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Study of the plasma flow and magnetic filed in the Earth's magnetosheath

by
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Abstract of Doctoral thesis

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Introduction

In the interaction region between the solar wind and the Earth's magnetic field, complicated physical processes take place in a wide range of spatial and temporal scales. This region, which is called the magnetosheath, is full of the solar wind plasma distorted by the bow shock that changes the direction of the plasma flow and heats it. On the other side, the magnetosheath is bounded by the magnetopause that represents, in a first approximation, an impenetrable obstacle to the solar wind flow.

First information about the magnetosheath was obtained by the Explorer 12 spacecraft launched in 1961. During its path out from the outer magnetosphere, it found the magnetopause and bow shock and the transition region between them. Subsequent investigations have shown that the characteristics of the magnetosheath, such as its shape and thickness, the compression of the magnetic field toward the magnetopause, or mixing of particles from the magnetosheath and the magnetosphere depend on the solar wind parameters. Especially, the role of upstream dynamic pressure, and strength and direction of the interplanetary magnetic field (IMF) are important. Moreover, the changes in the solar wind plasma and IMF are important sources of many dynamic features observed in the magnetosphere (*Elphic* and *Southwood*, 1987, [1]; *Song et al.*, 1992, [2]; *Russell et al.*, 1992, [3]).

One of early experimental investigation of the magnetosheath has been carried out by *Howe* and *Binsak* (1972) [4]. They studied the flank magnetosheath 20-60 R_E downstream from the Earth using Explorer 33 and Explorer 35 plasma data. They found that occasionally magnetosheath speed adjacent to the magnetopause can be 10-20% greater than that of the solar wind.

Simultaneously with spacecraft observations, first magnetosheath models were developed. One of first theoretical models that described the magnetosheath plasma flows was proposed by *Spreiter et al.* (1966) [5]. In their model, the solar wind flows along the Sun-Earth line, strikes the subsolar magnetopause and then is diverted radially from this point. The model predicts that flow velocities decrease from the bow shock to the magnetopause, whereas the density and temperature increase in a vicinity of the stagnation streamline. At the flanks, the density and the velocity decrease but the temperature increases along radial profiles from the bow shock to the dayside magnetopause. Along flanks of the near-Earth magnetotail, minimum velocities and maximum temperatures occur in the middle magnetosheath. The flow accelerates up the solar wind speed and becomes increasingly like solar wind toward the flanks of the bow shock, as the shock becomes weaker.

Song et al. (1990) [2] and *Song et al.* (1992) [6] studied processes in the magnetosheath using data from ISEE-1 and 2 and discovered a region of the plasma density enhancements and magnetic field depression near the magnetopause, with relatively large spatial extent. They inferred that in some cases, this slow-mode structure was locally generated in the magnetosheath as a part of the interaction of the magnetosheath with the magnetosphere. The slow-mode structure is followed by a density decrease adjacent to the magnetopause which was earlier reported as the plasma depletion layer (PDL). Using a two-dimensional MHD simulation, *Lee et al.* (1991) [7] showed that such structure could be formed close to the stagnation region. *Southwood* and *Kivelson* (1992) [8] suggested that slow-mode structures would be a product of MHD nature of the solar wind – magnetopause interaction.

Sibeck and *Gosling* (1996) [9] studied of the transient variations of the ion flux in the magnetosheath. They observed magnetosheath plasma density reduction behind the quasi-parallel bow shock. They interpreted this change as an evidence for a radial magnetosheath motion induced by the IMF variations.

Zhang et al. (1996) [10] used the observations of the solar wind plasma and IMF from ISEE-3 as an input to the gasdynamic convected field model (GDCF). For three case studies, the model output is compared with the magnetosheath quantities observed by ISEE-2 in order to identify the sources of observed variations in the magnetosheath. It is found that some variations in the magnetosheath plasma and magnetic field are well correlated with corresponding variations in the solar wind and hence have their sources in the solar wind. The authors showed that other variations in both plasma and magnetic field in the magnetosheath do not exhibit appreciable correlations with variations in the solar wind. Most of these variations occur in the inner magnetosheath, indicating that they are endogenous in nature.

Based on the observations from the GEOTAIL spacecraft, *Petrinec et al*. (1997) [11] examined the plasma flow and magnetic field within the nightside magnetosheath (25-45 R_E downstream of the Earth). They examined two cases when the spacecraft passed through the equatorial magnetosheath. The authors found that the magnetosheath flow near the magnetopause is controlled by the direction of the local magnetic field with respect to the local velocity vector, and this behavior is not reflected in the solar wind. In the absence of reconnection at the magnetopause, the flow speed of the magnetosheath plasma is slowest when the velocity and magnetic field vectors are aligned and is fastest when two vectors are perpendicular one another. Through the magnetosheath, flow is slower than the corresponding speed of the solar wind. Other result of this study is that the magnetosheath plasma flows much faster than the solar wind can be occasionally observed close to the magnetopause for certain orientations of the local magnetic field. The source of these fast plasma flows is the low-latitude boundary layer (LLBL), it is not the shocked solar wind plasma.

Seon et al. (1999) [12] studied the dayside magnetosheath and used also data from GEOTAIL. The authors assumed that there is no reason to expect that a plasma depletion layer remains for the flanks of the magnetosheath. In addition, they reported a presence of significant density fluctuations with a long oscillation period away from the local noon sector of the magnetosheath. Based on the presented observations, they made the conclusion that the plasma density is in anti-correlation with the strength of the magnetic field.

Song et al. (1999a) [13] and *Song et al.* (1999b) [14] investigated the changes of the ion density in the dayside magnetosheath using the ISEE–2 measurements. The authors used the solar wind data as input parameters in the gasdynamic convected magnetic field (GDCF) model and thus they normalized magnetosheath density by the density just upstream of the bow shock. The authors showed that a clear compressional front stands out near one-third of the distance from the magnetopause to the bow shock and found two regions before and after the front which defined as depletion regions. *Nemecek et al.* (2002) [15] studied the density profile of the magnetosheath near the flanks. They reported that a similar density profile to that in *Song et al.* (1999a) [13] and *Song et al.* (1999b) [14] can be found in the dusk side magnetosheath, if the bow shock upstream is quasiparallel. According to *Nemecek et al.* (2002) [15], the location of the compressional front is at about 0.3 of the distance from the magnetopause to the bow shock. Since these observations were made in the range of $-2\ R_E < X_{GSE} < 5\ R_E$, this may imply that the slow shock is backward concave and extends to the nightside magnetosheath.

Fuselier et al. (2002) [16] used observations from INTERBALL-1 and Polar to study magnetosheath plasma near the high-latitude magnetopause and cusp during a period of the strongly northward IMF. Both spacecraft observed high-latitude magnetic reconnection between magnetosheath and lobe field lines. Measurements showed depressed magnetosheath density and enhanced magnetic field that are consistent with PDL just adjacent to the high-latitude magnetopause. The comparison of the observations with the gasdynamic and MHD predictions shows that in the region adjacent to the magnetopause, the gasdynamically predicted value of the plasma flow speed is larger than that observed. MHD simulations that include the effects of reconnection predict lower flow velocities than observed.

The brief analysis of previous investigations demonstrated that the main attention was paid to the dayside magnetosheath, whereas the physical processes in the nightside magnetosheath have been investigated less intensively. However, several recent studies have been concentrated on this topic. For example, *Paularena et al.* (2001) [20] showed a significant dawn-dusk asymmetry of the plasma density in the magnetosheath near solar maximum, with larger density values on the dawn than dusk side. According to their investigations, the observed density asymmetry does not depend on the in-ecliptic IMF orientation, apparently ruling out both foreshock effects and different compression by parallel and perpendicular shocks as causes. The authors noted that the asymmetry is strongest when the upstream magnetic field is within 22.5° of the ecliptic plane. Because the gasdynamic model assumes axial symmetry, it could not reveal features resulting from the magnetic field configuration, in particular the dawn-dusk asymmetry, which may arise from the average IMF orientation along the Parker spiral. For this reason, the authors compared MHD model predictions with their magnetosheath observations and showed that a clear asymmetry is present in the width of the magnetosheath region with the dusk sheath roughly 15% thicker than the dawn sheath at both experimental and simulation observations.

Interesting magnetosheath results were obtained in the context of the INTERBALL project (*Galeev et al.*, 1995, [18]). *Zastenker et al.* (2002) [19] based on multispacecraft measurements (INTERBALL-1, MAGION-4, GEOTAIL, and IMP-8 spacecraft) confirmed that small-scale (from several seconds up to a minute) and middle-scale (from several minutes up to an hour) variations of the ion flux and magnetic field magnitude in the magnetosheath are significantly larger (on average by factor of 3) than simultaneous variations in the solar wind. A comparison of their measurements with calculations according to the gasdynamic model (*Spreiter et al.,* 1966, [5]) of the magnetosheath plasma flow and magnetic field magnitude showed that, on average, the behavior of mentioned parameters are predicted rather well by this model. However, their large variations in the magnetosheath are not predicted by these models using simultaneous interplanetary measurements and taking into account the scanning of the magnetosheath profile across the spacecraft position due to the dynamics of solar wind parameters in the most cases.

Nemecek et al. (2000a) [20] studied the relationship between the solar wind and magnetosheath fluxes. Their study dealt with the region from $-2\ R_E$ to $-15\ R_E$. The authors used measurements of the WIND, INTERBALL-1 and GEOTAIL spacecraft. They found that magnetosheath ion flux profile can to be well described by the gasdynamic model (*Spreiter et al.,* 1966, [5]) on the scale of hours but on a shorter scale, it exhibits random fluctuations that can exceed the gasdynamic prediction by a factor of 5. The value of the fluctuations is a function of the IMF cone angle. In their study, *Nemecek et al.* (2000b) [21] showed that a difference between the averaged ion flux and its gasdynamic prediction decreases with increasing ion plasma beta and/or Alfvénic Mach number. Father, the authors discussed the radial profile of the normalized magnetosheath magnetic field and found that it is nearly constant in the nightside magnetosheath and its value decreases with a distance from the Earth.

Nemecek et al. (2002) [15] presented superposed epoch analysis of the magnetosheath flux profile near the flanks again based on the INTERBALL–1 and WIND data. The profile was normalized by simultaneous solar wind density and separated by two factors into four situations, dawn or dusk side, and downstream of quasiparallel and quasiperpendicular shocks. The result of their study is a strong dawn-dusk asymmetry of the magnetosheath ion flux with higher flux on the dawn flank. The authors showed that the observed asymmetry is not caused by the prevailing IMF orientation but the whole magnetosheath profile depends on

IMF B_Z. They observed a depletion layer at the magnetopause only in the dusk side for positive B_Z. This case of the IMF orientation is in a good agreement with *Southwood* and *Kilevson* (1995) [22] considerations.

The aim of thesis

From a short overview of previous magnetosheath investigations it follows that our present knowledge of this crucial region of the solar wind – magnetosphere interaction is still insufficient. Current theoretical understanding of the magnetosheath plasma flow is still qualitative and not complete. Gasdynamic and MHD models predict a presence of some structures in the magnetosheath and experiments bring a convincing evidence of the existence of these structures there. However, many authors reported that the different magnetosheath parameters were observed for the same solar wind conditions. Thus, the detailed comparison of model predictions with experimental data may show which parameter or a set of parameters is important and would be included into models.

The first statistical studies based on hourly averaged data and presented by *Zastenker et al.* (1999) [23] and *Nemecek et al.* (2000a) [20] indicated only a qualitative agreement of the magnetosheath ion flux with its gasdynamic prediction. The present thesis would perform a comprehensive analysis of the ion flux and magnetic filed magnitude in the nightside magnetosheath involving statistical and case studies, and comparison of experimental profiles with MHD model(s).

This complex task could be divided into following particular topics:

1. Statistical study of the ion flux and magnetic field strength which would reveal dependences of both profiles on: (a) upstream parameters (velocity, density, dynamic pressure, Mach number, etc.), (b) IMF orientation, (c) location in the magnetosheath.
2. Statistical study of an influence of the internal magnetospheric state on the magnetosheath ion flux.
3. Comparison of both ion flux and magnetic field profiles with their MHD predictions. This part would concentrate on IMF and tilt angle effects.
4. Comparison of single magnetosheath passes with predictions of global MHD models.
5. Study of energetic particles in the magnetosheath and their correlation with the ion flux.

For these topics, we should start with a creation of a database of magnetosheath measurements and with development of a software for their processing. The software for this processing would take into account different time resolutions of data coming from different sources and missing data.

Data set and data processing

Our database for statistical studies was created from INTERBALL-1 magnetosheath observations through 1995 – 1999 years. The spacecraft was crossing the dawn flank during August – October, and during January – March, it was crossing the dusk flank for every year. The ion flux was measured by the omnidirectional plasma detector, VDP (*Safrankova et al.,* 1997, [24]). The source of the magnetic field data was the MIF-M magnetometer (*Klimov et al.,* 1997, [25]). The flux of the high-energy particles was measured by the DOK-2 instrument (*Kudela et al.,* 1995, [26]). This instrument consisted of narrow surface–barrier silicon detectors measuring fluxes of particles with energy in three different ranges; we use the energy range of 22 - 29 *keV* in our study. To display the satellite trajectories, IMF observations, and solar wind data, we used Geocentric Solar Ecliptic (GSE) or Geocentric Solar Magnetospheric (GSM) coordinate systems (*Russell*, 1971, [27]).

Corresponding values of the ion flux and magnetic field in the solar wind were taken from the WIND spacecraft. In order to compare magnetosheath ion flux profiles with solar wind values, we calculated the propagation time of the solar wind flow between both spacecraft using two–step approximation.

To define the INTERBALL-1 position in the magnetosheath, we used the relative distance of a particular magnetosheath point to the magnetopause given in units of the magnetosheath thickness (*Nemecek et al.* (2000a) [20]):

$$D = \frac{R - R_M}{R_{BS} - R_M} \times 100\%,$$

where $R = \sqrt{Y^2 + Z^2}$ is the coordinate of measuring point perpendicular to the Sun-Earth line, R_M and R_{BS} are model distances to the magnetopause and bow shock, respectively. The determination of both boundary positions is important and can influence the result.

A formula for determination of the bow shock location was derived as the best fit of INTERBALL-1 bow shock crossings and its form is:

$$R_{BS} = \frac{41.97}{\sqrt[6]{v_{SW} n_{SW}^{2}}} \times \sqrt{530 - 0.43X^2 - 47X} \times \frac{0.66 \cdot M_A^{2} + 2}{2.66 \cdot M_A^{2} - 1},$$

where n_{SW} and v_{SW} is the solar wind number density and velocity, respectively and M_A is the Alfvénic Mach number.

According to the *Safrankova et al.* (2002) [28] study, we have used the *Petrinec* and *Russell* (1997) [29] magnetopause model which provides the best prediction (especially at high latitudes and the nightside magnetopause). In this model, the magnetopause shape is described by two separate functions for the dayside and nightside magnetopauses. For the nightside magnetopause, the magnetopause distance is calculate according to formula:

$$R_M = \frac{-2}{0.085} \times \left[\arcsin\sqrt{\frac{d \cdot e^{0.085}}{p_{SW}^{0.524}}} - \arcsin\sqrt{\frac{d}{p_{SW}^{0.524}}} \right] + \frac{14.63}{\sqrt[6]{\frac{p_{SW}}{2.1}}},$$

where $d = 2.98 \times (0.152 + m_2 B_Z)$ and m_2 = - 00137 for $B_Z > 0$ and m_2 = - 00644 for $B_Z < 0$.

In order to combine the measurements carried out under different conditions, we have used predictions of the gasdynamic theory that the plasma parameters in a particular point of the magnetosheath are directly proportional to their upstream values for a given Mach number, and we computed flux compression coefficient, FCC_M, as a ratio of downstream and upstream ion fluxes:

$$FCC_M = \frac{v_{Msh} \times n_{Msh}}{v_{SW} \times n_{SW}},$$

The magnetic field strength would follow the compression of the plasma flow and thus, we define the magnetic field compression coefficient:

$$BCC_M = \frac{B_{Msh}}{B_{SW}}.$$

The trajectories of the INTERBALL-1 spacecraft covered a region from $X_{GSE} \sim 0\ R_E$ to $X_{GSE} \sim -19\ R_E$. The set of observations contains the measurements in the ecliptic plane as well as at high latitudes (from $Z_{GSE} \sim -14\ R_E$ to $Z_{GSE} \sim 13\ R_E$). Figure 1a shows a radial projection of data points onto the *X-Y* plane together with mean model magnetopause and bow shock locations. The positions of boundaries were calculated for solar wind dynamic pressure, p = 2.0 *nPa* and *IMF* B_Z = 0 *nT*. The latitudinal coverage is demonstrated in Figure 1b, where all points were projected onto the *Y-Z* plane. Both panels of the figure show relative good homogeneous coverage of the region under study at low and middle latitudes. The points below the model magnetopause or above the model bow shock belong to the magnetosheath and their locations in Figure 1 represent the uncertainty of the models used.

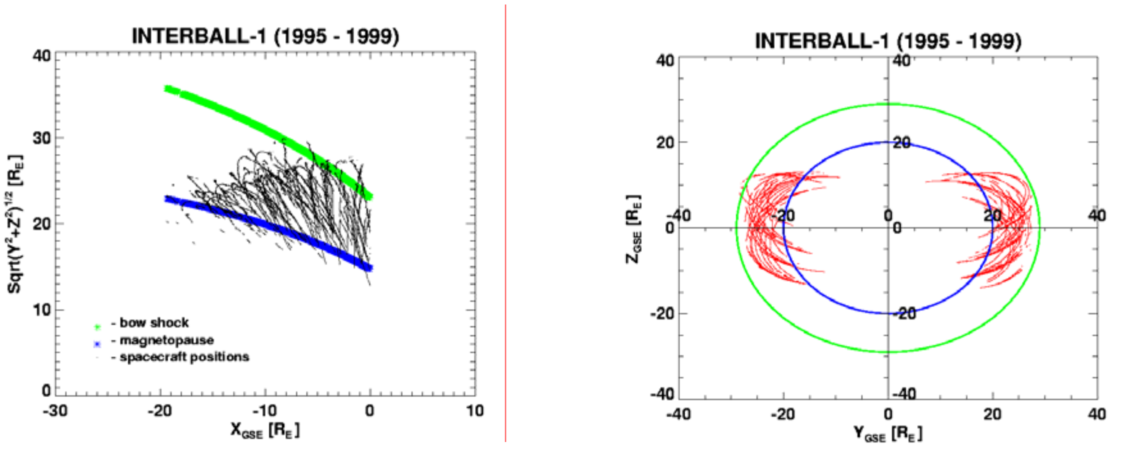

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Figure 1. Spatial coverage of magnetosheath measurements by INTERBALL-1. a) The radial projection of data points together with the mean model magnetopause (*Petrinec* and *Russell,* 1996, [29]) and bow shock [A5] locations. b) Positions of both model boundaries (at X_{GSE} = -10 R_E) and distribution of experimental points. For presentation, we used the GSE coordinate system.

Experimental results

As a first step, we described the magnetosheath flow by the *Spreiter et al.* (1966) [5] gasdynamic model and by two MHD models:

- BATS-R-US (*Darren et al.*, 2000, [30]), the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme which was developed by the Computational Magnetohydrodynamics (MHD) Group at the University of Michigan
- UCLA-GGCM (*Raeder*, 2002, [31]) originally developed as a magnetohydrodynamic model of Earth's magnetosphere at UCLA in the early 1990's.

We compared FCC_M with the values predicted by models (FCC_{Pr}) for one magnetosheath crossing during August 8 and 9, 1997. These comparisons [A1] result in a conclusion that the BATS-R-US model predicts the magnetosheath ion and magnetic field profiles better than the UCLA-GGCM and gasdynamic *Spreiter et al.* (1966) [5] models. For this reason, we use the BATS-R-US model for further comparison of simulations with observations. Moreover, our analysis suggests that the dawn – dusk magnetosheath asymmetry found by *Paularena et al.* (2001) [20] and *Nemecek et al.* (2003) [32] can be a result of latitudinal distributions of both ion flux and magnetic field in a combination with influences of the IMF direction or/and the tilt angle of the Earth's dipole.

Thus, we created a new data set where we limited the magnetosheath in a range $-5\ R_E < X_{GSM} < 5\ R_E$ and $-5\ R_E < Z_{GSM} < 5\ R_E$. To reduce the influence of solar wind parameters, we have chosen the quiet solar wind periods. In our set, the solar wind speed was in the interval from 350 *km/s* to 450 *km/s*, the density from 3 cm^{-3} to 8 cm^{-3}, and *IMF* B_X and B_Z components were close to zero. The reduced data set contained mainly the negative *IMF* B_Y component and due to the specified INTERBALL-1 trajectory, our set did not have enough data with positive tilt angles under such limitations. Examples of comparisons for tilt angles near zero are presented in Figures 2 and 3.

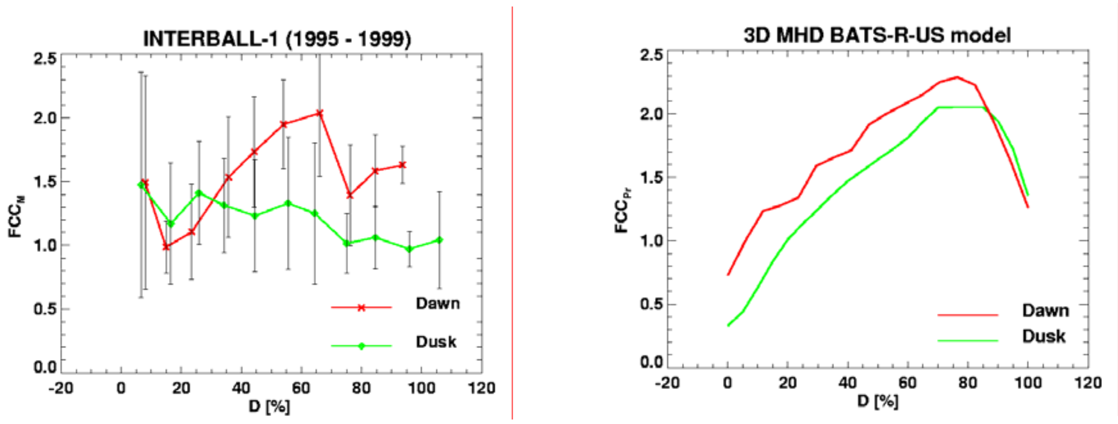

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Figure 2. The observed dawn-dusk asymmetry (a) and its prediction by the BATS-R-US model (b) for high latitudes and tilt angles close to zero.

The spread of measurements is large at high latitudes (Figure 2a). We show this spread as error bars for both flanks in the figure. As can be seen, the error bars are very wide but trends of profiles are clear enough. At low latitudes (Figure 3a), the measurement coverage is compact and both flank profiles are within the same error bar. The large spread of measuring points at high latitudes suggests that our limitations did not exclude some factors which influence magnetosheath plasma. The model prediction (Figure 2b) corresponds to observations rather well, however, significant difference between measured and simulated profiles is observed for the dusk side at high latitudes (Figure 2). We assume that this difference can be caused by the plasma entry to the cusp region with a combination of the influence of the *IMF* B_Y sign.

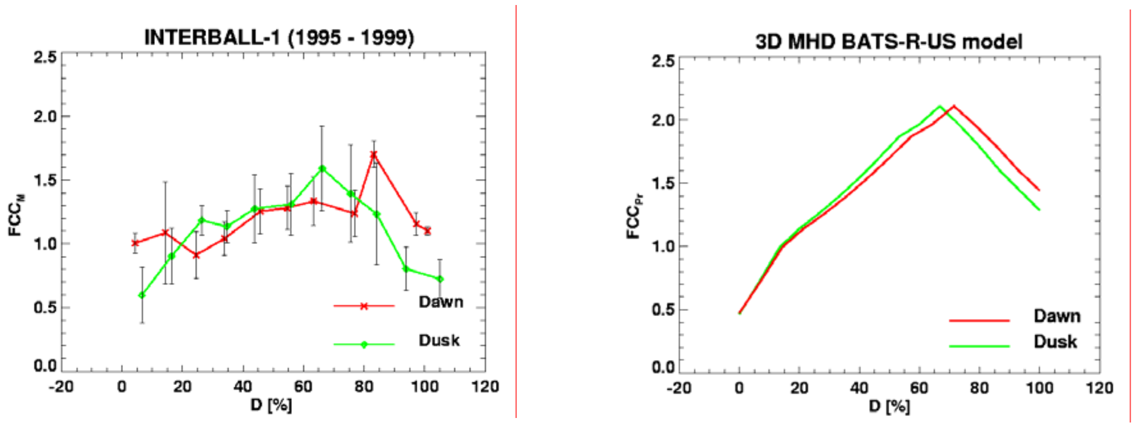

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Figure 3. The observed dawn-dusk asymmetry (a) and its prediction by the BATS-R-US model (b) for low latitudes and tilt angles close to zero.

For negative tilt angles (not shown), the predictions were also similar to the measurements. At low latitudes, both simulations and observations show a clear dawn-dusk asymmetry with larger values of FCC_M on the dusk side. On the other hand, at high latitudes, the dawn-dusk asymmetry disappears [A1].

Summarizing a comparison of observed magnetosheath ion fluxes with predictions of the models, we can say that:

1. The BATS-R-US MHD model simulates the magnetosheath properties better than the gasdynamic (*Spreiter et al.,* 1966, [5]) and UCLA-GGC MHD models.
2. The results of BATS-R-US model predictions describe the magnetosheath parameter changes qualitatively but not quantitatively.
3. Both MHD simulations and experimental data show a significant change of the magnetosheath parameters with latitudes in the considered interval of X_{GSM}.
4. The IMF direction plays an important role in the formation of the magnetosheath ion flow.
5. The Earth's tilt influences the dawn - dusk asymmetry more for the high-latitude than for low-latitude magnetosheath.

Since we observed the dependence of model results on the latitude and the sign of the *IMF* B_Y component, we simulated two transitions through the magnetosheath at high and low latitudes and then compared they with observations as it is demonstrated in Figure 4. Conditions of the magnetosheath passes differ for these two events: during August 26, 1997 (Figure 4a), the satellite moved through the dawn side at low latitudes; the tilt angle was changing from 21.32 to 1.21 and *IMF* B_Y was negative. In the second case (February 26-27, 1998), INTERBALL-1 crossed the dusk magnetosheath at high latitudes (Figure 4b). The tilt angle changed from -20^0 to -2^0 and the *IMF* B_Y component was mainly positive.

We can say that measured and modelled ion flux profiles are in a good agreement with a slightly larger value of the BATS-R-US ion flux (Figure 4a, low-latitude pass). Moreover, the model relatively well describes large (10 minutes) fluctuations of the ion flux. On the other hand, for our second case (Figure 4b), the difference between measured and modelled values is significantly larger. In [A2], we discussed in detail possible causes of such differences, as a limitation of the Faraday cup aperture, an influence of kinetic processes, a different bow shock geometry, a presence of the cusp region at high latitudes, and an influence of changing *IMF* B_X component on the MHD simulation.

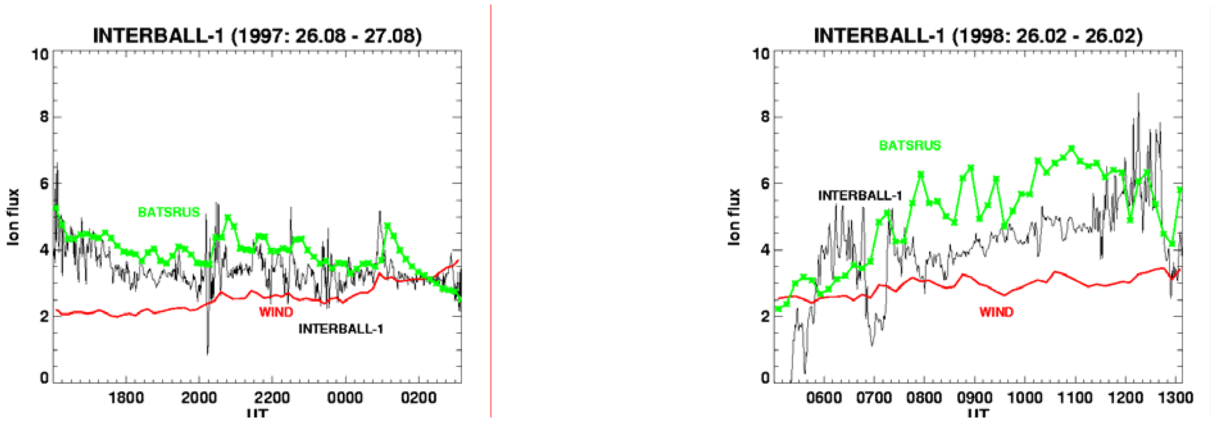

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Figure 4. A comparison between predicted and observed ion fluxes with corresponding fluxes of solar wind.

As a conclusion of this particular study, we can note that the comparison between MHD predictions and single satellite passes [A2] showed that the MHD ion flux is larger than that measured through the whole magnetosheath. Moreover, the model relatively well describes large (10 minutes) fluctuations of the ion flux. Examination of the magnetosheath magnetic field simulations showed that results of predictions are sensitive also to the sign of *IMF* B_X and it is necessary to pay an attention to the value and sign of this IMF component during simulations and following comparisons.

The correlation between the magnetosheath ion flux and geomagnetic indices

Our study [A3] presents a statistical investigation of relations between geomagnetic activity characterized by changes of the K_P, D_{ST}, and *AE* indices and the ion flux represented by FCC_M. These geomagnetic indices describe the response of the magnetosphere on the solar wind flow in latitudes and, as we show above, the magnetosheath parameters change with latitude. The *AE* index is closely connected with auroral electrojets, whereas D_{ST} is a measure of the strength of the ring current intensity. The K_P index is a measure of irregular magnetic field variations and reflects primarily an auroral zone activity because the stations nearer to the auroral zone have higher sensitivity. We assumed that there are two reasons for a possible correlation:

(1) Indices are correlated with solar wind parameters but the magnetosheath region is located between the solar wind and magnetosphere.

(2) Indices depend on processes inside the magnetosphere and these processes could affect the magnetosheath properties via, for example, a leakage of magnetospheric particles. Although the geomagnetic activity would be determined by dayside magnetosheath parameters, we think that our study should bring relevant results because *Zastenker et al*. (2002) [33] have shown that magnetosheath parameters are well correlated over a distances of tens of R_E along the streamline.

However, in [A3], we found only a weak correlation between the D_{ST} index and ion flux in the inner magnetosheath and we suppose that it is probable related to the magnetopause displacement caused by a decrease of the magnetosheath pressure. The analysis of the influence of magnetosheath ion flux fluctuations showed a possible weak dependence on the K_P index. The connection between magnetosheath density enhancements and auroral precipitation or the D_{ST} index does not exist in a statistical sense. We think that these negative results are connected with the fact that geomagnetic indices describe a global state of the magnetosphere, whereas the magnetosheath variations are a ”local” feature. A more local parameter than indices should be chosen for a future evaluation of the influence of magnetosheath fluctuations on the geomagnetic field.

Influence of the IMF orientation on flux and magnetic field compression coefficients

In this study [A4], we continued the search for other possible source of the changes of magnetosheath parameters - the influence of the IMF orientation on the difference between the dawn and dusk night–side magnetosheaths.

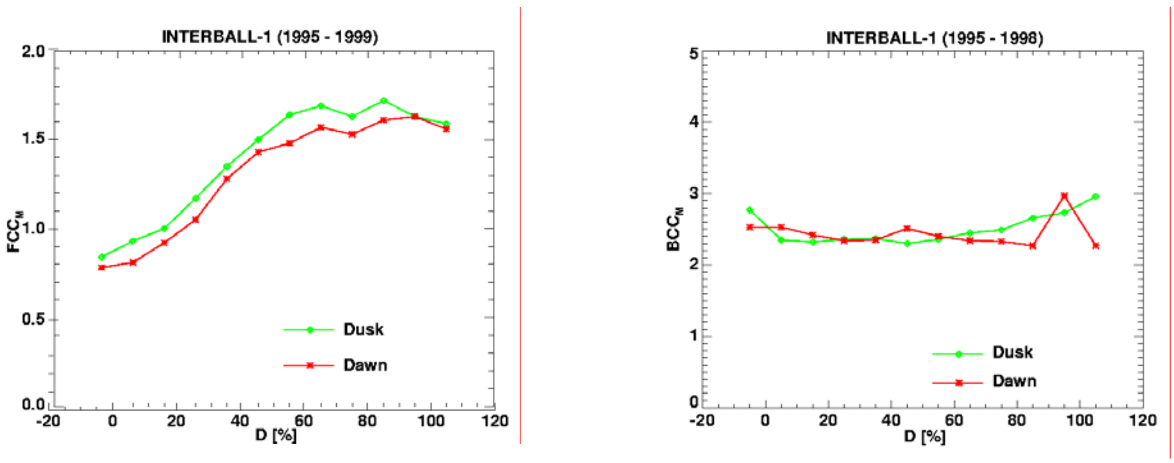

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Figure 5. Radial profiles of the magnetosheath ion flux (FCC_M) and magnetic field (BCC_M) for the dawn and dusk flanks.

Figure 5 presents the averaged values of FCC_M (Fig 5a) and BCC_M (Fig 5b) as a function of the normalized distance for the dawn and dusk magnetosheath. A comparison of the flanks shows that dawn FCC_M is slightly lower than dusk FCC_M in all points along the magnetosheath thickness. On the other hand, the normalized magnetic field, BCC_M exhibits a very flat profile with a small enhancement near the boundaries. The difference between dawn and dusk BCC_M profiles is small.

Since the observed dawn-dusk asymmetry could be connected with the IMF direction, we investigated two limit cases – radial (cone angle < 15^0) and perpendicular (cone angle > 75^0) IMF orientations.

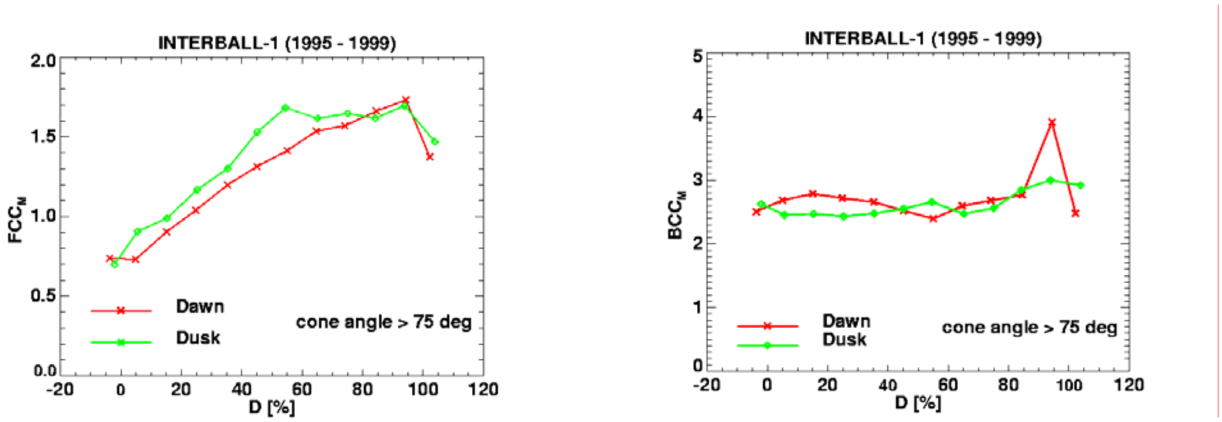

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Figure 6. The dawn-dusk difference between normalized ion flux (a) and magnetic field (b) profiles for perpendicular IMF.

Figure 6 demonstrates that the dusk ion flux is larger during intervals of perpendicular IMF, whereas BCC_M does not exhibit any dawn-dusk asymmetry. On the other hand, the situation is opposite during intervals of radial IMF, FCC_M is, within statistical errors, the same on both flanks but dawn BCC_M is generally larger as can be seen from Figure 7.

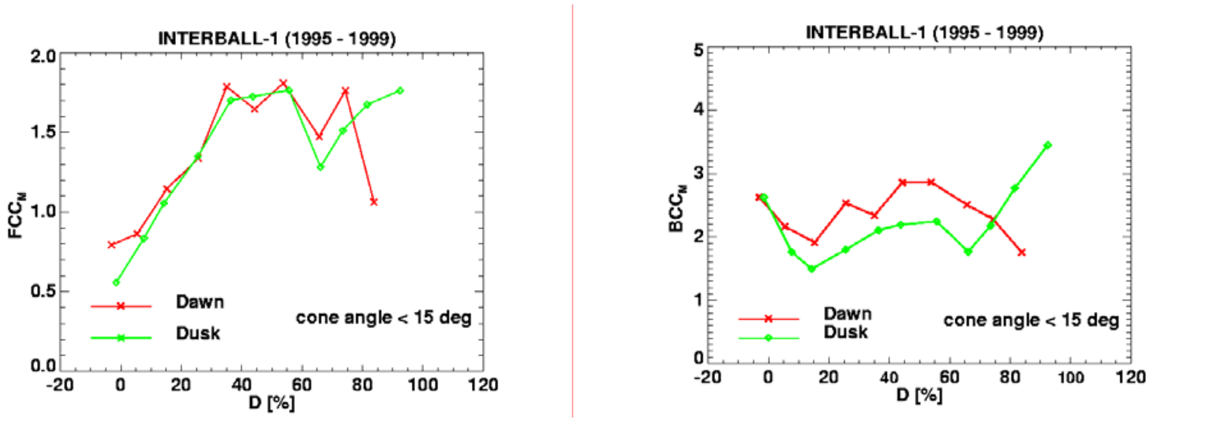

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Figure 7. The difference between FCC_M (a) and BCC_M profiles for radial IMF.

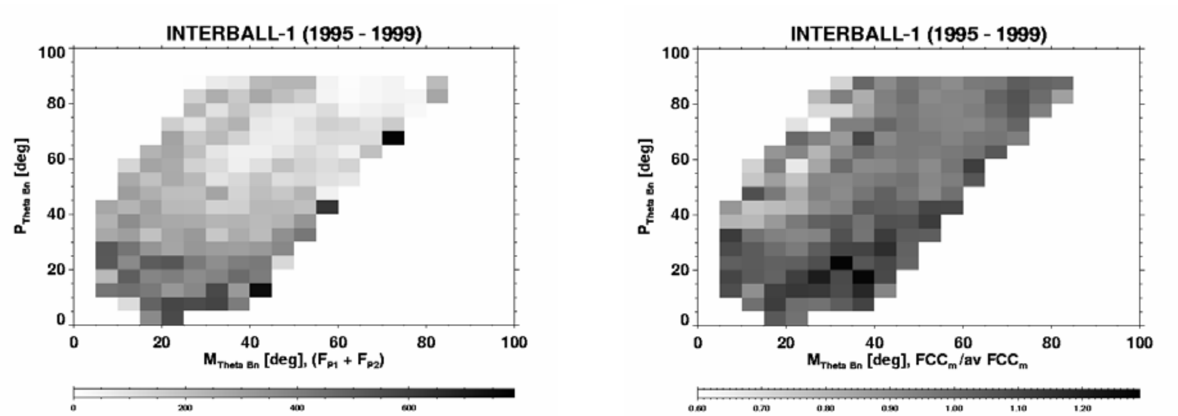
Our investigations showed that a connection between the magnetosheath proton flux and magnetic field is rather weak. The magnetic field magnitude neither follows the plasma compression nor compensates the total pressure but it is nearly constant across the magnetosheath. On the other hand, the flux profile is strongly affected by the IMF orientation. A maximum of the plasma compression shifts from the bow shock region toward the magnetosheath center when IMF becomes more radial. It means that expected weaker plasma compression at the quasiparallel shock is compensated by a further compression in the magnetosheath. This fact can explain why the bow shock location does not depend on the angle between IMF and bow shock normal (*Safrankova et al.,* 2003, [34]) but the source of this additional compression is unknown.

Relation between the ion flux and high-energy particles

The main difference between quasiparallel and quasiperpendicular shocks is in production of energetic particles. To elucidate this problem, we discussed the mutual connection between ion and high-energy particle fluxes in the contribution [A5]. The role of reflected and accelerated particles in the upstream region is well understood in terms of wave excitation and creation of disturbances like hot flow anomalies or foreshock cavities (e.g., *Kudela et al.,* 2002, [35]). However, the situation is much more complicated within the magnetosheath because energetic particles observed in a particular point can come from several sources.

According to the previous investigations (e.g., *Kudela et al.,* 2000, [36]), the angle between the magnetic field and the shock normal (θ_{Bn}) is a good parameter controlling the high-energy fluxes in near upstream region. Assuming a dependence of the magnetosheath energetic particle population on the bow shock type, we calculated θ_{Bn} at two locations. First, we calculated the $P\theta_{Bn}$ angle at the point where the investigated magnetosheath fluid parcel crosses the bow shock. We applied the gasdynamic model (*Spreiter et al.*, 1966, [5]) to map the plasma flow along the streamline. Further, we defined the $M\theta_{Bn}$ angle at the point on the bow shock to which the magnetic field currently connects the fluid parcel.

Since the main task of this part was a correlation of energetic particles and plasma fluxes, we present these quantities as a function of both $M\theta_{Bn}$ and $P\theta_{Bn}$ angles in Figure 8. These angles are not fully independent because they are defined as angles between the IMF vector and normals to the model bow shock in two different locations. For this reason, the measurements are concentrated along the line determined by an equality of both angles. The highest fluxes of energetic particles (Figure 8a) are observed when the $P\theta_{Bn}$ angle is lower than 30^0, and these fluxes do not depend on the $M\theta_{Bn}$ angle.



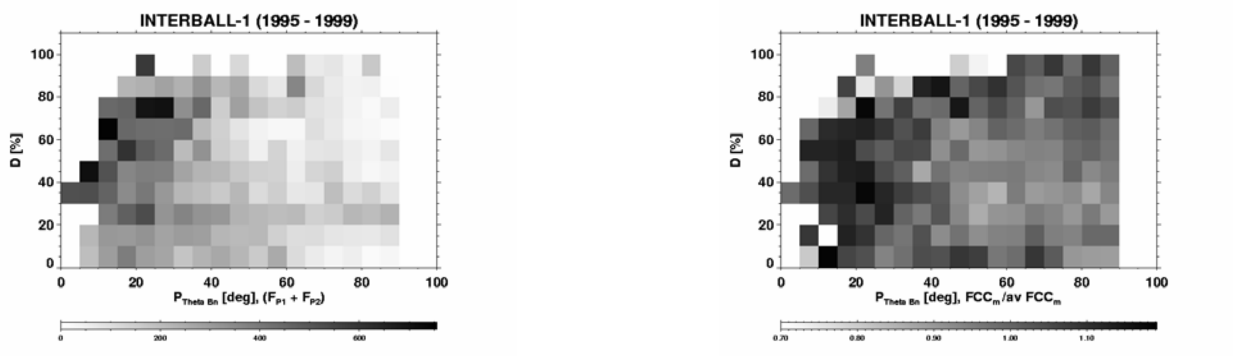
a b

Figure 8. A connection between $M\theta_{Bn}$ and $P\theta_{Bn}$ for two parameters: (a) – high-energy particle flux (Fp1 + Fp2); (b) - normalized ion flux ($FCC_M/avFCC_M$). The grey scale bars in panels represent analyzed quantities.

It confirmed our hypothesis that the observed particles are generated at the quasiparallel bow shock, trapped in local magnetic field inhomogenities and carried downstream with the magnetosheath flow. A portion of particles coming to the measuring point along magnetic field lines is notable but much lower. These particles are observed when $P\theta_{Bn}$ is large and $M\theta_{Bn}$ is low.

Figure 8b brings a surprising result because it shows that larger plasma fluxes are observed when the $P\theta_{Bn}$ angle is low, i.e., when streamlines connect magnetosheath points to the quasiparallel bow shock. On the other hand, when $P\theta_{Bn}$ is high (top part of the panel), we can see an opposite trend - the plasma flux increases with increasing $M\theta_{Bn}$. Comparing Figures 8a and 8b, one can note that the plasma and energy particle fluxes are roughly anticorrelated when $P\theta_{Bn} > 40^0$ but they are nearly in correlation for lower values of $P\theta_{Bn}$.

However, sorting of the data according to θ_{Bn} angles does not reflect the position of investigated points in the magnetosheath. We have described this position by the distance from the magnetopause in units of the magnetosheath thickness D. Since we cannot exclude that a mutual relation of plasma and energetic particle fluxes would be different in the inner and outer magnetosheath, we have plotted the energetic particle and ion fluxes as a function of this distance in Figure 9. $P\theta_{Bn}$ is plotted on horizontal axes of both panels in Figure 9 and the D distance is on vertical axes. Figure 9a clearly reveals that the largest fluxes of energetic particles can be observed in the region of the quasiparallel ($P\theta_{Bn} < 30^0$) bow shock and this flux decreases toward the magnetopause. This means that energetic particles can come to a particular magnetosheath point either along the magnetic field line or that the plasma can carry these particles embedded in local magnetic inhomogenities and the both sources are probably equally important. The other possible source - leakage of particles from the magnetosphere - can be probably excluded because Figure 9a show a clear minimum of energetic particles near the magnetopause (D = 0 %) regardless of the θ_{Bn} angle.



(a) (b)

Figure 9. Distributions of high-energy particle fluxes (a) and normalized ion fluxes (b) as a function of normalized magnetosheath distance and parameter, $P\theta_{Bn}$.

Figure 9b confirms our finding that the ion flux compression ratio is higher when connected via the streamline to the quasiparallel bow shock. However, this excess of the flux is observed only for D < 70 %, whereas a depletion can be found in a closer vicinity to the bow shock. This complicated dependence of the plasma flux on two parameters can explain why the attempts to find a clear dependence of the plasma flux on one of these parameters only were not too successful.

Conclusion

In this thesis, we performed an analysis of the ion flux and magnetic field in the night part of the magnetosheath. Statistical part of the study was based on five-year observations onboard the INTERBALL-1 spacecraft. Moreover, the solar wind data, and geomagnetic indices were at our disposal and, at least, two global MHD models were available for use. Thus, the thesis starts with a creation of the database of parameters for the statistical study.

An elementary unit (one point) of our statistical study consisted of eleven components bringing information about plasma and magnetic field parameters in the magnetosheath and in the solar wind as well as information on the magnetospherical internal state. All components were either interpolated to or averaged over 5 or 10-minute intervals for particular purposes. The resulting data set contained more than 23 000 points of 5-minute averages. Our statistics was complemented with a few cases of single magnetosheath passes to explain particular peculiarities of magnetosheath variability. The analysis of our results leads to following conclusions:

1. MHD simulations of the magnetosheath properties as well as spacecraft observations showed significant changes of the magnetosheath parameters with latitudes in the considered interval of the X_{GSM} coordinate. The comparison between MHD predictions and experimental data suggested that the MHD ion flux is larger than that measured through the whole magnetosheath and that used MHD predictions are sensitive to the *IMF* B_Y sign.

2. We observed that the IMF direction in a combination with the orientation of the Earth's dipole plays an important role in a formation of the magnetosheath ion flow. Moreover, the tilt angle influences the dawn-dusk asymmetry more for the high than for low latitudes. The magnetosheath ion flux does not exhibit a radial symmetry as it is generally expected. Profiles on both flanks evolve along the Sun-Earth line and they are nearly linear in the nightside magnetosheath.

3. The magnetosheath ion flux profile is strongly affected by the IMF orientation. A maximum of the plasma compression shifts from the bow shock region toward the magnetosheath centre when IMF becomes more radial. On the other hand, the magnetic field magnitude neither follows the plasma compression nor compensates the total pressure but it is nearly constant across the magnetosheath for all IMF orientations.

4. The correlation between the magnetosheath ion flux and all investigated geomagnetic indices is rather weak. The level of magnetosheath fluctuations also does not affect any of geomagnetic indices probably due to the fact that the fluctuations are a local effect but the indices describe global changes.

5. We found a weak dependence of the ion plasma flux on the angle between the magnetic field and the shock normal computed at the point where the investigated magnetosheath fluid parcel crosses the bow shock. We observed a correlation of these quantities near the bow shock but anti-correlation near the magnetopause.

6. A dominant portion of high-energy particles is generated at the quasiparallel bow shock, trapped in local magnetic field inhomogeneities and blown downstream with the plasma flow. However, this mechanism cannot transport streaming particles from the quasiperpendicular bow shock because the plasma turbulences are not so intensive and probably not sufficient for particle trapping. A fraction of energetic particles blown with the magnetic field line into the magnetosheath behind the quasiperpendicular shock excites magnetosheath waves that scatter their pitch-angle distributions.

7. Our analysis shows that the plasma flux and flux of energetic particles are anticorrelated behind the quasiparallel bow shock but no dependence was found for the quasiperpendicular case.

The comprehensive study of the magnetosheath carried out in frame of the present thesis explained many controversial magnetosheath features but a further effort in experimental and theoretical investigations is still desirable.

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A1 Hayosh, M., J. Safrankova, Z. Nemecek, 2003. MHD-simulations of the magnetosheath parameters and their comparison with observations, in WDS'03 Proceedings of Contributed Papers: Part II - Physics of Plasmas and Ionized Media, ed. by J. Šafránková, Prague, Matfyzpress, 261-269.

A2 Hayosh, M., Z. Nemecek, J. Safrankova, 2004a. MHD-modeling of the magnetosheath ion plasma flow and magnetic field and their comparison with experiments, Adv. Space Res., accepted.

A3 Hayosh, M., Z. Němeček, J. Šafránková, and G. Zastenker, 2004b. Variations of the magnetosheath ion flux and geomagnetic activity, Adv. Space Res., accepted.

A4 Němeček, Z., M. Hayosh, J. Šafránková, G. Zastenker, and J. Richardson, 2003. The dawn-dusk asymmetry of the magnetosheath: INTERBALL-1 observations, Adv. Space Res.: Plasma processes in the near-Earth space: Interball and beyond, ed. by D. G. Sibeck and G. N. Zastenker, 31 (5), 1333-1340.

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Other papers related to the topic

Hayosh, M., Z. Nemecek, J. Safrankova, K. Paularena, 2001. Radial profile of the nightside magnetosheath, in WDS'01 Proceedings of Contributed Papers: Part II - Physics of Plasmas and Ionized Media, ed. by J. Šafránková, Prague, Matfyzpress, 226-232.

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