WDS'12 Proceedings of Contributed Papers, Part II, 176–181, 2012. ISBN 978-80-7378-225-2 © MATFYZPRESS

Dynamics of the Small-scale Solar Wind Structures with Sharp Boundaries Under Transfer from the Solar Wind to Magnetosheath

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Abstract. This paper is based on the study of small-scale and sharp plasma structures in the solar wind (SW) and their evolution during propagation through the bow shock (BS) to the magnetosheath (MSH). We have used data obtained from two closely separated THEMIS spacecraft upstream and downstream from the BS. We compare the changes of the plasma density, magnitude of the magnetic field and the duration of the same structures both in SW and in the MHS. 15 events are analyzed. We have found that these structures maintain their sharp boundaries while crossing the Earth's bow shock and coming to the magnetosheath. However, the amplitudes of changes are increased in average by 30% and the front durations are increased on average by 40%. These changes are different for the plasma density and magnetic field amplitude.
We analyzed the dependence of variations of the front duration and plasma density amplitude on the upstream solar wind parameters and didn't found any correlation between them.

Introduction

One of the interesting features of solar wind variations is the existence of the large and very sharp changes of the ion flux. Sharp ion flux changes [*Riazantseva et al.,* 2005] have durations about several minutes or less and are observed not only at shock's front, but also at other types of discontinuities. The bulk velocity is changed by 2–3 % during the flux changes that means that a sharp flux increase (or decrease) is caused by the ion density change. These sharp and large density changes are the boundaries of small-scale structures of the solar wind, which are regions with concentrated or rarefied plasma on time scales of about ten minutes. The origin of these structures is not known till now.

The magnetosheath is the region between the solar wind and magnetosphere, so any solar wind disturbances firstly reach to MSH and then affect the magnetopause being transformed. The plasma in MSH is highly compressed in comparison with the SW. A high level of fluctuations of magnetic field and plasma parameters is permanently observed in a wide range of frequencies [*Shevyrev et al*., 2003].

Zastenker et al, [2002] show that while the level of variations in the SW increases, the level of variations in the MSH increases also. This means that the variations are amplified in the MSH. However, high level variations in the MSH are observed even in the absence of variations in the SW. So, every essential plasma and magnetic field changes have an influence on variations of these parameters in the MSH, but not every variations in the MSH is related to variations in the SW. Many of MSH fluctuations are generated on the bow shock (BS) and through the MSH.

Numerous papers are dedicated to the study of plasma and magnetic field parameters in the MSH, but only a small number of studies is devoted to the problem of a propagation of sharp structures through the SW and MSH. *Koval et al.*[2006] and *Safrankova et al.*[2007] consider the propagation of interplanetary (IP) shocks through the SW and MSH and their modification near the bow shock and inside MSH.

In this study, we analyze the propagation of structures with very sharp boundaries which differ from shocks through the SW and MSH.

Observations

To analysis, we used THEMIS mission data [*Angelopoulos,* 2008*; Sibeck and Angelopoulos,* 2008]. Five THEMIS satellites move on elliptical orbits around the Earth, thus, it is possible to find such time intervals, when one spacecraft is placed in the solar wind and another one is placed in the magnetosheath. The time shift of solar wind propagation from one to another satellite at a distance smaller than 20 Re was determined to be shorter than 10 minutes. Plasma parameters are measured by electrostatic analyzers [*McFadden et al.,* 2008], and the magnetic field magnitude is measured by fluxgate magnetometers [*Auster et. al.,* 2008]. Data are taken from *http://cdaweb.gsfc.nasa.gov.*

We looked through the density data of the Themis spacecraft during two time ranges: 01/06/2008–01/11/2008 and 01/06/2009–01/11/2009, which were the periods when orbits of the spacecraft were located along the Sun–Earth line, and we found the events with large changes of the SW density. Then, we looked if there are data from another spacecraft in the MSH. We selected intervals with duration less than 1 min when a relative amplitude change is more than 20% (determination of the amplitude of the large density change will be given below). We didn't use any automatic selection as the process of searching events is highly difficult taking into account the solar wind turbulence and a high level of fluctuations in the magnetosheath.

Our statistics isn't large because it is difficult to find appropriate time periods with the spacecraft located in such places as we need for the study.

Case study

As an example, we analyzed in details the June 4th 2009 event. Figure 1 shows Themis-B and Themis-C positions during the event in the X-YZ plane.

Figure 2 shows the ion density (top panel), magnitude of the magnetic field (second panel) and bulk velocity (bottom panel) on June 4, 2009. Themis-B observations in the SW are shown by the thick line, while Themis-C observations in the MSH are shown by the thin line. The time shift is equal to 332 s and is produced to coincide the start of the density change in both SW and MSH. The figure shows that the large density increase is observed at 05:13:13 UT.

To calculate duration of the event, we take the point on the time scale with a smallest value of the density before the sharp front as a beginning of the event and a highest value of the density as the end of the event (or vice versa in the case of density decreasing). The front duration in the SW is 9 seconds (shown by thick dashed lines). One can see a similar structure in the MSH, where the front duration is

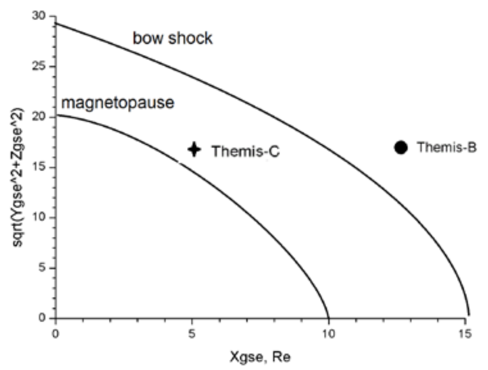

Figure 1. Satellite positions on June 04, 2009.

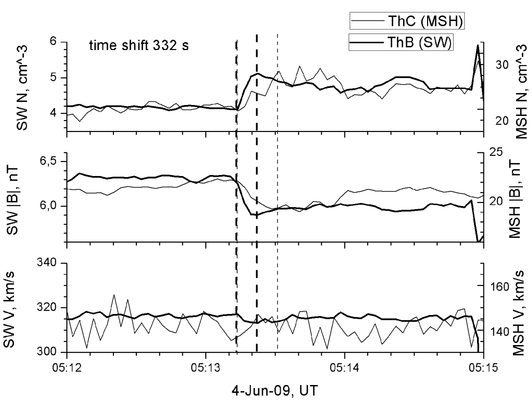

Figure 2. The ion density, MF amplitude and bulk velocity in the SW (thick line) and MSH (thin line). Fronts are denoted by dashed lines.

much longer and constitutes 18 seconds (thin dashed lines). Using the smallest and highest values, we calculate the amplitudes of events. The density amplitude in the SW and MSH is defined as $\mathbf{A_{den}} = (A_{max} - A_{min})/A_{max}$, where A_{max} and A_{min} are the highest or smallest values of density. The density amplitude in the SW is $\mathbf{A_{den}}$=20% and in MSH is $\mathbf{A_{den}}$=26% during the event.

The decrease of the MF magnitude is observed both in the SW and MSH in the analyzed case (Figure 2, middle panel). We use values of the magnetic field magnitude measured at the beginning and end of the event to calculate the amplitude of the MF change $\mathbf{A_{mf}}$. For our event this parameter is equal $\mathbf{A_{mf}}$=3,7% in the SW and $\mathbf{A_{mf}}$=12% in MSH. Furthermore, Figure 3 shows magnetic field components. Decreases of Bx and By components of the magnetic field vector are observed both in the SW and MSH, whereas the Bz component changes only slightly. Simultaneously, small changes of the bulk velocity are observed in the analyzed period of time (Figure 2, bottom panel).

In order to estimate a modification of the structure through the transition from the SW to MSH, we analyzed the ratios of the density amplitude, magnetic field amplitude, and the duration of the event in the MSH to corresponding quantities measured in the SW. In June 4, 2009, these values are: front duration change **dT** = 2; density amplitude change $\mathbf{dA_{den}}$ = 1.3; magnetic field amplitude change $\mathbf{dA_{mf}}$ = 3.2.

The angle between the bow shock normal and interplanetary magnetic field (IMF) is Θ_{Bn} =79.7°. The Θ_{Bn} angle was estimated at the BS by the method described in *Shevyrev et al.*[2005]. For this calculation, Themis-C was shifted by tracing to the BS along the flow lines (estimated according to the Spreiter's model) and the Θ_{Bn} angle was calculated at this point. We use the ACE spacecraft as a monitor of solar wind conditions. As a result, we get an average value of the angle to estimate if the event is related to the crossing of quasi-parallel or quasi-perpendicular shocks.

Figure 4 demonstrates the total pressure change equal to ≈ 11% in the SW and ≈ 20% in MSH. We suppose that the event of June 4, 2009 is a tangential discontinuity as the density and magnitude of the

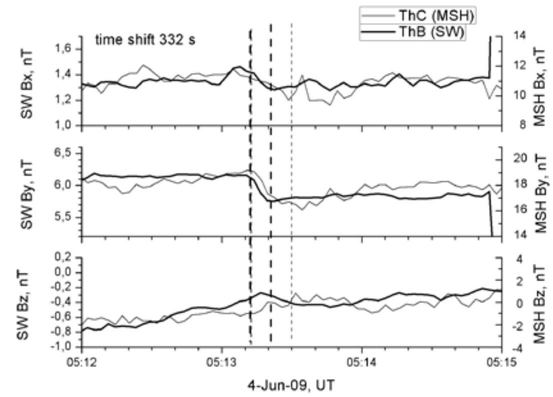

Figure 3. Magnetic field components in the SW (thick line) and MSH (thin line) on June 04, 2009. Fronts are denoted by the dashed lines.

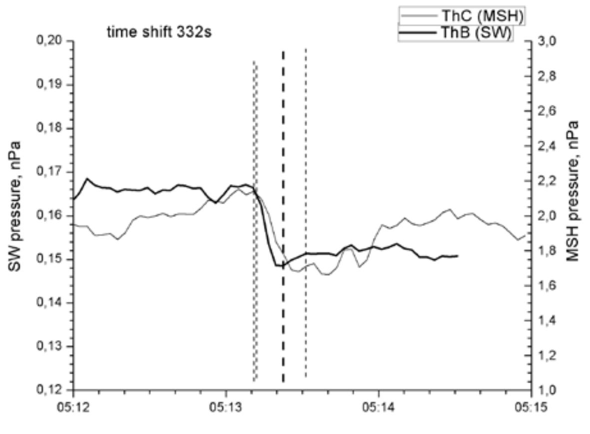

Figure 4. Total (magnetic + thermal) pressure.

magnetic field changes are large, while there is a small change of the bulk velocity, and also the total pressure changes slightly.

In this study, we analyzed 15 events similar to the above one. These events were observed in the 2008–2009 years. Three characteristics are studied for each event: 1) front duration (**T**), 2) density amplitude (**A_{den}**), 3) magnetic field amplitude (**A_{mf}**) in the solar wind and magnetosheath.

Statistical results

For analyzed events, we have plotted following statistical distributions. Figure 5 shows the distribution of the front duration of events. It is possible to allocate two groups:

(1) 7 events have a small (≈ 25%) duration of the change;

(2) 4 events have a high (≈ 2 times) duration of the change

Figure 6 presents the distributions of events for changes of the density and magnetic field amplitudes. These distributions show that for the most events (10 of 15) the increase of the density amplitude is within 50%, but there are also events with the amplitude 2 times larger. The magnetic field amplitude increases from 2 to 7 times.

We tried to find any dependence between duration of the change and changes of the density and magnetic field amplitudes. Figure 7 shows the dependence of a change of the density amplitude on the duration and Figure 8 depicts the dependence of a change of the magnetic field amplitude on the duration. There is a large spread of obtained values. However, it is possible to select some groups of events. The two groups of events which we observed in a distribution of the change duration are also seen in this figure. For the events with a small duration of the change the increases of the density and magnetic field amplitude vary weakly (within 50% for the density and by 1–4 times for the magnetic field) and strongly (by 2 times for the density and by 4–7 times for the magnetic field). The density amplitude changes are only within 50% and the magnetic field amplitudes increase less than by 4 times for the second group (with a high duration of the change).

We consider the dependence of a duration of the change on solar wind parameters. Figure 9 presents the dependence of this change on the solar wind velocity. One can see that both for low (300–400 km/s) and high (400–500 km/s) solar wind velocities a duration of the change can be again small (within 25%) and high (at 2 times). On the other hand, Figure 10 presents a dependence of the change on the velocity ratio in the MSH and SW (this ratio is a more objective parameter that shows plasma

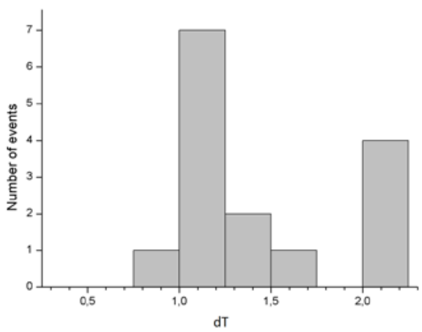

Figure 5. Distribution of events for the duration change.

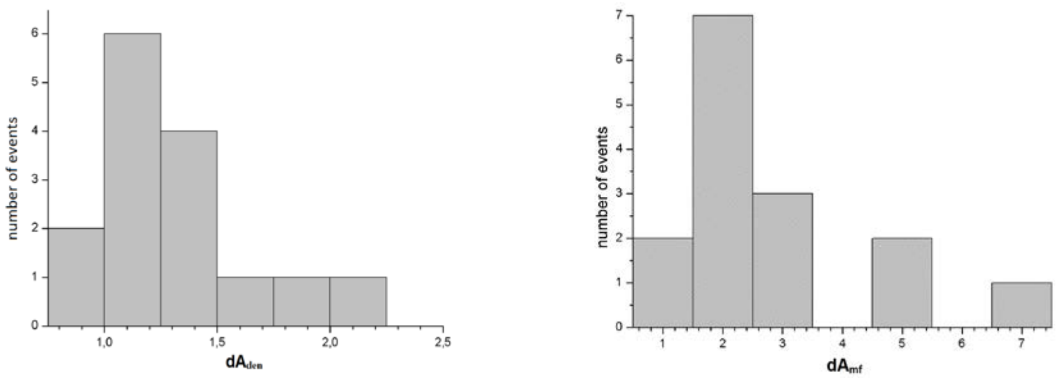

Figure 6. Distribution of the change of (a) the density amplitude, (b) the magnetic field amplitude.

conditions at the point, where the spacecraft is located in the MSH relatively to its boundaries). The figure shows that for both the subsolar point (Vmsh/Vsw ≈ 0.05) and the flanks both groups of the duration of changes are observed. That means that the duration doesn't depend on the spacecraft position of in the MSH.

The dependences of event characteristics on the Θ_{Bn} angle were analyzed, as it shown in Figure 11 that presents a dependence of the change duration on Θ_{Bn}. Nearly all Θ_{Bn} >45°, so all events are related to the crossings of the quasi-perpendicular shock. It is quite reasonable because we know that a level of fluctuations depends on the Θ_{Bn} angle. The fluctuation level is lower for high Θ_{Bn}, than for the cases of Θ_{Bn} < 45° (quasi-parallel shocks) [*Shevyrev and Zastenker*, 2005].

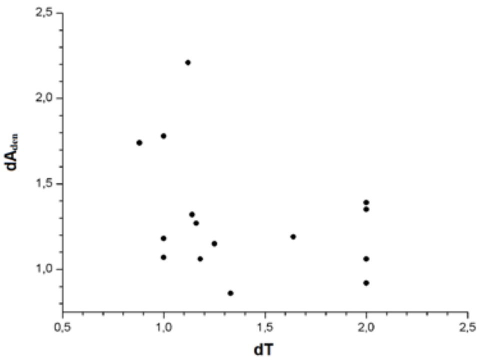

Figure 7. Dependence of the change of density amplitude on duration change.

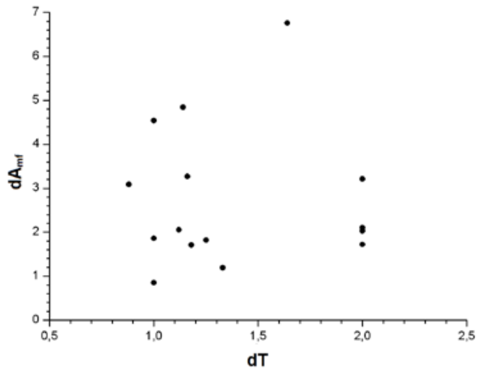

Figure 8. Dependence of the change of MF amplitude on duration change.

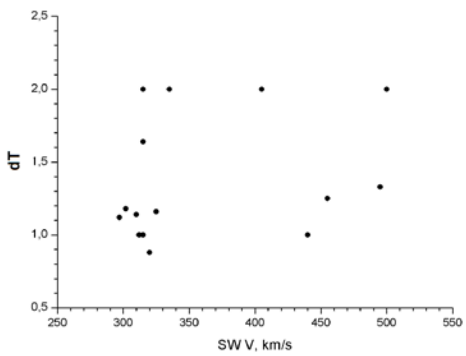

Figure 9. Dependence of the duration on the solar wind bulk velocity.

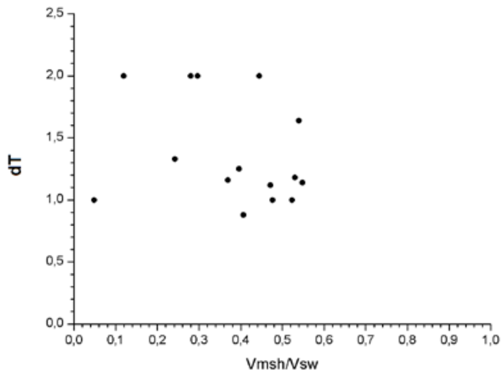

Figure 10. Dependence of the duration on the ratio of the MSH and SW bulk velocities.

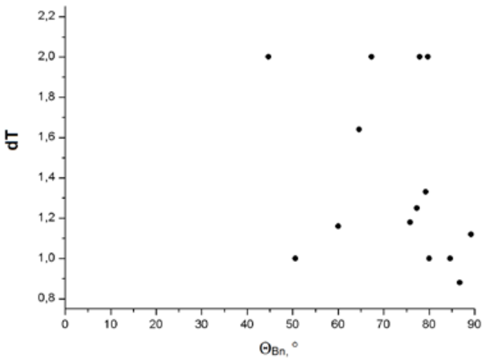

Figure 11. Dependence of the duration of the on the Θ_{Bn} angle.

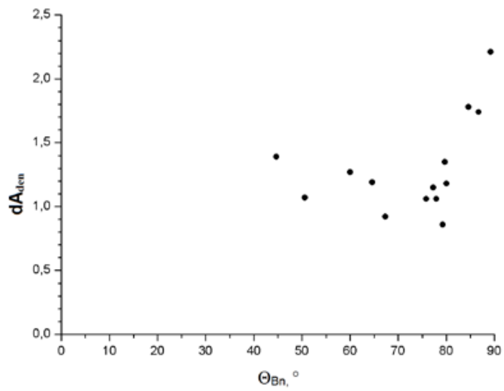

Figure 12. Dependence of the change of the density amplitude as a function of the Θ_{Bn} angle.

Figure 12 demonstrates a dependence of the change of density amplitude on Θ_{Bn}. We see that the change is ranged from 0.8 to 1.4 for Θ_{Bn} for the Θ_{Bn} angle between 45° and 85°. There were much larger changes of the density amplitude for the events with Θ_{Bn} >85° and they ranged from 1.7 to 2.3. Note here that only 14 of 15 events are shown in Figures 11 and 12. We are not able to calculate Θ_{Bn} for these cases because of the absence of the suitable ACE data.

Conclusions

We have analyzed 15 events of sharp boundaries of small-scaled structures of the solar wind that move from the solar wind to magnetosheath. All events are observed when the bow shock normal has the quasi-perpendicular orientation. The results of our analysis are:

(1) Small-scaled structures of the solar wind save their sharp boundaries moving from the solar wind to magnetosheath.

(2) A front duration of these structures increases while the structures are transported from the SW to MSH. Two groups of events can be selected: the events with a small (≈ 25%) duration and the events with a high (≈ 2 times) duration of the change.

(3) Density amplitude changes from 0.9 to 2 times are observed when the structure transfers from the SW to MSH. For the most events this value changes within 50%. We suppose that an increase of the density amplitude is caused by the non-linear increase of the plasma density at the bow shock.

(4) Magnetic field amplitude changes from by 0.8 to 7 times are registered when the structure transfers from the SW to MSH. This value changes ≈ 2–3 times for half of the events.

(5) A preliminary analysis shows that there isn't any dependence of the changes of the density and magnetic field amplitude on the duration of the change.

(6) The duration also doesn't depend on the ratio of bulk velocities between the MSH and SW.

(7) It was found that no dependence of the density amplitude change on Θ_{Bn} is observed, except 3 events, when Θ_{Bn} > 85°. Density amplitudes for these 3 events increase by nearly 2 times.

In this paper, we present only the preliminary results of the study and the work will be continued to expand our statistics.

Acknowledgements. The authors acknowledge the THEMIS Group, and in particular, Vassilis Angelopoulos, for providing the data. The work was supported by the grants the Russian Foundation for Basic Research, 12-05-00984-a, 10-02-01063-a and program "Scientific and pedagogical Personnel of Innovative Russia" №8527.

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