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Observations of almost simultaneous crossings of two boundaries (bow shock and magnetopause) using Interball 1 and Geotail data

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Abstract. The problem of the motion of boundaries (bow shock and magnetopause) was studied using several nearly simultaneous crossings of the bow shocks and/or magnetopause identified by plasma and magnetic field measurements onboard Interball 1 and Geotail satellites. One of such observations, on 11 October 1996, when the satellites were at a distance of up to 30 R_E from each other, shows two different events: simultaneous bow shock and magnetopause sunward motion as a response to solar wind plasma and IMF disturbances and almost simultaneous bow shock sunward and magnetopause earthward motions. Some causes of such behavior of the boundaries, including the influence of hot flow anomalies of the solar wind, are discussed.

1. Introduction

To study the dynamics of solar-terrestrial relations, it is rather important to know the instant magnetospheric response to solar wind disturbances. Comparison of the reaction of different boundaries, such as the magnetopause and bow shock, at large distances to changes of solar wind conditions is of a special interest. Studies of this kind can help answer some questions on spatial/temporal interconnection between the boundaries occurring in the subsolar region and distant magnetotail. They make it possible to evaluate the influence of bow shock processes on the magnetopause location.

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It is known that the equilibrium position of the magnetopause is determined by solar wind conditions: the dynamical pressure and B_z component of the interplanetary magnetic field (IMF). The magnetopause shape is described by a conical surface with coefficients that depend on the solar wind condition [*Petrinec et al.*, 1996; *Shue et al.* 1997; *Sibeck et al.* 1991; *Roelof et al.* 1993].

The magnetospheric boundary moves according to the pressure balance between the solar wind plasma and the Earth's magnetic field. Dynamical pressure variations in the magnetosheath can also result in magnetopause motion [e.g., *Nikolaeva et al.*, 1998]. The pressure decrease related to the hot plasma fluxes flowing across the antisolar direction (HFA stands for hot flow anomaly events) can lead to large amplitudes (up to 5 R_E) of wave motion of the magnetopause [e.g., *Sibeck et al.*, 1999].

The main task of this work is to study the magnetospheric

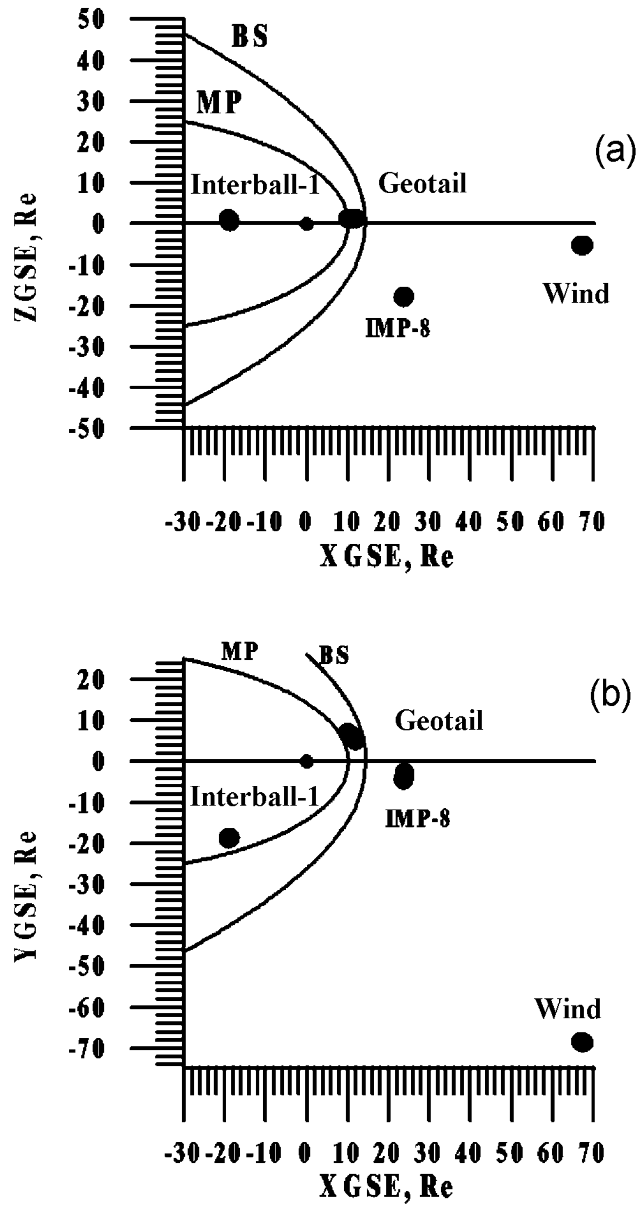

Figure 1. Positions of Interball 1, Geotail, IMP 8, and Wind spacecrafts for the 11 October 1996, event in the (a) meridional and (b) equatorial projections of the GSE coordinate system.

boundary motion at large distances (30 R_E). We have analyzed a few almost simultaneous crossings of the bow shock at the subsolar region and of the magnetopause in the remote magnetotail. These boundaries were identified using plasma and magnetic field data obtained onboard Interball 1 and Geotail satellites [*Klimov et al.*, 1997; *Kokubun et al.*, 1994; *Mukai et al.*, 1994; *Safrankova et al.*, 1997; *Sauvaud et al.*, 1997]. To determine interplanetary magnetic field and solar wind conditions, the measurements at Wind and partly at IMP 8 [e.g., *Lepping et al.*, 1995; *Ogilvie et al.*, 1995] were used.

2. Observations and Discussion

The magnetospheric boundary crossings observed on 11 October 1996, are interesting because the interaction of the solar wind disturbance with magnetosphere near the subsolar region and remote magnetotail took place almost simultaneously.

Figure 1 shows the spatial position of the Interball 1, Geotail, Wind, and IMP 8 satellites during the 11 October event in the meridional (Figure 1a) and equatorial (Figure 1b) projections of the geocentric solar ecliptic (GSE) coordinate system. One can see from this figure that the Interball 1 satellite moved near the magnetopause predicted by the model on the low-latitude dusk flank of the remote magnetotail, Geotail crossed the subsolar bow shock region, and Wind and IMP 8 were located within the solar wind.

Figure 2 presents one interval of the high-resolution (10 s) plasma and magnetic field measurements obtained by Interball 1 (the electron temperature T_e (eV), plasma flux F_i (10^8 cm^{-2} s^{-1})), and by Geotail (the magnetic field strength $|B|$ (nT), ion temperature T_i (eV), longitudinal component of plasma velocity V_x (km s^{-1}), and plasma density N (cm^{-3})). The strip with a different degree of shadowing (on top of the first and third panels) indicates the regions passed by the satellites. The regions for Interball 1 are as follows: the magnetosheath (MSH), boundary layer (BL), and plasma sheet (PS). For Geotail they are the solar wind (SW), magnetosheath (MSH), and hot flow anomaly events (HFA). It should be noted that the magnetic field and plasma velocity in Figures 2, 3, and 5 are presented in the Geocentric Solar-Magnetospheric (GSM) coordinates.

Figure 3 shows for the same time interval the solar wind parameters (the magnitude $|B|$ and GSM components of interplanetary magnetic field B_x, B_y, B_z (nT), dynamical pressure P_d (nPa)) and also the density N_p (cm^{-3}), and velocity $|V|$ (km s^{-1}) of the plasma measured by Wind and partly by IMP 8. The time delay caused by the solar wind propagation from Wind to Interball 1 was taken into account. This value is about $T_{\rm lag} = 28$ min. This time delay being taken into account, the magnetic field data obtained by IMP 8 and Wind became very similar.

One can see in Figure 3 the passage of a large solar wind disturbance region, edged by two irregularities observed in the plasma and magnetic field data at 0840 and 0920 UT, respectively. Both edges of this disturbance region are characterized by an abrupt magnetic field turning. The dynamical pressure of the plasma within the region of the solar wind disturbance is decreased, and the interplanetary magnetic field is northward. Lines I and III show the moments of simultaneous BS and MP crossings. Line II shows the moment of the first HFA reaching Geotail. The moments I, II, and III are considered in more detail below.

2.1. Boundary Crossing at 0840 UT

At this moment in response to the passage of solar wind pressure depletion related to the arrival of the leading front of the disturbance, almost simultaneous movement (in the same direction: from the Earth) of the outer boundaries was

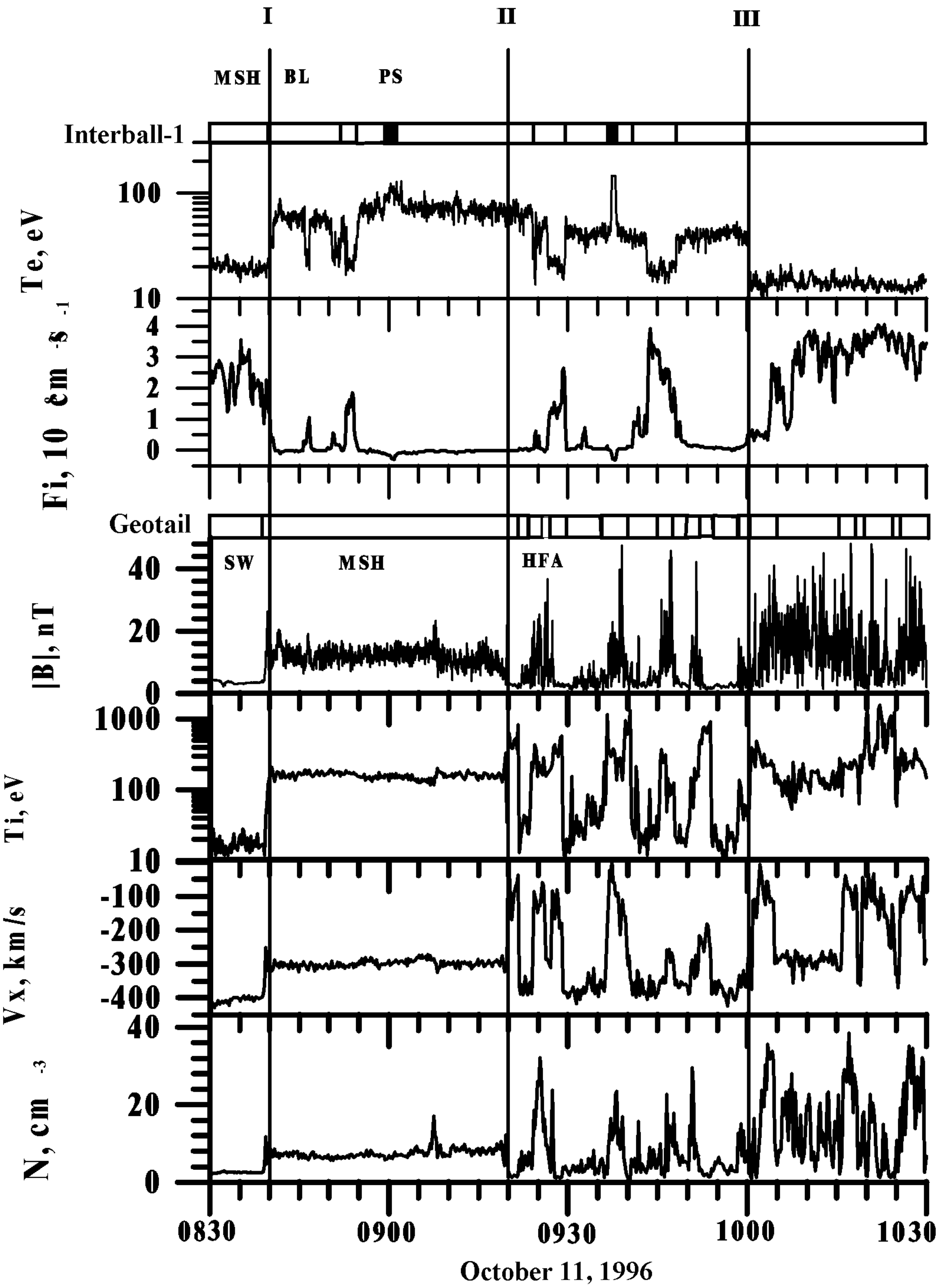

Figure 2. Detailed (10 s resolution) data on the plasma and magnetic field measurements onboard the Interball 1 and Geotail satellites. The identification of space regions is shown by the bars with different shadowing over the data: SW, solar wind; MSH, magnetosheath; HFA, hot flow anomaly; BL, boundary layer; and PS, plasma sheet.

observed: Interball 1 crossed the magnetopause at ~0840 UT (entered the magnetosphere from the magnetosheath, i.e., from the boundary layer), and Geotail passed the bow shock (entered the magnetosheath from the solar wind) 2 min earlier.

Figures 4a and 4b show the distance between the point of measurements and magnetopause predicted by the *Shue et al.* [1997] empirical magnetopause model (Figure 4b) and the bow shock calculated from the *Spreiter et al.* [1966] hydrodynamic model (Figure 4a). Figure 3 shows the dy-

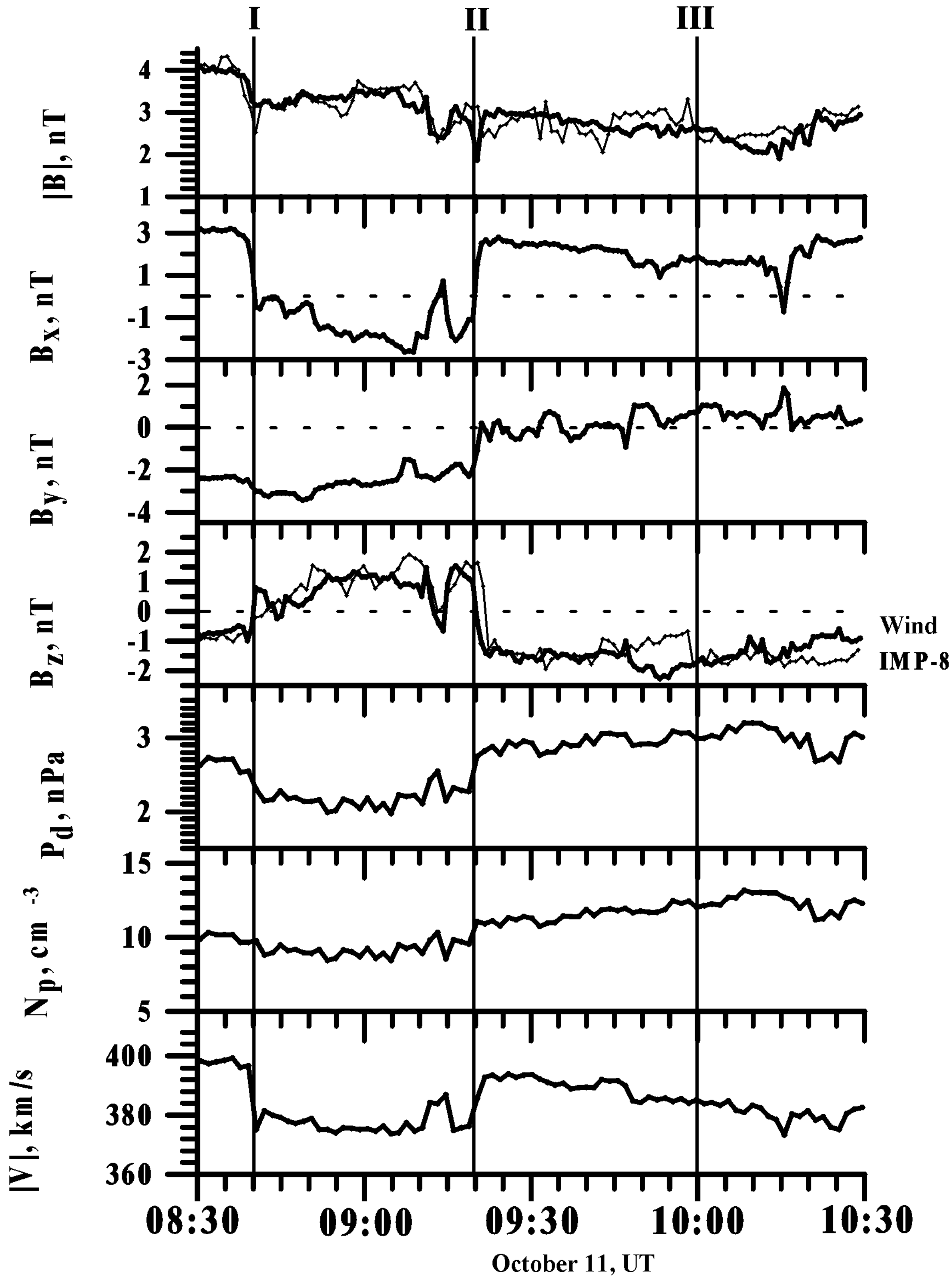

Figure 3. Solar wind parameters (the plasma parameters and interplanetary magnetic field (IMF)) were measured by Wind and partly by IMP 8 (the magnitude $|B|$ and the IMF B_z component). The timescale is shifted by $T_{\mathrm{lag}} = 28$ min.

namical pressure and the B_z (GSM) component of the interplanetary magnetic field measured by Wind which were used calculating the model position of the magnetopause.

One can see in Figure 4b that the predicted magnetopause was located at a larger distance from the Earth than the measured one; the calculated magnetospheric boundary expanded outward responding to the variations of the solar wind parameters (Figure 3). One can assume that this de-

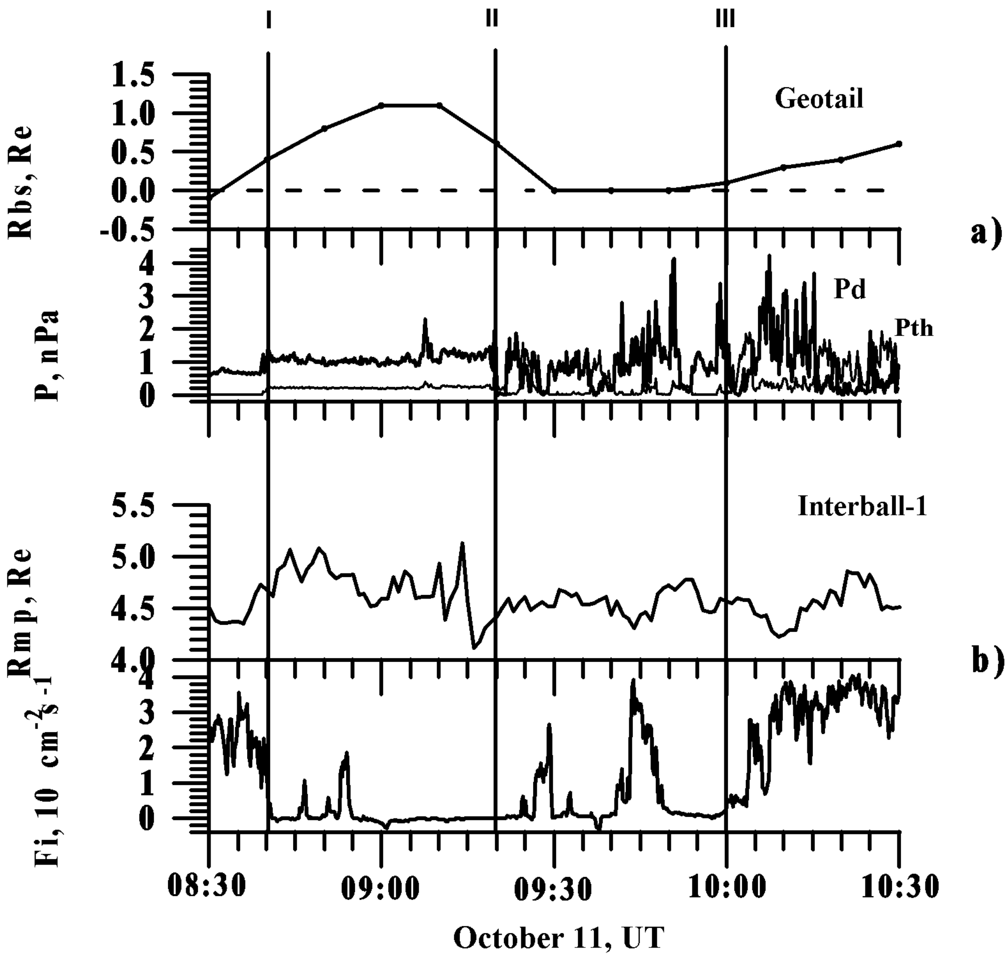

Figure 4. (a) Comparison of the measurements with the bow shock model calculations for Geotail. The dynamic and thermal pressure values (bottom panel) are calculated from the Geotail plasma measurements. (b) Distance between the observed and predicted magnetopause for Interball 1 and the plasma flux measured onboard Interball 1.

gree of the relative boundary movement (0.8 R_E away from the Earth) is sufficient to explain the magnetopause crossing observed at 0840 UT.

It follows from Figure 4a that the bow shock model prediction explains well the observed bow shock crossing: before the arrival of the disturbance leading front (0840 UT), Geotail was located in the solar wind, and after interaction with this irregularity, the satellite entered the magnetosheath.

The time delay between the boundary crossings, detected by the two satellites separated by a distance of 30 R_E, occurred 2 min instead of 10 min evaluated from the solar wind propagation, if one assumes that the front of the disturbance was plane and directed perpendicular to the Sun–Earth line. This discrepancy in time can be explained only by a large (38°) inclination angle of the solar wind disturbance front and the Sun–Earth line. The components of the vector normal to the irregularity shows that the disturbance front was inclined to the ecliptic plane by an angle of 62°. Such an angle of the front inclination of the solar wind disturbance helps in understanding the very similar magnetic field behavior observed by the Wind and IMP 8 satellites, which were located on the ecliptic plane and under it, respectively.

This orientation of the disturbance corresponds to the results obtained by the statistic analysis of inclination angles of solar wind disturbances [e.g., *Shukhtina et al.*, 1999]. It follows from the latter paper that only a part (20%) of the solar wind disturbances have the normal to an irregularity front directed along the Sun–Earth line, and in the majority of events (80%), they have large angles of the front inclination about 30°–60°. Moreover, a significant value of the vertical component of the normal was often observed, and sometimes this component was the main one.

Thus the observed magnetopause and bow shock positions are in a qualitative agreement with the model predictions. By varying solar wind parameters, one can explain the observed almost simultaneous boundary crossings.

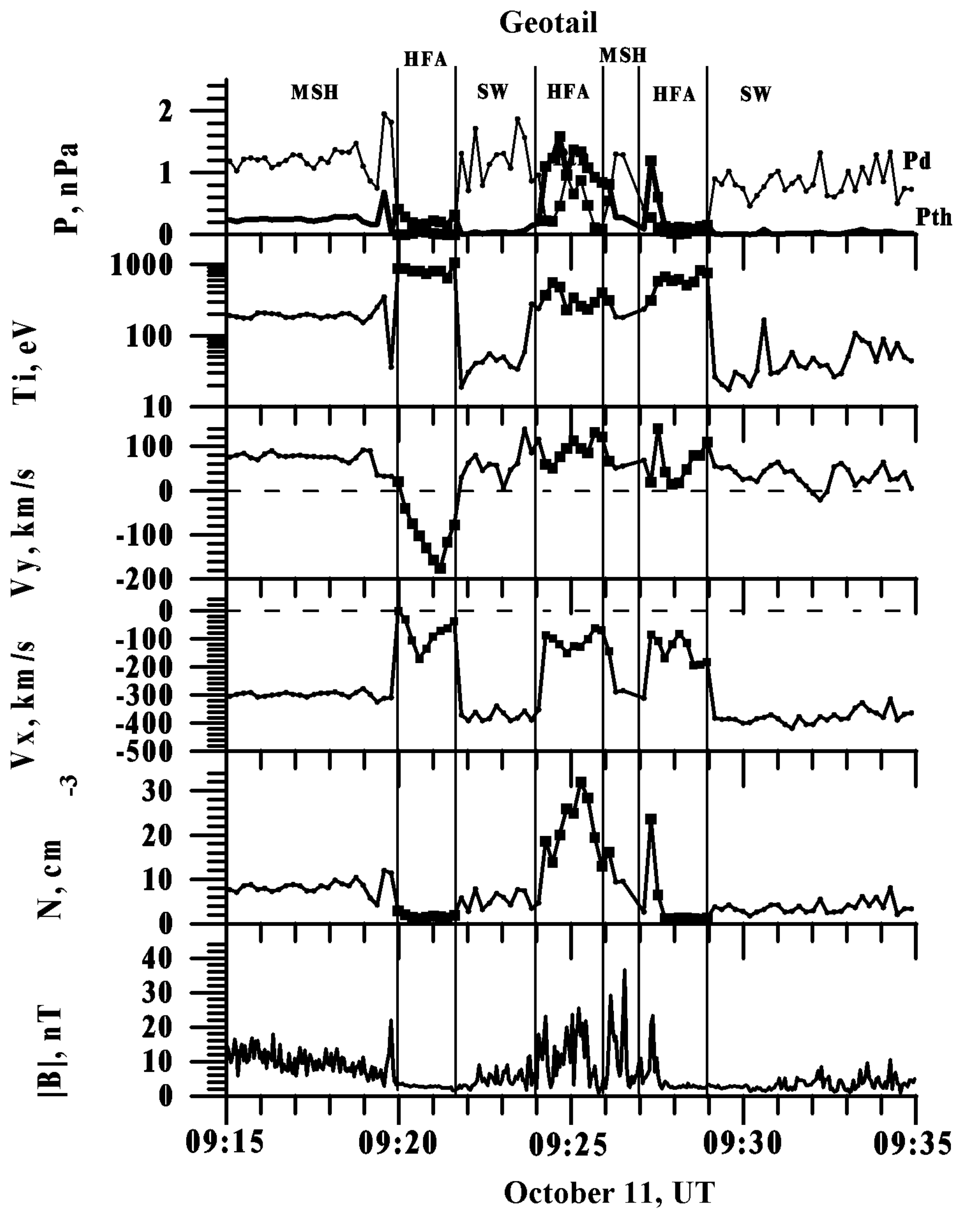

Figure 5. High-resolution plasma (12 s) and magnetic field (3 s) data measured onboard Geotail. The dynamic (P_{d}, thin line) and thermal (P_{th}, thick line) pressure values were calculated from the Geotail data. The vertical lines show the boundaries of three HFA regions coming to Geotail. The squares mark the parameter values within the HFA.

2.2. Bow Shock Crossing at 0920 UT

This bow shock crossing, observed by Geotail at the moment II (0920 UT), coincided with the arrival of the trailing front of the solar wind disturbance. At this time, Interball 1 was still located within the magnetosphere. On its way from the magnetosheath into the solar wind, Geotail crossed several areas with unusual features (HFA), similar to the structures described, for example, by *Paschmann et al.* [1988], *Thomsen et al.* [1993], and *Vaisberg et al.* [1998]. These structures were filled with hot tenuous plasma; the plasma moving fairly quickly transverse to the Sun–Earth line and only slowly antisunward.

Figure 5 presents from top to bottom the calculated values of the dynamic and thermal pressure for the high-resolution (12 s) plasma measurements (ion temperature, T_i, (eV); velocity, V_x, V_y, (km s^{-1}), and density (cm^{-3}) and the magnetic field strength (3 s) data for the 0915–0935 UT interval.

One can see in Figure 5 that the HFA event observed by Geotail at 0920 UT has the following features: a sharp rise of the ion temperature T_i (up to 1000 eV), an abrupt decrease in the V_x component of the plasma velocity and a significant increase in the V_y and V_z components of the velocity, a sharp decrease in the plasma density; and a depletion of the magnetic field magnitude. One can see in Figure 5, top panel, the thermal pressure increase inside HFA (second event) up to 1.5 nPa, the latter value being close to the dynamic pressure in MSH. HFA-like regions were observed by Geotail during a long time interval of approximately 40 min (see Figure 2).

HFA events are characterized by a high temperature of ions (higher than in the solar wind and magnetosheath) and by a large transversed component of the plasma velocity $V_y = 200 - 300$ km s^{-1}, whereas the Sun–Earth velocity is decreased down to -50 km s^{-1}. The magnetic field value within a HFA is the same or slightly lower than in the solar wind. The HFA events have a duration of about some minutes (up to 15 min) and spatial dimensions of about several R_E. These events may be intrinsic features of quasi-parallel bow shocks, which in such a way react to changes in solar wind conditions, [e.g., *Thomsen et al.*, 1993].

The formation of a hot flow anomaly near the Earth's bow shock seems to be due to the interaction between the bow shock and the impinging irregularity in the upstream plasma [*Thomsen et al.*, 1993]. Such an interaction will produce a HFA if the electric field in the ambient plasma is pointed toward the irregularity, thereby focusing the shock-reflected ions into it. Assuming that the irregularities are tangential, the predicted electric field orientation is found on the irregularity observed at 0920 UT. It is essential that HFA are observed not only in the solar wind but also within the magnetosheath, that is, these cavities can pass through the bow shock to the magnetosheath; and move downstream. Its propagation toward the magnetopause can induce changes of the magnetopause shape [e.g., *Sibeck et al.*, 1999].

The top panel in Figure 5 presents a trace of the dynamic and thermal pressures associated with the observed HFA events. One can use the pressure variations during such events to predict their effects on the magnetosphere. One would expect the local magnetopause to expand rapidly outward as the cavity passes and to contract rapidly inward as the trailing edge of the first cavity passes (see the 0920–0922 UT interval in Figure 5).

The increase of the dynamic pressure at 0922 UT and the exit of Geotail to solar wind caused by it (see Figure 5, top panel) can produce the rapid magnetopause movement inward which could be seen at Interball 1 5–7 min later (see its passage through the magnetopause at 0925). The pressure decrease within the third HFA event can expand the magnetosphere as it is seen at 0938 UT when Interball 1 entered the plasma sheet. The plasma pressure increase observed by Geotail when it entered the solar wind at 0930 UT and the corresponding magnetosphere contraction can explain the Interball 1 entry to the magnetosheath observed at 0943–0948 UT (see Figure 2). However, this comparison is very approximate, and additional studies of the influence of the HFA events on the boundary position in the magnetotail are needed.

2.3. Magnetospheric Boundary Crossings at 1000 UT

At this moment, Interball 1 left the magnetosphere and entered the magnetosheath. Approximately 2 min earlier, Geotail crossed the bow shock and moved from the solar wind region into the magnetosheath (see Figure 2). Thus we observed an unusual situation: the dayside bow shock was expanded outside the Earth, but the magnetotail flank of the magnetopause was contracted inward.

In order for Interball 1, located inside the magnetosphere, to appear in the magnetosheath, the flank boundary should have been shifted to the Earth. At the same time, in order for Geotail to exit the solar wind and enter the magnetosheath, the subsolar bow shock and probably the magnetopause should have been moved away from the Earth.

A similar magnetopause behavior when the dayside boundary moves outward and the distant magnetotail boundary moves to the Earth follows from the magnetopause models especially for the case of a very low dynamic pressure [e.g., *Roelof et al.*, 1993]. Then it is the interplanetary magnetic field that provides the main influence on the boundary location. However, in our case, the dynamic pressure was rather large (up to 3 nPa), and the IMF B_z component was changed only from -2 to -1 nT.

The other possible explanation includes an abrupt increase in the magnetosheath thickness in such a way that the bow shocks were moved outside the Earth in spite of the contraction of the entire magnetosphere. This situation is possible only if the Mach number in the solar wind was very low (<3). However, in our case, the Mach number varied only between 7 and 10.

One can see in Figure 4 that the observed variation of the solar wind parameters is not sufficient to explain the boundary crossing observed by Interball 1 at 1000 UT (see Figure 4b). At the same time, the bow shock model predictions are in a good qualitative agreement with the boundary crossing observed by Geotail (Figure 4a).

Thus the large-scale boundaries motion observed from the subsolar region to the distant magnetotail (the dayside bow shock expansion and distant magnetopause contraction) is poorly consistent with variations of the solar wind parameters.

An alternative explanation involves a boundary wave propagation along the magnetopause. Since the HFA events are identified near the bow shock, it is possible that the boundary wave could have been produced by hot flow anomalies. A propagation of HFA events dawnward of the magnetotail can alter the local magnetopause shape [e.g., *Sibeck et al.*, 1999].

3. Summary

1. Two cases with very different types of boundaries motion have been observed during the 2-hour interval on 11 October 1996: the bow shock in the dayside region of the magnetosphere and the magnetopause at the magnetotail

morning flank, the motions being detected by the Geotail and Interball 1 satellites, which were separated by a distance of about $30R_E$: (1) in the first case, the two boundaries (bow shock and magnetopause) almost simultaneously moved outward due to the decrease of the solar wind plasma dynamic pressure; that is, the whole magnetosphere was expanded in a qualitative agreement with the model predictions; (2) in the second case, unusual boundaries behavior was observed: almost simultaneously the dayside bow shock was expanded from the Earth and the flank magnetopause was contracted to the Earth.

2. The interaction between the solar wind tangential irregularity and the subsolar bow shock produced a whole set of the HFA-like events characterized by brief intervals of hot, relatively low density plasma with the bulk flow strongly deflected from the antisolar direction.

3. We suggest that the observed unusual boundary motions, which cannot be explained by variations of solar wind parameters, might be due to the background of the HFA effects observed by Geotail before and after the bow shock crossings. The plasma thermal pressure increase associated with HFA may influence the magnetotail magnetopause position because the action of the dynamic pressure in this region decreases less than the thermal pressure found within HFA.

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