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Observations of the ion signatures of double merging and the formation of newly closed field lines

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[1] Observations from the Thermal Ion Dynamics Experiment (TIDE) on the Polar spacecraft, taken during a period of northward interplanetary magnetic field (IMF) show magnetosheath ions within the magnetosphere with velocity distributions resulting from two widely separated (~30 R_E) merging sites along the same field lines. These results are consistent with the hypothesis that double merging can produce closed field lines populated by solar wind plasma under northward IMF. While the merging sites cannot be unambiguously located, the directions of the flowing magnetosheath populations and the convection of merged field lines are consistent with locations of two merging sites northward of the spacecraft and the analyses favor one site poleward of the northern cusp and a second site at lower latitudes equatorward of the northern cusp.
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1. Introduction

[2] A model of the formation of the low-latitude boundary layer (LLBL) under northward IMF conditions was first proposed by *Song and Russell* [1992]. In their 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. These reconnected magnetosheath flux tubes subsequently shorten as they convect to the dayside and submerge into the magnetosphere forming the LLBL. This mechanism for LLBL formation was given support through in-situ observations [e.g., *Le et al.*, 1996; *Onsager et al.*, 2001; *Vaisberg et al.*, 2001; *Lavraud et al.*, 2005; *Petrinec et al.*, 2006; *Imber et al.*, 2006, 2007] and by simulations [e.g., *Ogino et al.*, 1994; *Raeder et al.*, 1997; *Lin and Wang*, 2006]. This phenomenon has been discussed in the context of double, post-cusp merging only, while a similar situation can, theoretically, occur with a mix of post-cusp and sub-solar component merging. Simulations predict that for a northward IMF with a non-zero B_Y component an "S"-shaped X-line may exist providing the possibility for merging both poleward and equatorward of the cusp [e.g., *Moore et al.*, 2002]. Signatures of component merging under northward IMF have been previously detected at the dayside magnetopause [*Paschmann et al.*, 1990; *Chandler et al.*, 1999; *Chandler and Avanov*, 2003].

[3] While statistics of double merging have been reported [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 observations made by the Polar spacecraft on March 18, 2006 Earthward of the magnetopause during a long period of northward IMF. Accelerated magnetosheath plasma originated from two different merging sites and was observed as two distinct velocity-time dispersions. These dispersions are consistent with two widely separated merging sites. The direction of the flow of the accelerated magnetosheath ions (antiparallel to the local magnetic field) and the location of Polar (at $\mathbf{R}$ = [6, −2.3, −3.4] R_E in GSM coordinates) within the magnetosphere near the southern cusp are consistent with locations of both merging sites northward of the spacecraft. In addition, the observed convective motion of the merged field lines is not consistent with that of expected following double post-cusp merging, suggesting a combination of merging sites at high and low latitudes. 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. 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.

2. Data and Analysis

[4] The ion observations were obtained by the Thermal Ion Dynamics Experiment ion spectrometer [*Moore et al.*, 1995]. They consist of several distinct populations including two velocity-dispersed magnetosheath distributions and outflowing ionospheric ions. Figure 1 is an overview spectrogram that clearly shows the two overlapping magnetosheath populations and their velocity dispersion with time. Also evident is the characteristic "V"-shape that results from velocity filtering consistent with distant locations of injection sites [*Burch et al.*, 1986]. Along with the ion data, Figure 1 includes solar wind data taken from the Geotail Magnetic Field Experiment (IMF) [*Kokubun et al.*, 1994] and the Comprehensive Plasma Instrumentation [*Frank et al.*, 1994] (dynamic pressure). Geotail was located close to the magnetopause at $\mathbf{R}_{GSM}$ = [11, −8, −10.]R_E., therefore the time delay was minimal (less than 1.5 min.). Figures 1b–1e show that the IMF was moderately northern during most of

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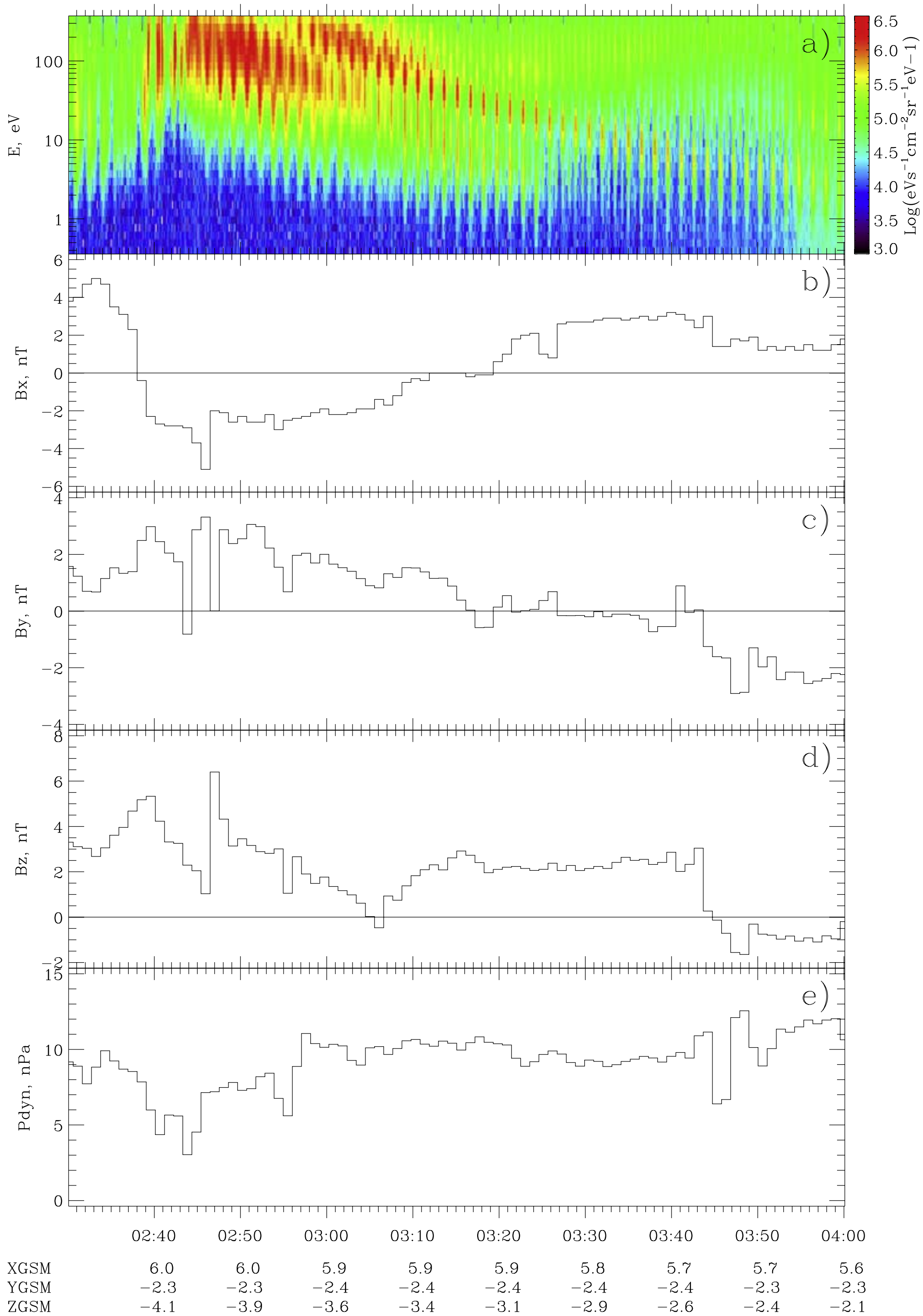

Figure 1. (a) Overview of TIDE observations in a spin-energy-time format that has multiple spin-energy spectrograms arranged in a time series; (b–d) the solar wind magnetic field in GSM coordinates; (e) the solar wind dynamic pressure.

the event and definitely northward at the time of these injections. Also, and importantly, the dynamic pressure was high ~ 10nPa at times during these observations, which caused the subsolar magnetopause to move from ~10 to ~8.2 R_e. Figure 2a shows the location of the spacecraft with respect to a modeled magnetospheric configuration (T96) for solar wind parameters appropriate to the estimated time of the nearer injection at ~2:28UT (estimated in analysis section below). The location of the spacecraft relative to the model field is consistent with the observed fields (not shown). Figure 2b represents the distance between the equatorial crossing points of the geomagnetic field lines crossed by the spacecraft (derived from the T96 model [*Tsyganenko*, 1995]) and the magnetopause as determined from the *Shue et al.* [1998] model. The magnetic field lines crossed by Polar are within $1R_E$ of the magnetopause current layer. This suggests that these field lines belong to the low latitude boundary layer and

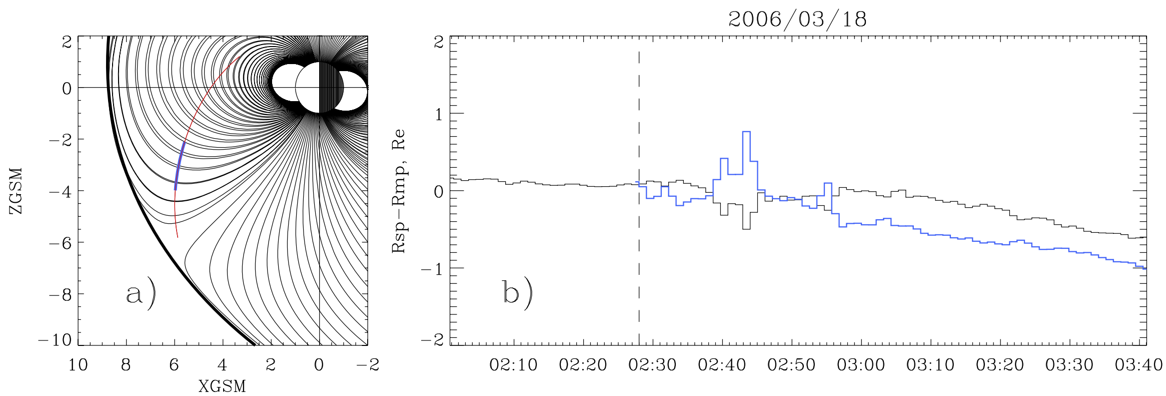

Figure 2. (a) Spacecraft location relative to the modeled magnetospheric field appropriate to the estimated time of the equatorial merging onset; (b) estimates of the distance between the modeled magnetopause location and the field lines crossed by Polar projected into the equatorial plane using the modeled magnetopause location at the time Polar crossed a given field line (black) and the magnetopause location at the time of onset of the equatorial merging (blue) at 2:28UT (dashed vertical line).

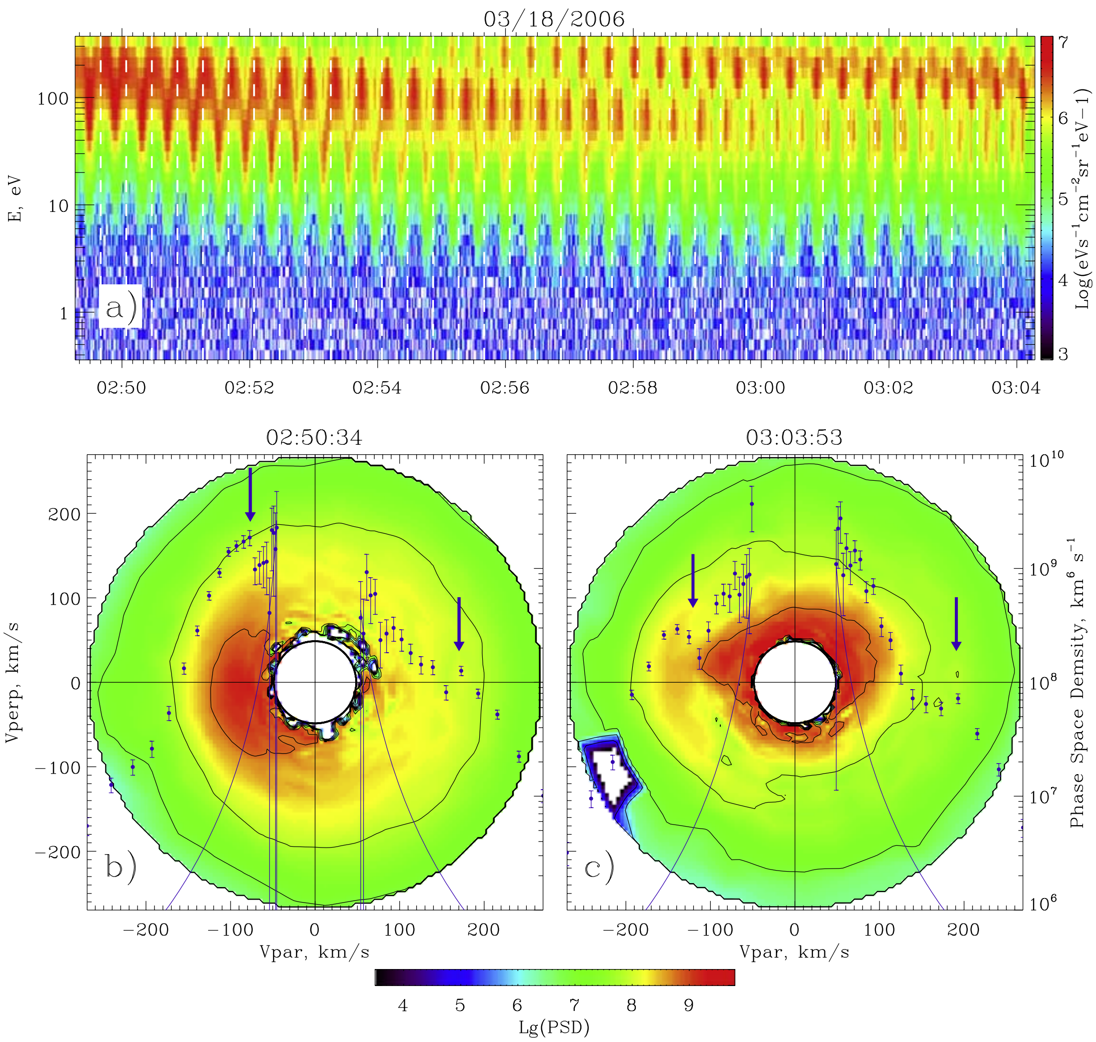

Figure 3. (a) Spin-energy-time spectrogram of the observed energy flux in a format that has multiple spin-energy spectrograms arranged in a time series with the start and stop of the spin denoted by vertical white lines; (b) observed phase space density at 02:50:34UT (units are $km^{-6}s^{3}$); (c) observed phase space density at 03:03:53UT (units are $km^{-6}s^{3}$). See text for details.

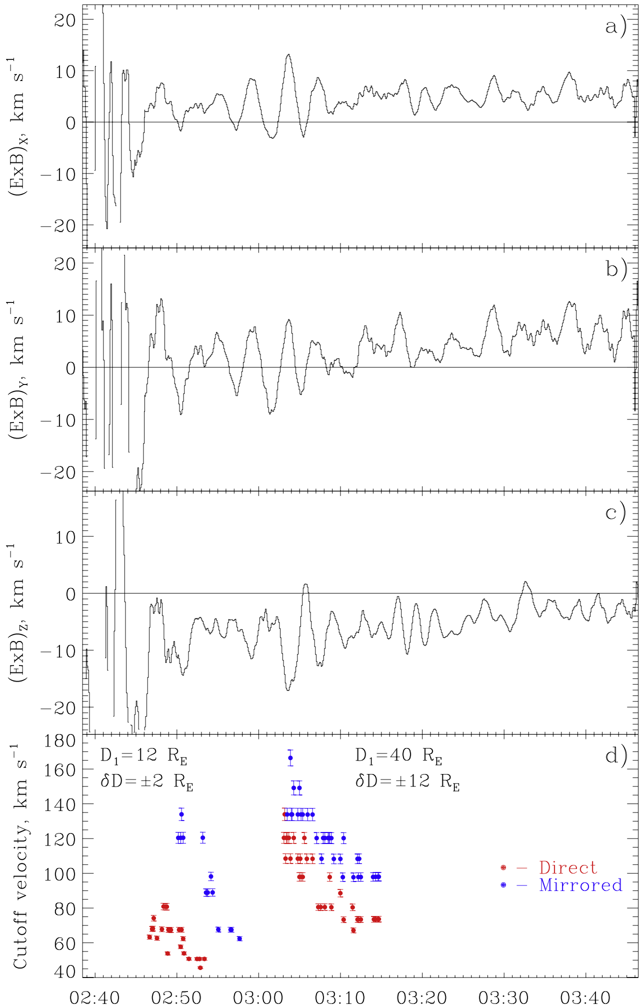

Figure 4. (a–c) Convection velocities in GSM coordinates; (d) velocity cutoffs for both dispersions. See text for details.

were near enough to the magnetopause to participate in merging.

[5] Figure 3a shows a spin-energy-time spectrogram for a time period in which the two magnetosheath populations can be seen to overlap. Also shown are one- and two-dimensional plots of ion phase space density representing both the first (D1) dispersion (3b) and the second (D2) dispersion (3c). In Figure 3b the injected ions are evident moving antiparallel to the magnetic field at speeds near 100 km s^{-1} and the mirrored ions are seen parallel to the field at speeds greater then 100 km s^{-1}. An outflowing, ionospheric population is moving parallel to the field with a bulk speed near 70 km s^{-1}. In 3c, both accelerated magnetosheath populations can be seen. At this later time ions from the more distant injection site appear antiparallel to the magnetic field at speeds greater than 100 km s^{-1}, while the slower ions from the nearer injection are visible below 100 km s^{-1}. Also, mirrored ions from the near injection can be seen parallel to the magnetic field at speeds near 100 km s^{-1}. Arrows in each figure indicate the characteristic drops in the phase space density indicative of the low-speed cutoffs for each distribution. It is evident in Figure 3a that the magnetosheath ions exhibit the characteristic "V"-shape associated with ions injected at a distant source [cf. *Burch et al.*, 1986] and coexisted on the same field lines. Convection velocities were derived using data from the Electric Field Instrument (EFI) [*Harvey et al.*, 1995] and Magnetic Field Experiment (MFE) [*Russell et al.*, 1995] instruments on the Polar spacecraft. During the time period of the injections these velocities showed wave motions superposed on relatively steady convective motions (Figures 4a–4c). In general the convection is southward (in the GSM coordinate system) which translates to a poleward motion in the southern ionosphere.

[6] The distance to each merging site was estimated using the formula of *Onsager et al.* [1991] given by,

$$R_{inj} = \frac{2V_{inj}R_{mirror}}{V_{mirror} - V_{inj}} \quad (1)$$

where, V_{inj} is the lowest speed of the injected magnetosheath ions, V_{mirror} is the lowest speed of the mirrored magnetosheath ions, R_{inj} is the distance from the initial injection site to the spacecraft, and R_{mirror} is the distance from the spacecraft to the ionospheric mirror point.

[7] The proper speeds to use in this equation are the lowest speed existing in the injected distribution both parallel and anti-parallel to the magnetic field at any time [e.g., *Lockwood and Smith*, 1994; *Lockwood*, 1997]. This can be accomplished by finding the low-speed cutoff for each observed distribution parallel or anti-parallel to the magnetic field. The resulting values for both injections are shown in Figure 4d. In order to find R_{inj} from equation 1 the speeds were used if they were from the same sampled distribution or from consecutive distributions that are separated by 6 seconds. Uncertainties in the velocities are derived from the widths of the TIDE energy (velocity) bandpass and incorporating the fact that consecutive data bins overlap in energy. The resulting distances to the merging sites are D1 = 12 ± 2 R_E and D2 = 40 ± 12 R_E respectively. In addition, using these distances and the measured velocities provides estimates of the time of the initial injections. These are 2:28UT ± 6min (D1) and 2:17UT ± 20 min (D2).

3. Discussion and Conclusions

[8] The purpose of this report is to show direct 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 contain magnetosheath plasma, are closed, and the ion distributions bear the signatures of interaction with two separate merging sites. The two observed magnetosheath populations exhibit the velocity dispersion signatures associated with particle injections at distant sources. 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 (Figure 2a), 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 injected populations are seen traveling

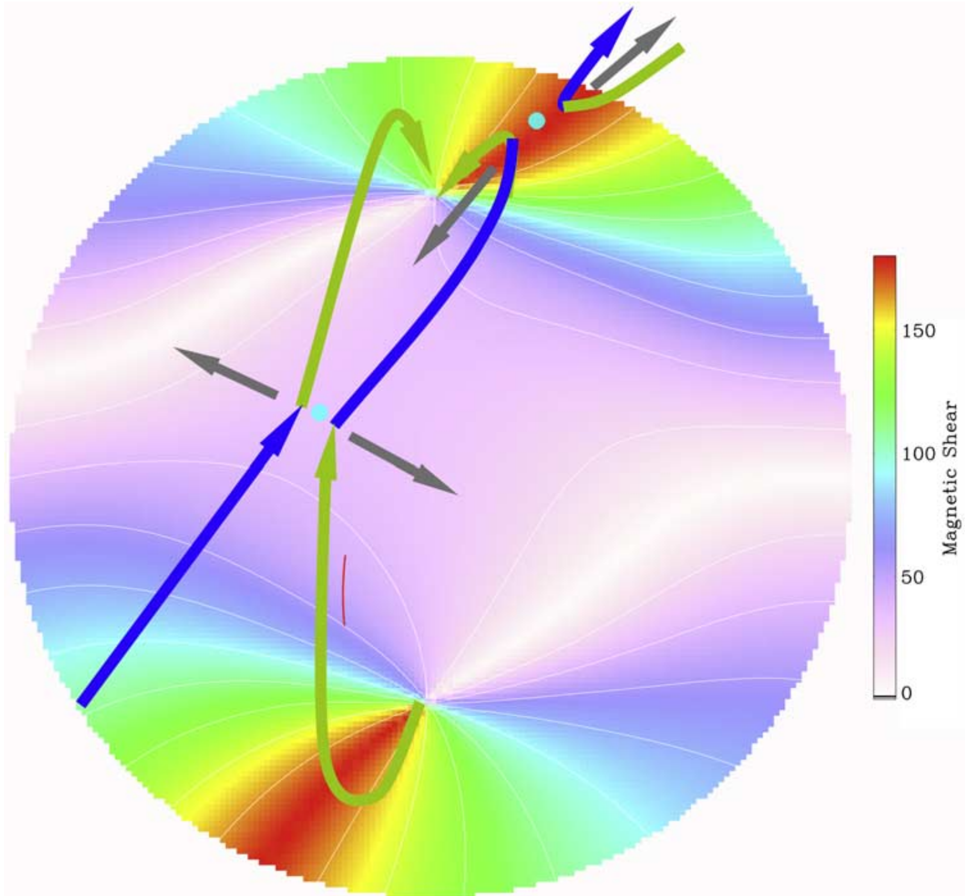

Figure 5. Illustration of the magnetic field topology superposed on calculations of the local magnetic shear. See text for details.

Earthward, antiparallel to the magnetic field. The spectrogram in Figure 3a shows the spatial overlap of the two magnetosheath populations confirming the existence of two merging sites on the same field lines. Finally, the location of Polar and the presence of magnetosheath ions that have mirrored in the ionosphere are proof that one end of these field lines is anchored in the southern, high latitude ionosphere. Analysis shows a merging site relatively near ($\sim$12R_E) Polar which means the other end of these field lines extends into the magnetosheath. This fact, combined with the existence of a second, more distant merging site, leads to the conclusion that the far end of these field lines is, once again, in the ionosphere.

[9] While the idea of double merging is most often discussed in terms of two, post-cusp locations, this scenario is inconsistent with these observations. Given the location of Polar with respect to the local magnetic field configuration at the time of the observations, a field line that merged tailward of the southern cusp would have to be reconfigured to the more dipole-like shape suggested by comparing the observed field and the model. In order to achieve this reconfiguration, equatorward convection of the field lines would be required. However, the observations show poleward (southward) convection. Given this inconsistency a second possibility arises with respect to the merging sites. That is, one site located poleward of the northern cusp at distance $\sim$40 R_E away from the spacecraft and a second in the sub-solar region at $\sim$12 R_E. Assuming a merging site equatorward of the northern cusp leads naturally to a magnetic field configuration at the spacecraft consistent with the observations. It further allows for the possibility of a convective motion containing a significant negative z component (in GSM coordinates) in agreement with the observations. Figure 5 illustrates this scenario. It shows the magnetopause surface as seen from the Sun with the color coded shear angle between the geomagnetic field (T96) and a draped magnetosheath magnetic field derived from the model outlined by *Cooling et al.* [2001] for an averaged clock angle $\sim$30°, (defined as $\tan^{-1}(B_Y/B_Z)$). Blue dots mark the merging sites. Blue lines denote the magnetosheath magnetic field and the green lines denote the terrestrial. Gray arrows show the direction of motion of the merged field lines. This scenario provides motion of the injected plasma that is antiparallel to the local magnetic field and consistent with observed convective motion of the merged field lines.

[10] The results of these analyses show that 1) two separate magnetosheath ion injections occurred at well-separated distances and 2) the two injections occurred on the same group of field lines. From the direction of the injections and their estimated distances it can be inferred that these field lines were closed. While it is not possible to distinguish between these two definitively, the observations favor a scenario in which a group of newly closed field lines were created by a combination of antiparallel merging at

high latitudes in the northern hemisphere and component merging at lower latitudes at the dayside magnetopause.

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