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Interball-1 observations of flux transfer events

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Abstract. We present the results of a survey of 807 FTEs observed by Interball-1 on the mid- and high-latitude dayside and flank magnetopause. Dayside magnetosheath events show a strong tendency to occur for southward magnetosheath magnetic fields suggesting origin via component (or perhaps antiparallel) reconnection near the equatorial plane. Flank FTEs occur for both magnetosheath magnetic field orientations with only a slight preference for southward magnetosheath magnetic fields. These events are consistent with generation along an extended subsolar component reconnection line for all IMF orientations or a combination of reconnection along a subsolar component reconnection line for southward IMF and antiparallel reconnection at higher latitudes for northward IMF. The distribution of direct and reverse magnetosheath FTEs and the tilt angle of the reconnection line for dawnward and duskward IMF are in a good agreement with the theoretical predictions of the component merging model. The clear anticorrelation between the magnitude of the east/west (Bm) perturbation observed within magnetosphere FTEs versus Bm in the magnetosheath also demands an explanation of the FTEs in terms of reconnection along a tilted subsolar merging line, e.g. in terms of component merging.

Keywords. Space plasma physics (Magnetic reconnection)

1 Introduction and predictions

Southward IMF orientations enhance current densities on the dayside equatorial magnetopause, creating conditions favorable for the current-driven instabilities that trigger magnetic reconnection (Rijnbeek et al., 1984; Berchem and Russell, 1984). Pressure gradient and magnetic curvature forces remove the newly reconnected magnetic field lines from the dayside and deposit them in the magnetotail (Russell and Elphic, 1978; Cowley and Owen, 1989). Consistent with this prediction, southward IMF turnings depress dayside magnetospheric magnetic field strengths, move the dayside magnetopause Earthward, enhance antisunward plasma convection over the polar cap, increase the radius of the magnetotail, and enhance magnetotail magnetic field strengths (Aubry et al., 1970; Burch, 1972). By contrast, northward IMF orientations enhance current densities and the likelihood of reconnection on the high-latitude magnetopause poleward of the magnetic cusps (Crooker, 1979). As magnetospheric magnetic field lines poleward of the cusps are already open, merging poleward of either cusp does not result in magnetopause motion or the net transfer of magnetic flux. However, near simultaneous merging poleward of both cusp regions can append magnetosheath magnetic field lines and dense magnetosheath plasma to the dayside magnetosphere.

Merging may be steady or transient (Cowley, 1982). Bursty reconnection may represent the dominant mode of solar wind-magnetosphere interaction (Lockwood et al., 1995). Events exhibiting bipolar magnetic field signatures normal to the nominal magnetopause, transient enhancements in the total magnetic field strength, rotations in the magnetic field orientation, accelerated plasma flows, and streaming energetic particles are common in the vicinity of the magnetopause, where they are termed flux transfer events (FTEs) and interpreted in terms of magnetic reconnection (Russell and Elphic, 1978). Even a multitude of small FTEs (Kawano and Russell, 2005) may still contribute significantly to the overall solar wind-magnetosphere interaction.

Bursts of reconnection along single merging lines generate bubbles of interconnected magnetosheath and magnetospheric magnetic field lines (Southwood et al., 1988; Scholer, 1988), while simultaneous bursts along parallel reconnection

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lines produce both bubbles and true flux ropes (Lee and Fu, 1985). Energetic magnetospheric particles flow outward into the magnetosheath along the interconnected magnetic field lines, while reconnection and magnetic curvature forces accelerate and eject magnetosheath plasma entering reconnection sites. Both bubbles and ropes displace ambient magnetosheath and magnetospheric magnetic field lines as they move away from the reconnection site along the magnetopause. Events moving northward along the dayside magnetopause during periods of southward IMF orientation generate outward/inward (+, −) "direct" magnetic field signatures normal to the nominal magnetopause on both sides of that boundary, while those moving southward under the same conditions generate inward/outward (−, +) "reverse" magnetic field signatures (Rijnbeek et al., 1984). In incompressible fluids, the outward displacement of the field lines draped over the bubbles enhances only the component of the draped magnetic field that lies perpendicular to the axis of the flux rope and in the plane of the magnetopause, resulting in a transient magnetic field rotation towards the direction perpendicular to the bubble/flux rope axis and an increase in the total magnetic field strength (Farrugia et al., 1987). For typical ratios of magnetospheric to magnetosheath magnetic field strengths, magnetic curvature forces within the magnetosphere greatly exceed those in the magnetosheath. Consequently, the perturbations extend further into the magnetosheath than it does into the magnetosphere and generate far greater magnetic field signatures in the magnetosheath than in the magnetosphere (Ding et al., 1991). As a result, magnetosheath events dominate statistical studies (Kuo et al., 1995; Wang et al., 2005) and will be the focus of the present study. Curvature forces associated with draped magnetosheath and magnetosphere magnetic field lines tend to flatten events against the magnetopause (Cowley, 1982). Furthermore, events moving antisunward encounter progressively weaker magnetospheric and magnetosheath magnetic field strengths. Consequently, event perturbations should diminish with distance downstream (Sibeck and Lin, 2010).

FTEs are often attributed to component and antiparallel merging. According to the component reconnection model, reconnection occurs along a curve passing through the subsolar magnetopause whose tilt depends upon the IMF orientation (Sonnerup, 1974; Gonzales and Mozer, 1974). According to the antiparallel reconnection model, reconnection occurs along the locus of points where magnetosheath and magnetospheric magnetic fields lie nearly antiparallel (Crooker, 1979).

Statistical surveys of FTEs offer an opportunity to learn about the occurrence pattern, location, and spatial extent of transient reconnection on the magnetopause. Events observed by the ISEE-1/2 and UKS/IRM spacecraft on the equatorial dayside and post-terminator magnetopause generally moved poleward and azimuthally antisunward away from a subsolar component reconnection line whose tilt depended upon the IMF orientation (Russell et al., 1985; Kawano and Russell, 1997a). Curiously, events on the post-terminator magnetopause occur equally often for northward and southward IMF orientations (Kawano and Russell, 1997b), while those on the dayside occur predominantly for southward IMF orientation (Rijnbeek et al., 1984; Berchem and Russell, 1984). In an effort to reconcile this discrepancy, Kawano and Russell (1997a) suggested that re-reconnection (Nishida, 1989) on the dayside magnetopause at local times between 10:00 and 14:00 MLT impedes the antisunward motion of events generated during periods of northward IMF orientation and thereby prevents them from being observed. By contrast, they argued that re-reconnection was less likely at earlier and later times near the edge of the re-reconnection region, enabling events formed during periods of northward IMF orientation to be observed on the flanks. Kawano and Russell (1997a) acknowledged the possibility that post-terminator FTEs observed during periods of strongly northward IMF orientation might originate via antiparallel reconnection at high-latitude high-magnetic shear regions on the magnetopause. Fear et al. (2005) employed multipoint Cluster observations to infer the velocities of several FTEs observed under precisely these conditions to demonstrate that they were indeed consistent with event generation at such a high magnetic field shear region on the lobe.

To make predictions for comparison with Interball-1 observations of FTE occurrence patterns, we make the assumptions:

1. FTEs at high latitudes and on the flanks move antisunward under the influence of pressure gradient forces.
2. FTEs have cylindrical cross-sections, and their axes have a finite component in the z-direction.
3. Magnetosheath and magnetosphere magnetic fields have finite components perpendicular to the axes of these cylindrical FTEs.
4. The passage of FTEs disturbs the ambient media and generates bipolar signatures in the component of the magnetic field normal to the magnetopause.

Figure 1 presents predictions for the perturbations associated with an FTE generated between two parallel component reconnection lines. In this model reconnection lines (and corresponding FTEs) tilt from southern dawn to northern dusk for duskward IMF orientations (−Bm), but from northern dawn to southern dusk for dawnward IMF orientations (+Bm) (e.g. Sibeck and Lin, 2011). The (northward) magnetospheric magnetic field drapes dawnward (+Bm) under FTEs that tilt from southern dawn to northern dusk (dotted curve in figure), but drapes duskward (−Bm) under FTEs that tilt from northern dawn to southern dusk (not shown). The magnetic field under the FTE is also enhanced because the FTE presses in on the magnetopause. As illustrated in Fig. 1, the passage of an FTE therefore generates transient dawnward perturbations in the magnetosphere during periods of duskward IMF orientation. During periods of dawnward IMF orientation, FTEs generate transient duskward perturbations in magnetospheric magnetic fields. Consequently, the component reconnection model predicts an anticorrelation between the east-west component of the interplanetary/magnetosheath magnetic field and the east-west component of the perturbed magnetospheric magnetic field attending FTEs.

The antiparallel reconnection model makes very different predictions. First, the antiparallel reconnection model predicts event formation at and along the locus of points where magnetosheath and magnetospheric magnetic fields lie antiparallel to each other. Secondly, by contrast to the component reconnection model, the antiparallel reconnection model predicts events whose axes run from northern dawn to southern dusk during intervals of duskward IMF orientation, but from southern dawn to northern dusk during intervals of dawnward IMF orientation (e.g. Sibeck and Lin, 2011). With regards to the first point, in the absence of any magnetic field component transverse to event axes, there is no dawnward or duskward perturbation in the magnetosphere beneath the events. Simulations (e.g. Sibeck and Lin, 2011) indicate that the events retain their orientations; they move away from the locus of points where they originate. By analogy to the discussion above, the fact that orientations for events generated by antiparallel reconnection differ from those for component reconnection means that events generated by antiparallel reconnection produce duskward magnetic field perturbations in the magnetosphere during periods of duskward IMF orientation, but dawnward perturbations during intervals of dawnward IMF orientation. The distinctly different predictions of the two models afford an opportunity to determine which mode of reconnection produces events on both a case-by-case and statistical basis.

Now consider the magnetic field perturbations normal to the nominal magnetopause. To pass under the FTE, the magnetospheric magnetic field is deflected inward (−Bn) on its southern edge, but outward (+Bn) on its northern edge. Similarly, to pass over the FTE, the magnetosheath field is deflected outward (+Bn) on the northern side of the FTE but inward (−Bn) on the southern side. As a result, the passage of the FTE generates a bipolar signature normal to the nominal magnetopause. Since events north of the reconnection line move northward and those south of the line move southward, the tilted component reconnection line divides locations where direct (+,−) Bn and reverse (−,+) Bn bipolar signatures will be observed.

Figure 2 illustrates the polarities of the Bn components expected for magnetosheath FTEs moving antisunward through the X-Y GSM plane during intervals when the draped magnetosheath magnetic field points dawnward (a) and duskward (b) (blue arrows). Red arrows show the direction of the antisunward FTE and magnetosheath plasma motion. Antisunward moving events should produce reverse (−,+) signatures at pre-noon local times, but direct (+,−) signatures at post-noon local times for dawnward IMF $B_y <$ 0 (Bm > 0). They should produce direct (+,−) signatures at pre-noon local times and reverse (−,+) signatures at post-noon local times for duskward IMF $B_y > 0$ (Bm < 0).

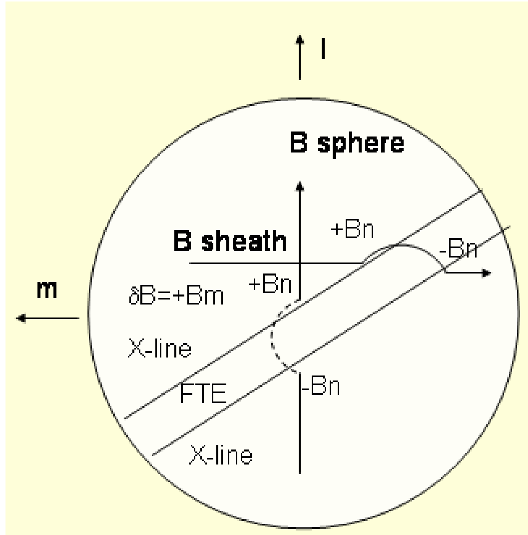

Fig. 1. Predictions for the perturbations associated with an FTE generated between two parallel component reconnection lines. Reconnection (X) lines (and corresponding FTEs) tilt from southern dawn to northern dusk for duskward IMF orientation (−Bm). The (northward) magnetospheric magnetic field drapes dawnward under FTEs that tilt from southern dawn to northern dusk (dotted curve in figure).

Events generated by bursty merging on the equatorial magnetopause during periods of southward IMF orientation might move antisunward to the magnetotail, where they would encounter lobe magnetic field lines. Figure 3a and b illustrate expected polarities of lobe FTEs in the Northern and Southern Hemispheres. Red arrows show the direction of antisunward magnetosheath plasma and FTE motion. Blue arrows indicate sunward (antisunward) directions of the Earth's magnetic field in the northern (southern) lobe. The antisunward moving events generate (−,+) Bn reverse signatures in the northern lobe, but (+,−) Bn direct signatures in the southern lobe.

We describe and survey Interball-1 observations to confirm that events on the dayside tend to occur for southward IMF orientations, but that those on the flank do not. We demonstrate that FTE amplitudes decay with distance downstream from the dayside magnetopause. We show that the inferred event motion and tilt are consistent with their generation along a subsolar merging line whose tilt depends upon the east/west component of the interplanetary magnetic field.

2 Interball-1 orbital characteristics and data sets

Interball-1 was launched on 3 August 1995 into an elliptical orbit with an apogee of 31.4 R_E, inclination of 62.8°, and

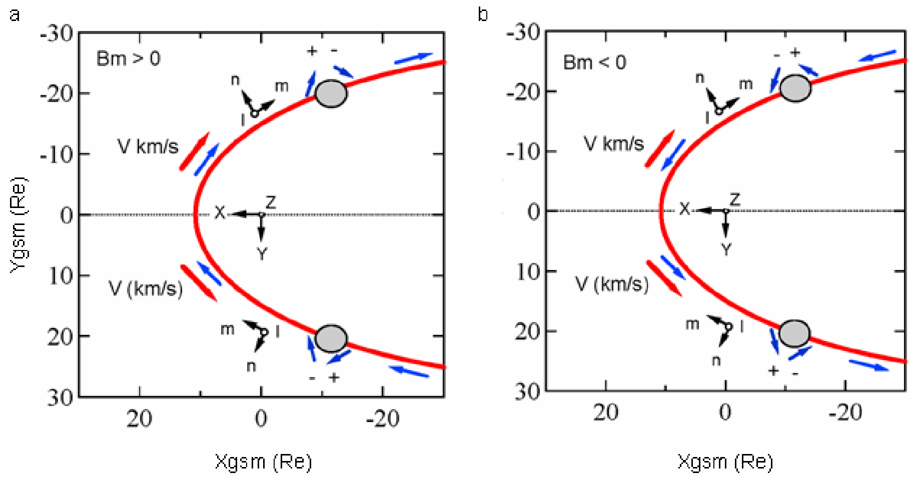

Fig. 2. Polarities of magnetosheath FTEs in the GSM X-Y plane expected for **(a)** dawnward and **(b)** duskward interplanetary magnetic fields (blue arrows). Red arrows show direction of antisunward motion of plasma in the magnetosheath. Antisunward moving events should produce reverse (−,+) signatures at pre-noon local times, but direct (+,−) signatures at post-noon local times for dawnward IMF $B_y < 0$ (Bm > 0) and direct (+,−) signatures at pre-noon local times and reverse (−,+) signatures at post-noon local times for duskward IMF $B_y > 0$ (Bm < 0).

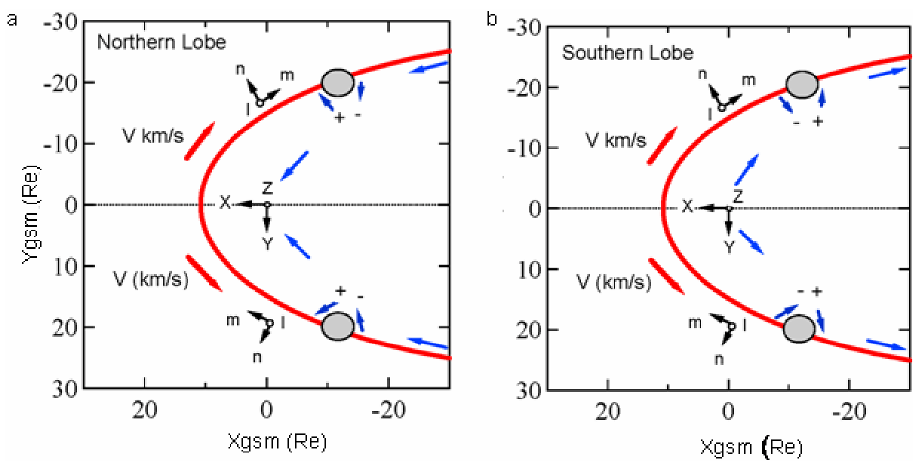

Fig. 3. Polarities of lobe FTEs in the Northern and Southern Hemispheres, respectively. Red arrows show direction of antisunward motion of plasma in the magnetosheath. Blue arrows indicate direction of the Earth's magnetic field that in the northern (southern) lobe is directed sunward (antisunward). The antisunward moving events generate direct (+,−) signatures in the southern lobe and reverse (−,+) signatures in the northern lobe.

period of 92 h (Zelenyi and Sauvaud, 1997). Interball-1 encountered the high-latitude northern dayside magnetopause at GSM $Z > 10\,R_E$ and the magnetotail magnetopause at distances up to 20 R_E downstream from Earth. Observations from the two fluxgate magnetometers, MIF-M (Klimov et al., 1997) and FM-3I (Nozdrachev et al., 1998), on the spacecraft have been intercalibrated and averaged to produce the merged data set with 6 s time resolution that we employ for this study. Electron spectrometer (Sauvaud et al., 1997) and VDP Faraday cup (Safrankova et al., 1997) measurements of electron spectra and the integral ion flux vector help identify both transient events and magnetopause crossings. In general, the magnetopause can be identified as a transition between high density, cold flowing plasmas on turbulent magnetic fields (magnetosheath) and low density, hot, stagnant plasmas on steady magnetic fields (magnetosphere).

FTEs are most readily identified on the basis of their bipolar magnetic field signatures normal to the nominal magnetopause. It is therefore often helpful to plot the Interball-1 observations in boundary normal (LMN) coordinates (Russell and Elphic, 1978), where N points outward along the local model normal determined from the Roelof and Sibeck (1993) model magnetopause for nominal solar wind conditions (solar wind dynamic pressure = 2 nPa, IMF $B_z = 0$), L

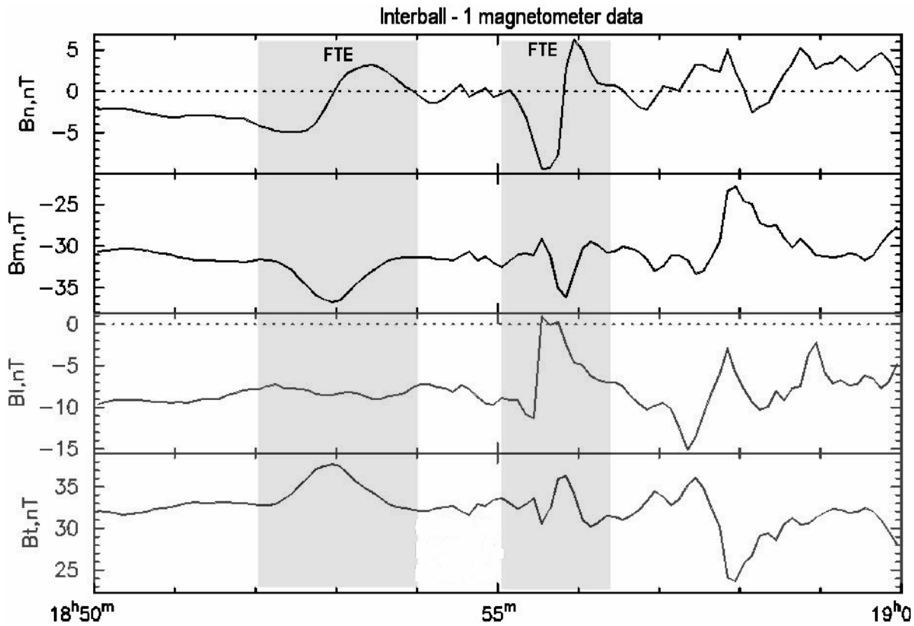

Fig. 4. Interball-1 magnetometer observations in LMN coordinates for the interval from 08:50 to 09:00 UT on 11 September 1998. Of the three candidate FTEs during this interval, only those at 08:53 and 08:56 UT satisfy the event identification criteria used in this study.

lies in the plane of the magnetopause and points northward, while M lies in the plane of the magnetopause and points dawnward ($M = N \times L$). Often FTEs exhibit plasma signatures, but these signatures were not a requirement for events to enter our database. Instead, we employ conservative criteria based upon the magnetic field observations alone:

1. FTEs exhibit clear symmetric bipolar signatures in the magnetic field component (Bn) normal to the nominal magnetopause with peak-to-peak amplitudes exceeding 3 nT.

2. FTEs exhibit either monopolar and bipolar (crater-like) enhancements in the total magnetic field strength. The latter are rare in our database.

3. We note, but do not require, the occurrence of unipolar signatures in the Bl and Bm components.

4. We exclude events with bipolar signatures centered on magnetopause crossings and events in which the bipolar Bn variations are not centered on peaks (or craters) in the magnetic field strength.

5. We survey all available Interball-1 observations during the period from 1995 to 1999 and found 807 events.

The inter-calibrated and merged data for this interval have been used for our previous Interball-1 FTE studies. Sibeck et al. (2005) presented results from case and statistical studies of dayside FTEs observed less than 10 R_E from the $Y = 0$ plane. They demonstrated that events observed equatorward of the cusp show a marked tendency to occur for antiparallel (northward) magnetospheric and (southward) magnetosheath magnetic field orientations, whereas events observed poleward of the cusps tend to occur for either strongly parallel or antiparallel configurations. Sibeck et al. (2005) suggested that events observed poleward of the cusps originate both locally and on the equatorial magnetopause. To study the seasonal dependence of Interball FTEs, Korotova et al. (2008) limited their study to events that occurred in Northern Hemisphere summer (from day of year 120 to 210), within 10 R_E of local noon ($|Y| < 10\,R_E$) and during intervals of southward IMF orientation. They concluded that these events showed a strong tendency to occur in the Southern (winter) Hemisphere, as predicted by the Raeder (2006) model.

3 Example event

Figure 4 presents Interball-1 magnetometer observations in LMN coordinates for the interval from 08:50 to 09:00 UT on 11 September 1998. The spacecraft was in northern dawn high-latitude magnetosphere at GSM $(X, Y, Z) = (-6.1, -10.9, 12.6)\,R_E$ where it observed southward (Bl < 0) and duskward (Bm < 0) magnetospheric magnetic fields. During this 10-min interval, Interball-1 observed three transient fluctuations in the Bn component at 18:53, 18:56, and 18:58 UT. According to our criteria, the first two events are classic "reverse" FTEs marked by $(-,+)$ bipolar signatures in the Bn component and enhanced magnetic field strengths corresponding to increases in the (predominant) Bm component. The third event at 18:58 UT did not exhibit a clear bipolar

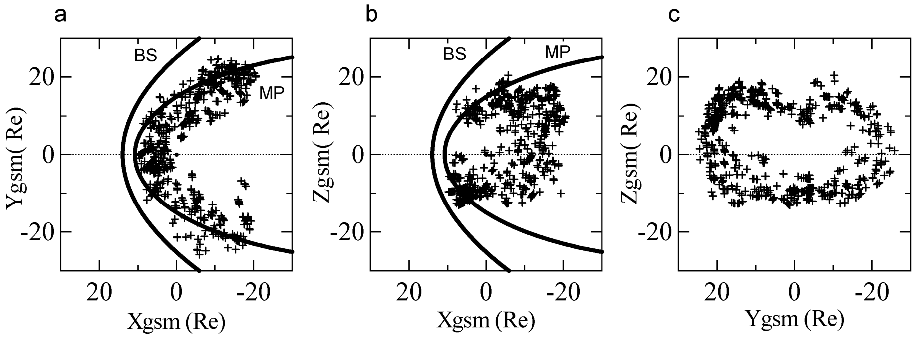

Fig. 5. The locations of FTEs in the GSM X-Y, X-Z and Y-Z planes. Events can be observed throughout the full range of locations surveyed by Interball-1.

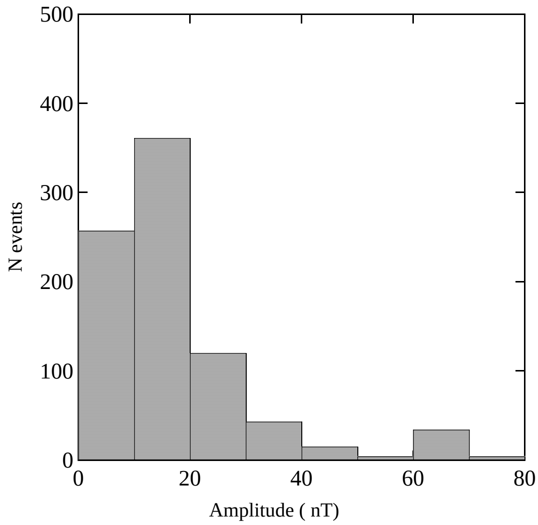

Fig. 6. A histogram of Interball-1 FTE amplitudes. The mean and median values are 15 and 13 nT, respectively.

magnetic field signature centered on an increase in magnetic field strength and was therefore not included in our database. In view of previous reports indicating the predominance of "direct" (+,−) bipolar signatures at northern latitudes (Rijnbeek et al., 1984), it is interesting to note the occurrence of these reverse FTEs on the northern dawn magnetopause.

4 Statistical survey

Interball-1 had the opportunity to observe events at higher latitudes than any other mission yet surveyed. Here we first examine those characteristics of the database that resemble results from previous missions to demonstrate the validity of our methods. Then we present new results that pertain to Interball-1. In contrast to Korotova et al. (2008), the database contains events that occur in all seasons, at all locations relative to the $Y = 0$ plane, and all interplanetary/magnetosheath magnetic field orientations.

Figure 5 demonstrates that FTEs were observed over the full range of magnetopause locations surveyed by Interball-1, including latitudes both poleward and equatorward of the dayside cusps (at $Y = 0\,R_\mathrm{E}$, $Z \sim 10\,R_\mathrm{E}$) and up to $\sim$20 R_E downstream on the flanks. As noted by Ding et al. (1991), who predicted that FTEs extend further into the magnetosheath than into the magnetosphere, Interball-1 observed far more magnetosheath than magnetospheric events. Of the 807 FTEs in our database, 638 were observed in the magnetosheath (79 %) but only 169 in the magnetosphere (21 %). For comparison, 75 % of the low-latitude Equator-S events reported by Neudegg et al. (2000) occurred in the magnetosheath, whereas only $\sim$69 % of the low-latitude ISEE-1/2 events reported by Rijnbeek et al. (1984) and Kuo et al. (1995) occurred in the magnetosheath.

Figure 6 presents a histogram of all the event amplitudes, as measured by the peak-to-peak variation in Bn. As noted by Kuo et al. (1995), Sanny et al. (1998), and Wang et al. (2005), the distribution falls off very rapidly with increasing amplitude. The median of our Interball-1 distribution is 13 nT, while the mean is 15 nT. For comparison, Kawano and Russell (1996) reported a median of 14 nT for ISEE-1/2 events, and Sanny et al. (1996, 1998) averages of 10 and 17 nT for two separate studies of events observed by AMPTE/CCE, while Wang et al. (2005) reported a median of 11 nT and a mean of 13 nT for Cluster events. Judging by these values, similar events were surveyed in each study.

Interball-1 observations confirm predictions that FTEs on the dayside magnetopause tend to occur for southward magnetosheath magnetic field orientation, whereas those on the flank do not. First, consider events in the magnetosheath. For these we can directly inspect the magnetosheath magnetic field applied to the magnetosphere. Figure 7a and b present a projection of the locations where 585 Interball-1 magnetosheath FTEs were observed into the GSM Y-Z plane. The events are color-coded to indicate the north/south (Bl) orientation of the prevailing magnetosheath magnetic field: red crosses for $\mathrm{Bl} > 0$ (Fig. 7a), blue minuses for $\mathrm{Bl} < 0$ (Fig. 7b). Many events were observed in

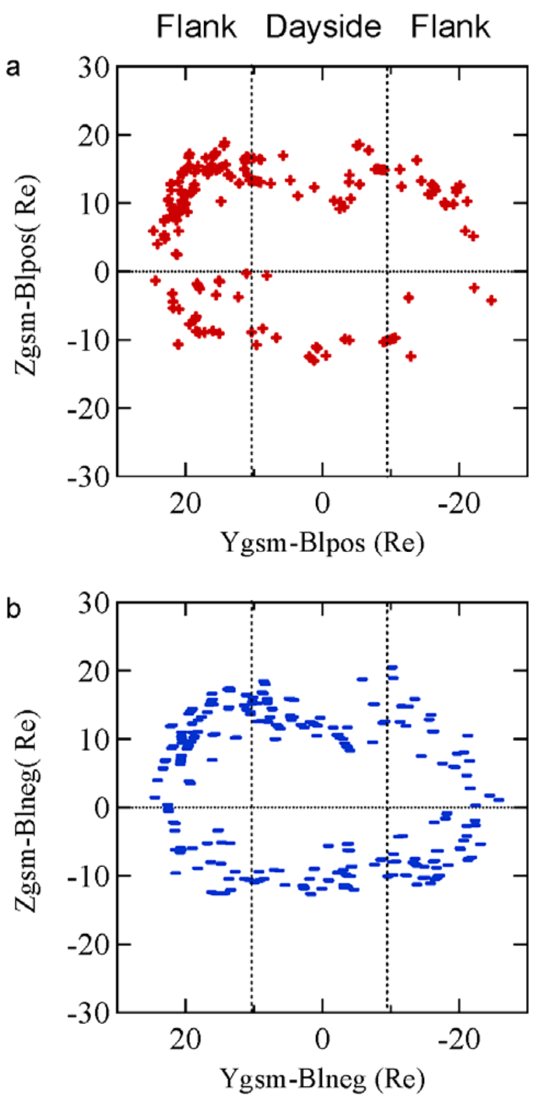

Fig. 7. Distribution patterns for FTEs occurring for **(a)** northward and **(b)** southward magnetosheath magnetic fields projected into the Y-Z plane.

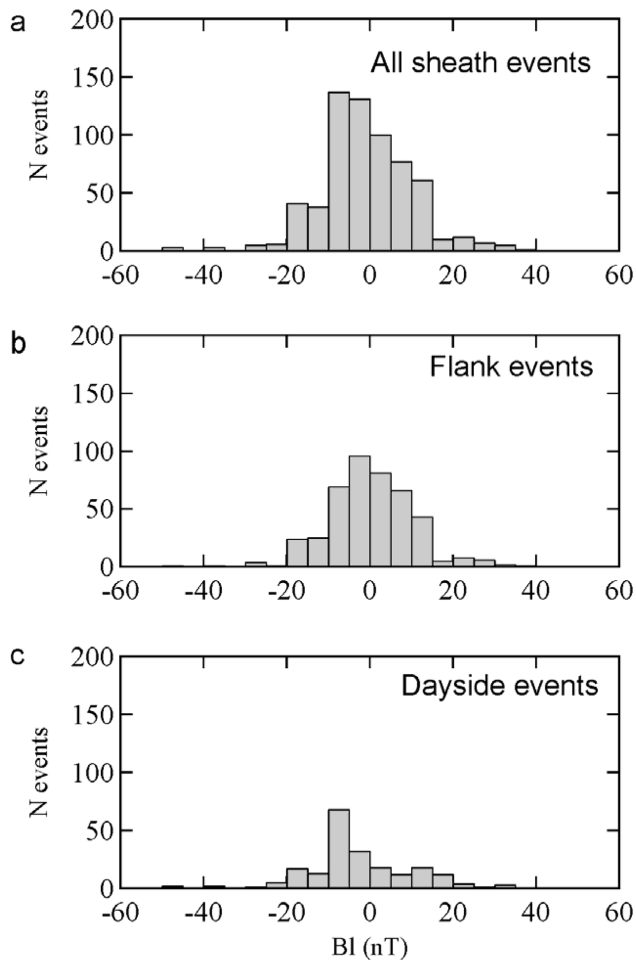

Fig. 8. Histograms of event occurrence as a function of Bl for **(a)** all magnetosheath events, **(b)** magnetosheath FTEs with $|Y_{\mathrm{GSM}}| > 10\,R_{\mathrm{E}}$, and **(c)** magnetosheath FTEs with $|Y_{\mathrm{GSM}}| < 10\,R_{\mathrm{E}}$.

the dayside Northern Hemisphere, only during the northern winter, spring, and fall seasons in agreement with the predictions of Raeder (2006). The locations of 53 magnetosheath FTEs that occurred during intervals of very weak north/south magnetic field orientations are not shown. Although there is a tendency for events on the dayside ($|Y_{\mathrm{gsm}}|) < 10\,R_{\mathrm{E}}$ to occur for southward magnetosheath magnetic field orientations, there is no such tendency for those on the flanks at $(|Y_{\mathrm{GSM}}|) > 10\,R_{\mathrm{E}}$. Kawano and Russell (1997a) reached a similar conclusion following a survey of ISEE-1/2 events.

To quantify this conclusion, Fig. 8a, b, and c present histograms of event occurrence as a function of Bl for all (638) sheath events, for magnetosheath FTEs with $|Y_{\mathrm{GSM}}| > 10\,R_{\mathrm{E}}$, and for magnetosheath FTEs with $|Y_{\mathrm{GSM}}| < 10\,R_{\mathrm{E}}$, respectively. Events occurring for $|\mathrm{IMF}\ B_z| < 0.5$ nT were assigned to the IMF $B_z = 0$ category. When presented in histograms, they were divided equally and added to the two bins bounding 0 nT. Of 203 dayside $|Y_{\mathrm{GSM}}| < 10\,R_{\mathrm{E}}$ magnetosheath events, 128 (63 %) occurred for magnetosheath Bl < 0 nT, but only 50 (25 %) for Bl > 0 nT, and 25 events were observed for Bl = 0. By contrast, of 435 flank ($|Y_{\mathrm{GSM}}| > 10\,R_{\mathrm{E}}$) magnetosheath events, 209 (48 %) occurred for magnetosheath Bl < 0 nT, and 198 (45 %) for Bl > 0 nT, and 28 events were observed for Bl = 0. Sibeck et al. (2005) interpreted the dayside Interball-1 events that occurred for southward magnetosheath magnetic field orientations as evidence for component reconnection on the equatorial magnetopause but those that occurred for northward magnetosheath magnetic field orientations as evidence for antiparallel reconnection poleward of the cusps. Consistent with this interpretation, they found that events seen at dayside latitudes below the cusp occurred almost exclusively for southward magnetosheath magnetic field orientations, whereas those seen at latitudes poleward of the dayside cusp occurred equally often

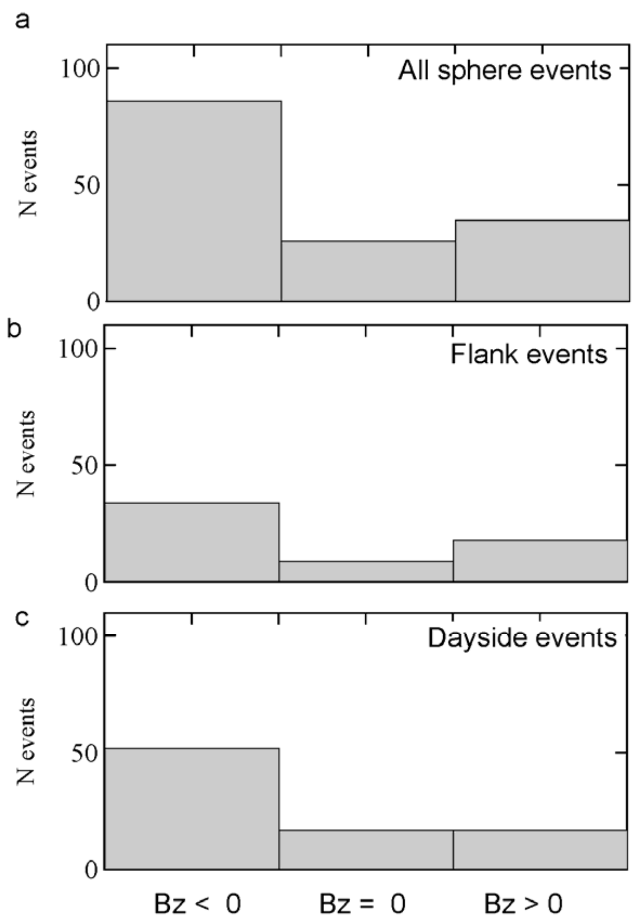

Fig. 9. Histograms of event occurrence as a function of IMF for **(a)** all magnetosphere events, **(b)** magnetosphere FTEs with $|Y_{GSM}| > 10\,R_E$, and **(c)** magnetosphere FTEs with $|Y_{GSM}| < 10\,R_E$.

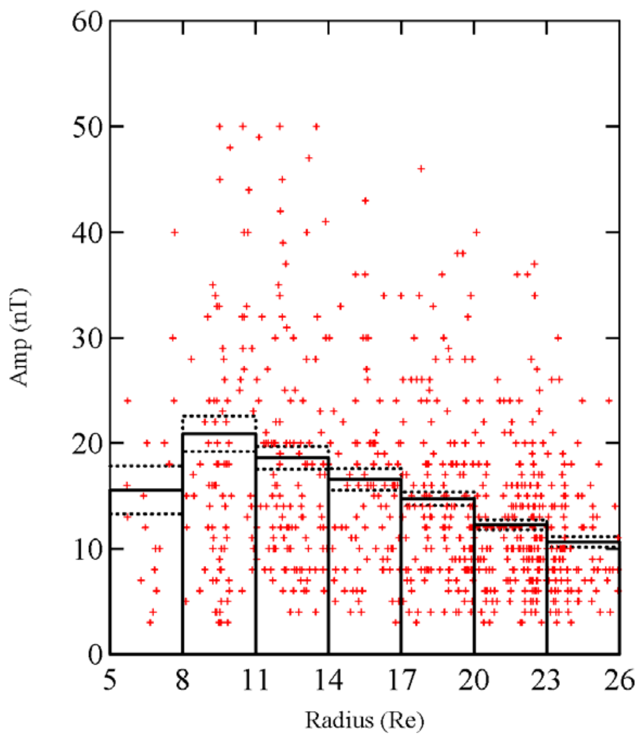

Fig. 10. Distribution of Bn perturbation amplitudes for all FTEs as function of radius. Red bars show the mean value for each bin. The dashed horizontal bars show the standard errors on the means ($\sigma/n^{1/2}$) for each bin.

for northward and southward magnetosheath magnetic field orientations.

Now consider events in the magnetosphere. For these, we inspected lagged IMF observations in GSM coordinates from the WIND (Lepping et al., 1995), IMP-8 (King, 1982), GEOTAIL (Kokubun et al., 1994) spacecraft for 169 Interball-1 magnetosphere FTEs. To reduce errors in estimating lag times from the IMF monitor to the magnetopause, we preferentially chose to use GEOTAIL or IMP-8 observations over those from WIND. When both GEOTAIL and IMP8 were available, we used observations from the spacecraft nearest the Sun–Earth line. For simplicity, we calculated arrival times under an assumption that the normals to the solar wind discontinuities lie along the Sun–Earth line, i.e. that the discontinuities were advected anti-sunward with the solar wind velocity. Events occurring for $|\text{IMF } B_z| < 0.5$ nT were assigned to the IMF $B_z = 0$ category. We were unable to determine IMF conditions at the times of 22 FTEs when the spacecraft were not able to serve as solar wind monitors, either because GSM Y exceeded 40 R_E, the spacecraft were in the tail or no data were available. Several events corresponding to abrupt north/south changes in the IMF Bz component were also excluded from the study.

Figure 9a, b, and c show histograms for this survey in which 86 events were observed for $B_z < 0$, 35 events for $B_z > 0$, and 23 events for $B_z = 0$. The majority of the magnetosphere events observed on both the dayside and the nightside occurred for southward IMF orientation, though a substantial minority occurred for northward IMF orientation. As noted by Sibeck et al. (2005), the events that occurred on the dayside for northward IMF orientation probably resulted from antiparallel reconnection poleward from the cusps. Those that occurred on the flanks resulted either from component reconnection along an extended subsolar line (Kawano and Russell, 1997a) or antiparallel reconnection at high latitudes (Fear et al., 2005).

As predicted, event amplitudes diminish with distance downstream from the subsolar magnetopause. Figure 10 shows the distributions of all peak-to-peak Bn signature amplitudes as a function of radial distance from the Sun–Earth line, a measure of the distance from the subpolar point along the Sun–Earth line. Large (>40 nT) amplitude events are far more common in the 8–11, 11–14 and 14–17 R_E bins than they are in the 17–20, 20–23, and 23–26 R_E bins. The mean amplitude, as shown by the solid bars, increases from the

5–8 R_E bin to the 8–11 R_E bin, but then steadily decreases to the 23–26 R_E bin and beyond. These results are consistent with previous reports indicating low event occurrence rates on the dayside equatorial (subsolar) magnetopause (Southwood et al., 1986) and the prediction discussed above that event amplitudes decrease with downstream distance because they become flattened (Cowley, 1982). Note, however, that Wang et al. (2005) presented results from a statistical study of Cluster and showed that Bn peak to peak magnitude increases from ∼20 nT to ∼40 nT with increasing absolute geomagnetic latitude MLAT.

Next we will show that the patterns of magnetosheath and magnetosphere event motion inferred from bipolar magnetic field signatures normal to the nominal magnetopause agree with the predictions of the component reconnection model. Figure 11a and b present the distributions of bipolar magnetic field signatures normal to the nominal magnetopause observed by Interball-1 for duskward (Bm <0) and dawnward (Bm >0) magnetosheath magnetic field orientations. During intervals of duskward IMF orientation, magnetosheath events marked by outward/inward (+,−) signatures predominate northward from a tilted dashed line running from southern dawn to northern dusk, while those marked by inward/outward (−/+) signatures predominate southward from the same line. During intervals of dawnward IMF orientation, events marked by outward/inward (+,−) signatures predominate southward from a tilted line running from northern dawn to southern dusk, while those marked by inward/outward (−/+) signatures predominate northward from the same line. We shifted the notional reconnection lines slightly to better separate events with inward/outward signatures from those with outward/inward signatures. The inferred tilts of the reconnection lines are clearly consistent with the predictions of the subsolar component reconnection model. The same conclusion was also reached by Kawano and Russell (1997b), who used the predicted orientations of subsolar component reconnection lines to sort bipolar signatures observed by the more equatorial ISEE-1/2 spacecraft on the low-latitude dawn and dusk flanks of the magnetosphere. Likewise, they are consistent with the work of Fear et al. (2012), who demonstrated that FTE occurrence patterns depend on the IMF clock angle and showed a tendency for events to move away from a tilted subsolar reconnection line into the winter hemisphere. Our observations indicate that the subsolar component reconnection line is typically tilted some 45° out from the equator, not unreasonable for IMF orientations that generally lie near the ecliptic.

There are some exceptions in the data plotted in Fig. 11. We tested the hypothesis that the "strange" events that do not obey the pattern resulted from antiparallel reconnection on the high-latitude flanks of the magnetosphere. They are moving sunward away from these sites and generating bipolar magnetic field signatures opposite to those of the events moving antisunward away from a dayside component reconnection line. We found that the majority of the "strange" events for −Bm support the hypothesis on antiparallel reconnection.

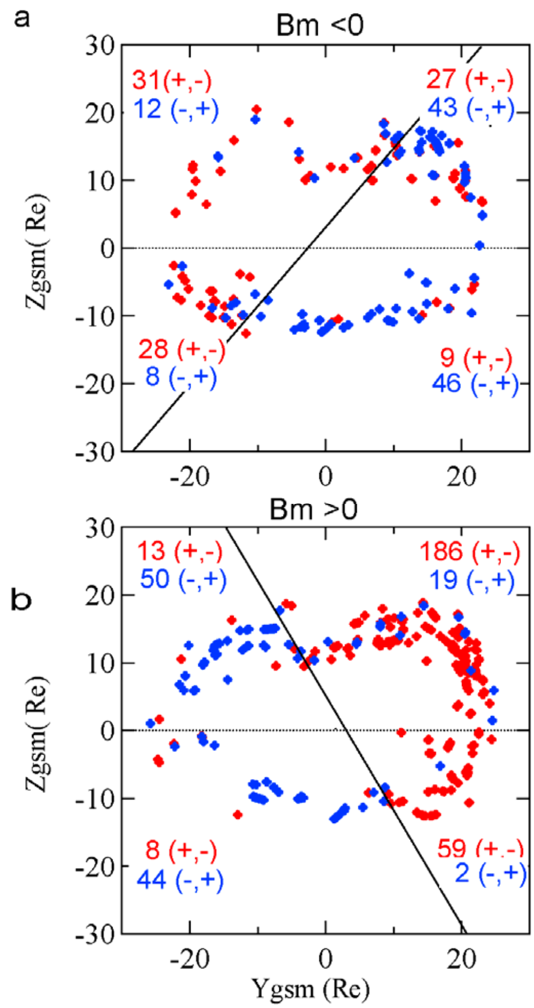

Fig. 11. Distributions of bipolar magnetic field signatures normal to the nominal magnetopause in the GSM Y-Z plane for duskward (Bm <0) and dawnward (Bm >0) magnetosheath magnetic field orientations. Red and blue crosses denote direct (+,−) and reverse (−,+) signatures in Bn component. The figure calls out the number of magnetosheath events in sectors bounded by the equator and notional tilted reconnection lines.

Now consider the locations where inward/outward and outward/inward signatures occur in the magnetosphere. Figure 12a and b show the locations where magnetosphere FTEs marked by these signatures occurred in the GSM Y-Z plane for northward and southward magnetosheath magnetic field directions (see Fig. 1). We determined the magnetosheath magnetic field orientations by inspecting the nearest magnetopause crossing. Only events that occurred at more than 10 R_E from the Sun–Earth line are presented. A comparison of the two panels demonstrates that direct signatures (red crosses) occur almost exclusively south of the geomagnetic equator and reverse signatures (blue crosses) occur almost

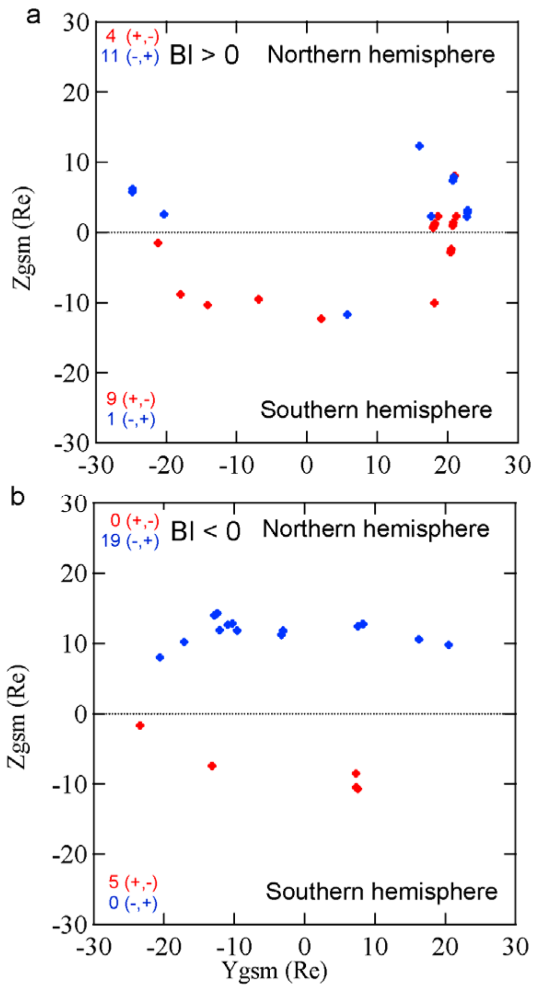

Fig. 12. Locations of magnetosphere FTEs with direct and reverse signatures for $R_E > 10\,R_E$ for northward and southward Bl magnetosheath magnetic fields, respectively. Red and blue crosses denote direct (+,−) and reverse (−,+) signatures in Bn component.

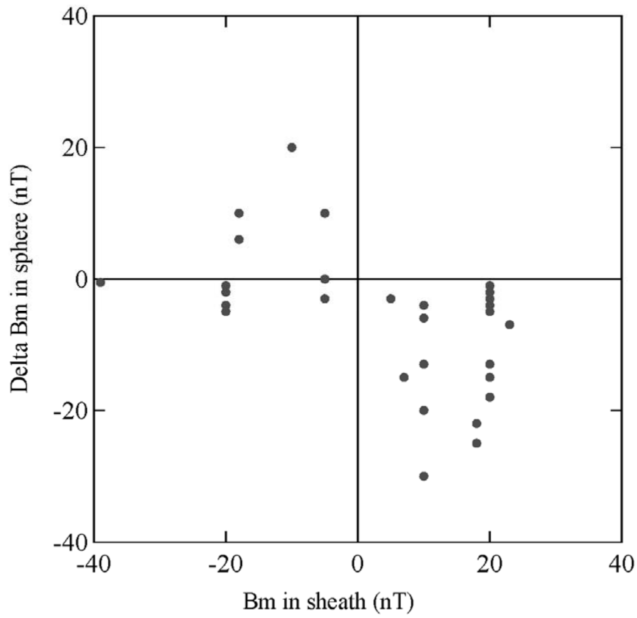

Fig. 13. Magnitude of the east/west (Bm) perturbation observed within magnetosphere FTEs versus Bm in the magnetosheath at the nearest magnetopause crossing.

exclusively north of the geomagnetic equator, regardless of the north/south IMF orientation. The distributions are consistent with the predictions for FTEs moving antisunward along the magnetotail magnetopause illustrated in Fig. 3.

To further test the predictions of the component merging model for a subsolar X-line whose tilt depends upon the direction of the interplanetary/magnetosheath magnetic field (Fig. 1), we compared the relationship of the magnetospheric magnetic field deflections to the magnetosheath magnetic field direction. For this analysis we chose the subset of magnetospheric FTE events with clear impulsive single-peak Bm perturbations. There were 39 such events. Figure 13 presents the magnitude of these Bm perturbations versus Bm in the magnetosheath at the nearest magnetopause crossing. Our results indicate that 32 FTE events are in good agreement with the predicted pattern; namely, the sense of the Bm perturbations in the magnetosphere is opposite Bm in the magnetosheath. However, 7 events are inconsistent with this pattern: they show slight −Bm perturbations for −Bm in the magnetosheath. Further inspection showed that 5 of these problematic events occurred within a 35 min time interval on the same day. The nearest magnetopause crossing was observed half an hour before that interval. WIND solar wind observations indicate that the lagged IMF B_y component changed sign about the time when the FTEs were generated. For the alternative IMF orientation, the event signatures would fit the component model prediction. As discussed in the introduction, the clear anticorrelation of B_y signatures in the magnetosphere and magnetosheath seen in Fig. 13 demands an explanation of these FTEs in terms of reconnection along a tilted subsolar merging line, e.g. in terms of component merging.

5 Summary and conclusions

We surveyed Interball-1 observations of FTEs on the high-latitude dayside and mid- to low-latitude flank magnetotail magnetopause and identified 807 FTEs during 1995–1999. They occurred in the vicinity of magnetopause over a wide range of latitudes and longitudes. The number of magnetosphere FTEs is less than one-fourth that of magnetosheath FTEs. This difference may result from magnetosphere FTEs exhibiting a smaller peak-to-peak bipolar Bn signature because their dimensions are less. On average event amplitudes diminish with distance downstream from the subpolar point and were similar to those in previously reported studies.

Dayside magnetosheath events (at small Y) show a strong tendency to occur for southward magnetosheath magnetic fields suggesting origin via component reconnection near the equatorial plane. Flank FTEs (at large Y) occur for both magnetosheath magnetic field orientations with only a slight preference for southward magnetosheath magnetic fields. These events are consistent with generation along an extended subsolar component reconnection line for all IMF orientations or a combination of reconnection along a subsolar component reconnection line for southward IMF and antiparallel reconnection at higher latitudes for northward IMF.

However, the distribution of direct and reverse magnetosheath FTE signatures for dawnward and duskward IMF orientations is most readily interpreted in terms of extended subsolar component reconnection line model. During periods of duskward IMF orientation, this line runs from southern dawn to northern dusk, dividing direct $(+,-)$ Bn signatures at northern latitudes from reverse $(-,+)$ Bn signatures at southern latitudes. During periods of dawnward IMF orientation, this line runs from northern dawn to southern dusk, dividing direct $(+,-)$ Bn signatures at northern latitudes from reverse $(-,+)$ Bn signatures at southern latitudes.

We also inspected occurrence patterns for transient magnetosphere events on the flanks. The magnetosphere events produce reverse bipolar Bn signatures $(-,+)$ in the northern lobe but direct signatures $(+,-)$ in the southern lobe, consistent with predictions for FTEs moving antisunward along the magnetotail magnetopause.

Furthermore, the clear anticorrelation between the east/west (Bm) perturbation observed within magnetospheric FTEs and Bm in the nearby magnetosheath also demands an explanation of the FTEs in terms of reconnection along a tilted subsolar merging line, e.g. in terms of component merging.

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