Observation of the magnetospheric "sash" and its implications relative to solar-wind/magnetospheric coupling: A multisatellite event analysis

N. C. Maynard,[1] S. Savin,[2] G. M. Erickson,[3] H. Kawano,[4] Z. Němeček,[5]
W. K. Peterson,[6] J. Šafránoková,[5] I. Sandahl,[7] J. D. Scudder,[8] G. L. Siscoe,[3]
B. U. Ö. Sonnerup,[9] D. R. Weimer,[1] W. W. White,[1] and G. R. Wilson[1]

Abstract

Using a unique data set from the Wind, Polar, Interball 1, Magion 4, and Defense Meteorological Satellite Program (DMSP) F11 satellites, comparisons with the Integrated Space Weather Model (ISM) have provided validation of the global structure predicted by the ISM model, which in turn has allowed us to use the model to interpret the data to further understand boundary layers and magnetospheric processes. The comparisons have shown that the magnetospheric "sash" [*White et al.*, 1998], a region of low magnetic field discovered by the MHD modeling which extends along the high-latitude flank of the magnetopause, is related to the turbulent boundary layer on the high-latitude magnetopause, recently mapped by Interball 1. The sash in the data and in the model has rotational discontinuity properties, expected for a reconnection site. At some point near or behind the terminator, the sash becomes a site for reconnection of open field lines, which were previously opened by merging on the dayside. This indicates that significant reconnection in the magnetotail occurs on the flanks. Polar mapped to the high-density extension of the sash into the tilted plasma sheet. The source of the magnetosheath plasma observed by Polar on closed field lines behind the terminator was plasma entry through the low field connection of the sash to the central plasma sheet. The Polar magnetic field line footprints in each hemisphere are moving in different directions. Above and below the tilted plasma sheet the flows in the model are consistent with the corresponding flows in the ionosphere. The turbulence in the plasma sheet allows the convection patterns from each hemisphere to adjust. The boundary layer in the equatorial plane on the flank for this interplanetary magnetic field B_Y condition, which is below the tilted central plasma sheet, is several R_E thick and is on tailward flowing open field lines. This thick boundary layer shields the magnetopause from viscous forces and must be driven by magnetic tension. Above the plasma sheet the boundary layer is dominated by the sash, and the model indicates that the open region inside the sash is considerably thinner.

1. Introduction

Recent Interball 1 measurements have discovered that the turbulent boundary layer over the high-altitude cusp, originally identified by *Haerendel* [1978] from Heos data, extends in wings back along the flanks [*Klimov et al.*, 1997; *Savin et al.*, 1998a, 1998b, 1999]. These regions of strong ULF turbulence, Alfvénic in nature, are also regions of low magnetic field magnitude and are described as magnetic bubbles [*Savin et al.*, 1999]. Statistically, they are present a large percentage of the time in the high-latitude dayside regions and extend in wings from the cusp back around and down the flank to X_{GSM} distances of -20 R_E. The most intense events are located above the cusp at X_{GSM} values between -2 and +7 R_E. *Savin et al.* [1999] have suggested that these regions/events are sources for magnetosheath plasma entry into the magnetosphere and might provide plasma entry into the near-Earth magnetotail via the flanks.

In an MHD simulation for positive interplanetary magnetic field (IMF) B_Y, *White et al.* [1998] found a deep, narrow band of weak magnetic field strength which was located on the high-latitude magnetopause, running tailward on the dusk (dawn) side from the cusp in the Northern (Southern) Hemisphere back along the flanks into the tail, where it closed through the plasma sheet. This feature, named the "magnetospheric sash," is similar in location to the separator line determined by *Luhmann et al.* [1984] using *Crooker's* [1979] concept of antiparallel merging. Topologically, the separator line is a locus of magnetic merging sites in the model. White et al. showed that the sash merged with the extremities of the tilted plasma sheet in the tail, forming an "S" configuration. The cross-tail S configuration was qualitatively confirmed at X = -30 R_E by comparing the model results to IMP 8 averaged data of *Kaymaz and Siscoe* [1998] for similar conditions. The existence of the sash was confirmed by an independent model [*Nishikawa*, 1998].

In a parallel study using an MHD simulation from a different model, *Crooker et al.* [1998] investigated merging sites for positive IMF B_Y and the division of potentials between merging cells and lobe cells. Conditions for merging were fulfilled in regions concentrated in northern-dusk and southern-dawn, extended diffusive regions. They point out that mismatched potentials between the two hemispheres are consistent with the fact that field lines that pass near the magnetopause acquire parallel potentials in the diffusion region as required by theory [*Cowley*, 1973; *Hesse and Schindler*, 1988]. The diffusion in the simulation is numerical, which approximates, to some degree, the role of physical diffusion required by theory. This means that at a given instant of time a field line can be traced from the ionosphere to the solar wind, but at the next instant the solar wind ends are connected to different ionospheric ends. Crooker et al. use *Cowley's* [1973]terminology of "changing partners." Differences in potential between the merging cells are in an embedded lobe cell in the larger merging cell [see *Crooker*, 1992; *Burke et al.*, 1994]. They also rationalized sunward flow of open field lines in the ionosphere as part of the ionospheric global response to the solar wind driving, recognizing that magnetic tension does not control the motion of field lines overdraped over the high-latitude magnetosphere because of changing partners. Crooker et al. also noted that reconnection of open field lines along the ionospheric equipotential contour which they followed did not occur in the center of the tail but on the flank. *Kaymaz et al.* [1995] in comparing their IMP 8 magnetic perturbation vectors with the Fedder-Lyon MHD results noted concentration of perturbation vectors to the flanks.

Empirical convection patterns for B_Y-dominated conditions such as those of *Heppner and Maynard* [1987] (HM) have always had the problem of how to reconcile potentials in both hemispheres with very different patterns in each hemisphere. For positive B_Y conditions the HM "BC" pattern with the large cell at dusk applies to the Northern Hemisphere while the HM "DE" pattern with the large cell at dawn applies to the Southern Hemisphere.

On January 12, 1997, Interball 1 skimmed the high-latitude magnetopause for over 12 hours between 0635 and 1850 UT, transitioning in and out of the turbulent boundary layer [*Savin et al.*, 1999]. Because of the uniqueness of this event and the availability of applicable data from other satellites, this event was selected as a study event for the Inter-Agency Consultative Group (IACG) Campaign 2 for boundary layer studies. The purpose of this campaign is to apply data from multiple satellites in diverse locations to constrain and improve our understanding of boundary layer processes. Between 1300 and 1700 UT of this interval the IMF was dominated by an average 4 nT B_Y component, which had significant intervals near 5 nT, and with the B_Z component slowly changing back and forth between weak positive to weak negative values. In addition to Interball 1 and its companion satellite Magion 4, Polar, Geotail, and Defense Meteorological Satellite program (DMSP) F11 were strategically located for this study. The run of the Integrated Space Weather Model (ISM) that was used by *White et al.* [1998] to identify the sash was for a constant 5 nT B_Y; hence results from the model run are directly comparable to the satellite data.

In this paper we will first use the satellite data to establish the general validity of the simulation. We will then use the model to interpret the satellite data, establishing (1) that the wings of the turbulent boundary layer are, at least in part, identifiable with the sash, (2) that reconnection in the sash behind the terminator serves to reconnect previously opened field lines, completing the convection circulation, and (3) that the sash is a location for entry of magnetosheath particles into the magnetotail. We will use insight gained from the simulation to infer the character of ionospheric convection and the flank boundary. After a brief description of the model run, the paper presents the satellite data and then compares it to the model results. Discussion of the above points follows.

2. Integrated Space Weather Model

The Integrated Space Weather Model (ISM) is based on standard MHD equations to which have been added an additional neutral thermospheric fluid such that the equations transform continuously into the correct ionospheric equations at low altitudes. Modeling continuously from the base of ionosphere to its boundaries in the solar wind (a cylinder of radius 60 R_E with ends at $X = 40$ and -300 R_E), the finite difference grid resolution varies from a few hundred kilometers in the ionosphere to several R_E at the boundary [*White et al.*, 1998]. The simulation reported here had inputs similar to that reported by *White et al.* [1998]. However, in this run there was no explicit viscosity in the momentum equation, and the explicit resistivity only turned on when the current density exceeded a threshold, limiting the introduced dissipation to the dayside magnetopause and central plasma sheet. For boundary conditions the solar wind velocity, density, temperature, and magnetic field were 400 km s^{-1}, 5 protons cm^{-3}, 20 eV, and 5 nT, respectively. For the first 2 hours the IMF was northward. It was then rotated to pure positive B_Y for the remainder of the run. Results will be shown in sections 3 and 4 at 1 hour and 49 min after the westward turning. This time was chosen because of the availability of an output data set, because it was far enough from the change to B_Y to provide relatively steady conditions, and because it was roughly a similar time interval away from the turning to positive B_Y in the IMF data shown in section 3.2.

3. Observations: January 12, 1997

3.1. Data Sources

In the following event analysis we will present data from six satellites: Wind, Polar, Interball 1, Magion 4, Geotail, and DMSP F13. The satellite locations are given in Table 1 along with the relevant measured parameters. Applicable instrument descriptions may be found in the footnoted references. Particular instrument characteristics that might affect interpretation are highlighted in the data presentations. Table

The afternoon of January 12, 1997, from 1500 to 1700 UT presented a unique configuration of International Solar Terrestrial Physics (ISTP) satellite locations as well as a relatively constant positive IMF B_Y. Interball 1 and Magion 4 were in the high-latitude boundary layer and magnetosheath. Polar was behind the dusk terminator in a basically dawn-dusk orbit. Geotail was located in the central tail. DMSP F13 crossed the dusk auroral region near 1712 magnetic local time (MLT). In this section we will introduce data from each satellite, placing each data set into the global context, using ISM. In section 4 we will compare the data sets in more detail to results from the ISM model run to qualitatively verify the existence of the sash and advance our understanding of solar wind/magnetosphere coupling.

To set the context, Plate 1 shows the ISM potential patterns and magnetic field mappings of the satellite locations for this event. Plate 1a presents a three-dimensional view of magnetic field lines, tracing in both directions from each satellite position given in Table 1 using the ISM magnetic field. Blue indicates field lines that connect to both hemispheres. Yellow or green field lines are open, connecting to one hemisphere. Red field lines are open to the solar wind on both ends. Several lines from satellite positions 10 min apart are traced for each satellite. Plate 1b shows a surface generated by the last closed magnetic field line in the model. The surface is colored by the strength of the magnetic field with red as strong and green as weak. On the dayside this surface is the magnetopause. The hole in the surface around the pole is from open lobe field lines. Note the green structure, which extends from the cusp back along the flank to the tail. This is the feature identified as the sash by Plate 1

White et al. [1998]. Note that the Magion 4 and Interball 1 field lines pass near or through the sash, with the Interball 1 field line that bends sharply (colored red in Plate 1a and white in plate 1b) turning in the sash. These points will be explored in more detail after the data presentation. Plates 1c and 1d present the ISM calculated potential patterns for the Northern and Southern Hemispheres. The footprints of the magnetic field lines passing through the satellite locations that come down to the ionosphere are shown in each plot. The orbit track for DMSP F13 is also shown on the Northern Hemisphere potential plot.

3.2. Interplanetary Conditions

The IMF Y and Z magnetic field components as
re 1 measured by Wind are presented in Figure 1 along with the dynamic pressure from 1300 to 1700 UT. The data have been lagged by 20 min to account for the propagation time from Wind to the magnetopause. All UTs referring to solar wind data will include this lag and be for the arrival time at the magnetopause. After turning positive at 1440 UT, B_Y, the dominant component, reached an average level of approximately 4 nT near 1530 UT and remained there with long excursions up to 5 nT through 1630 UT. IMF B_Z oscillated between ± 2 nT, resulting in an average magnitude of B near 5 nT.

The ISM run that was used to identify the sash [*White et al.*, 1998] was driven by a constant IMF B_Y of 5 nT ($B_Z = 0$). Because of the similarity of this condition to the actual condition, qualitative comparisons are possible with the ISM model. Data will be presented to show five specific matches of observations to the model.

3.3. DMSP F13 Data

DMSP F13 crossed the evening auroral zone at 1712 hours MLT between 1552 and 1600 UT, crossing very near the ionospheric footprints of Interball
e 2 1 and Magion 4. Plate 2 shows the electron and number fluxes as well as the horizontal, cross-track ion drift. All measured particle fluxes are downgoing. Plates 2a and 2b show the total number flux and average energy of the electrons. Plasma sheet electrons are seen initially, before more intense lower-energy, boundary-layer-like fluxes, starting on sunward flowing field lines and straddling the first convection reversal near 1554:30 UT, appear. The ion drift alternates between sunward and antisunward flow until 1557:30 UT, where the potential minimum, or closest approach to the center of the convection cell, is observed near 83° magnetic latitude. This potential minimum location corresponds very well to the center of the Northern Hemisphere cell in Plate 1. Note that the potential pattern in Plate 1 is a snapshot at a single time from the large-scale model and should not be expected to reflect all the mesoscale temporal/spatial structure observed in the data. In the layer at the first convection reversal we also see ions ranging between 500 V and 1 kV. The multiple ion drift reversals are associated with low-energy electron fluxes (negative reversals) or no fluxes (positive reversals), indicating structure in what probably is a lobe cell.

3.4. Polar Data

Plate 3 depicts from 1500 to 1700 UT the electric Plate 3
field and energetic electron data from the Polar spacecraft, located at $\sim 6\ R_E$ radial distance and behind the terminator near 1900 MLT. Polar crosses the evening auroral zone ~ 2 hours later in MLT than DMSP. The second panel shows the electric field along the velocity vector, from which the potential along the orbit track can be integrated (shown in the top panel). The electric field used in this calculation is measured in the spin plane, where the measurement is not contaminated by density variations. The initial electric field reversal is at 1530 UT with the flow turning weakly antisunward. The flow stays this way until after 1600 UT, where the direction reverses back and forth similar to the DMSP data in the region of the lobe cell. The four electron spectrograms, from top to bottom, depict the differential energy flux antiparallel to B, parallel to B, the anisotropy, and the total. Blue (yellow) anisotropy indicates fluxes that are more perpendicular (parallel). The higher-energy fluxes before 1530 UT are trapped plasma sheet electrons, while the lower-energy fluxes with a mean energy of 100 eV after 1530 UT are more field-aligned. The top two spectrograms indicate that they are flowing in both directions. Note that the trapping boundary is at the first field reversal boundary, which is the potential minimum.

Plate 4 shows ion composition data from the Toroidal Plate 4
Imaging Mass-Angle Spectrograph (TIMAS) instrument on Polar. From 1530 to 1600 UT, in the boundary layer defined by the electrons, there are intense fluxes of H^+ between 500 eV and 1 keV which are accompanied by He^{++} of similar energy. The energy tends to increase slightly with time. He^{++} is a tracer of solar wind origin particles. Similar energy ions are

also seen by HYDRA (not shown). Both instruments show the ion fluxes to be relatively isotropic, which indicates that the particles have been on closed magnetic field lines connected to Polar long enough to be bouncing between both ends of the magnetic bottle, formed either by connection to both ionospheres or between one ionosphere and a potential that closes the bottle, but not long enough to develop an empty loss cone. The HYDRA moments indicate that the ions are flowing with velocities between 20 and 100 km s^{-1} with variable direction, primarily in the XZ_{GSM} plane. Note from Plate 1 that the Polar field lines map back to positions near the dusk flank with increasing negative X distance with time. This will be treated further in the model comparison discussions in sections 4 and 5.

Comparison between Polar data near 1900 MLT and DMSP F13 data near 1700 MLT shows that the two spacecraft are seeing a similar boundary in potential as well as similar characteristics in the particles. Both satellites are seeing flow that has an antisunward component in the boundary layer flux region, although the quadrature flow component may be significant and different. The plasma sheet fluxes extend out to the first reversal in flow. Boundary layer and/or magnetosheath origin fluxes are seen in the region with a tailward component to the flow. The Polar observation of He^{++} and the mapping stress again the magnetosheath origin for the observed ions.

3.5. Interball 1 Data

The Interball 1 spacecraft was located in the high-latitude boundary layer, behind the terminator near X = -10 R_E (see Table 1). Tracing the Interball 1 position within the magnetic field model (displayed in Plate 1) indicated that Interball 1 was on Northern Hemisphere open field lines that traversed near the boundary or on magnetosheath field lines that did not intersect either hemisphere.

Figure 2 displays the ion velocity, density and temperature, magnetic field components and the magnitude, and a spectrogram showing the energy of the ions for the interval between 1500 and 1900 UT. The regions of strong positive B_X are indicative of magnetospheric locations, while transitioning to negative B_X is an indicator of crossing the high-altitude magnetopause into the magnetosheath. There are many of these crossings during the interval, which indicates that Interball 1 was hovering near the boundary. Note that V_X is always negative, which indicates that the boundary layer adjacent to the magnetopause is flowing tailward as well as is the magnetosheath. We will focus on the structure between 1550 and 1610 UT, which is within a few minutes of the period when Polar was observing He^{++}.

Figure 3 presents two high-resolution data segments from 1552:30 to 1556:30 UT and from 1602:30 to 1606:30 UT showing magnitude of B, B_X, ion fluxes observed by the detector in the spin plane, and the pitch angle of those fluxes. Pitch angles greater (less) than 90° when B_X is positive (negative) indicate ion velocities with a tailward component. In the bottom interval, B_X is primarily positive, indicating that Interball 1 was on the magnetospheric side of the boundary. The top interval is dominated by two periods of negative B_X corresponding to magnetosheath magnetic field directions. The ion spectra are modulated with the 2-min spin period, which creates the pitch angle variation. In the bottom interval the gaps in the distribution near 1604:30 and 1606:10 UT correspond to pitch angles of less than 90° with positive B_X, indicating that the principal flow is tailward. Correspondingly, the high fluxes just after 1603 UT and at 1605 UT have pitch angles greater than 90°, indicating that these fluxes on the boundary layer side are flowing tailward. The top interval near 1555:30 UT with negative B_X and small pitch angles indicates tailward velocities on the magnetosheath side. The large velocities in Figures 2a and 2b at the times of the two intervals in Figure 3 are consistent with accelerated tailward flow associated with the boundary crossings, which suggests that Interball was tailward of an active reconnection site. This is also consistent with the field line mapping within the ISM model shown in Plate 1. This will be further explored below in more detailed comparisons with the model. The core energy of the ions is near 1 keV, which is at the high end of the energy range of ions observed at Polar, with higher energy tails at greater than 7 keV. The characteristic energy of the higher-energy ions corresponds to that of the plasma sheet.

Most of these boundary crossings also involve a distinct minimum in the magnitude of B. The B minimums reach as low as 2 nT in short intervals. Low magnetic field is a signature of the sash, while near-zero magnetic field is a characteristic of reconnection [see *White et al.*, 1998]. To further explore these crossings, a minimum variance analysis was performed, and the hodogram shown in Figure 4 was constructed for the inward crossing between 1558 and 1600 UT, which had the smallest of the magnetic field minimums in the interval. A boundary normal is distinguishable with a rotation that changes sense in the other two components. The ratio between the intermediate to minimum variance is 4.3:1. The normal direction components of (-0.315, -0.606, -0.730) describe a vector whose direction points inward and slightly tailward, qualitatively consistent with a nominal flaring magnetopause. The normal component of B was found to be 0.08 nT with a statistical error of 0.25 nT calculated by the method of *Kawano and Higuchi* [1995] and 0.22 nT calculated by the method of *Khrabrov and Sonnerup* [1998]. Since the normal component is within the statistical error (as is often the case in this type of analysis), we cannot conclude whether the discontinuity was rotational or tangential, nor is either case ruled out. We may infer that there is time dependence relative to possible reconnection associated with this location from the multiple minimums in B and the intensifications in the tailward paricle fluxes seen over the time interval.

3.6. Magion 4 Data

The Magion 4 satellite (companion to Interball 1) was located $\sim$1 R_E sunward of Interball 1 in the high-latitude boundary layer. Plate 5 shows ion and magnetometer data from 1430 to 1630 UT. Plate 5a presents the total current registered by the ion trap oriented sunward. The units are arbitrary, but the levels provide a rough estimate of 7 cm^{-3}. A better determination is not possible owing to the highly fluctuating velocity, as will be discussed later. Plates 5b and 5c show the B_X component of the magnetic field (the principal component) and $|B|$, respectively. The depicted interval contains several boundary crossings which are characterized by a sharp change in sign of B_X and by a change of the magnitude. Note that in the intervals of strong ion flux around 1500 UT, just before 1600 UT, and at 1615 UT the magnitude of the field approaches zero, reaching below 5 nT. This is similar to the minimums seen in the Interball data.

Plates 5d - 5f present the ion energy flux measured by the sunward oriented analyzer and the bulk and thermal speeds computed from these data. The analyzers oriented in the other directions (antisunward and perpendicular to the Sun-Earth line) registered significantly lower counts, just corresponding to the thermal velocity.

The most intense fluxes are seen moving antisunward in the regions of low magnetic field strength. The energy of these bursts is around 1 keV, similar to the ions seen by Interball 1 and on the high end of the energy range of ions observed by Polar. Comparison of the Interball 1 and Magion 4 data indicates that the low magnetic field region, which is characteristic of the sash, extended sunward from Interball 1 to the Magion 4 location.

Careful inspection of the energy spectrogram reveals two plasma populations, one with a typical energy near 1 keV and the second with an energy of $\sim$400 eV. These populations are observed either separately (high energies at 1437 UT and low energies at 1443 UT) or coexisting (at 1635 UT). As a rule, the deepest depressions of the magnetic field coincide with the appearance of the low-energy population. The presence of the two ion populations makes impossible the determination of the bulk velocity which oscillates between 150 and 400 km s^{-1}. These values roughly correspond to the energies of the observed ion populations. The magnetosheath flow at the Interball location is supersonic, and thus the newly reconnected field lines are moving tailward rapidly. The ions accelerated in the sunward direction in the plasma rest frame are observed as a decelerated, low-energy population in the satellite frame [*Šafránková et al.*, 1998]. These observations suggest that at times, Magion 4 may be close to and occasionally sunward of an active reconnection site in the sash.

3.7. Geotail Data

Figure 5 presents Geotail magnetometer and plasma data for the interval from 1400 to 1700 UT. Geotail oscillated between the plasma sheet boundary layer and the lobe during the interval as seen by the density and temperature panels near the bottom. The top four traces show the components and magnitude of the magnetic field. B_X is negative and nearly equal to B, confirming the location to be near the boundary layer/southern lobe interface. The ion velocity data show bursty earthward flows of 2-keV ions in the boundary layer between 1500 and 1520 UT. Near 1440 UT the boundary layer flow is tailward with higher-energy particles. The lobe flow between 1520 and 1610 UT is weakly tailward. In the later encounter with the boundary layer the flow is weak and tailward. Of particular note is the low energy of the boundary layer ion fluxes. Away from the bursts, the energy is near 1 keV, more typical of the magnetosheath than of the central plasma sheet. This is true both near 1505 UT and in the brief reentry into the boundary layer near 1630 UT. The source of this lower-energy population is not clear as the satellite is located near midnight in local time.

4. Model Results

The ISM model provides a "magnetosphere in a box," which can be probed and checked at points corresponding to the satellite locations. Comparison of model parameters with data provides a check on the consistency of the model. The model, in turn, can suggest features that should be present in the data. The sash is a case in point [*White et al.*, 1998]. We have taken each satellite location and traced in both directions the magnetic field line passing through the satellite. This provides an indication of the possible source/sink region in the magnetosphere for phenomena seen in the data as well as the corresponding location of the source/sink region in the ionosphere. Using these traced field lines shown in Plate 1, we have developed a series of plots to compare with the data presented in section 3. These will be presented and contrasted to their respective data in sections 4.1 and 4.2.

4.1. Magnetopause Comparisons

By displaying model quantities on a plane within a three-dimensional (3-D) image, we obscure the portion of magnetic field lines traced in three dimensions that extend behind the plane. Thus the precise location of those field lines at any X distance can be determined. Plate 6 shows the magnetic field strength (left) and ion mass density (right) on a plane at X = -10.2 R_E, which is in between the Interball 1 and Magion 4 locations. The yellow magnetic field lines, which are open and connected to the Northern Hemisphere, connect to Interball 1 and Magion 4. The red field line, which is open on both ends, is the last one mapped from Interball 1. The point where these field lines cross the plane is in the low magnetic field strength (green) and high ion mass density (red) region at the top of the sash (dark green region in left panel). The bend in the red and yellow field lines is in front of the plane.

This particular plane was also chosen because it is where the second mapped Polar magnetic field line crossed the plasma sheet. It is in the low magnetic field, high-density extension of the sash into the plasma sheet. We will come back to this point later.

By moving the plane forward we were able to find that the distance at which the red field line turns into the magnetosheath is X = -5.5 R_E. The left panel of Plate 7 shows the X component of the magnetic field at X = -5.5 with the turning point at the reversal or the magnetopause boundary. The right panel is a two dimensional plot of the magnetic field magnitude (color bar) and the vector magnetic field in the plane. The field lines as they project into this plane are shown in their entirety. Note that the magnetic field lines form an X configuration centered in the low magnetic field magnitude sash. By comparing with the left panel, one can see that in the red region the vectors have a component out of the paper, while to the right of the sash in the green region the vectors have a component into the paper. The last two Interball 1 field lines bend in opposite directions at this point in the center of the sash, one into the solar wind and the other toward the northern ionosphere. Magion 4 field lines are turning but not as sharply, indicating that the particular ones that we traced are staying in the boundary layer on the edge of the sash. Thus we conclude that ISM places the satellite locations ~5 R_E tailward of a reconnection region, with Interball 1 actually crossing the extension of the X-line or separatrix.

The low magnetic field and magnetopause crossings observed by both Interball 1 and Magion 4 agree remarkably well with the configuration predicted by ISM. Remember that the model run was with a constant magnetic field driver, a good approximation of but not the actual driving conditions. Also, reconnection in the model is the result of numerical diffusion and may not conform exactly to reality. The flow behind the X-line would be expected to remain tailward across the boundary as it does in the data. The normal to the magnetopause points to the rear as well as inward, which is qualitatively consistent with the X-line defined in the model. Hence the data and the model qualitatively agree. A major question would be whether the actual X-line was closer to the satellites than the model predicts. The Magion 4 results are suggestive of this with the occasional observance of a lower-energy (decelerated) ion population, which indicates that the actual reconnection site may have been intermittently tailward of that location.

4.2. Boundary Layer Comparisons

Geotail was located at X = -30 R_E near the center of the tail. Its magnetic field lines map to both hemispheres and are closed in the model as seen in Plate 1. The left panel of Plate 8 shows the plane at $X = -30$ painted with the magnitude of the magnetic field. Geotail maps to the edge of the low-field region of the central plasma sheet. As such, it could be expected to be traversing between the plasma sheet boundary layer and the southern lobe as was observed. This provides an additional check on how well the model configuration matches the actual conditions, extending confidence in the comparisons.

Plate 6 shows that the second mapped magnetic field line passing through the Polar location penetrated the extension of the low-field region from the sash into the edge of the plasma sheet. This is also a higher ion mass density region. The third mapped Polar field line cuts through the low-field extension of the sash at X = -25.5 R_E. The right panel of Plate 8 shows that plane painted with magnetic field magnitude. The mapped contact with this plane is again in the low magnetic field and high-density region. From Plate 1a, the fourth Polar field line maps quite a bit further back on the flank. Thus ISM maps Polar to a long region of the flank in the extension of the sash where the sash connects to the plasma sheet. The magnetic field lines are closed as they map to both hemispheres.

Polar observed He^{++} during this interval, which is a signature of magnetosheath origin, and ions of the order of 1 keV, which are of typical magnetosheath energies. We can infer from ISM that these fluxes could have entered through the low magnetic field region associated with the sheath and traveled up and down the closed field lines, accounting for their nearly isotropic distribution.

Comparing the electric field data and ISM potential patterns leads to several conclusions and dilemmas. From Plate 1, Polar maps in the Northern Hemisphere to a region where the convection is equatorward with a sunward component. It is a region where the flow is returning from the nightside, completing the circulation. Magion 4 and Interball 1 also map to points in the convection pattern that are far from the dayside merging locations and are returning from the nightside. The Southern Hemisphere mapping of Polar is also to field lines that are flowing equatorward, but with an antisunward component. Again, it is a region which is completing the convection flow. For comparison, the flow would be turning from tailward to sunward through the poleward extension of the Harang discontinuity in the HM "DE" pattern, again completing the circulation pattern of the small dusk cell. The conclusion from ISM would be that Polar was observing flows on closed field lines away from a reconnection site where fluxes previously opened on the dayside were reconnected to complete the circulation pattern typically observed in the ionosphere. However, ISM also presents a dilemma. The potential contours intersected by the footprints in each hemisphere differ by 6-10 kV. This will be addressed further in section 5.

Polar and DMSP both see ions of apparent magnetosheath origin. The DMSP drift measurements indicate a sunward component to the flow, which reversed to antisunward between 1554 and 1555 UT at the time of observation of the ions between 0.5 and 1 keV. The flow turned back sunward shortly after the first observation of the ions. The brief period of antisunward flow also has a significant poleward component, as determined from the retarding potential analyzer, which is used to measure the ram component of drift. A subsequent reversal also had associated ions. These small-scale features are embedded in a larger pattern of sunward flow, characteristic of the large Northern Hemisphere afternoon cell with B_Y positive. The potential minimum is well poleward of the ions. The DMSP pass crosses very close to the mapped locations of Interball 1 and Magion 4 with the direction reversal approximately at the mapped location. Since Magion 4 and Interball 1 have been located at the high-latitude magnetopause, this would indicate that the additional negative potential poleward of the DMSP ions would be part of a lobe cell in which the whole circulation is within the open field line region.

Two hours later in local time, the protons and He^{++} are observed by Polar just after the potential minimum (1530 UT) and before subsequent relative maximum (1605 UT) and minimum (1627 UT); however, because of the long time it takes to traverse the cell, relative maximums and minimums may be part temporal and part spatial. The structure has similarities to the DMSP observations. The Polar ions are on field lines that are locally flowing antisunward, rather than straddling the local convection reversal as in DMSP.

5. Discussion

5.1. Magnetospheric Configuration

The correspondence of the data to the model is very close. For instance, Geotail measurements place the satellite transiting between the plasma sheet boundary layer and the lobe, south of the plasma sheet. The model maps Geotail to a similar position on the southern edge of the plasma sheet. Interball 1 and Magion 4 data place them at the high-latitude magnetopause. ISM also maps these satellites on open field lines at the magnetopause boundary. Polar is located behind the terminator in the high-altitude magnetosphere and is observing particles of magnetosheath origin. ISM maps Polar to just inside the sash on the flank, in the low magnetic field extension of the sash into the tilted plasma sheet. DMSP F11 ion drift observations fit reasonably well into the ionospheric convection pattern determined by ISM, with the convection reversals near the open-closed boundary in the model and the potential minimum near that of the model cell. These correlations provide a reasonable five-point qualitative comparison between actual measured conditions and the ISM model. That ISM describes actual conditions in these five diverse locations provides confidence that the model run is a reasonable facsimile of the magnetosphere. This allows us to probe the model to provide additional insight into the interpretation of the data and into the overall physics of boundary layer processes.

5.2. The Sash as a Reconnection Site

The Interball 1 data show a minimum in the magnetic field as the magnetopause was crossed, but we were unable to specifically conclude whether or not reconnection was taking place at the time of the field line tracing. The velocity at the boundary is tailward in both the Interball 1 and Magion 4 data. The mapping of the Interball 1 field line, which cuts the YX plane in the ISM run at 5.5 R_E as it turns out into the magnetosheath, infers that an actual X-line or reconnection site is located at that point. To see this better, Plate 9 shows a plane that cuts through the X location in the 5.5 R_E YZ plane perpendicular to the long axis of the sash. Both panels are colored with the magnetic field magnitude. The top panel shows velocity vectors, while the bottom shows magnetic field vectors. The magnetic field vectors are antiparallel in this plane at the merging site as would be expected from the antiparallel merging criteria of *Crooker* [1979]. The velocity vectors are flowing tailward all around the reconnection site. From this we infer that the reconnection site must have a tailward velocity or there must be a flow through that is tangent to the site and commensurate with the background sheath flow. *La Belle-Hamer et al.* [1995] have modeled reconnection on the flanks with both velocity and density shears. They conclude that the most probable observation sunward of the separator would be a decelerated tailward flow. If the shear is large enough it suppresses reconnection. To see sunward flow from the reconnection, it would be necessary to transform into the proper rest frame of the discontinuity. In actual fact, the reconnection separator inferred from the mapping may have been closer to Magion 4's and Interball 1's physical locations. The mixing of lower-energy ions with the 1-keV ions in the Magion 4 ion data could infer that a separator may have been close to and tailward of Magion 4. However, the comparison of the ISM run with the Interball 1 data substantiates that the sash at this location in the model is a reconnection site. In fact, considering the variability of the data, there may be multiple separator locations in the low magnetic field region along the boundary. On the basis of *Luhmann et al.'s* [1984] locus of antiparallel reconnection sites, we further infer that the sash comprises the same locus of sites.

Savin et al. [1999] have identified regions of high-level ULF turbulence and low magnetic field strength at the high-latitude magnetopause, which they have called the turbulent boundary layer [after *Haerendel*, 1978], and they suggest that it is a region of plasma penetration associated with the cusp. This turbulent boundary layer is a common feature at high latitudes. Their statistical study of 1 year's data show that there are wings of turbulence extending back downtail from the cusp to X = -20 R_E at high latitudes in the vicinity of the boundary between open and closed field lines. These wings are both above and below the equator. They note that the absence of events at the equator may be from orbital restrictions. However, associating the turbulence and low magnetic field strength of these events with merging or reconnection sites, as we have done for the case on January 12, it is easy to infer that the wings follow the sash. Keeping in mind the antiparallel merging constraint, the sash can be expected to vary somewhat in Y and Z loci, dependent on the relative strength of the IMF components, resulting in a spread in the locus of reconnection sites and a width to the wings. Having said this, we must remember that these are inferences from a single example, and the sash may not be the only source for the turbulent boundary layer.

5.3. Convection Patterns

The ISM model allows us to probe the magnetosphere to better understand the processes that the satellites are observing. Having established that reconnection is occurring in the sash, and noting where the Interball 1 field lines map in the Northern Hemisphere (Plate 1), it is clear that the reconnection process must close previously opened field lines from the dayside. Thus, somewhere near or behind the terminator, the sash changes from a primary dayside merging site and becomes a site for reconnecting flux from the lobe, which serves to complete the convection cycle. This was first seen by *Crooker et al.* [1998]. The conclusion is that significant amounts of reconnection in the tail occur on the flanks away from the center of the tail.

Heppner and Maynard's [1987] empirical convection model (HM) recognized that two very dissimilar patterns are applicable to opposite hemispheres when IMF B_Y dominates. It has not been clear how the HM "BC" pattern for positive B_Y in the Northern Hemisphere matched the negative B_Y "DE" pattern, applicable to the Southern Hemisphere for positive B_Y conditions. Obviously, the polar caps could be different, but the large cell in the patterns did not easily map to the smaller cell at auroral zone latitudes. This same situation is present in Plate 1 as highlighted in the mapping of the Polar field lines within the ISM model to each hemispheric convection pattern. Results from ISM in Plate 10 provide clues as to the resolution of this dilemma. Plate 10a shows the magnetic field magnitude with ion velocity vectors in the YZ plane at X = -10.2 R_E. This is the location where the second mapped Polar field line crosses the plasma sheet. The sash is seen as the dark green region. We have defined an arbitrary plane (plane C) that passes through the Polar field line and is approximately parallel to the tilt of the plasma sheet. Parallel planes above (plane B) and below (plane D) are also noted. The magnetic field magnitude and ion velocity vectors in each of these planes are shown in the respective panels. In all three planes the tailward flow in the magnetosheath is seen in the upper right. In Plate 10b the sash is clearly seen (dark green), and the flow near the Polar field line is sunward and toward the flank. This is similar to the flow (equipotential contours) in Plate 1c. In Plate 10d the flow near the Polar field line is antisunward. This is similar to that in Plate 1d. Thus the flow above and below the plasma sheet is consistent with that in the respective hemispheres. In the plasma sheet in Plate 10c the flow is mixed in direction, implying mesoscale turbulence. At the actual mapping point, the flow is sunward, but adjacent to that is antisunward flow. Vortices are seen which vary with time. We may infer that there is continuous $\partial B/\partial t$, which could account for the differences in potential on field lines between the two hemispheres. We may also infer that the mapping is good for any one instance; however, the mapping may be different a short interval later. Thus we have a means for resolving the above dilemma. The sash and its extension into the plasma sheet provide a constantly changing vortex structure that adjusts the potential differences between the two hemispheres as reconnection brings together open field lines of different potentials from opposite hemispheres which are moving in different directions. *Crooker et al.* [1998] called the process by which potentials near the merging site adjust "changing partners" and suggested that it was a diffusion region associated with reconnection. We suggest that this process extends into the plasma sheet, at least through the low field extension of the sash. In a study of ISEE data, *Borovsky et al.* [1997] determined that the plasma flow in the near-Earth plasma sheet was dominated by fluctuations of the same or greater order of magnitude. They inferred a mixing length scale size of $\sim$2 R_E for the turbulent flow. The turbulent mixing was suggested as a source of enhanced viscosity and randomization of magnetic field lines.

5.4. Plasma Entry

Plasma entry through the flanks has long been speculated [e.g., *Heppner et al.*, 1967]. The newer measurements with increased data rates and capabilities have been able to add new insight to this question. Geotail has observed cold ions in the low-latitude boundary layer on the flanks, which under some conditions extend well into the magnetosphere [e.g., *Fujimoto et al.*, 1998; *Savin et al.*, 1997]. Thus the flanks are a source of magnetosheath particle entry. *Savin et al.* [1999] suggested that the turbulent boundary layer near the cusp and its wings with its associated low magnetic field regions, or magnetic bubbles, as they described them, were locations of plasma entry into the magnetosphere. We have further associated these regions with the sash and reconnection, which provides a mechanism for plasma entry. The observations of He^{++} by Polar behind the terminator are tracers of plasma of magnetosheath origin. Following the same logic, this plasma must have entered through the low-field extension of the sash in the outer plasma sheet and traveled along the field lines to Polar. The right panel of Plate 6 shows that the density is larger in this low-field region. The changing flow patterns in Plate 10b suggest that the mesoscale turbulence may be involved in the entry process. We note also that similar proton and electron precipitation to that seen by Polar was seen by DMSP at the same UT, but 2 hours earlier in MLT, at the mapped feet of the Interball 1 and Magion 4 field lines. Since we infer that Interball penetrated the sash and Polar is seeing He^{++} from the extension of the sash into the edge of the plasma sheet, this suggests that the sash along the whole flank is a source region for entry of magnetosheath plasma during the reconnection process.

An additional curiosity is the existence of cold ions of magnetosheath-like energies observed simultaneously by Geotail in the southern boundary layer in the central part of the magnetotail. It is not clear whether these came from the near-Earth flank through a turbulent plasma sheet [e.g., *Borovsky et al.*, 1997] or from more distant flank access down the tail. The weak magnetic field and higher plasma density at the ends of the plasma sheet, where they merge with sash, indicate that magnetosheath plasma is present inside the nominal magnetopause and provides a possible way for plasma to become entrained in vortices and transported as those features evolve with time. In any case, we infer from these measurements that the flank is a significant source region for magnetosheath plasma entry and that those fluxes may reach areas large distances from the boundaries.

5.5. Boundary Layer Character

A point of discussion over the years has been whether the boundary layer consisted of open or closed field lines. For example, the model of *Lotko et al.* [1987] describes a boundary layer on closed field lines whose outer layer is viscously driven tailward. *Lyons et al.* [1996] suggest that the boundary layer is on open field lines. If the tailward flowing boundary layer is on open field lines, it would be driven by magnetic tension as the solar wind moves tailward [*Atkinson*, 1972]. ISM provides the MHD answer to the question for IMF B_Y positive. Initiating magnetic field line traces from plane B of Plate 10 between the Polar trace and the sash, one finds mostly closed field lines until getting very close to the sash. Thus the dusk boundary layer above the plasma sheet has a sunward flowing part on closed field lines and a thin antisunward flowing part on open field lines. There must be a sunward flowing portion of open field lines between the two to provide flux for the reconnection. In plane D the field lines near the boundary are mostly open. Below the dusk plasma sheet for IMF B_Y positive, the boundary layer is tailward flowing on open field lines, and the boundary layer is several R_E thick. Note that this thick boundary layer on open field lines must be driven by magnetic tension, since the open magnetic field lines are connected through the magnetosheath and shock and frozen into the faster solar wind flow. The thick open field line region effectively shields the closed field line region from any viscous forces from the magnetosheath flow, while performing the same function of initiating tailward boundary layer flow by magnetic tension.

While the conclusions from ISM below the plasma sheet can not be checked here, we can look at Interball 1 data relative to above the plasma sheet. Near 1540 UT while Interball 1 is on the magnetosphere side of the magnetopause, there is evidence of bidirectional or counterstreaming electrons. This is an indicator, but not conclusive proof, of closed field lines in relatively close proximity to a boundary crossing near 1545 UT (note the brief reversal of B_X at that time in Figure 2). This may be a closed field line that has resulted from the reconnection of two open field lines, or the counterstreaming may result from a reflection from an intermediate point along the field line. Several other examples of counterstreaming electrons exist over the several hour interval in which crossings are being observed. We suggest that this argues for a thin open boundary layer in this region where flux is approaching the sash to reconnect and that closed field lines must be produced by the reconnection. We note also that within the whole region of He^{++} fluxes observed by Polar, counterstreaming electrons were observed (Plate 3), agreeing with ISM that the mapped Polar field lines were closed.

6. Conclusions

This unique data set and model comparison has provided validation of the global structure of the ISM model, which in turn has allowed us to use the model to interpret the data to further understand boundary layers and magnetospheric processes. The following conclusions can be drawn from this study.

1. The magnetospheric "sash," a region of low magnetic field discovered in MHD modeling which extends along the high-latitude flank of the magnetopause, is related to the turbulent boundary layer on the high-latitude magnetopause recently discovered by Interball 1.

2. The sash in the model shows a clear X configuration, expected for a reconnection site. The rest frame of the observed reconnection was moving tailward along the boundary. The high-latitude magnetopause crossing data confirm the sash location and the minimum in B but are not able to conclusively prove reconnection at the time used for the mapping.

3. The potential patterns in the ISM model require at some point near or behind the terminator

that reconnection must be reconnecting open field lines which were previously opened by merging on the dayside. The mappings of magnetic field lines passing through the location of Polar to locations just inside the flank magnetopause in Plate 6 and to ionospheric equipotentials in Plate 1 indicate that ISM places that reconnection in or near the sash. These field lines pass to the dawnside of the dusk potential minimum, and the DMSP data in Plate 2 support that the field lines toward dawn from the potential minimum were open in the polar cap. The model thus implies that a significant fraction of the reconnection in the magnetotail occurs on or near the flanks, as concluded by *Crooker et al.* [1998].

4. Polar mapped to the high-density extension of the sash into the tilted plasma sheet. The Polar magnetic field line footprints in each hemisphere are moving in different directions. Above and below the tilted plasma sheet the flows in the model are consistent with the corresponding flows in the ionosphere; however, there is a potential difference across the plasma sheet. The structure in the plasma sheet is time dependent. We suggest that induction electric fields from the constantly changing structure of the outer plasma sheet may account for the potential differences and allow the convection patterns from each hemisphere to adjust.

5. Magnetosheath-like plasma was observed at Polar on closed field lines behind the terminator as evidenced by the He^{++}. The ISM model comparison implies that the source of the magnetosheath plasma observed by Polar was plasma entry through the low field connection of the sash to the plasma sheet.

6. Cold plasma also reached Geotail in the plasma sheet boundary layer in the central magnetotail.

7. The boundary layer in the equatorial plane on the flank for this IMF B_Y condition, which is below the tilted central plasma sheet, is several R_E thick and is on tailward flowing open field lines. This thick boundary layer shields the magnetopause from viscous forces and must be driven by magnetic tension. Above the plasma sheet the boundary layer is dominated by the sash, and the model indicates that the open region inside the sash is considerably thinner.

Acknowledgments. This work is a study of an Inter-Agency Consultative Group (IACG) Campaign 2 event. We acknowledge support from the National Aeronautics and Space Administration, the Defense Threat Reduction Agency, and the Air Force Office of Scientific Research in the United States, the Institute of Space and Astronautical Science of Japan, the Russian Space Agency, and the European Space Agency. We thank A. Federov for making the CORALL data available and for help in the Interball 1 data processing at the DD-System facilities, F. S. Mozer and C. T. Russell for the Polar electric and magnetic field data, the Geotail MFI and LEP teams for the Geotail magnetic field and plasma moments, R. Lepping and K. Ogilvie for the Wind magnetic field and plasma data, and W. J. Burke for the DMSP F13 data. We are grateful to E. Budnick and S. Romanov for helpful discussions and D. Ober for help with the data presentation. Work at Lockheed was supported by NASA contract NAS5-30303, and W.K.P. thanks D. Baker and the staff at LASP for their hospitality. Work at the University of Iowa was supported under NASA grants NAG5-2231, NAG5-8119, and NAG5-7883. Work at MRC was partially supported through the University of California at Berkeley under NASA grant NAG5-7721. S.S. was supported through grants INTAS 96-2346 and RFFR 98-02-17402.

Janet G. Luhmann thanks Zerefsan Kaymaz and another referee for their assistance in evaluating this paper.

References

Atkinson, G., Magnetospheric flows and substorms, in *Magnetospheric-Ionospheric Interactions*, edited by K. Folkestad, p. 203, Universitetsforlaget, Oslo, 1972.

Borovsky, J. E., R. C. Elphic, H. O. Funsten, and M. F. Thomsen, The Earth's plasma sheet as a laboratory for flow turbulence in high β MHD, *J. Plasma Phys., 57*, 1, 1997.

Burke, W. J., E. M. Basinska, N. C. Maynard, W. B. Hanson, J. A. Slavin, and J. D. Winningham, Polar cap potentials during periods of positive B_Y and northward IMF, *J. Atmos. Terr. Phys., 56*, 209, 1994.

Cowley, S. W. H., A qualitative study of the reconnection between the Earth's magnetic field and an interplanetary field of arbitrary orientation, *Radio Sci., 8*, 903, 1973.

Crooker, N. U., Dayside merging and cusp geometry, *J. Geophys. Res., 84*, 951, 1979.

Crooker, N. U., Reverse convection, *J. Geophys. Res., 97*, 19,363, 1992.

Crooker, N. U., J. G. Lyon, and J. A. Fedder, MHD model merging with IMF B_Y: Lobe cells, sunward polar cap convection, and overdraped lobes, *J. Geophys. Res., 103*, 9143, 1998.

Fujimoto, M., T. Terasawa, and T. Mukai, The low-latitude boundary layer in the tail flanks, in *New Perspectives on the Earth's Magnetotail, Geophys. Monogr. Ser.* vol. 105, edited by A. Nishida, D. N. Baker, and S. W. H. Cowley, p. 33, AGU, Washington, D. C., 1998.

Haerendel, G., Microscopic plasma processes related to reconnection, *J. Atmos. Terr. Phys., 40*, 343, 1978.

Hardy, D. A., K. L. Schmidt, M. S. Gussenhoven, F. J. Marshall, H. C. Yeh, T. L. Shumaker, A. Huber, and J. Pantazis, Precipitating electron and ion detectors (SSJ/4) for the block 5D flights 4-10 DMSP satellites: Calibration and data presentation, *Tech. Rep. AFGL-TR-84-0317*, Air Force Geophys. Lab., Hanscom Air Force Base, Mass., 1984.

Harvey, P., et al., The electric field instrument on Polar, *Space Sci. Rev., 71*, 583, 1995.

Heppner, J. P., and N. C. Maynard, Empirical high-latitude electric field models, *J. Geophys. Res., 92*, 4467, 1987.

Heppner, J. P., M. Sugiura, T. L. Skillman, B. G. Ledley, and M. Campbell, OGO-A magnetic field observations, *J. Geophys. Res.,72*, 5417, 1967.

Hesse, M., and K. Schindler, A theoretical foundation of general magnetic reconnection, *J. Geophys. Res., 93*, 5559, 1988.

Kawano, H., and T. Higuchi, The bootstrap method in space physics: Error estimation for minimum variance analysis, *Geophys. Res. Lett., 22*, 307, 1995.

Kaymaz, Z., and G. Siscoe, The geometry of the open tail cross section, *J. Geophys. Res., 103*, 14,829, 1998.

Kaymaz, Z., G. Siscoe, J. G. Luhmann, J. A. Fedder, and J. G. Lyon, Interplanetary magnetic field control of magnetotail field: IMP 8 data and MHD model compared, *J. Geophys. Res., 100*, 17,163, 1995.

Khrabrov, A. V., and B. U. Ö. Sonnerup, Error estimates for minimum variance analysis, *J. Geophys. Res., 103*, 6641, 1998.

Klimov, S., et al., ASPI experiment: Measurements of fields and waves onboard Interball-1 spacecraft, *Ann. Geophys., 15*, 514, 1997.

Kokubun, S., T. Yamamoto, M. H. Acuńa, K. Hayashi, K. Shiokawa, and H. Kawano, The Geotail magnetic field experiment, *J. Geomagn. Geoelectr., 46*, 7, 1994.

La Belle-Hamer, A. L., A. Otto, and L. C. Lee, Magnetic reconnection in the presence of sheared flow and density asymmetry: Applications to the Earth's magnetopause, *J. Geophys. Res., 100*, 11,875, 1995.

Lepping, R. P., et al., The Wind magnetic field investigation, *Space Sci. Rev., 71*, 207, 1995.

Lotko, W., B. U. Ö. Sonnerup, and R. L. Lysak, Nonsteady boundary layer flow including ionospheric drag and parallel electric fields, *J. Geophys. Res., 92*, 8635, 1987.

Luhmann, J. G., R. J. Walker, C. T. Russell, N. U. Crooker, J. R. Spreiter, and S. Stahara, Patterns of potential magnetic field merging sites on the dayside magnetopause, *J. Geophys. Res., 89*, 1739, 1984.

Lyons, L. R., G. Lu, O. de la Beaujardière, and F. J. Rich, Synoptic maps of polar caps for stable interplanetary magnetic field intervals during January 1992 geospace environment modeling campaign, *J. Geophys. Res., 101*, 27,283, 1996.

Mukai, T., S. Machida, Y. Saito, M. Hirahara, T. Terasawa, N. Kaya, T. Obara, M. Ejiri, and A. Nishida, The low energy particle (LEP) instrument onboard the Geotail satellite, *J. Geomagn. Geoelectr., 46*, 669, 1994.

Němeček, Z., A. Fedorov, J. Šafránková, and G. Zastenker, Structure of the low-latitude magnetopause: Magion-4 observation, *Ann. Geophys., 15*, 553, 1997.

Nishikawa, K., Particle entry through reconnection grooves in the magnetopause with a dawnward IMF as simulated by a three-dimensional particle code, *Geophys. Res. Lett., 25*, 1609, 1998.

Ogilvie, K. W., et al., SWE, A comprehensive plasma instrument for the Wind spacecraft, *Space Sci. Rev., 71*, 55, 1995.

Rich, F. J., and M. Hairston, Large-scale convection patterns observed by DMSP, *J. Geophys. Res., 99*, 3827, 1994.

Russell, C. T., R. C. Snare. J. D. Means, D. Pierce, D. Dearborn, M. Larson, G. Barr, and G. Le, The GGS/Polar magnetic fields investigation, *Space Sci. Rev., 71*, 563, 1995.

Šafránková, J., G. Zastenker, Z. Němeček, A. Fedorov, M Simersky, and L. Přech, Small scale observation of the magnetopause motion: Preliminary results of the Interball project, *Ann. Geophys., 15*, 562, 1997.

Šafránková, J., Z. Němeček, D. G. Sibeck, L. Přech, J.

Měrka, and O. Santolík, Two point observation of high-latitude reconnection, *Geophys. Res. Lett., 25*, 4301, 1998.
Savin, S., et al., Interball magnetotail boundary case studies, *Adv. Space Res., 19*, 993, 1997.
Savin, S. P., et al., Interball-Tail probe measurements in the outer cusp and boundary layers, in *Geospace Mass and Energy Flow, Geophys. Monogr. Ser.*, vol. 104, edited by J. L. Horwitz, D. L. Gallagher, and W. K. Peterson, p. 25, AGU, Washington, D. C., 1998a.
Savin, S. P., S. A. Romanov, A. O. Federov, L. Zelenyi, S. I. Klimov, Y. I. Yermolaev, E. Y. Budnik, N. S. Nikolaeva, C. T. Russell, X.-W. Zhou, A. L. Urquhart, and P. H. Reiff, The cusp/magnetosheath interface on May 29, 1996: Interball-1 and Polar observations, *Geophys. Res. Lett., 25*, 2963, 1998b.
Savin, S., E. Budnik, M. Nozdrachev, V. Romanov, Y. Yermolaev, L. Zelenyi, J. Blecki, J. Buechner, and B. Nikutowski, On the plasma turbulence and transport at the polar cusp outer border, *Czech. J. Phys., 49*, 679, 1999.
Scudder, J. D., et al., HYDRA, A 3-dimensional electron and ion hot plasma instrument for the Polar spacecraft of the GGS mission, *Space Sci. Rev., 71*, 459, 1995.
Shelley, E. G., et al., The toroidal imaging mass-angle spectrograph (TIMAS) for the Polar mission, *Space Sci. Rev., 71*, 497, 1995.
White, W. W., G. L. Siscoe, G. M. Erickson, Z. Kaymaz, N. C. Maynard, K. D. Siebert, B. U. Ö. Sonnerup, and D. R. Weimer, The magnetospheric sash and cross-tail S, *Geophys. Res. Lett., 25*, 1605, 1998.
Yermolaev, Y. I., A. O. Federov, O. L. Vaisberg, V. M. Balenamov, Y. A. Obed, R. Jiminez, J. Fleites, L. Llera, and A. N. Omelchenko, Ion distribution dynamics near the Earth's bow shock: First measurements with the two-dimensional ion energy spectrometer CORALL on the Interball-Tail-probe satellite, *Ann. Geophys., 15*, 533, 1997.

G. M. Erickson and G. L. Siscoe, Center for Space Physics, Boston University, 725 Commonwealth Avenue, Boston, MA 02543.

H. Kawano, Department of Earth and Planetary Sciences, Kyushu University, 6-10-1 Hakozake Higashi-ku, Fukuoka, 812-81, Japan.

N. C. Maynard, D. R. Weimer, W. W. White, and G. R. Wilson, Mission Research Corporation, One Tara Boulevard, Suite 302, Nashua, NH 03062. (nmaynard@mrcnh.com; dweimer@mrcnh.com; bwhite@mrcnh.com; gwilson@mrcnh.com)

Z. Němeček and J. Šafránoková, Department of Electronics and Vacuum Physics, Charles University, V Holešovičkách 2, 180 00 Praha 8, Czech Republic.

W. K. Peterson, Lockheed Martin Palo Alto Research Laboratory, 701 Birch Street, Denver, CO 80220.

I. Sandahl, Swedish Institute of Space Physics, P. O. Box 812, S-981 Kiruna, Sweden.

S. P. Savin, Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, GSP-7, Moscow, 117810, Russia.

J. D. Scudder, Department of Space Physics and Astronomy, University of Iowa, Iowa City, IA 52240. (jds@space-theory.physics.uiowa.edu)

B. U. Ö. Sonnerup, Thayer School of Engineering, Dartmouth College, Hanover, NH 03755. (sonnerup@dartmouth.edu)

Received March 10, 2000; revised July 12, 2000; accepted August 2, 2000.

[1]Mission Research Corporation, Nashua, New Hampshire.
[2]Space Research Institute, Russian Academy of Sciences, Moscow.
[3]Center for Space Physics, Boston University, Boston, Massachusetts.
[4]Department of Earth and Planetary Sciences, Kyushu University, Kyushu.
[5]Department of Electronics and Vacuum Physics, Charles University, Prague.
[6]Lockheed Martin Palo Alto Research Laboratory, Palo Alto, California.
[7]Swedish Institute of Space Physics, Kiruna.
[8]Department of Physics and Astronomy, University of Iowa, Iowa City.
[9]Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire.

This preprint was prepared with AGU's LaTeX macros v5.01. File sashconrv2Jpp formatted January 12, 2001.

Figure 1. The Y and Z components of the interplanetary magnetic field (IMF) and the dynamic pressure plotted for the interval from 1300 to 1700 UT on January 12, 1997.

Figure 2. (a-i) Interball 1 data showing velocity, density, temperature, magnetic field and ion energy spectra from 1500 to 1900 UT on January 12, 1997. Reversals in B_X (Figure 2g) from positive to negative are indicative of magnetopause transitions from the magnetosphere to the magnetosheath. The X component of the ion velocity (Figure 2b) is tailward, or near zero, throughout the interval.

Figure 3. High-resolution Interball 1 magnetometer data and ion spectra for the intervals (top) 1552:30-1556:30 UT and (bottom) 1602:30-1606:30 UT. Because of spin and changing magnetic field, the pitch angles for the ion spectra are constantly changing. Note also the low magnetic field values near the reversals of B_X. The principal ion fluxes are tailward flowing as evidenced by pitch angles greater (less) than 90° combined with B_X positive (negative).

Figure 4. Hodogram of the Interball 1 magnetic field data for the magnetopause crossing between 1558 and 1600 UT. The arrows indicate direction along trace for advancing time.

Figure 5. Geotail magnetometer and plasma data for the interval from 1400 to 1700 UT. B_X, B_Y, B_Z, and B are shown in the top four traces. V_X, V_Y, V_Z, and V are shown in the next four traces. Density, temperature, and pressure are shown in the bottom three traces. General locations of where the densities and temperatures correspond to the lobe and the plasma sheet boundary layer (PSBL) are noted.

Plate 1. Overview of Integrated Space Weather Model (ISM) model results. (a) Depiction in three dimensions of the mappings of magnetic field lines from each of the satellites. The yellow and red lines are open and interplanetary field lines passing through Interball 1 and Magion 4 locations. The blue lines are closed field lines passing through the Polar and Geotail locations. (b) Depiction of the last closed field line surface painted with the magnitude of the magnetic field. The green low-magnitude region extending from the cusp back across the high-latitude dusk flank is the sash. The Interball 1 and Magion 4 field line traces are seen just above the surface. (c,d) Depictions of the ISM convection patterns for the Northern and Southern Hemispheres. The footprints of those field lines reaching the ionosphere are seen with blue designating closed field lines and green designating open field lines.

Plate 2. (a-f) DMSP F13 data between 1552 and 1600 UT. Plates 2a and 2b show the total number flux and average energy of the electrons. Plates 2c and 2d show the energy spectrograms of the electron and ion fluxes, respectively. Plates 2e and 2f show the cross-track drift and the integrated potential along the track.

Plate 3. Electric field and energetic electron data from the Polar spacecraft from 1500 to 1700 UT. The top two panels show the integrated potential and the component of the electric field along the spacecraft track. The four energy flux versus time spectrograms from the HYDRA instrument depict the flux antiparallel to B, the flux parallel to B, the anisotropy ratio of the parallel to perpendicular fluxes, and the total energy flux.

Plate 4. Ion energy spectra and pitch angles differentiated by mass (H^+, O^+, He^+, and He^{++}) from the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) instrument on the Polar spacecraft for the interval from 1500 to 1700 UT. The units in these plots are number fluxes.

Plate 5. (a-f) Magion 4 magnetic field and particle data for the interval 1430-1630 UT. Plate 5a records the total current into ion traps looking toward (flowing away from) the Sun, while the Plate 5d shows the energy spectra. Plate 5b shows B_X, while Plate 5c registers the intensity of the magnetic field. Plate 5e and 5f record the bulk and thermal speeds computed from the ion data. Note the very low magnetic field values at the polarity reversals in B_X (transitions between the magnetosphere and the magnetosheath), especially just before 1600 UT, when Interball 1 was also observing crossings of the magnetopause. The most intense fluxes are observed moving antisunward in the regions of low magnetic field strength.

Plate 6. ISM results at X = -10.2 R_E. The left panel shows the magnetic field magnitude and the traced magnetic field lines from the satellite locations that are in front of the plane. Note that the second Polar trace just cuts this plane in the center of the low field extension of the sash. The right panel depicts ion mass density in the same panel with the traced field lines. Note that the density fills in the low field region at the edge of the plasma sheet. In both panels the turning point for the Interball 1 and Magion 4 traces is well in front of this plane.

Plate 7. ISM results at X = -5.5 R_E. The left panel is a 3-D view of the magnitude of B_X in the plane with the traced field lines. The turning point of the red Interball 1 magnetic field trace is just in front of this plane at the point where B_X reverses polarity, or at the magnetopause. The right panel shows the 2-D view of this plane colored with the magnitude of the magnetic field and overlaid with magnetic field vectors as well as the projection of the traces. Note that the red trace turns in the center of the sash.

Plate 8. ISM results for the magnetotail. The left panel shows the plane at X = -30 R_E painted with the magnitude of the magnetic field. Geotail maps to the southern edge of the low magnetic field region of the central plasma sheet. The right panel shows the plane at X = -25.5 R_E, which is the location where the third Polar field trace cut into the low field extension of the sash.

Plate 9. ISM results from an arbitrary plane defined as perpendicular to a line through the long axis of the sash, and the point where the field line passing through the Interball 1 location turned abruptly out into the magnetosheath and solar wind at X = -5.5 R_E. This plane cuts through the reconnection site at the center of the sash. The top (bottom) panel shows velocity (magnetic field) vectors overlaid on contours of the magnitude of the magnetic field.

Plate 10. (a) The edges of three parallel planes passing above, through and below the plasma sheet connection to the sash at $X = -10.2 R_E$ where the second mapped Polar magnetic field line intersected the plasma sheet. (b-d) The ion velocity vectors overlaid on the magnetic field intensity in each of these planes.

Table 1. Satellite Locations on January 12, 1997, Instruments, and Measurement Parameters

Satellite	*UT*	$X_{GSM}(R_E)$	$Y_{GSM}(R_E)$	$Z_{GSM}(R_E)$	*Instruments/Parameters*
Wind					
	15:00	105.4	-53.4	10.2	MFI,[a] SWE[b]
					IMF B and dynamic pressure
Polar					
1	15:24	-1.75	3.94	3.51	EFI,[c] HYDRA,[d] TIMAS,[e] MFI[f]
2	15:33	-1.87	3.88	3.78	
3	15:42	-1.98	3.82	4.05	E, B, electron energy flux,
4	15:51	-2.08	3.74	4.31	ion mass-differentiated spectra
Geotail					
1	15:24	-30.17	2.24	-3.00	MFE,[g] LEP[h]
2	15:36	-30.19	2.16	-2.99	B, ion velocity, density, temperature
3	15:48	-30.21	2.09	-2.98	and pressure
Interball-1					
1	15:24	-10.05	13.84	13.80	ASPI,[i] CORALL[j]
2	15:33	-10.12	13.83	13.89	
3	15:42	-10.19	13.82	13.98	B, ion energy and velocity
4	15:51	-10.27	13.80	14.07	
Magion-4					
1	15:24	-9.19	13.79	12.92	SGR-8,[k] VDP-S[l]
2	15:33	-9.28	13.81	13.00	
3	15:42	-9.37	13.83	13.08	B, ion energy and velocity
4	15:51	-9.45	13.84	13.16	
DMSP-F13		(Ionosphere)			
	15:52	830 km	17.2 MLT	65.4° MLAT	SSJ/4,[m] SSIES[n]
	15:57	830 km	17.2 MLT	82.8° MLAT	ion and electron fluxes, ion drift

[a] *Lepping et al.* [1995]

[b] *Ogilvie et al.* [1995]

[c] *Harvey et al.* [1995]

[d] *Scudder et al.* [1995]

[e] *Shelley et al.* [1995]

[f] *Russell et al.* [1995]

[g] *Kokubun et al.* [1994]

[h] *Mukai et al.* [1994]

[i] *Klimov et al.* [1997]

[j] *Yermolaev et al.* [1997]

[k] *Němeček et al.* [1997]

[l] *Šafránková et al.* [1997]

[m] *Hardy et al.* [1984]

[n] *Rich and Hairston* [1994]