Small- and Middle-scale Solar Wind Structures, Transferring from the Solar Wind to Magnetosheath: A Correlation Analysis

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Abstract. The paper is based on the correlation analysis of small- and middle-scale plasma structures of the solar wind (SW) and their evolution during propagation through the bow shock (BS) to the magnetosheath (MSH). We use data from two closely located THEMIS satellites upstream and downstream from the BS. We compute the correlation coefficient as a function of UT and the time lag between SW and MSH data. The correlation coefficient is calculated for the primary and smoothed data. The smoothing time varies from 10 to 170 seconds. We examine a dependence of the correlation coefficient on the smoothing time, which is equivalent to removing of high-frequency fluctuations. We find that the correlation coefficient doesn't significantly depend on the smoothing time for data with this time exceeding 50 seconds (which corresponds to 0.02 Hz on the variation scale). So this value can represent a rough boundary between the density variations coming generally from the solar wind, and the density variations produced mainly by the bow shock and inside the magnetosheath. We also examine continuous 20-hour interval of plasma density measurements and time evolution of the correlation coefficient during this interval. We find that correlations can decrease to rather small values in several minutes and then increase again. The influence of various parameters on the value of the correlation is discussed.

Introduction

Solar wind (SW) parameters vary in a wide frequency range. These variations are modified significantly by the bow shock (BS) and during a plasma flow though the magnetosheath (MSH) which is a transition region between the bow shock and magnetopause. Each solar wind disturbance which flows to MSH is modified by it. The typical changes of plasma parameters from SW to MSH are: high compression of the flow, bulk velocity decrease and ion temperature increase (*Spreiter et al*., 1966). In the same time, the MSH is a highly turbulent region with much higher level of fluctuations of all plasma and magnetic field parameters (*Shevyrev et al.*, 2003). MSH is also filled with waves that lead to the energy redistribution during transport from the bow shock to the magnetopause *(Schwartz et al.*, 1996*).*

Shevyrev and Zastenker (2005) have shown that a level of MSH variations is controlled by the θ_{Bn} angle (the angle between a direction of the interplanetary magnetic field and normal to BS at the point of plasma entering to the MSH) and that the bow shock is a dominant source of fluctuations in the frequency range of 0.02–1 Hz.

Zastenker et al. (2002) have shown that every essential plasma and magnetic field changes in SW have an influence on variations of these parameters in MSH, but many MSH fluctuations are generated on the BS and in MSH and are not related to variations in SW.

So, solar wind structures can be strongly modified by the BS and MSH. For example, a modification of interplanetary (IP) shocks by the BS and MSH was studied by *Safrankova et al.* (2007). It was shown that an interaction of the IP shock with BS results in two discontinuities. One of them is supposed to be a fast forward shock and another one is characterized by the density increase and decrease of the temperature. Also in (*Rakhmanova et al.*, 2012), it was shown that small-scale ion density structures sometimes save their sharp boundaries while their amplitude and duration increase during a propagation from SW to MSH.

A comparison of simultaneous data from SW and MSH using correlation analysis is the effective method to study structures flowing through the BS. For example, this method was used by *Gutynska et al.* (2012). The multi-spacecraft study of MSH was presented. It was suggested that the coherent low frequency (10^{-4}–10^{-3} Hz) fluctuations of the magnetic field are generally observed in the dayside MSH. This means that a source of such fluctuations is located in SW. The higher frequency variations (up to 0.1 Hz) of SW and MSH parameters are not correlated. It implies that the source of such variations is local.

In this paper, we present the results of the study of small- and middle-scale (from several seconds to several minutes) plasma structures and their modification by the BS and MSH using a correlation analysis of data of two closely separated Themis satellites.

Observations

We use the Themis mission data with a 3 second time resolution (*Angelopoulos,* 2008*; Sibeck and Angelopoulos,* 2008). Five THEMIS satellites move on elliptical orbits around the Earth. So it is possible to find time intervals, when one satellite is placed in the solar wind and another one is located in the magnetosheath, and the distance between them is rather small (less than 20 Re). The time of a solar wind propagation from one to another satellite doesn't exceed 10 min. Plasma parameter measurements received from the electrostatic analyzer (*McFadden et al.,* 2008) (ion density and velocity) and the magnetic field magnitude measured by the fluxgate magnetometer (*Auster et. al.,* 2008) were used in this work. Data were taken from http://cdaweb.gsfc.nasa.gov .

We analyzed 64 hours of plasma density time series and used following algorithm to study:

1) Searching of continuous (with duration above 3 hours) time intervals when one of the THEMIS satellite is located in SW and another one is located in MSH. Moreover, considered intervals may contain large and abrupt density changes. We also avoid periods with foreshock observations.
2) Calculation — the correlation coefficient (R) between SW and MSH plasma density is defined as:

$$\mathbf{R}=\frac{\sum_{i=1}^{N}(x_i-x_{av})(y_i-y_{av})}{\sqrt{\sum_{i=1}^{N}(x_i-x_{av})^2\sum_{i=1}^{N}(y_i-y_{av})^2}}$$

where x_i and y_i — SW and MSH density time series x_{av} and y_{av} — average density value over the analyzed interval in SW and MSH; N — number of data values at the analyzed interval. R is defined as a function of the time lag between SW and MSH time series for each UT value.
3) Calculation of the correlation coefficient for smoothed plasma density time series. The smoothing time ranges from 10 to 170 seconds. Smoothing removes high-frequency variations from time series.
4) Determination of the dependence of the correlation coefficient on the smoothing time.
5) Performing of all calculations at first for 2 hour intervals to suggest that there was a large-scale correlation of SW and MSH time series, and then for 30 min intervals to study small- and middle-scale structures.

Example of the analysis

We present the analysis of data from August 31, 2008 as an example. Data set was presented as 6-hour ion density from SW (Themis-B) and MSH (Themis-D). Figure 1 shows the density for the observed period. Themis-B observations are shown by the black line, Themis-D observations are shown by the grey line. The SW time series are shifted on UT scale by 369 seconds. This time lag is defined as the time shift of a maximum value of the correlation coefficient for the whole time interval and corresponds to the time lag of the plasma propagation from one spacecraft to another.

The average values of the magnetic field magnitude and bulk velocity in SW and MSH for considering time interval were: B_{sw} = 4 nT, B_{msh} = 25 nT, V_{sw} = 315 km/s, V_{msh} = 25 km/s. Such small value of the MSH plasma velocity is caused by the Themis-D location near the MSH subsolar point. The location of Themis satellites during time interval is presented in Figure 2. The solar wind flow was slowed during the whole time interval. The correlation coefficient of SW and MSH density time series is equals to 0.73 on the whole interval.

At first, we calculate correlation coefficient on 2 hour data intervals; intervals are overlapped by 1 hour. The time shift is necessary to avoid errors associated with our separation of continuous data set into intervals. Figure 3 presents dependence of the correlation coefficient on UT (X-axis) and on time lag between SW and MSH data (Y-axis) for full 6-hour time interval on 31 August 2008. The gray scale shows the value of the correlation coefficient.

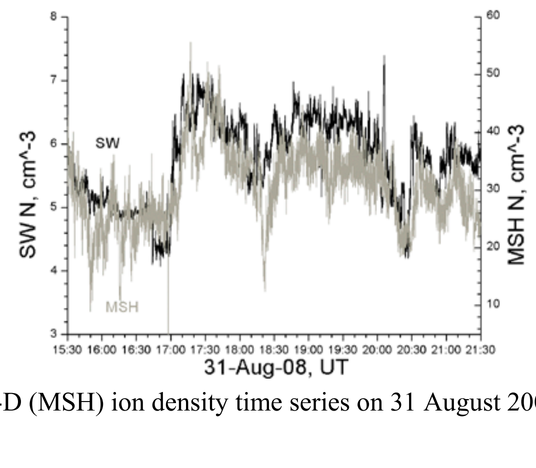

Figure 1. Themis-B (SW) and -D (MSH) ion density time series on 31 August 2008.

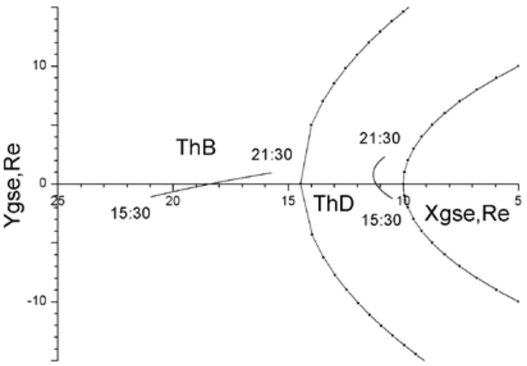

Figure 2. Themis-B and -D location in GSE coordinates on 31 August 2008.

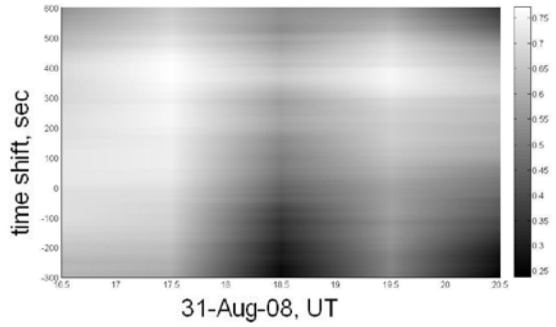

Figure 3. The correlation coefficient calculated on 2 hour intervals on 31 August 2008. The X axis presents UT, Y presents the time lag between SW and MSH data, the gray map presents the correlation coefficient.

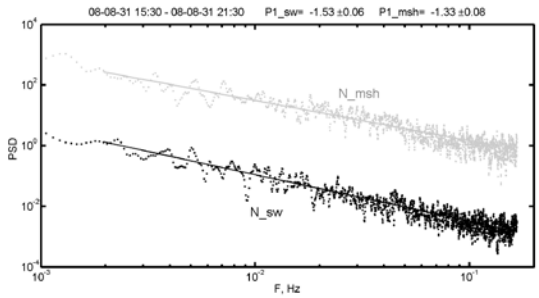

Figure 4. Fourier spectra of density fluctuations in SW (black line) and MSH (grey line).

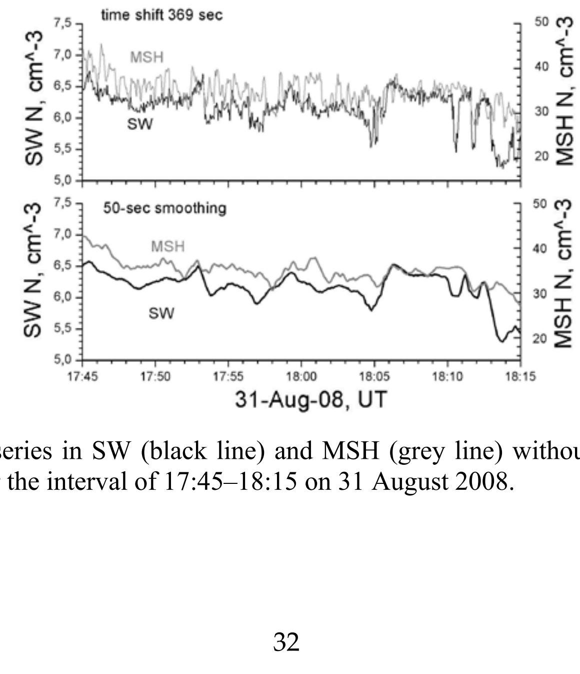

Figure 5. Ion density time series in SW (black line) and MSH (grey line) without smoothing (top panel) and with 50 second smoothing for the interval of 17:45–18:15 on 31 August 2008.

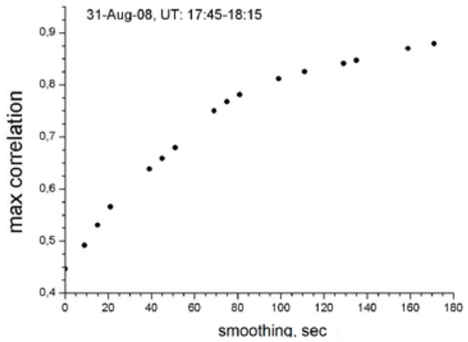

Figure 6. The dependence of the correlation coefficient on the smoothing time for interval of 17:45–18:15 on 31 August 2008.

Looking in Figure 3, one can see that a maximum of the value of the correlation coefficient exceeds 0.7 for the time lag from 300 to 500 seconds. It represents a high large-scale correlation between SW and MSH densities during the whole interval.

After that, we calculated Fourier spectra of plasma density fluctuations. Figure 4 presents the result of our calculation for SW (black line) and MSH (grey line). A slope of the spectrum in SW equals to 1.53 ± 0.06 that is nearly Kolmogorov's spectrum. In MSH, the spectrum is more flat and its slope equals to 1.33 ± 0.08. Spectra only illustrate the increasing of a fluctuation level in MSH and don't explain in which frequency range plasma fluctuations are saved during transport of SW to MSH. So we continued analysis and calculated the correlation coefficient on 30 minute intervals that are overlapped by 15 minutes.

Figure 5 shows the example of a 30 minute interval of the ion density data in SW (black line) and MSH (grey line). Top panel presents time series without any smoothing, bottom panel presents time series with 50 second smoothing. The dependence of the correlation coefficient on the time lag is observed and the time lag of the maximum correlation is defined for each interval. The same calculations are made also for smoothed data. Smoothing time ranges from 10 to 170 seconds. Then, we have analyzed the dependence of maximum value of the correlation coefficient on the smoothing time, it is presented in Figure 6. One can see that the correlation coefficient for data without smoothing is equal to 0.45 and for data with 170-second smoothing is increased to 0.88. So smoothing (that is equivalent of removing high-frequencies component of plasma variations) leads to significant correlation increases.

Statistical study

In the presented study, we analyze the 64 hours of the ion density data selected on 248 30-minute intervals (intervals are overlapped by 15 minutes). Figure 7 shows the distribution of the value of the correlation coefficients of these intervals for data without smoothing (grey bars) and for data with 50-second smoothing (black bars). The value of the correlation coefficient for data without smoothing ranges from –0.5 to 1.0, the maximum of distribution is at 0.45 and the width at half-height is equal 0.6. For smoothed data, the distribution moves to the range of higher values: for 50-second smoothing maximum is at 0.75, the peak of distribution becomes more clear. So smoothing of data moves the distribution from insignificant correlation values to the high enough correlation values.

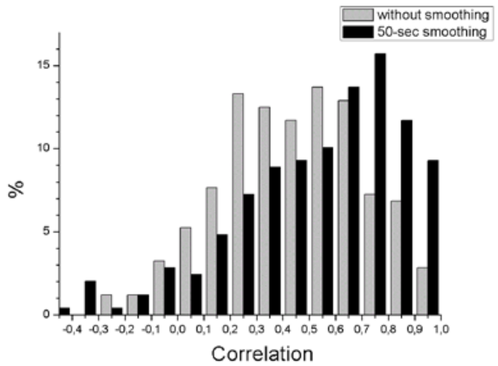

Figure 7. Distribution of the value of the correlation coefficients for data without smoothing (grey bars) and for data with 50-second smoothing (black bars).

Figure 8 presents the distributions of the value of correlation coefficient changes for time series with 10, 50 and 170-seconds smoothing. The change of the correlation coefficient is defined as dR(0–N) = R(N) – R(0), where **R(N)** is the value of the correlation coefficient for time series with N-seconds smoothing, R(0) is the correlation coefficient for time series without smoothing. Distributions show that smoothing by 10-second doesn't change the correlation coefficient (the average change is 0–0.1). The time series with 50-second smoothing shows the change of correlation coefficient values in a wide range (from –0.2 to 0.4). The maximum of this change is at 0.1–0.2 value. For data with smoothing time over 50 seconds distributions have the same shape and its maximum is also at 0.1–0.2. It means a slight change of the correlation coefficient for smoothing times exceeding 50 seconds. Also one can see that for smoothing time exceeding 50 seconds more than for 35 % of intervals the correlation coefficient increases by more than 0.2 for both SW and MSH data.

The presented analysis was done for all 30-minute intervals. The statistics thus includes the cases where the SW and MSH densities don't correlate at all. To study modification of structures it's necessary to consider intervals with a good primary correlation. We chose intervals with R(0) > 0.4 and R(170) > 0.8, where R(0) is the correlation coefficient for non-smoothed data and R(170) is the correlation coefficient for data with 170-sec smoothing. We have chosen 97 of 248 intervals that satisfy to our conditions. Figure 9 presents the dependence of values of correlation coefficients for these 97 intervals on smoothing time: thin line shows the average value, error bars show the standard deviation for each smoothing time, thick line shows the dependence of average rate of change of the correlation coefficient on smoothing time. The average rate of the change of the correlation coefficient is defined as: [R(N)-R(N-1)]/dT, where R(N), R(N-1) are values of the correlation coefficient for different smoothing times, dT is the difference of these smoothing times.

The correlation coefficient and the rate of correlation coefficient changes depend strongly on smoothing time for smoothing time range from 10 to 50 seconds; for smoothing times over 50 seconds these two values don't change significantly. We consider that the variations on the scale less than 0.02 Hz (which corresponds to minimum variation scale on 50 s smoothing data) generally penetrate from SW to MSH, while the variations on the scale more than 0.02 Hz are generated predominantly by the bow shock and inside the magnetosheath.

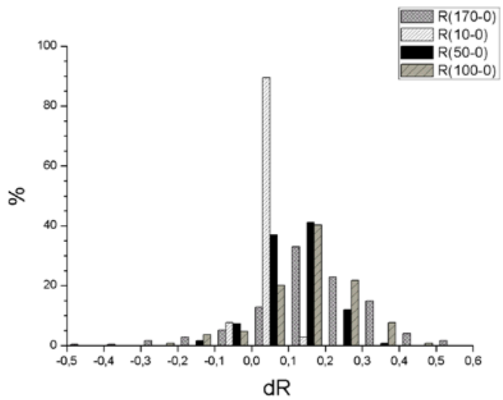

Figure 8. Distribution of the change of the value of correlation coefficients for data with different smoothing times.

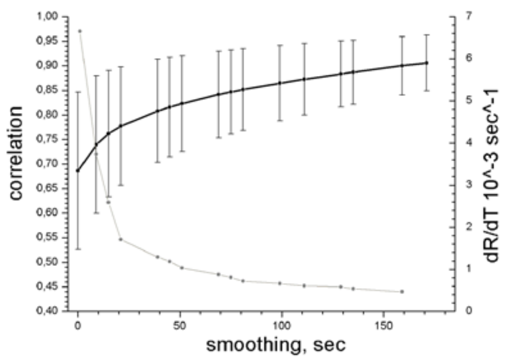

Figure 9. Dependence of the average value of the correlation coefficient on smoothing time for intervals with a significant correlation (black line) (error bars show standard deviations for each smoothing time) and dependence of average rate of the correlation coefficient change (grey line)

Study of continuous interval

We also considered continuous 20-hour time interval on 4 June 2009. Figure 10 presents the ion density (panel *a*) in SW (black line) and in MSH (grey line).

Panel *b* presents time evolution of the correlation coefficient between density on SW and MSH with maximum smoothing time — 170 seconds. An average value of the correlation coefficient for the whole interval is equal to 0.79 and the correlation tends to decrease after 12:00 UT but one can observe the separated intervals with abrupt decreasing of the correlation coefficients during the whole time interval (e.g., at 04:15 *R* changed from 0.9 to –0.2 in 30 minutes). It's important to understand why such abrupt changes of the correlation coefficient can take place.

Panel *c* in Figure 10 shows an evolution of the distance between satellites along the Y_{GSE} axis. The X_{GSE} coordinate ranges from 11.5 to 12.5 Re for the SW satellite and from 5.8 to –0.3 for the MSH satellite. The Z_{GSE} coordinate changes insignificantly and equals ≈ –3.5 Re for both satellites. One can see that satellites are moving apart during the observed interval. This fact can explain decreasing trend of the correlation coefficient after 12:00 UT. The other reason of decreasing trend of the correlation coefficient can be explain by less number of abrupt changes of the ion density observed past 12:00 UT, however, one can see that in first part of the interval, practically all SW density abrupt changes are observed in MSH, while in the second part, the SW density changes don't penetrate inside MSH at all, which can be explain by increasing distance between the spacecraft.

Panel *d* presents evolution of the θ_{Bn} angle during the same period. One can see that the angle exceeds 60° till 14:00 UT. After 14:00 UT θ_{Bn} tends to decrease but doesn't equal less than 40°. Thus, the decreasing trend of the correlation coefficient may be associated with the transition to the quasi-parallel bow shock orientation. On the other hand, the abrupt changes of the correlation coefficient taking place before 12:00 UT are accompanied by the quasi-perpendicular bow shock orientation (e.g., at 04:15, 09:45, 10:30).

At last, panel *e* shows evolution of the IMF θ and φ angles, that are defined as $tg\theta = B_z/\sqrt{(B_x^{2}+B_y^{2})}$, $tg\varphi = B_y/B_x$. Some of the IMF sharp rotations lead to the abrupt changes of the correlation coefficient (e.g., at 04:15 UT), but not every IMF rotation affects the correlation value (e.g., at 09:45, 10:30).

Thus, the abrupt correlation coefficient changes may be caused by different reasons. The changes of the θ_{Bn} angle and increasing of a distance between points of observations lead to large-scale decreasing of the correlation level with large numbers of abrupt correlation coefficient changes. At the same time, the IMF sharp rotations, the number of abrupt changes of the ion density can influence on the appearance of the separated abrupt changes of the correlation coefficient, i.e., on the structure modification. However, studying of a role of each parameter requires a more detailed analysis.

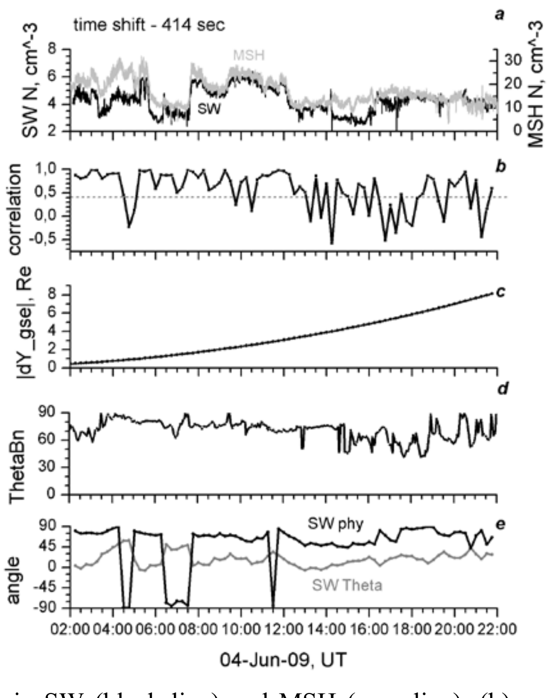

Figure 10. (a) — Ion density in SW (black line) and MSH (grey line); (b) — time evolution of correlation coefficient; (c) — distance between satellites along Y_{GSE} axis; (d) — time series of θ_{Bn} angle; (e) — time series of the IMF θ (grey line) and φ (black line) angles for the interval 02:00–22:00 UT on 4 June 2009.

Conclusions

In this study, we analyzed the 64 hours of SW and MSH data using an correlation analysis. We found that:

- The comparison of data from two closely located satellites in SW and MSH shows a wide range of values of correlation coefficients. The correlation coefficients (calculated on 30-min intervals) are changed from –0.5 to 1.0; the maximum of the correlation coefficient distribution for non-smoothed plasma density data is equal 0.45 and the width at half-height is equal 0.6.
- The peak of distribution of the values of the correlation coefficient becomes clearer for data with 50-sec smoothing; the maximum of distribution is equal 0.75. The correlation coefficient increases in average on 0.1–0.2 for smoothed data. For more than 35 % of intervals the increase of correlation coefficients exceeds 0.3.
- The correlation coefficient depends strongly on smoothing time if plasma density data are smoothed in 10–50 s intervals, and doesn't depend significantly on it, for smoothing for more than ≈ 50 s. So this value (50 s or 0.02 Hz) can be represented as a rough boundary between the density variations coming generally from the solar wind, and the density variations produced mainly by the shock wave and inside the magnetosheath.
- The number of reasons can lead to the modifications of small- and middle-scale plasma structures at the propagation through the bow shock and magnetosheath. It is possible to select the θ_{Bn} angle, a distance between observation points in the YZ_GSE plane, fast IMF rotation and the absence of abrupt changes of ion density as important factors which can lead to decreasing of the correlation.

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References

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

Auster H. U., K. H. Glassmeier, W. Magnes, O. Aydogar et al., The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, 141, 235–264. doi: 10.1007/s11214-008-9365-9, 2008.

Gutynska O., Simunek J., Safrankova J., Nemecek Z., Prech L., Multipoint study of magnetosheath magnetic field fluctuations and their relation to the foreshock, J. Geophys. Res., 117, A04214, 2012.

McFadden J. P., Carlson C. W., Larson D., Ludlam M., Abiad R., Elliott B., Turin P., Marckwordt M., Angelopoulos V., The THEMIS ESA plasma instrument and in-flight calibration, *Space Sci. Rev.,* 141, 277–302, doi: 10.1007/s11214-008-9440-2, 2008.

Rakhmanova L. S., M. O. Riazantseva, and G. N. Zastenker, Dynamics of the small-scale solar wind structures with sharp boundaries under transfer from the solar wind to magnetosheath, in *WDS'12 Proceedings of Contributed Papers: Part II – Physics* of Plasmas and Ionized Media (eds. J. Safrankova and J. Pavlu), Prague, Matfyzpress, pp. 176–181, 2012.

Safrankova J., Nemecek Z., Prech L., Samsonov A. A., Koval A. and Andreeova K., Modification of interplanetary shock near the bow shock and through the magnetosheath, *J. Geophys. Res,* 112, A08212, 2007.

Schwartz S.J., Burgess D., Moses J.J., Low-frequency waves in the Earth's magnetosheath: present status, *Ann. Geophys.,* 14, 1134, 1996.

Shevyrev N., Zastenker G. N., Nozdrachev M. N. et al., High and low frequency large amplitude variations of plasma and magnetic field in the magnetosheath: radial profile and some features, *Adv. Space Res*.,31, 1389–1394, 2003.

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

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

Spreiter J.R., Summers A.L., Alksne A.Y., Hidromagnetic flow around the magnetsphere*, Planet. Space Sci*., 14, 223, 1966.

Zastenker G., Nozdrachev M. N., Nemecek Z. et al., Multispacecraft measurements of plasma and magnetic field variations in the magnetosheath: comparison with Spreiter models and motion of the structures, *Planet. Space Sci.*, 50, 601–612, 2002.