Example of WDS style article: IMF tangential discontinuity

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Abstract. This is an example of the WDS style article in LATEX. The original article has been heavily truncated. We present a multipoint observational study of the magnetosheath response to the interplanetary magnetic field tangential discontinuities which form hot flow anomaly-like structures. We identify these structures (HFAs) in the vicinity of the bow shock as well as deeper in the magnetosheath. Two or more points of simultaneous observations allow us to describe the gradual evolution and propagation of these HFAs through the magnetosheath. From tens of events recorded by INTERBALL-1, we present two cases. In the first, GEOTAIL identified HFAs in the solar wind near the bow shock, and INTERBALL-1 and MAGION-4 observed related events in the magnetosheath. During the second interval, all three spacecraft observed the HFA features in the magnetosheath. Our analysis of reported events suggests the negligible evolution of these structures in the magnetosheath. A survey of the INTERBALL-1 data has shown that magnetosheath HFAs are observed predominantly during periods of fast solar wind.

Introduction

The interaction of the solar wind with the Earth's magnetosphere generates a population of backstreaming ions directed from the bow shock into the solar wind. This high-energy population was invoked to explain Hot Flow Anomalies (HFAs) [*e.g., Schwartz et al.*, 1985; *Thomsen et al.*, 1986] identified as heated regions of solar wind plasma flowing nearly perpendicular to the Earth-Sun line. The main observational features of HFAs include *Schwartz* [1995]: (1) Central regions with hot plasma flowing significantly slower than that in the ambient solar wind in a direction highly deflected (nearly 90^o) from the Sun-Earth line. The flow velocities are often roughly tangential to the nominal bow shock shape [*Schwartz et al.*, 1988]. (2) HFAs are bounded by regions of enhanced magnetic field strength, density, and temperature. The outer edges of these enhancements are fast shocks generated by pressure enhancements within the core region. The inner edges of the enhancements are probably tangential discontinuities [*Paschmann et al.*, 1988]. Published examples indicated that many HFAs are bounded by only one enhancement. (3) HFAs occur in conjunction with significant changes in the IMF direction. The angle between pre- and post event orientations is typically $\sim 70^o$.

Thomsen et al. [1986, 1988] have shown that many HFAs occur when the geometry of the bow shock is changing and large fraction of specularly reflected ions are present. These and others observations led to many theoretical/numerical studies. One-dimensional simulations with a finite length backstreaming ion beam suggested that the interaction of the beam and background plasma can produce hot, low-density regions from which the solar wind plasma is largely excluded [*Onsager et al.*, 1990b]. However, an examination of the ion temperature inside HFAs indicated that complete thermalization of the ion beam and subsequent adiabatic expansion of the heated plasma leads to final ion temperatures that are generally below those observed [*Onsager et al.*, 1990a]. *Thomas and Brecht* [1988] presented a 2-D hybrid simulation for a beam of backstreaming ions relative to the ambient solar wind. The authors demonstrated that the thermalized backstreaming ions create a diamagnetic cavity of depressed magnetic field strengths and densities. According to numerical simulations of *Thomas et al.* [1991] and *Lin* [1997], kinetic effects at the intersection of the magnetic discontinuities with the bow shock can create very deflected flows of heated plasma surrounded by enhanced densities and magnetic field strengths.

Observations

To demonstrate HFA properties, we have chosen two representative examples with favourable positions for all mentioned spacecraft. The first case study shows an interval when two of three IMF tangential discontinuities identified in WIND solar wind data resulted in HFAs. These HFAs are observed in the bow shock region by GEOTAIL, and simultaneously by INTERBALL-1 in the magnetosheath. The second case is related to the propagation of HFAs through the magnetosheath. We have found an interval when the same HFA is observed by GEOTAIL in the dayside magnetosheath and by INTERBALL-1 and MAGION-4 in the dusk magnetosheath flank, about $\sim 20\, R_E$ downstream.

In order to show that the solar wind velocity can be an important factor for the HFA creation, we have reanalyzed data published in [*Onsager et al.*, 1990a] and complemented their survey of ISEE and AMPTE observations by our analysis of INTERBALL-1 measurements.

Case 1

On August 31, 1996, the INTERBALL-1 satellite registered a series of HFA-like events in the dawn magnetosheath at $(-0.2; -17.2; -5.1)_{GSE}\, R_E$. Figure 1 shows observations during two of these events. This figure presents 15 s time resolution VDP ion flux [*Safrankova et al.*, 1997] and 1 s time resolution MIF-M magnetic field [*Klimov et al.*, 1997] observations for the interval from 0740 to 0820 UT. The first HFA at 0740-0750 UT as well as the second one at 0805-0815 UT can be identified by rapid decreases of the ion flux bounded by transient enhancements (top panel in Figure 1). The time resolution of the measurements does not allow us to see the full amplitude of the enhancements in this case but our analysis of similar events has shown that they can exceed the mean magnetosheath flux by a factor of 3. The cone angle (second panel in Figure 1) of the ion flux shows that the flow is highly deflected. Whereas the undisturbed magnetosheath flow is deflected by $\sim 20^o$ from the Sun–Earth's line, consistent with INTERBALL-1's location near the terminator, the ions inside the structures are highly deflected. They flow nearly perpendicularly to this line during our second event.

We can compute its normal from $(\vec{\mathbf{B}}_\mathbf{1} \times \vec{\mathbf{B}}_\mathbf{2})/(|\vec{\mathbf{B}}_\mathbf{1}| \cdot |\vec{\mathbf{B}}_\mathbf{2}|)$ where the subscripts 1 and 2 refer to the region upstream and downstream of a discontinuity, respectively. We tested the normal direction by minimum variance analysis of the WIND high-resolution (3 s) data. Both approaches yield the same direction of the discontinuity normal ($\mathbf{n} = 0.22, 0.67, 0.70$). The normal defines the discontinuity plane and we can compute the time lag for observations of the discontinuity at WIND, IMP-8 and GEOTAIL (GEOTAIL observations will be discussed in detail later).

Thus, we can conclude that both necessary conditions ($B_n = 0$ and $u_n = 0$ where B_n and u_n are normal components of the magnetic field and velocity, respectively) are fulfilled and that all discontinuities in this time interval are tangential discontinuities. Such discontinuities can create HFAs, when the motional electric field $\vec{\mathbf{v}}_\mathbf{sw} \times \vec{\mathbf{B}}$ is oriented toward the discontinuity on one or both sides of the current sheet [*Lin et al.*, 1997; *Thomsen et al.*, 1988]. We tested this criterion and found that it is obeyed for the first and third discontinuities but not for the second one. Thus only the first and third discontinuities can create HFAs when interacting with the bow shock. This is consistent with magnetosheath observations presented in Figure 1 where only two HFA-like events are seen during the time interval under question.

Case 2

A similar situation occurred on January 31, 1997. The IMF tangential discontinuity observed by WIND at $\sim$ 1953 UT resulted in the creation of an HFA observed in the dusk magnetosheath by three spacecraft: GEOTAIL, INTERBALL-1, and MAGION-4. For the sake of simplicity, Figure 2 shows only the ion flux and magnetic field magnitudes observed by these spacecraft but we have carefully examined all parameters to ensure that the magnetosheath event has HFA characteristics. It should be noted that the characteristics of the event differ a little at different spacecraft positions.

The locations of the spacecraft projected onto the ecliptic plane are schematically shown in the left part of Figure 3. GEOTAIL was located in the magnetosheath near the magnetopause and registered the leading enhancement of HFA at 2034 UT. Due to the decreased density in the core region of HFA, GEOTAIL crossed magnetopause and entered the plasma sheet. It exited into HFA at 2041 UT to observe the trailing enhancement of the ion flux.

A survey of INTERBALL HFA observations

Both cases analyzed above occurred during a period of relatively high solar wind speed (505 km/s for the first case and 495 km/s for the second case). In order to determine whether or not this is a random occurrence, we surveyed 3 months of the INTERBALL-1 observations (January - March, 1997). For our survey, we have taken into account only those events which had all basic HFA characteristics, i.e., a region of tenuous highly deflected flow and low magnetic field bounded by short regions of significantly enhanced ion density and magnetic field magnitude. We exclude events connected with bow shock or magnetopause crossings because the plasma and magnetic field behaviour are more complicated in such cases and a complex analysis of all parameters is needed to decide whether the particular event is connected with the HFA.

Discussion

We have presented two multipoint case studies of the magnetosheath response to the arrival of IMF tangential discontinuity at the bow shock. In both of them, an HFA is created at the bow shock and then observed in the magnetosheath. The INTERBALL-1 observation of HFA in the magnetosheath is supported by simultaneous GEOTAIL observation at the bow shock region in our first case. The analysis of this event shows that the characteristics of HFA in the solar wind and in the magnetosheath are basically the same. HFAs can be distinguished as regions of the hot tenuous plasma bounded by density enhancements in both regions.

In the second case, a single HFA was observed in the dusk magnetosheath near the magnetopause by three spacecraft. We suggested that the differing profiles of the events at different points of the magnetosheath could be attributed to the shape of a HFA cavity rather than to a temporal evolution of its dimensions on a time scale of several minutes. We suggest that the durations of HFAs depend on the locations where IMF discontinuities intersect the bow shock. Thus, the different durations of the events observed by INTERBALL-1 and GEOTAIL in our first case may result from GEOTAIL's separation from the subsolar region where the plasma observed by INTERBALL-1 enter the magnetosheath. Simulations indicate that HFAs need about 10 ion gyroperiods to develop into notable disturbances [*Thomas et al.*, 1991].

Conclusion

HFAs are an important magnetosheath phenomenon. They can be encountered throughout the magnetosheath from the bow shock to the magnetopause. Our observations are limited by the INTERBALL-1 satellite's orbit to the range $|X_{GSE}| < 10\,R_E$ but the negligible evolution of reported events suggests that HFAs should be observed further tailward, if the duration of the event ($\sim$ several minutes) and the temporal resolution of observations allows their identification.

We have pointed out a *double structure* of magnetosheath HFAs. A complete description of this feature requires a multidevice analysis of high-time resolution data.

The magnetosheath HFAs exhibit a clear tendency to occur predominantly during periods of enhanced solar wind speed. This needs more careful examination because high speed streams have different characteristics than slow speed streams, perhaps computer simulation can determine which factors are most important in HFA formation.

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