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Modification of small- and middle-scale solar wind structures by the bow shock and magnetosheath: Correlation analysis

L. Rakhmanova [a,b], M. Riazantseva [a,b], G. Zastenker [a], J. Šafránková [c,*]

[a] Space Research Institute, Russian Academy of Sciences, Moscow 117997, Russia
[b] Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia
[c] Charles University in Prague, Faculty of Mathematics and Physics, Prague, Czech Republic

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ABSTRACT

The paper is devoted to a modification of small- and middle-scale solar wind plasma and magnetic structures during their propagation through the bow shock and magnetosheath. We use data from two closely spaced THEMIS spacecraft in the solar wind and magnetosheath and we concentrate on the slow solar wind and quasiperpendicular bow shocks. We determine a cross-correlation function between time series of the solar wind and magnetosheath ion densities and magnetic field magnitudes. The correlation coefficient is calculated for data smoothed on different subintervals from 10 to 170 s and we show that the correlation coefficient between both quantities strongly depends on the duration of smoothing subintervals in the range of 10–50 s, whereas it is not significantly affected if the duration of the subintervals exceeds ≈ 50–100 s. It means that the fluctuations with frequencies below 0.01–0.02 Hz are of the solar wind origin, whereas bow shock and magnetosheath processes contribute to the enhanced level of density and magnetic field magnitude variations at higher frequencies. We also investigate an influence of different parameters on the modification of structures in the magnetosheath. We suggest that solar wind structures of larger amplitudes are less modified, especially if these structures are embedded in a dense solar wind and/or in the solar wind with a large interplanetary magnetic field magnitude. Under selected conditions, the modification of the structures does not depend on the interplanetary magnetic field direction with respect to the bow shock normal.

1. Introduction

The Earth's magnetosphere is strongly influenced by the supersonic solar wind (SW). In front of the magnetosphere, there are the bow shock (BS) and a turbulent region between the BS and magnetopause called the magnetosheath (MSH) formed by the solar wind–magnetosphere interaction. The SW flow passing the BS is further modified near the magnetopause, thus plasma and magnetic field parameters change in the MSH where these parameters vary more intensively than those in the SW. The interplanetary magnetic field (IMF) changes its direction also in this region. Pulinets et al. (2012) compared the IMF direction in the SW near the BS and in the MSH close to the magnetopause and showed that the B_Z component changes its sign in $\approx 30\%$ of the cases. Šafránková et al. (2009) studied a reliability of prediction of the magnetosheath B_Z component from IMF observations and found that this probability is close to 0.5 (a random coincidence) for IMF $|B_Z| < 1$ nT regardless of the solar cycle phase. The probability increases with the increasing $|Bz|$ but not always equal to 1 even for $|Bz| > 9$ nT.

A SW plasma is compressed, heated, decelerated and the flow direction changes at the BS. Plasma parameters roughly follow the gas dynamic model of Spreiter et al. (1966). More complicated MSH models include the influence of the magnetic field on the plasma flow (e.g., Zwan and Wolf, 1976; Wu, 1992; Southwood and Kivelson, 1992, 1995). Flow patterns and average values of plasma and magnetic field (MF) parameters are described satisfactorily by models but the fluctuations of parameters do not. This difference is especially significant for MF fluctuations (see a comparison of models and experimental data in Němeček et al., 2000; Zastenker et al., 2002). Thus, the magnetosheath is an important interface of the Sun–Earth interaction and a key segment of space weather forecasts.

The MSH is a highly turbulent region where the ion flux and MF usually fluctuate in a wide frequency range. Wave activity is a important source of the MSH fluctuations (e.g., Schwartz et al., 1996). The waves can be created at the BS or near the magnetopause. Moreover, further MSH variations can originate in the foreshock region (e.g., Němeček et al., 2002; Blanco-Cano et al., 2006).

Many papers were devoted to investigations of MSH fluctuations. Zastenker et al. (2002) showed two types of MSH plasma and magnetic field variations: (1) the disturbances of the SW plasma or

* Correspondence to: KFPP MFF UK, V Holesovickach 2, 180 00 Prague, Czech Republic.
E-mail address: jana.safrankova@mff.cuni.cz (J. Šafránková).

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IMF which pass through the bow shock and (2) the variations produced within the MSH. Shevyrev et al. (2003) studied radial profiles of low- (1–60 min) and high-frequency (1–60 s) ion flux and MF variations and they have shown that (1) their profiles are similar at the dawn and dusk MSH flanks for both high- and low-frequency variations; (2) the amplitude of high-frequency variations depends on the θ_{BN} angle (the angle between the bow shock normal and IMF direction); and that (3) variations are more powerful behind the quasi-parallel ($\theta_{BN} < 45^o$) bow shock. Moreover, Shevyrev and Zastenker (2005) found that ion flux and MF magnitude fluctuations observed behind the quasi-parallel BS in the frequency range of 0.02–1.00 Hz have two times larger amplitudes than the fluctuations behind the quasi-perpendicular BS. The authors suggested that such fluctuations are generated at the BS and then move into the MSH with the plasma flow along the streamlines. Gutynska et al. (2008) prepared a statistical correlation analysis of two close separated points in the MSH (using Cluster) and found that the correlation length of MF variations in the frequency range of 0.001–0.125 Hz is equal to 1 R_E and only slightly depends on the magnetic field orientation and the flow direction. This result was confirmed by Gutynska et al. (2009); the authors showed that the correlation length increases with the amplitude of variations in this frequency range.

To separate spatial and temporal variations of MSH parameters, multipoint studies are often used. Gutynska et al. (2012) used WIND (as a distant SW monitor), Geotail (as a close SW monitor), THEMIS B, C and Cluster 1, 2 (as closely separated pairs in the MSH) and such a data set allowed them to study MSH variations and their origin. The authors showed that low-frequency fluctuations (10^{-4}–10^{-3} Hz) are observed in a whole dayside MSH and argued that a source of such variations is the SW. On the other hand, for high-frequency SW and MSH variations, a good correlation is missing, thus these fluctuations are generated locally within the MSH, mainly near the magnetopause because their amplitudes increase as the spacecraft moves toward the magnetopause.

A useful method of the MSH study is a comparison of structures observed at various points during their propagation through the SW and MSH. Koval et al. (2006a,b) and Šafránková et al. (2007) investigated the interplanetary (IP) shock propagation over the BS and its evolution in the MSH and they found that the IP shock decelerates in the MSH. The IP shock–BS interaction also creates several new discontinuities of different types that are propagating in the MSH. Rakhmanova et al. (2012) analyzed the development of small-scale SW structures (with a duration of several seconds) and concluded that their amplitudes and durations increase in the MSH. In these cases, a high level of correlations between SW and MSH parameters was observed.

The case studies are important but they do not provide information about a typical behavior of structures at different spatial and temporal scales in a highly turbulent MSH environment. Moreover, case studies are often oriented to distinct events and they cannot answer the question why some structures are transferred from the SW to MSH, whereas others do not. We believe that a systematic correlation analysis followed by a statistical evaluation of results is more appropriate for this task.

In the present study, the correlation analysis of 89 h of simultaneous SW and MSH plasma and MF measurements from the multi-spacecraft THEMIS mission is performed. The main objects are SW structures of small- (tens of seconds) and middle- (from units to tens of minutes) scales. We use data from two spacecraft located simultaneously in the SW and MSH and analyze a dependence of correlation coefficients of the ion density and MF magnitude on the duration of averaging intervals. Relative numbers of intervals with a good correlation of plasma and MF parameters are considered in order to find the factors influencing the modification of SW structures in the MSH.

2. Data processing

We used the data of five THEMIS spacecraft moving along elliptical orbits (Angelopoulos, 2008; Sibeck and Angelopoulos, 2008) and we chose the time intervals when one spacecraft was located in the SW and second one simultaneously scanned the MSH. In selected events, the distance between two spacecraft in the X_{GSE} direction does not exceed 20 R_E. Plasma parameters were measured by electrostatic analyzers (McFadden et al., 2008) and the MF magnitude was registered by the fluxgate magnetometer (Auster and et al., 2008). Data were taken from http://cdaweb.gsfc.nasa.gov with a time resolution of 3 s.

We selected continuous (with the duration exceeding 3 h) time intervals during periods from June 15 to November 15, 2008 and from June 15 to September 30, 2009. In these periods, THEMIS orbits were stretched near the Sun–Earth line and the separation of a pair of s/c in the YZ_{GSE} plane did not exceed 20 R_E. We used THEMIS-B or C measurements in the SW and simultaneous THEMIS C, D or E measurements in the MSH depending on spacecraft locations and data availability during selected intervals. To avoid the foreshock region, we excluded the periods with a high level of high-frequency variations. Furthermore, we calculated the mean θ_{BN} angle (indicating the presence of the foreshock in the upstream SW) for all analyzed intervals to ensure that the foreshock influence is negligibly small. Although the observations were made in course of a prolonged solar minimum (2008–2009) characterized by the quiet solar wind, we were able to identify 9 intervals with the total duration of 89 h containing numerous distinct plasma structures. The structures consist of increases/decreases of the density and/or MF magnitude that reached 20% of mean values within tens of seconds (Riazantseva et al., 2005, 2007). The SW velocity did not exceed 500 km/s, thus we observe primarily the slow SW during investigated intervals.

After selection of intervals, we calculate correlation coefficients between time series of SW and MSH plasma densities and MF magnitudes as a function of the time lag first. Second, we calculate correlation coefficients for data smoothed on the different subintervals with durations from 10 to 170 s. We use moving averages as data smoothing and we will shortly write “smoothing on N seconds” or “N-s smoothed” as abbreviations. Finally, we determine a dependence of the correlation coefficient on the duration of smoothing intervals. A smoothing procedure decreases the relative amplitude of fluctuations shorter than the corresponding time interval and weakens their influence on the correlation level. At the beginning of data processing, we use 2-h intervals to check that a large-scale correlation of SW and MSH time series is observed and then, we calculate the correlation coefficients on 30-min intervals.

3. Correlation analysis: case study

As an example of our calculations, we present 25-h interval on June 11–12, 2009 in Fig. 1. Fig. 1a and b show the ion density and MF magnitude observed by THEMIS B (red lines) in the SW and by THEMIS C (green lines) in the MSH. SW measurements are shifted by 420 s to reflect the time of plasma propagation from one spacecraft to another. This time lag was determined from the maximum of the cross-correlation coefficient on a full time interval. Since the SW speed and the spacecraft separation vary during analyzed intervals, we calculate the time lag for each shorter (2 h or 30 min hereafter) subinterval using the time lag found for the full interval as a first approximation.

At the beginning, we calculate correlation coefficients on 2-h intervals overlapped by 1 h. Time profiles of the correlation coefficients of both quantities in the SW and MSH as a function of the lag are shown in Fig. 1c and d, respectively. We will call “absence of correlation” the cases where the correlation coefficient is lower than 0.5,