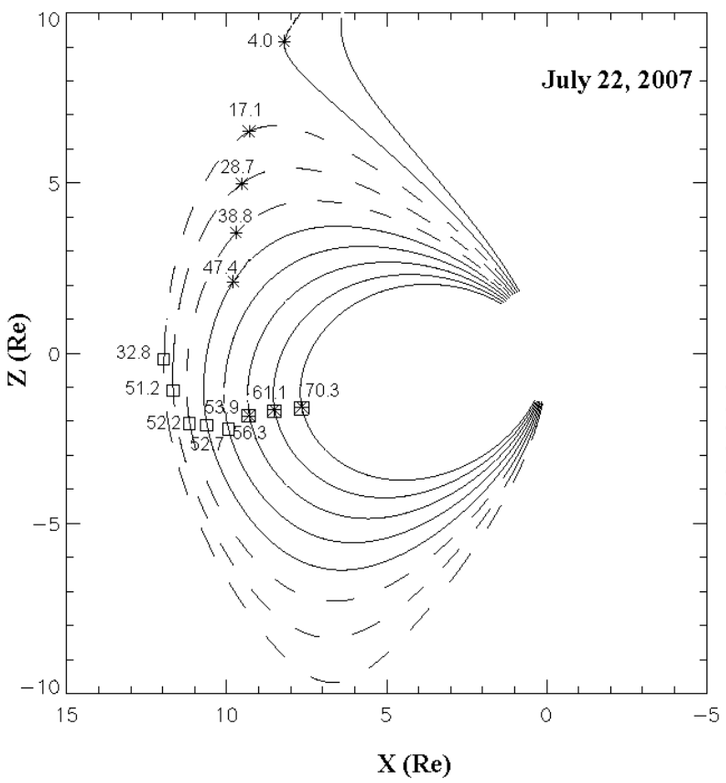


Fig. 9. Forms of the daytime magnetic field line at the Y=0 plane calculated using Tsyganenko-2001 model for solar wind parameters of the event July 22, 2007

Fig. 10 shows the example of magnetic field variations at the moment of THEMIS-D satellite crossing of the magnetopause July 22, 2007. It is possible to see great variations in the amplitude and direction of the magnetic field after the magnetopause crossing, typical for the magnetosheath. Fluctuations of magnetic field ~20 nT are observed. It is necessary to stress that magnetic field has the southward direction after magnetopause crossing in spite of the northward IMF orientating. The solar wind parameters are comparatively stable. Qualitatively the same pictures were observed on other THEMIS satellites. Comparison of the values of the model geomagnetic field (Fig. 9) and the measured geomagnetic field (Fig. 10) shows that amplitudes of magnetic fluctuations in the magnetosheath reach approximately 30 % of the value of magnetic field inside the magnetosphere at the subsolar point. Therefore, fluctuations of magnetic pressure in the magnetosheath can produce ~10% of fluctuations of the total pressure in the magnetosheath. Nevertheless, the same fluctuations at high latitudes, where the magnetic field at the magnetic field line is much smaller than the magnetic field at the subsolar point, the contribution of fluctuations of magnetic pressure is comparable with the magnetic pressure inside the magnetosphere.

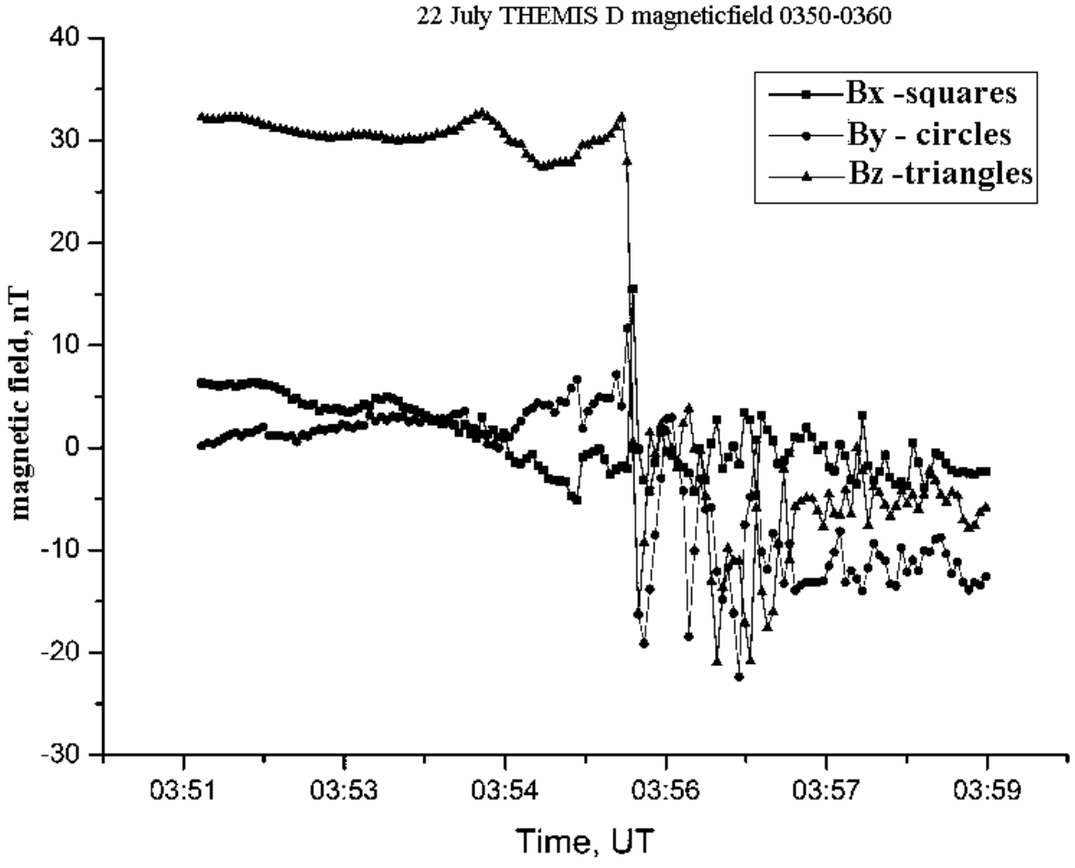


Fig. 10. Variations of THEMIS-D magnetic field July 22, 2007 on the interval 03:51-03:59 UT

The total pressure inside the magnetopause is calculated as a sum of static and magnetic pressure in accordance with the relation $P_{int}=P_{\perp}+(B^2/2\mu_0)$, where μ_0 is the magnetic permeability of vacuum; the integral pressure in the magnetosheath as a sum of dynamic, static and magnetic pressure $P_{int}= n_p\ m_p\ (v_p)^2+\ P_{\perp}+(B^2/2\mu_0)$ (see the results of Phan et al.

(1994) and discussion in (Znatkova et al., 2011)), where n_p and v_p are density and velocity (mainly X-component) of protons, m_i is the mass of proton, $P_\perp$ is the component of plasma pressure perpendicular to the magnetic field line. Fig. 11 a,b,c show the total plasma pressure for pairs of satellites for the periods when one satellite was inside the magnetosphere and the other one was inside the magnetosheath. Dashed line shows the results of calculations inside the magnetopause where the MHD analysis of pressure balance cannot be used due to dominance of kinetic effects. As it can be seen in Fig. 11 the total plasma pressure inside and outside magnetosphere is well balanced for all analyzed crossings of the magnetopause just as in the cases discussed by Znatkova et al. (2011). The main difference of the events July 22, 2007 and July 18, 2007 is connected to the total pressure dynamics. The total pressure is nearly constant for the event July 18, 2007 discussed by Znatkova et al. (2011). The total pressure growth is observed for the event July 22, 2007.

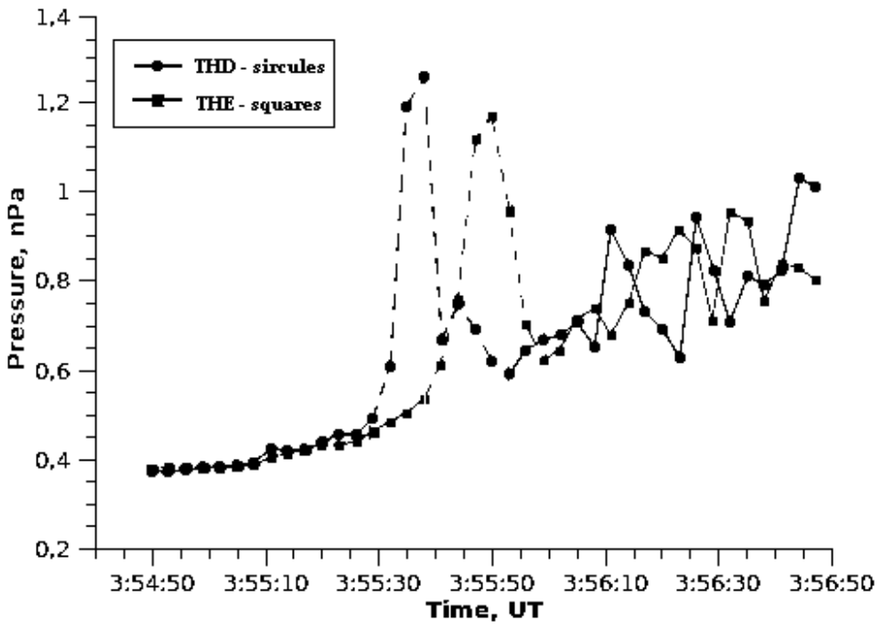


Fig. 11a. Simultaneous measurements of total pressure by the Themis-D and –E satellites for the event July 22, 2007

4. On the applicability of the frozen in condition to the processes in the magnetosheath

The most popular model of plasma flow in the magnetosheath is the gasdynamic model of Spreiter (see Spreiter et al. (1966), Spreiter & Alksne (1969), Spreiter & Stahara (1980)). The validity of this model was demonstrated by Němeček et al. (2000b), Zastenker et al. (2002). It was shown, that Spreiter model describes the parameters of averaged flows of the magnetosheath plasma rather well. MHD models also give the possibility to describe plasma flow parameters. The distribution of magnetic field in the magnetosheath is analyzed in such models using the frozen-in magnetic field approximation. However, it is

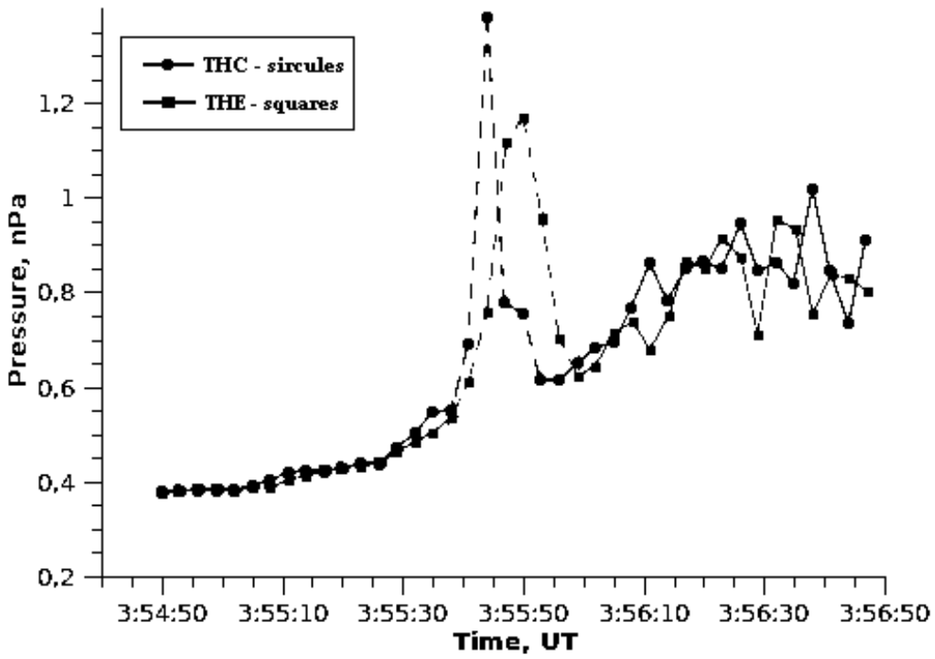


Fig. 11b. Simultaneous measurements of total pressure by the Themis-C and –E satellites for the event July 22, 2007

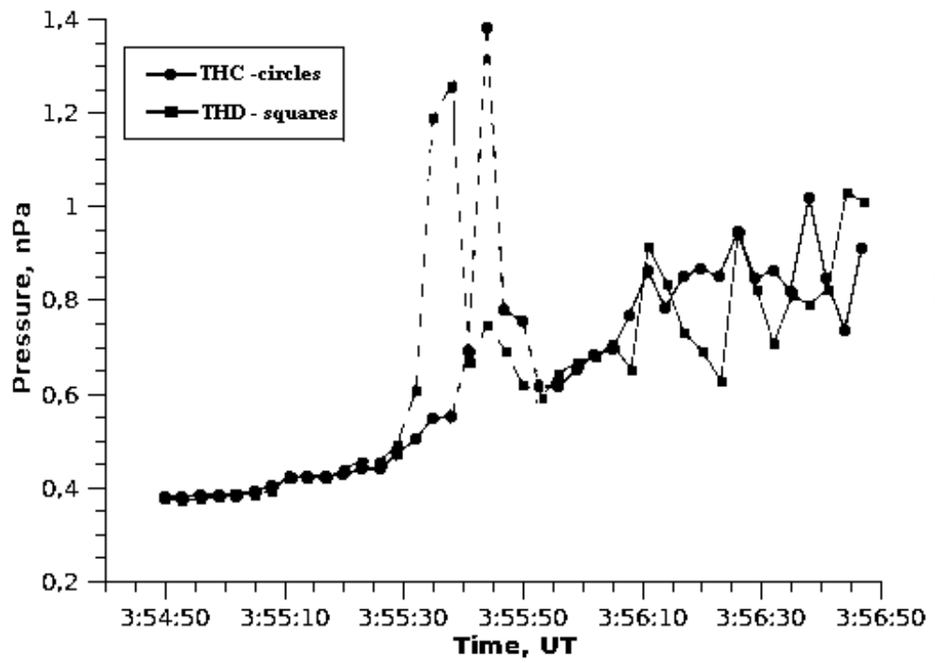


Fig. 11c. Simultaneous measurements of total pressure by the Themis-C and –D satellites for the event July 22, 2007

necessary to stress that frozen-in field condition is the result of the reduction of generalized Ohm's low which have the form in the case of isotropic plasma pressure (see Bittencourt (2004))

$$\mathbf{j}+\tau_{ei}\partial\mathbf{j}/\partial t=\sigma(\mathbf{E}+[\mathbf{VB}]+(\nabla p_e-[\mathbf{jB}])/en)$$

where **j** is the current density, τ_{ei} is the electron to ion collision time, **V** is the plasma velocity, **E** is the electric field, **B** is the magnetic field, σ is the conductivity, n is the plasma density and p_e is the electron pressure. $\mathbf{E}+[\mathbf{VB}]=0$ only if $\sigma\to\infty$ and it is possible to neglect by electron pressure gradient and Hall term. The Reynolds number in the case of Coulomb collisions in the magnetosheath is extremely high (2.5×10^{10} in accordance with (Borovsky & Gary, 2009)). However the existence of high level of turbulence requires the generalized definition of Reynolds number as a ratio of a dissipation time scale τ_{diss} to a convection time scale τ_{conv} for a flow structure ($R=\tau_{diss}/\tau_{conv}$) i.e. the introduction of an effective Reynolds number. Borovsky & Gary (2009) analyzing Landau damping and Bohm diffusion show that the effective Reynolds number is considerably reduced in the magnetosheath in comparison with the Coulomb collision Reynolds number. However, the evaluation of Reynolds number in the magnetosheath gives values >>1. That is why $\sigma\to\infty$ approximation can be used and $\mathbf{E}+[\mathbf{VB}]=([\mathbf{jB}]-\nabla p_e)/en$. Plasma velocity in the magnetosheath becomes low in comparison with Alfven and sound velocities near the subsolar magnetopause. This means that the equation of motion is reduced to the condition of magnetostatic equilibrium $[\mathbf{jB}]=\nabla(p_e+p_i)$. This means that $\mathbf{E}+[\mathbf{VB}]=\nabla p_i/en$ and frozen-in field condition can not describe the magnetic field in the magnetosheath. The observed plasma pressure anisotropy in the magnetosheath does not lead to principal changes of this conclusion. Results of Sections 2 and 3 also support this conclusion.

The violation of the frozen-in field condition is typical for the plasma sheet of the Earth (see, for example, Borovsky & Bonnell (2001), Troshichev et al. (2002), Stepanova et al. (2009, 2011)). Phan et al. (1994) considered the obtained using AMPTE/IRM results as an evidence for violation of the frozen-in field condition in the magnetosheath as well. Reconnection concept is based on the suggestion of the validity of frozen-in condition, which can be destroyed in a number of points or lines at the magnetopause. However, the results of observations and theoretical analysis show that frozen-in field condition is not applicable for the real magnetosheath and it is necessary to explain the observed penetration of plasma inside the magnetosphere using other suggestions.

5. Conclusions and discussion

Produced analysis demonstrates the real changes of the orientation of magnetic field in the magnetosheath in comparison with the magnetic field before the bow shock including the change of its sign. Poor correlation between the magnetic field in the magnetosheath with the IMF had been noted earlier (see Coleman (2005), Ŝafránková 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 magnetosheath, is connected with the magnetosheath turbulization. In this study, due to the limited statistics (limited number of crossings the magnetopause by one of the spacecrafts, when the other was performing measurements upstream the foreshock region)

we does not distinguish events with quasiperpendicular and quasiparallel shock waves. In accordance with the results of Shevyrev 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.

Presented results demonstrate the validity of the condition of pressure balance at the magnetopause with comparatively high accuracy and support the results obtained by Phan et al. (1994) using AMPTE/IRM observations. The main difference with Phan et al. (1994) results obtained in this work is connected to a possibility to make simultaneous measurements inside and outside the magnetopause at comparatively small distances using the particle and magnetic field data of the THEMIS satellite mission. Current analysis show that the total pressure is nearly constant during the all satellite crossing of the magnetosheath despite high level of turbulence constantly observed in the magnetosheath. These results show that the total pressure balance is the main condition determining the magnetosheath dynamics and the position of the magnetopause.

Significant number of observations in the magnetosheath, including the THEMIS satellite observations shows the great level of plasma turbulence. Fluctuations of the value and the direction of the magnetic field are constantly present even during periods of comparatively stable orientation of the interplanetary magnetic field. The amplitudes of these fluctuations are comparable with the minimal values of the magnetic field at the dayside magnetic field line (see Rossolenko et al. (2008) and Fig. 9 of this work). These fluctuations create an obstacle for the widely accepted picture shown on Fig. 1 of magnetic reconnection at the magnetopause. Real magnetic field near the magnetopause has different values and orientations at different points of the magnetopause. Which means that ordinarily discussed reconnection picture is nonapplicable for description of the processes near magnetopause. Fig. 12 shows more realistic then the scheme shown on Fig. 1 scheme of magnetic field in the magnetosheath when IMF has northward orientation. Large fluctuations of magnetic field at high latitudes where the magnetic field on the magnetospheric field lines is small (see Fig. 9) create the favorable conditions for field line interconnection and magnetosheath plasma penetration inside the magnetosphere. The events having large amplitudes will be selected as flux transfer events.

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, indicates that at different points of the magnetopause the magnetic field has different orientations, poorly correlated with the orientation of the IMF. Correspondingly [**VB**] also has different orientation at different points of the magnetosheath and near the magnetopause. That is why very popular idea on the solar wind electric field penetration inside the magnetosphere has the real obstacles. It is necessary to mention also that the suggestion about large-scale magnetospheric convection generation by boundary layer processes also meets with some obstacles (for example, boundary layers are mapped at the ionosphere near noon in accordance with Newell and Meng (1992)). However, this subject requires analysis that is more careful.

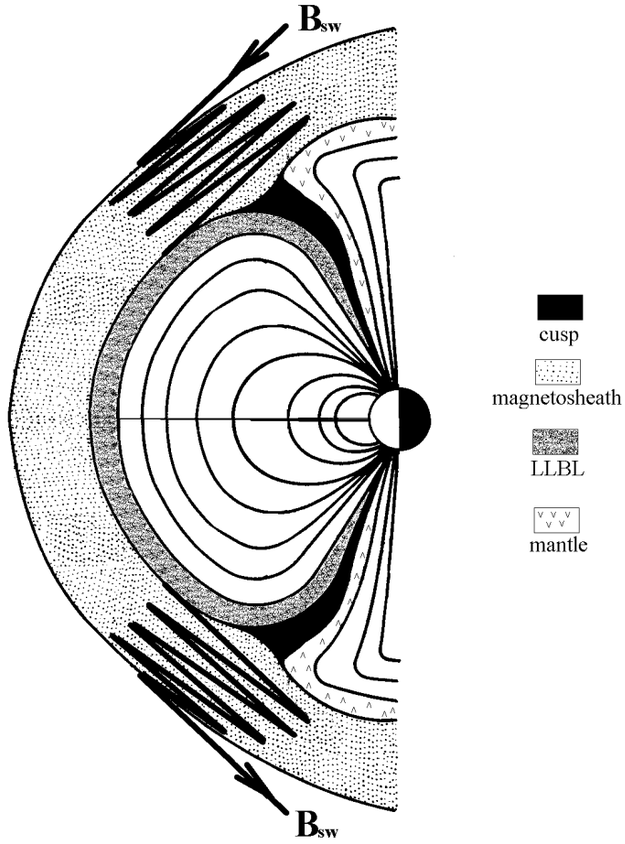


Fig. 12. Sketch illustrating the distribution of magnetic field in the magnetosheath when IMF has northward direction

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. However, it is possible to explain such correlation without postulating the dominant role of reconnection processes at the magnetopause. Let to remind that Sibeck et al. (1991) made a conclusion that "onion peel" model cannot explain the change of magnetopause position under the influence of the interplanetary magnetic field. Sibeck et al. (1991), Tsyganenko & Sibeck (1994), Sibeck (1994) focused on the changes of values of sources of magnetic field inside the magnetosphere under the influence of the IMF and show that such changes can explain the change of magnetopause position under the influence of IMF. Results obtained by Sibeck et al. (1991), Tsyganenko & Sibeck (1994), Sibeck (1994) select the pressure balance at the magnetopause as the main condition determining the dynamics of the magnetopause. It was also shown that the changes of the dayside part of Region 1 currents of Iijima and Potemra under the influence of IMF could produce comparatively large changes in the magnetopause position. Developed by Sibeck et al. (1991) approach is not based on the suggestion of the validity of frozen-in condition, which can be destroyed in a number of points or lines at the magnetopause. The only think, which requires the explanation, is the well-known dependence of the magnetic field inside the magnetosphere on the IMF value and orientation.

Observed distribution of the plasma pressure inside the magnetosphere and of the Region 1 currents of Iijima and Potemra show that Region 1 current generation is a consequence of the existence of azimuthal plasma pressure gradients inside the magnetosphere (see (Iijima et al., 1997; Wing & Newell, 2000; Stepanova et al. 2004; Xing et al., 2009)). These results support the scenario proposed by Antonova & Ganushkina (1997) based on the analysis of the geometry of the high latitude magnetosphere as **j**=rot**B**. In this model, the field-aligned currents appear due to divergence of transverse magnetospheric currents. Therefore, the modulation of currents inside the magnetosphere by large-scale IMF can explain the change of magnetopause position under the influence of IMF irrespective to the orientation of the magnetosheath magnetic field near the magnetopause. It was stressed that the external source of the magnetic field in the condition of magnetostatic equilibrium when the gradient of plasma pressure is equal to the Ampere's force (i.e.∇p=**[jB]**)) produces the increase of current in the case of the decrease of **B** (the addition of field with southward orientation) and the decrease of current in the case of the increase of **B** (the addition of field with northward orientation) when the plasma pressure gradients change slowly. Therefore, penetration of IMF inside the magnetosphere irrespective of magnetic field fluctuations in the magnetosheath can produce the necessary current modulation. The characteristic time of such modulation is determined by the Alfven travel time (i.e. the time of MHD wave flow from the magnetopause to the distances ~10R_E, where plasma pressure gradients which support the Region 1 currents are mainly concentrated according to Xing et al. (2009)). This time is ~2-3 min. Correspondingly, the characteristic time of the change of Region 1 currents and dawn-dusk electric field is of the same order of magnitude. Such estimation is in agreement with the results of radar observations of Ruohoniemi and Greenwald (1998), Ruohoniemi and Baker (1998), Ruohoniemi et al. (2001, 2002) who obtained a small time delay in the response of the high-latitude ionospheric convection to the IMF variations.

Change of the magnetic configuration under the influence of external magnetic field takes place even in the case of vacuum configuration. MHD models of magnetosphere, which do not suggest the validity of the frozen-in condition, clearly demonstrate such influence. Therefore, the solution of the problem does not require the action of reconnection processes at the magnetopause as a reason of IMF influence to the magnetosperic processes. Inversely, such reconnection processes can be a consequence of stress disbalance at the local regions of the magnetopause between the total pressure at the magnetosheth and the mainly magnetic pressure inside the magnetopause. Change of field line topology in such a case has a character of topological reconnection. Large-scale change of magnetic configuration leads to the magnetosheath plasma capture inside the magnetosphere. Such capture was observed, for example, 3 June 2007 by THEMIS satellites and interpreted as an action of double reconnection by Lee at al. (2008). It is interesting to mention that topological reconnection does not require local dissipation (and corresponding plasma heating). High level of magnetosheath turbulence (different values and orientation of magnetic field at different points near the magnetopause) suggests that the discussed reconnection have patchy character. The existence of topological reconnection does not exclude the action of different scenario of classical local reconnection with local destruction of magnetopause current due to development of local instabilities and current dissipation. It only gives the possibility to overcome difficulties related to the presence of high level of turbulence in the magnetosheath.

Suggested scenario helps to overcome difficulties connected with the discussed problem of particle penetration inside the magnetosphere in the conditions of high level of magnetic fluctuations in the magnetosheath. However, it does not exclude the traditionally discussed mechanisms of local destructions of magnetopause current sheet and flux transfer events formation, particle diffusion and development of Kelvin-Helmholts instability at the magnetopause. Future studies will give the possibility to evaluate the importance of each of such mechanisms.

6. 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/.

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.

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, FONDECYT grant 1110729.

7. References

Angelopoulos, V. (2008). The THEMIS Mission. *Space Sci. Rev.*, Vol. 141, pp. 5–34. doi: 10.1007/s11214-008-9336-1.

Antonova, E. E.; & Ganushkina, N. Yu. (1997). Azimuthal hot plasma pressure gradients and dawn-dusk electric field formation. *J. Atmos. Solar-Terr. Phys.* Vol. 59, No.11, pp.1343-1354.

Auster, H.U.; Glassmeier, K.H., Magnes, W. , Aydogar, O. , Baumjohann, W. et al. (2008). The THEMIS Fluxgate Magnetometer. *Space Sci. Rev.* Vol. 141, pp. 235–264.

Bittencourt, J.A. Fundamentals of Plasma Physics, Springer, 2004, 580 p.

Borovsky, J.E.; & Bonnell, J. (2001). The dc electrical coupling of flow vortices and flow channels in the magnetosphere to the resistive ionosphere. *J. Geophys. Res.* Vol. 106, No A12, pp. 28967-28994.

Borovsky, J. E.; & Gary, S. P. (2009). On shear viscosity and the Reynolds number of magnetohydrodynamic turbulence in collisionless magnetized plasmas: Coulomb collisions, Landau damping, and Bohm diffusion. *Physics of Plasmas.* Vol. 16, 082307. Available from http://pop.aip.org/pop/copyright.jsp

Chapman, S.; & Ferraro, V.C.A. (1931). *Terr. Magn.* Vol. 36, pp. 77.

Coleman, I. J. (2005). A multi-spacecraft survey of magnetic field line draping in the dayside magnetosheath. *Annales Geophysicae*. Vol. 23, pp. 885–900.

Dungey, J.W. (1961). Interplanetary magnetic field and auroral zone. *Phys. Rev. Lett*.. Vol. 6, No 1, pp. 47-49.

Fairfield, D. H. (1967). The ordered magnetic field of the magnetosheath. *J. Geophys. Res.* Vol. 72, No 23, pp. 5865-5877.

Gutynska, O.; Šafránková, J. & Němeček, Z. (2008). Correlation length of magnetosheath fluctuations: Cluster statistics. *Annales Geophysicae.* Vol. 26, pp. 2503–2513.

Iijima, T.; Potemra, T.A. & Zanetti, L.J. (1997). Contribution of pressure gradients to the generation of dawnside region 1 and region 2 currents. *J. Geophys. Res.* Vol. 102, No A12, pp. 27069-27081.

Lavraud, B.; Foulton, C., Farrugia, C.J. & Eastwood, J.P. (2011). The magnetopause, its boundary layers and pathways to the magnetotail. *The Dynamic Magnetosphere*, ed. W. Liu and M. Fujimoto, IAGA Special Sopron Book Series, Springer, pp. 3-28.

Li, W.; Raeder, J., Øieroset, M., & Phan, T.D. (2009). Cold dense magnetopause boundary layer under northward IMF: Results from THEMIS and MHD simulations. *J. Geophys. Res.* Vol. 114, A00C15, doi:10.1029/2008JA013497.

Luhmann, J. G.; Russell, C. T., & Elphic, R. C. (1986). Spatial distributions of magnetic field fluctuations in the dayside magnetosheath. *J. Geophys. Res.* Vol. 91, pp. 1711–1715.

Lucek, E. A.; Dunlop, M.W., Horbury, T. S., Balogh, A., Brown, P., Cargill, P., Carr, C., Fornacon, K.-H., Georgescu, E., & Oddy, T. (2001). Cluster magnetic field observations in the magnetosheath: four-point measurements of mirror structures. *Ann. Geophys.* Vol. 19. pp. 1421–1428.

McFadden, J.P.; Carlson, C.W. , Larson, D., Ludlam, M. , Abiad, R. Elliott, B. Turin, P. Marckwordt, M. , & Angelopoulos, V. (2008). The THEMIS ESA plasma instrument and in-flight calibration. *Space Sci. Rev.* Vol. 141, pp. 277–302.

Němeček, Z.; Šafránková, J., Přech, L., Zastenker, G. N., Paularena, K. I., & Kokubun, S. (2000a). Magnetosheath study: INTERBALL observations. *Adv. Space Res.* Vol. 25, pp. 1511–1516.

Němeček, Z.; Šafránková, J., Zastenker, G. N., Pišoft, P., Paularena, K. I., & Richardson, J. D. (2000b). Observations of the radial magnetosheath profile and a comparison with gasdynamic model predictions. *Geophys. Res. Lett.* Vol. 27, pp. 2801–2804.

Němeček, Z.; Šafránková, J., Zastenker, G., Pišoft, P., & Jelínek, K. 2002a. Low-frequency variations of the ion flux in the magnetosheath. *Planet. Space Sci.* Vol. 50, pp. 567–575.

Němeček, Z.; Šafránková, J., Zastenker, G. N., Pišoft, P., & Paularena, K. I. (2002b). Spatial distribution of the magnetosheath ion flux, *Adv. Space Res.* 30(12), 2751–2756.

Newell, P.T. & Meng, C.-I. (1992). Mapping the dayside ionosphere to the magnetosphere according to particle precipitation characteristics. *Geophys. Res. Lett.* Vol. 19, No 6, pp. 609-612.

Panov, E. V.; Büchner, J., Fränz, M., Korth, A., Savin, S. P., Rème, H., & Fornaçon, K.-H. (2008). High-latitude Earth's magnetopause outside the cusp: Cluster observations. *J. Geophys. Res.* Vol. 113, A01220, doi:10.1029/2006JA012123.

Phan, T.-D.; Paschman G., Baumjohanann W., Sckopke N., & Lühr H. (1994). The magnetosheath region adjacent to the dayside magnetopause: AMPTE/IRM observations. *J. Geophys. Res.* Vol. 99, No A1, pp. 121-141.

Phan, T.-D & Paschman G. (1996). Low-latitude dayside magnetopause and boundary layer for high magnetic shear: Structure and motion. *J. Geophys. Res.* Vol. 101, No A4, pp. 7801-7815.

Riazantseva, M.O.; Zastenker G.N., Richardson J.D., & Eiges P.E. (2005). Sharp boundaries of small- and middle-scale solar wind structures. *J. Geophys. Res.* Vol. 110, A12110, doi:10.1029/2005JA011307.

Riazantseva, M.O.; Khabarova O.V., Zastenker G.N., & Richardson J.D. (2007). Sharp boundaries of solar wind plasma structures and their relationship to solar wind turbulence. *Adv. Space Res.* Vol. 40, pp. 1802–1806.

Rossolenko, S. S.; Antonova, E. E. , Yermolaev, Yu. I., Verigin, M. I., Kirpichev, I. P., & Borodkova, N. L. (2008). Turbulent fluctuations of plasma and magnetic field parameters in the magnetosheath and the low-latitude boundary layer formation: Multisatellite observations on March 2, 1996. *Cosmic Research*. Vol. 46, No 5, pp. 373–382.

Ruohoniemi, J. M.; & Greenwald, R. A. (1998). The response of high latitude convection to a sudden southward IMF turning. *Geophys. Res. Lett*. Vol. 25, No 15, pp. 2913-2916.

Ruohoniemi, J.M.; & Baker, K.B. (1998) Large-scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.* 103(A9), 20797-20811.

Ruohoniemi, J.M.; Barnes, J.M., Greenwald, R.A., Shepherd, S.G., & Bristow, W.A. (2001). The response of high latitude ionosphere to the CME event of April 6, 2000: a practical demonstration of space weather now casting with the SuperDARN HF radars. *J. Geophys. Res.* Vol. 106, No A12, pp. 30085-30097.

Ruohoniemi, J. M.; Shepherd, S.G., & Greenwald, R.A. (2002). The response of the high-latitude ionosphere to IMF variations. *J. Atmosph. and Solar-Terr. Physics.* Vol. 64, No. 2, pp. 159-171.

Ŝafránková, J.; Hayosh, M., Gutynska, O., Němeček, Z., Přech, L. (2009). Reliability of prediction of the magnetosheath B_Z component from interplanetary magnetic field observations. *J. Geophys. Res.* Vol. 114, A12213, doi:10.1029/2009JA014552.

Savin, S.; Amata, E., Zelenyi, L., Budaev, V. et al. (2008). High energy jets in the Earth's magnetosheath: Implications for plasma dynamics and anomalous transport. *JETP Letters.* Vol. 87, No 11, pp. 593–599.

Shevyrev, N. N.; & Zastenker, G. N. (2005). Some features of the plasma flow in the magnetosheath behind quasi-parallel and quasi-perpendicular bow shocks. *Planet. Space Sci.* Vol. 53, pp. 95–102.

Shevyrev, N. N., Zastenker, G. N., & Du, J. (2007). Statistics of low-frequency variations in solar wind, foreshock and magnetosheath: INTIERBALL-1 and CLUSTER data. *Planet. Space Sci.* Vol. 55, No 15, pp. 2330–2335.

Sibeck, D.G.; Lopez, R.E., & Roelof, E.C. (1991). Solar wind control of the magnetopause shape, location and motion. *J. Geophys. Res.* Vol. 96, No A4, pp. 5489-5495.

Sibeck, D.G. (1994). Signatures of flux erosion from the dayside magnetosphere. *J. Geophys. Res.* Vol. 99, No A5, pp. 8513-8529.

Sibeck, D.G.; & Angelopoulos, V. (2008). THEMIS science objectives and mission phases,. *Space Sci. Rev.*. Vol. 141, pp. 35–59, doi: 10.1007/s11214-008-9393-5.

Sibeck, D.G.; Phan T.-D., Lin R.P. et al. (2000). A survey of MHD waves in the magnetosheath: International Solar Terrestial Program observations. *J. Geophys. Res*. Vol. 105, No A1, pp. 129–138.

Spreiter, J.R.; Summers, A.L., & Alksne, A.Y. (1966). Hydromagnetic flow around the magnetosphere. *Planet. Space. Sci.*. Vol. 14, No 3, pp. 223-253.

Spreiter, J.R.; & Alksne, A. Y. (1969). Plasma flow around the magnetosphere. *Rev. Geophys.*. Vol. 7, pp. 11-50.

Spreiter, J.R.; & Stahara, S.S. (1980). A new predictive model for determining solar wind-terrestrial planet interaction,. *J. Geophys. Res.* Vol. 85, No 12, pp. 6769- 6777.

Stepanova, M.V.; Antonova, E.E., Bosqued, J.M., Kovrazhkin, R. (2004). Azimuthal plasma pressure reconstructed by using the Aureol-3 satellite date during quiet geomagnetic conditions. *Adv. Space Res.* Vol. 33, No 5, pp. 737–741, doi:10.1016/S0273-1177(03)00641-0.

Stepanova M.; Antonova, E. E., Paredes-Davis, D., Ovchinnikov, I. L. & Yermolaev, Y. I. (2009). Spatial variation of eddy-diffusion coefficients in the turbulent plasma sheet during substorms. *Ann. Geophys.* Vol. 27, pp. 1407–1411.

Stepanova, M.; V. Pinto, J. A. Valdivia, & E. E. Antonova (2011) Spatial distribution of the eddy diffusion coefficients in the plasma sheet during quiet time and substorms from THEMIS satellite data. *J. Geophys. Res.,* Vol. 116, A00I24, doi:10.1029/2010JA015887.

Troshichev, O.A.; Antonova, E.E., & Kamide, Y. (2002). Inconsistence of magnetic field and plasma velocity variations in the distant plasma sheet: violation of the "frozen-in" criterion? *Adv. Space Res.* Vol. 30, No. 12, pp. 2683-2687.

Tsyganenko, N.A.; & Sibeck, D.G. (1994). Concerning flux erosion from the dayside magnetosphere. *J. Geophys. Res.* Vol. 99, No A7, pp. 13425-13436.

Tsyganenko, N.A. (2002a). A model of the near magnetosphere with a dawn-dusk asymmetry: 1. Mathematical structure. *J. Geophys. Res.* Vol. 107, No A8, doi: 10.1029/2001JA000219.

Tsyganenko, N.A. (2002b). A model of the near magnetosphere with a dawn-dusk asymmetry: 2. Parameterization and fitting to observations. *J. Geophys. Res.* Vol. 107, No A8, doi: 10.1029/2001JA000220.

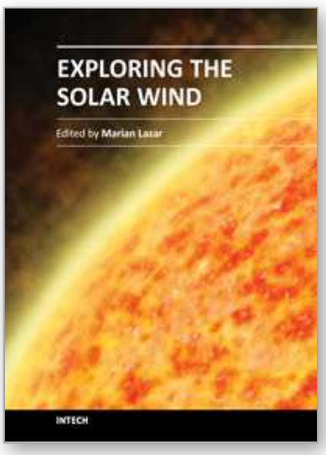
Zastenker, G. N.; Nozdrachev, M. N., Němeček, Z., Ŝafránková, J., Přech, L., Paularena, K. I., Lazarus, A. J., Lepping, R. P., & Mukai, T. (1999). Plasma and magnetic field variations in the magnetosheath: Interball-1 and ISTP spacecraft observations, in: Interball in the ISTP Program, edited by: Sibeck, D. G. and Kudela, K., *NATO Science Series*. Vol. 537, pp. 277–294.

Zastenker, G. N.; Nozdrachev, M. N., Němeček, Z., Ŝafránková, J., Paularena, K. L., Richardson, J. D., Lepping, R. P., & Mukai, T. (2002). Multispacecraft measurements of plasma and magnetic field variations in the magnetosheath: Comparison with Spreiter models and motion of the structures. *Planet. Space Sci*. Vol. 50, pp. 601–612.

Znatkova, S. S.; Antonova, E. E., Zastenker, G. N. &Kirpichev, I. P. (2011). Pressure balance on the magnetopause near the subsolar point according to observational data of the THEMIS project satellites. *Cosmic Research.* Vol. 49, No. 1, pp. 3–20.

Wing, S.; & Newell, P.T. (2000). Quite time plasma sheet ion pressure contribution to Birkeland currents. *J. Geophys. Res.* Vol. 105, No A4, pp. 7793-7802.

Xing, X.; Lyons, L.R, Angelopoulos, V., Larson, D., McFadden, J., Carlson, C., Runov, A., & Auster, U. (2009). Azimuthal plasma pressure gradient in quiet time plasma sheet. *Geophys. Res. Lett.* Vol. 36, No 14, L14105. doi:10.1029/2009GL038881.



Exploring the Solar Wind

Edited by Dr. Marian Lazar

ISBN 978-953-51-0339-4
Hard cover, 462 pages
Publisher InTech
Published online 21, March, 2012
Published in print edition March, 2012

This book consists of a selection of original papers of the leading scientists in the fields of Space and Planetary Physics, Solar and Space Plasma Physics with important contributions to the theory, modeling and experimental techniques of the solar wind exploration. Its purpose is to provide the means for interested readers to become familiar with the current knowledge of the solar wind formation and elemental composition, the interplanetary dynamical evolution and acceleration of the charged plasma particles, and the guiding magnetic field that connects to the magnetospheric field lines and adjusts the effects of the solar wind on Earth. I am convinced that most of the research scientists actively working in these fields will find in this book many new and interesting ideas.

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

IntechOpen