MSFC-104

Observations of the Ion Signatures of Double Merging and the Formation of Newly Closed Field Lines

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to be submitted to Geophysical Research Letters

Abstract

Observations from the Polar spacecraft, taken during a period of northward interplanetary magnetic field (IMF) show magnetosheath ions within the magnetosphere with velocity distributions resulting from multiple merging sites along the same field line. The observations from the TIDE instrument show two separate ion energy-time dispersions that are attributed to two widely separated (~20Re) merging sites. Estimates of the initial merging times show that they occurred nearly simultaneously (within 5 minutes.) Along with these populations, cold, ionospheric ions were observed counterstreaming along the field lines. The presence of such ions is evidence that these field lines are connected to the ionosphere on both ends. These results are consistent with the hypothesis that double merging can produce closed field lines populated by solar wind plasma. While the merging sites cannot be unambiguously located, the observations and analyses favor one site poleward of the northern cusp and a second site at low latitudes.

Introduction

Solar wind plasma enters the magnetosphere through openings created by magnetic merging. Under southward IMF conditions this entry generally occurs in the subsolar region equatorward of the cusps. Conversely, during periods of northward IMF merging is thought occur primarily poleward of the cusps. Recent observations have shown that at times this merging can occur along the same magnetosheath field line in both hemispheres and create a closed field line containing a mix of magnetosheath and magnetospheric/ionospheric plasmas. These field lines are expected to eventually move completely inside the magnetosphere and may be a source for the low-latitude boundary layer (LLBL) under northward IMF conditions. This phenomena has been discussed in the contest of double, post-cusp merging only while a similar situation can, theoretically, occur with a mix of post-cusp and sub-solar merging (assuming component merging.)

A model of the formation of the LLBL under northward IMF was proposed first by Song and Russell [1992] In this model solar wind enters the magnetosphere by nearly simultaneous merging between almost empty lobe field lines and the magnetosheath field lines poleward of the cusps in both hemispheres. The reconnected magnetosheath flux tube shortens as it convects to the dayside and submerges into the magnetosphere forming the LLBL. Later this approach to the LLBL formation was given support through in-situ observations [e.g. Le et al., 1996, Onsager et al., 2001] and by MHD simulations [e.g. Ogino et al., 1994, Reader et al., 1997]. In a case study Onsager et al. [2001] showed that counterstreaming electrons in the magnetosheath boundary layer are a signature of double merging. Based on the statistical study of 56 encounters of the magnetopause

Lavraud et al. [2006] have shown that bidirectional heated electrons are signatures of newly closed magnetosheath lines supporting the mechanism proposed by Song and Russell [1992].

While statistics of double merging have been reported by (e.g. Lavraud et al, 2006), the specifics of this phenomenon, such as location and relative timing of the two onsets, have yet to be determined. This paper presents a case study of a cusp crossing made by the Polar spacecraft on March 18, 2006 Earthward of the magnetopause during a long period of northward IMF. Accelerated magnetosheath plasma originating from two different merging sites was observed as two distinct velocity-time dispersions. These dispersions are consistent with two widely separated merging sites. Because Polar was located within the magnetosphere near the southern cusp the magnetosheath ions accelerated at both sites were observed streaming Earthward. Along with these populations outward-streaming components of each were present and represent the faster of the accelerated ions that had mirrored in the ionosphere. Additionally, counterstreaming cold ionospheric populations were observed providing evidence for the existence of newly closed field lines residing in the LLBL. These results support the idea that double merging on the same field lines can provide a source for formation of the LLBL under northward IMF conditions.

Data

The ion observations herein were obtained on March 18, 2006 by the Thermal Ion Dynamics Experiment ion spectrometer [Moore et al, 1995]. They consist of several distinct ion populations including two velocity-dispersed magnetosheath distribution and multiple, counterstreaming ionospheric populations. Figure 1 is an overview spectrogram that clearly shows the two overlapping magnetosheath populations and their energy dispersion with time. Figure 2 shows two consecutive two-dimensional plots of ion phase space density for both the first (top panels) and the second dispersions (bottom panels). It is evident in Figure 2 that the magnetosheath ions exhibit the shape associated with ions injected at a distant source (cf. Burch et al., 1986). Further, in the bottom panels, both accelerated magnetosheath populations can be seen which shows that they existed on the same field lines simultaneously. The existence of multiple colder ion populations attributed to an ionospheric source can also been seen in all panels and is evidence for closed field lines.

Along with these ion data, electric field and magnetic field observations from Polar's Electric Field Instrument [Harvey et al., 1995] and the Magnetic Field Experiment [Russell et al., 1995] are used to locate Polar within the magnetosphere and to provide convection velocities. Figure 3 shows the location of Polar within the magnetosphere based on results from the T96 model []. Superposed on that model are instantaneous vectors derived from the MFE data. The location of the spacecraft relative to the model field is consistent with the observed fields.

Using data from EFI and MFE convection velocities were computed. During the time period of the injections these velocities showed large amplitude waves superposed on relatively steady convective motions. The average velocities for the time interval of these observations (0250-0340UT) are **V**(GSM)=(4+/δ4, 2+/-6, -6+/-4). In general the convection is southward (in the GSM coordinate system) which translates to a polar motion in the southern ionosphere.

Additional data were taken from the Geotail Magnetic Field Experiment {Kokubun et al.,1994] and the Low Energy Particle Experiment [Mukai et al., 1994] to characterize the solar wind conditions (Figure 3b-e). These data show that the IMF was moderately northern during most of the event and, as will be shown, was definitely northward at the time of these injections. Also, and importantly, the dynamic pressure was relatively high at times during these observations.

Analysis

Under the assumption that these dispersions occurred along a "single" field line the time of and distance to the merging-induced injections can be determined. The ion time-of-flight is given by (Burch et al., 1986)

$$t_f = \left(\frac{m}{2E}\right)^{1/2} \int_0^s \left\{1 - \sin^2 a_s B(z)/B_s\right\}^{-1/2} dz$$

For zero pitch angle ions ($a_s = 0$) the following simple relationship between velocity and time applies:

$$V_{\parallel} = R(t - t_0)^{-1} \qquad \text{(eq. 1)}$$

where,

$V_{\parallel}$ is the speed of the ions along the local magnetic field
R is the distance from the initial injection site to the spacecraft
t is time
t_0 is the time of the initial injection.

The proper speed to use in this equation is the lowest speed existing in the injected distribution at any time [Lockwood??]. This can be accomplished, in principle, by finding the low-speed cutoff for each observed distribution parallel or anti-parallel to the magnetic field. This was done initially with limited success owing to the existence of multiple ionospheric populations that, at times, obscured the low-energy cutoff of the magnetosheath populations. In a complimentary approach drifting maxwellian distributions were fit to each velocity distribution (f(v) vs. v). A similar approach has been used previously with success [e.g. Trattner, Fuselier, etc]. This method provided a mean drift velocity and a temperature spread. The low-speed cutoff was calculated by subtracting a δv equivalent to 0.5kT from the drift speed derived from the fitted maxwellian. These two methods were compared and are used in the subsequent analysis.

The derived parallel speeds were fitted to the above equation and values for R and t_0 obtained for both dispersions (Fig 4). Note that the two different values of Vmin yield the same result within the uncertainty of the fitting. These results show that the injections occurred nearly simultaneously at distances separated by ~12R_e (25R_e and 13R_e.) The results of the curve-fitting using eq. 1 are given in Table I.

Discussion

The purpose of this report is to show evidence of magnetosheath plasma captured on field lines that are newly closed as a result of double merging. In so doing it must be shown that the field lines are closed, contain magnetosheath plasma, and the ion distributions bear the signatures of interaction with two separate merging sites.

The two meagnetosheath populations seen in these observations exhibit the velocity dispersion signatures typically associated with particle injection at a distant source. The analysis indicates that they were accelerated at distant merging sites. If such observations were made between the two merging sites (e.g. in the equatorial region in the case of two post-cusp sites) two counterstreaming populations, resulting from the reflection of a fraction of the magnetosheath plasma incident on the two equatorward moving merging kinks, would be observed. However, Polar was in the mid-altitude cusp, Earthward of both merging sites and, therefore, observed the reflected ions from one site superposed on the injected ions from the other site. Thus both populations are seen traveling Earthward, antiparallel to the magnetic field.

The presence of counterstreaming ions with narrow, beam distributions typical of outflowing Earth-borne ions is evidence that this field line has been populated on both end by the ionosphere. Thus it is concluded that these field lines are connected to the ionosphere on both ends and are closed.

The location of these two merging sites and the timing of the injections is of interest. While the idea of double merging is most often discussed in terms of two, post-cusp locations, this scenario is inconsistent with these observations in two aspects. First, given the location of Polar with respect to the local magnetic field configuration at the time of the observations it seems unlikely that a field line that merged tailward of the cusp could be reconfigured to the more dipole-like shape suggested by comparing the observed field and the model (Figure 3). Secondly, in order to achieve this reconfiguration, equatorward/sunward convection would be required while the observations show anti-sunward convection.

Given these inconsistencies a second possibility arises with respect to the merging sites. That is, one site located poleward of the northern cusp and a second in the sub-solar region. Assuming a merging site equatorward of the cusp in the near-equatorial region.leads naturally to a magnetic field configuration at the spacecraft consistent with the observations, It also allows for the possibility of a convective motion containing a significant negative z component (in GSM coordinates.)

Conclusions

The results of these analyses show that:

- two separate magnetosheath ion injections occurred at well-seperated (10Re) distances nearly simultaneously
- the two injections occurred on the same group of field lines
- counterstreaming ionospheric ion populations coexisted with the magnetosheath ions

From this it is evident that the observed field lines had experience merging in two different regions that resulted in a newly closed field line containing a mixture of ionospheric and magnetospheric ions. Two scenarios are considered with respect to the location of the sites. One in which nearly simultaneous merging occurred poleward of the northern cusp and in the near-equatorial region and a second in which both sites were post-cusp and in opposite hemispheres. While it is not possible to distinquish between these two definitively, the observations favor the former case. This idea leads to a previously unconsidered method of capturing magnetosheath field lines and formation of the LLBL under northerward IMF.

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Table I

	$V = R*6371.*(t-t_0)^{-1}$	Dispersion 1		Dispersion 2	
Method	Parameter	Value	Error	Value	Error
Curve-Fit	R - Distance to merging site (R_e)	13.	1.	25.0	0.4
	UT of initial injection (s)	9800	61	9780.	16
	Chi-squared of fit	3543.8		18674	
	Regression	0.894		0.980	
Velocity Cutoff	R - Distance to merging site (R_e)	12.	1.	27.0	1.
	UT of initial injection (s)	9900	56	9700	43
	Chi-squared of fit	938.1		10344	
	Regression	0.964		0.961	

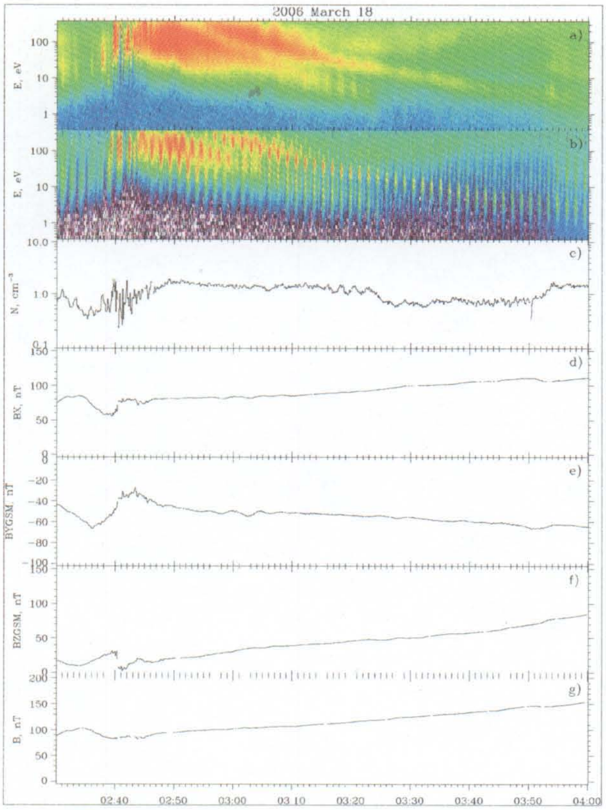

Figure 1 – Overview of observations on March 18, 2006 showing: (a) energy-time spectrogram of TIDE data; (b-d) components of the IMF in GSM coordinates; (e) solar wind dynamic pressure.

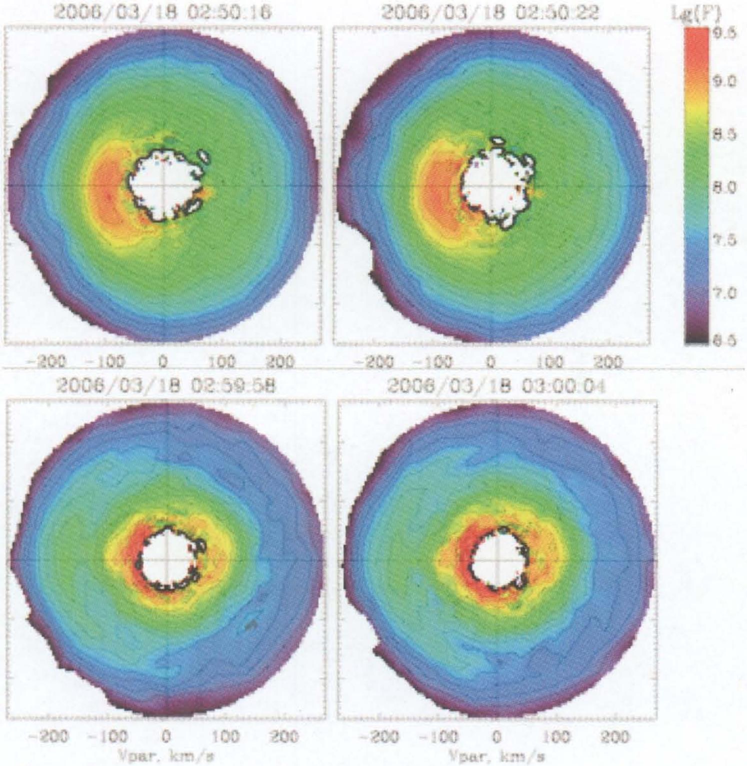

Figure 2 – (top panels) Superposition of ion populations including dispersion 1 at -100km^{-1} and terrestrial ions from southern hemisphere and/or outer plasmasphere near 75km^{-1}. (bottom panels) Superposition of ion populations including dispersion 1 below -100km^{-1}, dispersion 2 at -200km^{-1}, and terrestrial ions from northern hemisphere at -100km^{-1}.

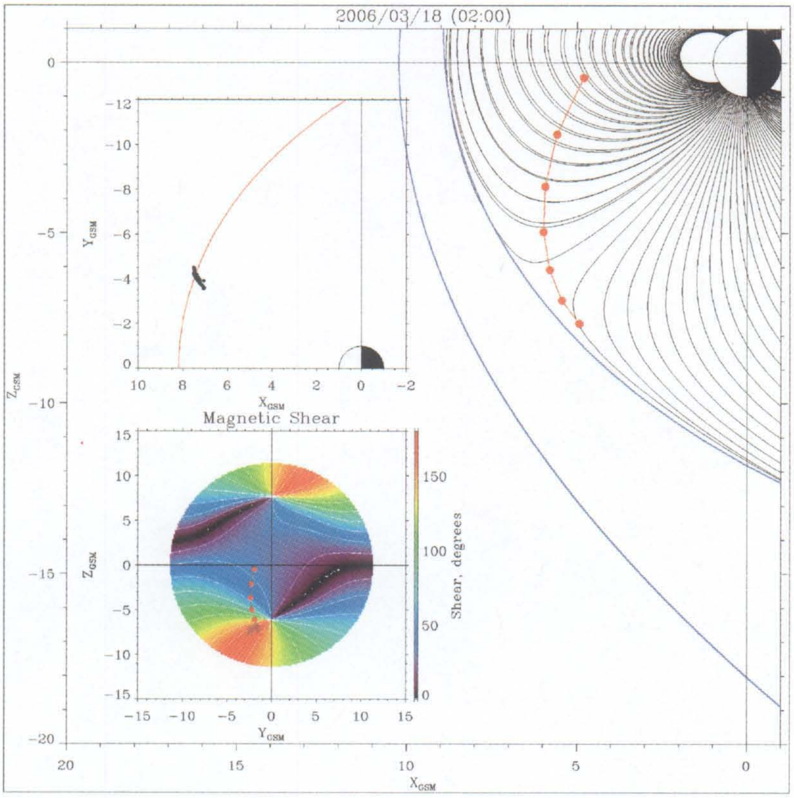

Figure 3 – Location of the Polar spacecraft with respect to a modeled magnetic field, bow shock, and magnetopause. The orbit track for Polar is plotted from 2300UT on March 17 to 0500Ut on March 18.

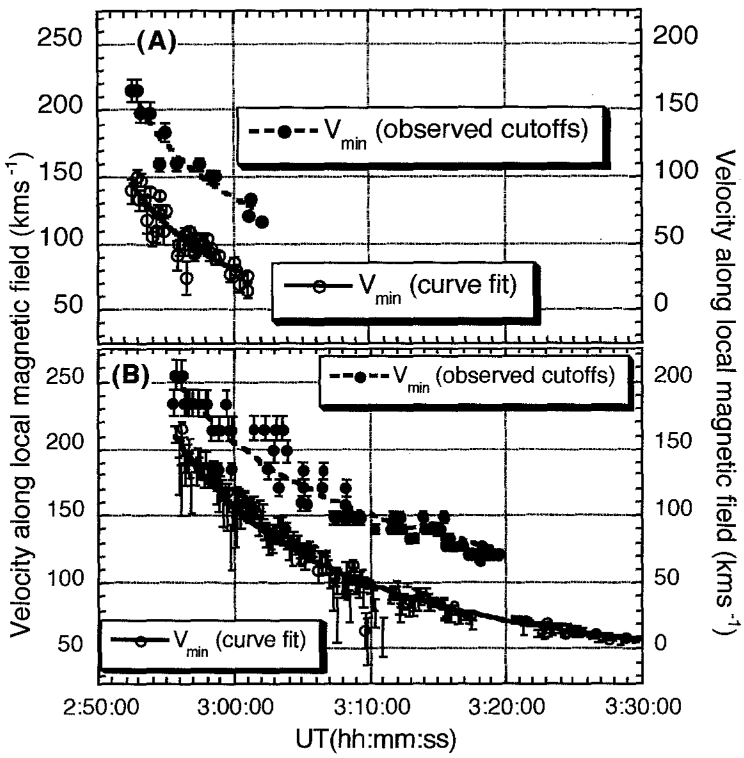

Figure 4 – (A) Low-speed cutoffs for dispersion 1 derived from curve fits and directly from data (see text). Fits to equation 1 are shown. (B) Low-speed cutoffs from dispersion 2 derived from curve fits and directly from data (see text). Fits to equation 1 are shown. Parameters are given in Table I.