MAGNETOPAUSE PRESSURE BALANCE AT THE SUBSOLAR POINT IN ACCORDANCE WITH DATA OF THEMIS MISSION: EVENT JULY 22, 2007

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Abstract. Magnetic field and plasma measurements onboard the THEMIS satellites are used to study the plasma pressure balance across the magnetopause July 22, 2007. The main feature of the event is the opposite orientation of the magnetic field in the solar wind and near the subsolar magnetopause. Both plasma flows and magnetic field vary significantly in the magnetosheath. Nevertheless, it has been shown, that despite such great variations and restrictions of the applicability of MHD approximation in case of the noncollisional plasma, the condition of stress balance is fulfilled with comparatively high accuracy. The amplitudes of magnetic field fluctuations in the magnetosheath are compared to the values of magnetic field inside the magnetosphere at high latitudes. It is shown that magnetic pressure in the magnetosheath is the important factor of magnetopause stress balance at high latitudes. The applicability of the concept of the formation of reconnection line at the magnetopause is discussed.

INTRODUCTION

Multiple results of observations demonstrate the high level of fluctuations of parameters of plasma and magnetic field in the magnetosheath. However the problem of the stress balance on the magnetopause is purely studied. Such analysis has the fundamental importance for the solution of mass, momentum and energy penetration inside the magnetosphere. Znatkova et al. (2010) analyzed the magnetopause stress balance for the event July 18, 2007, using data of THEMIS mission. It was found that the conditions of stress balance are fulfilled with accuracy ~ 10%. In this paper we analyze the event July 22, 2007 of crossing the magnetopause by 4 of 5 THEMIS probes when magnetic field in the solar wind have northward orientation and magnetic field near the magnetopause has comparatively stable southward orientation. We compare the values of pressure from different satellites when one is on the internal and the other is on the external borders of the magnetopause. Results of observations are compared with existing theory predictions. THEMIS instruments used in this study are the electrostatic analyzer (ESA) and the flux gate magnetometer (FGM) with time resolution of 3 sec (Angelopoulos, 2008; Sibeck and Angelopoulos, 2008).

THE CROSSING OF THE MAGNETOPAUSE BY THEMIS SATELLITES JULY 22, 2007

Five THEMIS satellites during summer 2007 weren't deployed into a 'string-of-pearls' configuration, planned to find the elusive substorm point of origin. July 22 satellites alternately or almost simultaneously crossed the magnetopause near the subsolar point (see Fig. 1). The interplanetary magnetic field (IMF) in the analyzed case has a northward orientation (Bz~2nT). Variations of the dynamic pressure of solar wind ions at the moment of crossing the magnetopause are small (~0.2 nPa). Correlation between the dynamics of the
magnetopause and the changes in solar wind pressure is not observed. The geomagnetic situation was calm. The amplitudes of the indices AU, AE, AO and AL did not exceed 100 nT. Dst index was −15 nT, which prevents rapid changes of the magnetopause position due to changes in the magnetic field inside the magnetosphere.

Fig. 2 shows spectrograms of THEMIS-A, B, C and D. THEMIS-A crossed the sharp boundary between the magnetosphere and magnetosheath (MPB) at 03:57:10 UT, THEMIS-C – at 03:55:41 UT, THEMIS-D – at 03:55:36 UT, THEMIS-E – at 03:55:44 UT. The sharp boundary was not observed at THEMIS-B. The vertical lines on the spectrogram panels show the position of the boundary between the magnetosphere and magnetosheath. Spacecrafts were inside the magnetosphere to the left of the line, as it is proved by the
registration of electrons and ions in a wide energy range (0.02 – 10 keV). Ions and electrons of magnetosheath characterized by high density and energy from 0.01 to ~1 keV are observed to the right of the vertical line on the spectrogram. The regions of two different populations of plasma for this case are clearly separated, which allows to determine the boundary location. Fig. 3 shows simultaneously measured three components of the magnetic field with time resolution 3 sec on THEMIS-A and THEMIS-C to clarify the position of the magnetopause. Magnetic field variations obtained by THEMIS-D and THEMIS-E look similar.

![Fig. 3. Three components of the magnetic field observed at THEMIS-A and THEMIS-C.](image)

The IMF had a northward orientation in the analyzed case which coincides with the direction of the magnetic field inside the magnetosphere. Therefore it is not possible to determine the current layer, where the magnetic field changes from the direction of the solar wind, to the direction determined by the geomagnetic dipole. The magnetic field in the magnetosheath fluctuates, which is typical for magnetosheath. Turbulent changes in the orientation of the magnetic field make an ambiguous the definition of the outer boundary of the magnetopause.

The magnetic pressure makes the dominant contribution to the total pressure near the subsolar point inside the magnetosphere. The fact of anisotropy of plasma pressure in the magnetosphere has no appreciable effect on the total pressure. The anisotropy of distribution functions is insignificant inside the magnetosphere near the subsolar point where magnetic field is large and plasma parameter $\beta \ll 1$. However, it must be taken into account in the magnetosheath. Pressure balance condition at the magnetohydrodynamic discontinuity, taking into account the anisotropy of plasma pressure has the form

$$\begin{bmatrix} \mu_0 \frac{B^2}{n_e m_e v_e^2} + \frac{B^2}{2 \mu_0} \end{bmatrix} + B_n \left\{ p_\perp - \frac{B^2}{B^2} \right\} = 0,$$

where curly brackets denote the difference between the values before and after the discontinuity, index $p$ denotes protons (ions), $e$ – electrons; $n$ is density, $v$ is the bulk flow velocity, $m_p$ is the proton mass, $m_e$ is the electron mass, $p_\perp$ and $p_\parallel$ are the thermal plasma pressures across and along the magnetic field, $B_n$ and $B_l$ are the magnetic field components perpendicular and parallel to the discontinuity plane, $\mu_0$ is the permeability of vacuum. In our case at the magnetopause $B_n = 0$, $B_l = B$, where $B$ is the value of the magnetic field and there is no flow of plasma through the magnetopause. Therefore, relation for the pressure balance near the magnetopause has the form

$$\begin{bmatrix} \mu_0 \frac{B^2}{2 \mu_0} \end{bmatrix} = 0.$$

Full pressure inside the magnetosphere: $P = p_\perp + \frac{B^2}{2 \mu_0}$. Full pressure in the magnetosheath (the dynamic pressure must be included): $P = n_p m_p v_p^2 + n_e m_e v_e^2 + p_\perp + \frac{B^2}{2 \mu_0}$. 
The value of the magnetic field inside the magnetosphere near the subsolar point is large and constitutes ~ 50 nT. Pressure of particles inside the magnetopause does not contribute significantly to the pressure balance. The minimal errors in the calculation of the dynamic pressure of magnetosheath plasma occur at the subsolar point, where the angle between the solar wind direction and the normal to shock wave is close to zero. Besides, magnetospheric magnetic field lines in the subsolar point have the minimal curvature compared with other areas.

We analyze the value of total pressure across the magnetopause in the subsolar point, using data obtained by THEMIS spacecraft instruments. The perpendicular to the magnetopause components of the ion and electron velocity in the magnetosheath $v_\perp$ were used for the calculations. We assume that $v_\perp \approx v_x$, where $v_x$ is the velocity component along the axis $X_{GSM}$. The pressure was near to isotropic for the analyzed case. The results of the calculations of pressure components, based on the data obtained by THEMIS satellite, are shown on the Fig. 4. The magnetic pressure dominates inside the magnetosphere, but it is only about 5 – 20% of the total pressure in the magnetosheath. Plasma pressure, both static and dynamic, begins to dominate in the magnetosheath. Also, it is clear that total pressure within the magnetosphere is determined by the magnetic pressure. The total pressure in the magnetosheath is determined by the thermal pressure of the ion component of plasma.

Analysis of changes of the components of pressure and total pressure on the interval of 30 seconds (see Fig. 5) shows that the magnitude of total pressure on the two boundaries of the magnetopause is almost the same (1.02 nPa at the magnetospheric boundary and 1.12 nPa at the magnetosheath border, i.e. after 18 seconds of flight) and their difference does not exceed 9% (this value is within the accuracy of measurements of plasma parameters). Here is also shown that there are the relatively smooth pressure changes inside the magnetopause despite the considered inapplicability of the MHD approach to the description of processes within the current sheets.

The calculated components of pressure on satellites THEMIS-C, -D and -E in the time interval of 30 seconds look similar. Pressure changes are observed within the magnetopause. At the edges of the magnetopause the difference of the total pressure is kept within 15% for THEMIS-C and -D and within 25% for the THEMIS-E.
The condition of pressure balance is better fulfilled (see Fig. 6) when we compare the values of pressure from different satellites when one is on the internal and the other is on the external boundary of the magnetopause (8% for couples -C and -D, -C and -E, and 10% for -D and -E)

**POSSIBLE REASONS FOR DEVIATIONS FROM THE PRESSURE BALANCE AT THE MAGNETOPAUSE**

The total pressure in the magnetosheath is determined mainly by thermal plasma pressure, i.e. by density and ion temperature. Using the estimations for other similar experiments (http://cdaweb.gsfc.nasa.gov/), we can assume that the accuracy of the absolute values of ion temperature usually doesn't exceed the value about 5 – 10%, i.e. is near to the obtained value of the pressure disbalance on the magnetopause. Then, there was
the relatively fast motion of the magnetopause. There remain some problems with the applicability of magnetohydrodynamic balance conditions for the noncollisional turbulent plasma.

The small deviation from the pressure balance can also be connected with small shift of the region of measurements from the subsolar point. The magnetic configuration was calculated for this case using Tsyganenko-2001 model (Tsyganenko, 2002a,b). It was shown that variations of the magnetic field in the magnetosheath are comparable with the minimum values of the magnetic field on the dayside magnetic field lines. This effect may be essential for the solution of the problem of plasma penetration inside the magnetosphere.

**CONCLUSIONS AND DISCUSSION**

The event July 22, 2007 of multiple THEMIS satellite crossings of the magnetopause is analyzed. The main feature of the event is comparatively stable northward IMF orientation and comparatively stable southward orientation of the magnetic field near the magnetopause. In spite of constantly observed high level of turbulence in the magnetosheath, the balance of pressure near the subsolar point is performed with comparatively high accuracy (disbalance is <10%).

The amplitude of the fluctuations of the magnetic field in the magnetosheath is comparable to the magnetic field inside the magnetosphere at high latitudes, which may lead to a local disbalance of pressures. Comparison of experimentally measured magnetic field in the magnetosheath with theoretically predicted picture with laminar plasma flow and laminar magnetic field demonstrate great discrepansy (see Fig. 7, 8). Magnetic field in the magnetosheath in the analyzed case not only greatly fluctuate, It has the inverse direction in comparison with the direction of the magnetic field in the solar wind. Such feature creates the great difficulty for the theories of formation large-scale reconnection line on the magnetopause.

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