INTERNATIONAL JOURNAL OF GEOMAGNETISM AND AERONOMY
VOL. 3, NO. 1, PAGES 51–56, JANUARY 2002

Properties of large and sharp impulses in the solar wind

P. A. Dalin, G. N. Zastenker, and M. N. Nozdrachev

Institute of Space Research, Moscow, Russia

I. S. Veselovsky

Institute of Nuclear Physics, Moscow State University, Moscow, Russia

Abstract. In recent time, the solar wind fine structure study is highlighted. This study is very important for a better understanding of the solar wind–magnetosphere interaction taking into account solar wind variations. In fact, the sharp fronts of large events have a strong impact on the magnetosphere. Meanwhile, the structure and the dynamics of sharp fronts in the solar wind have not been investigated in sufficient details up to now. We have studied the large and sharp impulses of the solar wind ion flux (or density) by measurements onboard Interball 1 satellite. The characteristic durations of these impulses are about 1–3 hours with a very short time of increasing/decreasing. The typical ion flux variations are about 3×10^8 cm^{-2} s^{-1}. The high-resolution 1-s second measurements were used to investigate in detail the fronts of these impulses in the solar wind plasma. Individual and statistical properties were determined for the set comprising about 200 such events. The duration of the fronts, absolute and relative amplitudes, the steepness of increasing or decreasing are described. Most of the plasma density fronts appear as strong variations of a factor of about 2 during the time intervals from 10 to 50 s. Possible solar and heliospheric origins of the observed large and sharp plasma impulses are discussed.

Introduction

There are many sharp and large disturbances in the solar wind plasma density (and in the ion flux). They present the impulses of increasing and decreasing in the solar wind density although the first ones are observed more often than the seconds. The typical time duration of such events is about 1–3 hours. The value of the density impulse can exceed the average level in 3–5 times. Several tens of such events in the solar wind plasma were studied by *Shodhan et al.* [1999]. They associated the origin of these high-density structures with the solar events (coronal mass ejections (CMEs)) and the processes in the interplanetary medium (corotating interaction regions (CIRs)). Usually, these variations and their interaction with the magnetosphere are investigated in the timescale of the order of hours or minutes [*Borodkova et al.,* 1995; *Gosling et al.,* 1987; *Sibeck et al.,* 1991]. In this paper, large and sharp fronts of such events are studied on the basis of high-resolution (1 s) measurements obtained on Interball 1 spacecraft.

Statistics of the Sharp Fronts

This work focuses on a detailed study of the sudden and sharp fronts of large disturbances in the solar wind ion flux. For this study we used Interball 1 ion flux measurements with the 1-s resolution data for 1996 and 1998. These measurements were performed by Faraday cup instrument VDP

Paper number GAI00363.
CCC: 1524–4423/2002/0301–0363$18.00

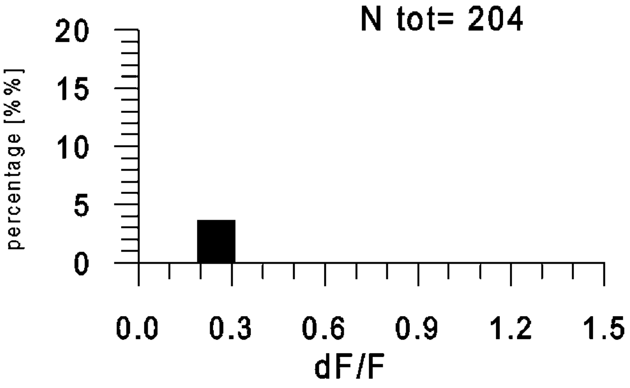

Figure 1. Distribution of the relative magnitude(dF/F) of flux variation.

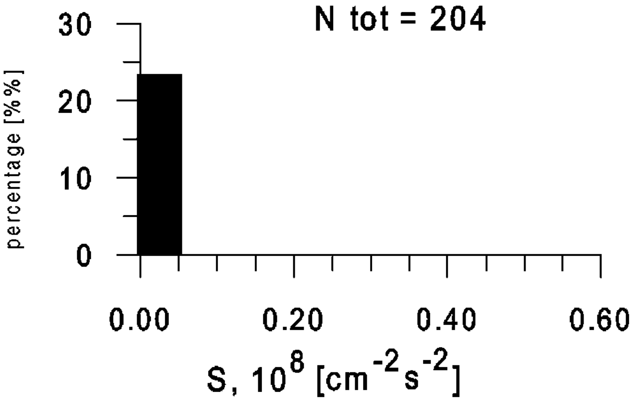

Figure 3. Normalized statistical distribution of the front steepness.

(see its description in the work of [*Safrankova et al.,* 1997]). We found more than 200 cases where the solar wind ion flux or density had large and sharp variations, that is, the absolute value of density changed on 20% or more, and the duration of the front was less than 15 min. We have concentrated on the examination of the statistical properties of these fronts: the absolute and relative values of the flux variation, durations, and steepness of the sharp change.

Figure 1 shows the distribution of the relative magnitude (dF/F) of flux variations. We can see that the most probable value of this magnitude is equal to 0.4–0.5. About 18% of all studied cases belong to the ion flux variations up to 0.4. Stronger variations with magnitudes from 0.4 to 1.0 were observed in 67% of the cases. The variations with a relative value of more than 1 had appeared in 14% of the events.

The distribution of the sharp front durations (dT, s) is presented in Figure 2. The most probable value of this duration is as small as 10–20 s. It is clearly seen that most of the events (65%) have a duration of fronts less than 50 s. Hence these fronts are usually observed as very fast and sharp ion flux changes on the leading and trailing sides of corresponding impulses (the duration up to several hours) in the solar wind. At the same time, there are 25% of cases with slower increasing/decreasing — the front duration is more than several minutes (not shown in this plot).

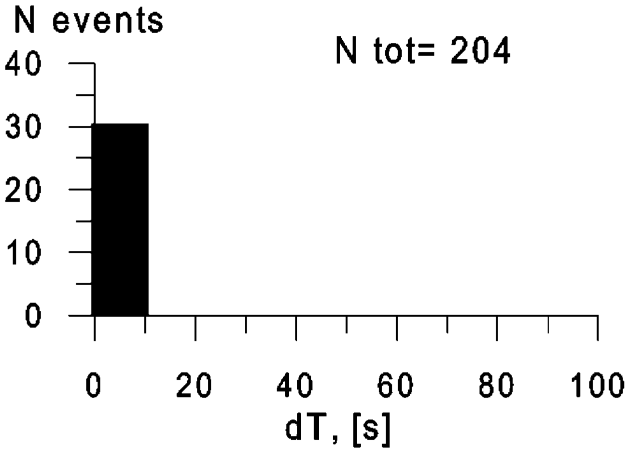

Figure 2. Distribution of sharp front durations.

Figure 3 presents the distribution of the front steepness (i.e., the speed of increasing or decreasing). We define steepness as $S = dF/dT$, where dF (10^8 cm^{-2} s^{-1}) is the absolute magnitude of ion flux variation and dT (s) is the front duration. As it is seen from Figure 3, the moderate steepnesses (up to 0.05×10^8 cm^{-2} s^{-2}) are most frequent in this distribution, but the long "tail" of the very fast increasing/decreasing is observed also.

The relation between the front duration dT and the absolute magnitude of plasma front dF is shown in Table 1. We can see that most events (45) are observed when the duration ranges from 10 to 60 s and the magnitude of the front varies from 3 to 6×10^8 cm^{-2} s^{-1}. The absolute values of more than 6×10^8 cm^{-2} s^{-1} are observed in 37% of the events. As the average value of the ion flux is about 5×10^8 cm^{-2} s^{-1}, it means that variations in plasma density appear as the enhancements of a factor of ~2 in one third of the examined events. Very short fronts (less than 10 s) were found in 30 cases (15% of the total number) and in 5 of them, we observed very fast increases with the very large magnitude, more than 10×10^8 cm^{-2} s^{-1}. It is necessary to mention that the duration of fronts, as small as several seconds, means that spatial dimension of large solar wind disturbances is less than about 10 proton gyroradii.

Table 1. Distribution of the Amounts of Studied Events Among dF (in 10^8 cm^{-2} s^{-1}) and dT (in Seconds) Ranges

dF/dT	< 10	10–60	60–180	> 180
< 3	11	25	8	8
3–6	10	45	13	9
6–10	4	15	6	2
10–15	2	6	5	2
> 15	3	18	7	5

Case Study of Large Plasma Impulses

Pressure Balance Structures

We have studied about 20 cases of large (about a factor of 2) solar wind density enhancements observed by two spatially separated spacecraft, Interball 1 (near the Earth) and Wind (near the L1 point, about 1,500,000 km sunward from the Earth). For all events we used measurements of velocity components and ion temperature (with about 1.5 min resolution) by Wind (shifted by solar wind propagation time to the Interball 1 position and interpolated to the moments of Interball 1 measurements) and data series of the ion flux and the magnetic field [*Nozdrachev et al.,* 1998] with a time resolution 1 s by Interball 1. The plasma density value was obtained from Interball 1 ion flux divided by Wind velocity value. Up to now, we did not classify these events by discontinuity analysis, but we investigated qualitatively the temporal and spatial dynamics of solar wind plasma enhancements propagating from L1 point to the Earth.

The characteristic feature of selected events is the rather small change in the bulk velocity and in the velocity components, no more than 5%. At the same time, the variations of the ion thermal speed (in the same cases) were rather strong, more then 50%.

The time behaviour of the magnetic field vector in each case was very different. Sometimes, strong synchronous plasma and magnetic field variations are observed. In some cases they can be interpreted as shock waves, rotational or tangential discontinuities. The magnetic field intensity drops up to very low magnitudes ("magnetic holes") were also observed. Approximately in the half of the selected cases there are no appreciable variations in the magnetic field vector components and in the strength of the field. However, the magnetic field intensity variations when it was observed has the clear tendency to anticorrelate with the solar wind density changes and to form sometimes the pressure balanced structures (i.e., the structures in the solar wind where the sum of plasma thermal pressure and magnetic field pressure across the variation is a constant).

Figure 4 shows an example of the "pressure balance" structure observed on June 29, 1996. In this case, the time delay of Wind data according to those of Interball 1 is 58 min. This structure is convecting with the solar wind flow. Note the remarkable constancy of pressure $P_{\mathrm{tot}} = P_{\mathrm{th}} + P_{\mathrm{mf}}$. It is the sum of the plasma thermal pressure defined as $P_{\mathrm{th}} = P_{\mathrm{el}} + P_{\mathrm{ion}} \simeq 2P_{\mathrm{ion}}$, and the magnetic pressure $P_{\mathrm{mf}} = B^2/8\pi$ where P_{el} and P_{ion} are the electron thermal pressure and the ion thermal pressure. It is necessary to note that we have no data for taking into account the electron thermal pressure in this case and we suppose that $P_{\mathrm{el}} \approx P_{\mathrm{ion}}$. This example demonstrates a significant decreasing of the ion flux during 1522–1524 UT against small variations of bulk and thermal velocities (second panel of Figure 4). At the same time this interval is characterized by the increasing of interplanetary magnetic field (IMF) magnitude (panel 3 of Figure 4), so the increasing of magnetic pressure completely compensates the decreasing of thermal pressure (panel 4 of Figure 4).

Inhomogeneous or Dynamical Structures

Another direction of this work is the investigation of the temporary and spatial variations of separated structures in the solar wind. The temporary dynamic changes can be estimated by simultaneous measurements on two or more spacecraft located along the Sun–Earth line. We used ion flux plasma measurements by Interball 1 and Wind. The main part of the investigated density enhancements in the solar wind registered on Wind reaches the Earth, not undergoing any appreciable changes. Nevertheless, in some cases (see Figure 5, for example) the disturbance fronts are registered not simultaneously on the spacecraft (taking into account the advection time). Point-to-point shifts were performed taking into account the current solar wind velocity values at given time moments as measured by Wind. Spacecraft GSE coordinates for this event were as follows: Wind, (211, 21, −12) R_E; Interball 1, (21, −16, 10) R_E. The time delays of the fronts registration (as seen in Figure 5) were about 5 and 13 min (above the advection time of about 59 min) around the time 2030 and 2152 UT accordingly. In such examples the absolute value of the disturbance remains constant, but the time profiles are not identical. Three factors could be important in the interpretation of such events: inclination of the fronts of the disturbances, the inhomogeneity of structures, and their time variations due to the dynamical processes during the propagation from L1 point to the Earth.

The inhomogeneities of the large-scale structures in the solar wind can be determined by measurements on spatially separated spacecraft in a plane perpendicular to the line of solar wind propagation. As was shown in our previous works [*Zelenyi et al.,* 2000], the solar wind plasma structures do not undergo essential changes on distances up to 100 R_E perpendicular to the Sun–Earth line. The solar wind plasma correlation lengths are very large (on average, from 600 to 800 R_E) in the plane perpendicular to its propagation. Thus the solar wind plasma structures have the average dimension exceeding the magnetosphere cross size of about 20 times. So, it seems that the inhomogeneity of the solar wind structures could not be the reason of the event shown in Figure 5.

Discussion

The origins of the observed impulses and their fronts remain unclear. They could be produced by the dynamical processes near the Sun or in the interplanetary space as was attributed in the paper [*Shodhan et al.,* 1999].

From the other side it seems that the very sharp solar wind ion flux (or density) fronts that we observed cannot survive on the way from the solar corona to the Earth orbit and have to be created in the interplanetary space not far from the point of observation.

The formation processes of these sharp fronts may be strongly dependent on the solar wind conditions. Such dependence is not evident up to now, but it is clear that the enhanced solar wind ion fluxes during the solar minimum

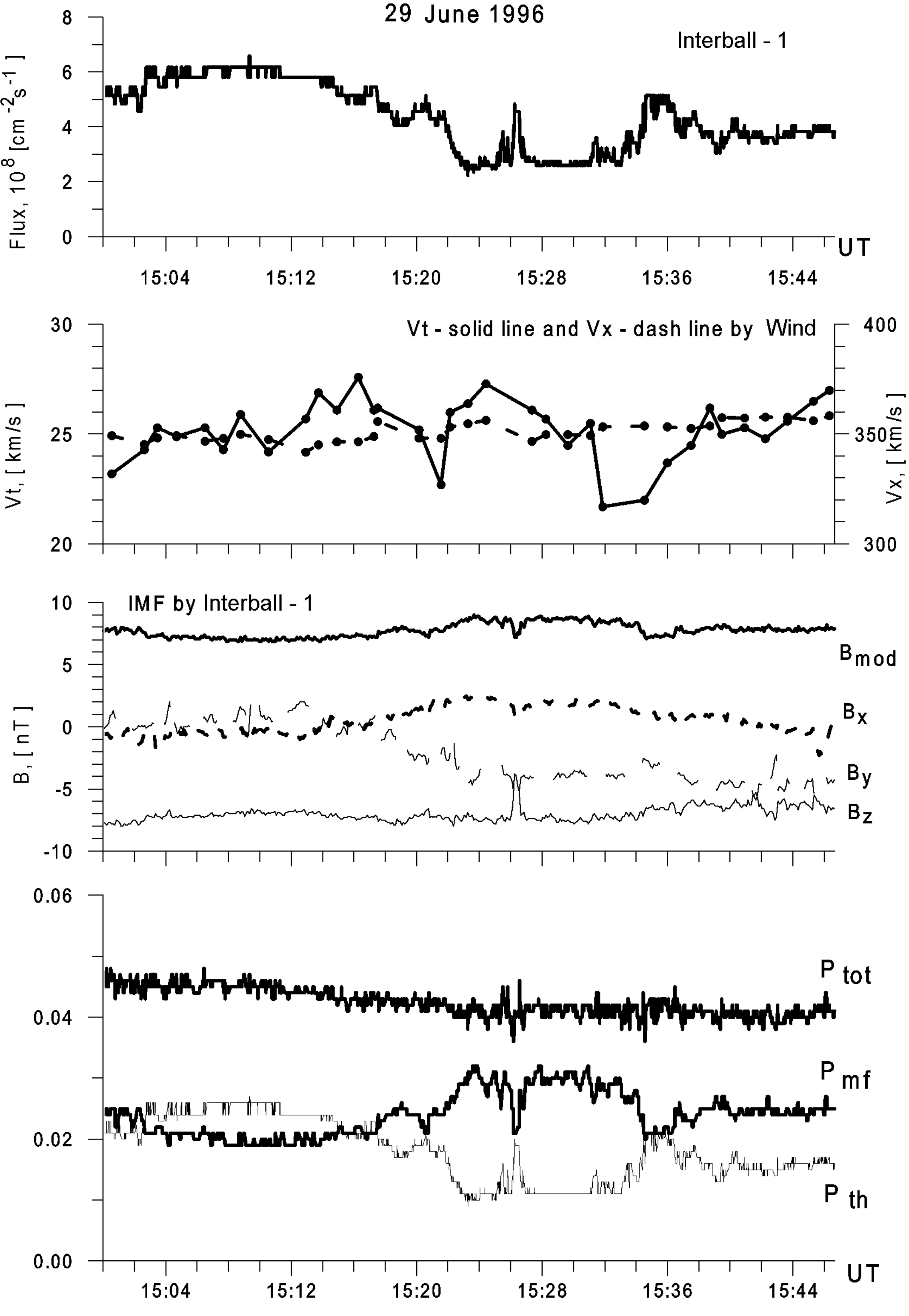

Figure 4. Solar wind structure with the "ion pressure balance" in the bottom panel.

periods are usually associated with coronal streamers producing slow, dense, and cold plasma flows [*Gosling et al.*, 1981]. The faster, hotter, and lower density solar wind originates from coronal holes [*Nolte et al.*, 1976].

The solar wind and IMF are remarkably variable in the scale of days, even during the solar minimum. It is mainly because of the streamer belt and adjacent polar coronal holes dynamics, continuously producing plasma outbursts, which

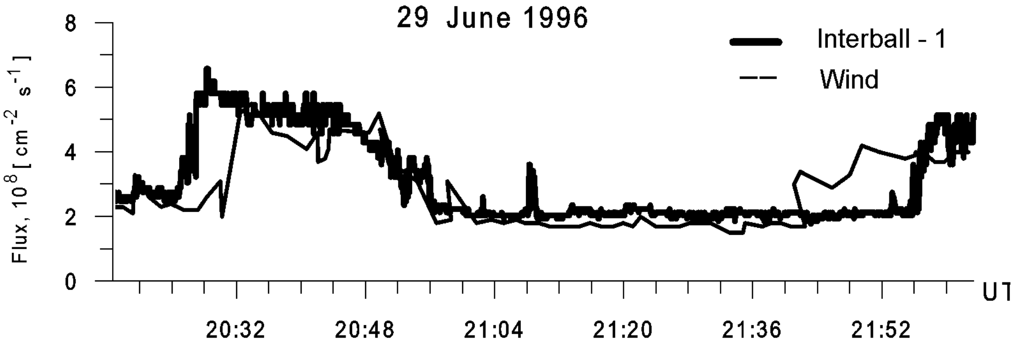

Figure 5. Example of not simultaneously registered fronts between Interball 1 and Wind (the advection time is taken into account).

are clearly seen in the SOHO–LASCO movies [*Sheeley et al.*, 2000] and in our solar wind measurements near the Earth [*Paularena et al.*, 1998]. During the May–June 1996 period the Sun is near the minimum of the solar activity cycle. The heliospheric current sheet is flat and the corona is rather tenuous. The Earth is immersed mainly in the heliospheric plasma sheet. Because of this, the observed impulses are presumably formed from the coronal streamer material.

It is necessary to mention that for long-scale intervals (about one solar rotation) a rather good correspondence between observed interplanetary structures and their parent solar sources was successfully demonstrated, especially regarding the streamer belt and the coronal hole associations [*Galvin and Kohl*, 1999]. Nevertheless, the interplanetary medium was still nonstationary in a scale of days, hours, and even minutes showing large variations that would be difficult to compare with rather slow observations of the solar corona and solar magnetic field structures.

Conclusions

1. Many cases of large and abrupt impulses are observed in the solar wind plasma. The most probable durations of increasing/decreasing plasma fronts are about 10–50 s. Shorter fronts are also observed. Most of the plasma density impulses appear as enhancements on about 2 times.

2. The physical nature of these large events is sometimes related to the convective "frozen-in" pressure balance structures in the plasma and the magnetic field. The remaining part is represented by nonlinear MHD perturbations probably generated locally in the interplanetary space. Hence both the "frozen-in" and the evolutionary structures are presented in the solar wind plasma presumably associated with the coronal streamer conditions.

Acknowledgments. Author thanks A. Lazarus for the possible use of Wind ion solar wind data. The work in ISR was partly supported by RFBR grant 00-15-96631 and 98-02-16297; INTAS grant 97-1372. The work in SINP MSU was partly supported by RFBR grants 98-02-17660 and 00-15-96623; INTAS grant 99-00727; Federal Program "Astronomy" project 1.5.6.2 and "Universities of Russia" grant 990600.

References

Borodkova, N. L., G. N. Zastenker, and D. G. Sibeck, A case and statistical study of transient magnetic field events at geosynchronous orbit and their solar wind origin, *J. Geophys. Res., 100*, 5643, 1995.

Galvin, A. B., and J. L. Kohl, Whole Sun Month at solar minimum: An introduction, *J. Geophys. Res., 104*, 9673, 1999.

Gosling, J. T., G. Borrini, J. R. Asbridge, S. J. Bame, W. C. Feldman, and R. T. Hansen, Coronal streamers in the solar wind at 1 AU, *J. Geophys. Res., 86,* 5438, 1981.

Gosling, J. T., D. N. Baker, S. J. Bame, W. C. Feldman, and R. D. Zwickl, Bidirectional solar wind electron heat flux events, *J. Geophys. Res., 92*, 8519, 1987.

Nolte, J. T., A. S. Krieger, A. F. Timothy, R. E. Gold, E. C. Roelof, G. Vaiana, A. J. Lazarus, J. D. Sullivan, and P. S. McIntosh, Coronal holes as sources of solar wind, *Solar Phys., 46*, 303, 1976.

Nozdrachev, M. N., A. A. Skalsky, V. A. Styazhkin, and V. G. Petrov, Some results of magnetic field measurements by the FM-3I flux-gate instrument onboard the Interball 1 spacecraft, *Kosm. Issled.* (in Russian), *36*(3), 268, 1998.

Paularena, K. I., G. N. Zastenker, A. J. Lazarus, and P. A. Dalin, Solar wind plasma correlation between IMP 8, Interball 1 and Wind, *J. Geophys. Res., 103*(A7), 14,601 1998.

Safrankova, J., G. Zastenker, Z. Nemecek, A. Fedorov, M. Simersky, and L. Prech, Small scale observation of magnetopause motion: Preliminary results of the Interball project, *Ann. Geophys., 15*(5), 562, 1997.

Sheeley, N. R., Jr., W. N. Hakala, and Y.-M. Wang, Detection of coronal mass ejection associated shock waves in the outer corona, *J. Geophys. Res., 105*, 5081, 2000.

Shodhan, S., N. U. Crooker, R. J. Fitzenreiter, R. P. Lepping, and J. T. Steinberg, Density enhancements in the Solar Wind, CP471, in *Solar Wind Nine,* edited by S. R. Habbal, R. Esser, J. V. Hollweg, and P. A. Isenberg, pp. 601–604, AIP press, New York, 1999.

Sibeck, D. G., and D. J. Croley Jr., Solar wind dynamic pressure variations and possible ground signatures of flux transfer events, *J. Geophys., Res., 96*, 1669, 1991.

Zelenyi, L. M., G. Zastenker, P. Dalin, P. Eiges, N. Nikolaeva, J. Safrankova, Z. Nemecek, P. Triska, K. Paularena, and J. Richardson, Variability and structures in the solar wind–magnetosheath–magnetopause by multiscale multipoint observations, in *Proceedings of the Cluster II Workshop on Multiscale/Multipoint Plasma Measurements*, ESA SP-449, pp. 29–38, Eur. Space Agency, Paris, France, 2000.

P. A. Dalin, M. N. Nozdrachev, and G. N. Zastenker, Institute of Space Research, 84/32 Profsoyuznaya Str., Moscow 117810, Russia.

I. S. Veselovsky, Institute of Nuclear Physics, Moscow State University, Moscow, Russia.

(Received 5 April 2001; accepted 18 October 2001)