Polar, Cluster and SuperDARN evidence for high-latitude merging during southward IMF: temporal/spatial evolution

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Abstract. Magnetic merging on the dayside magnetopause often occurs at high latitudes. Polar measured fluxes of accelerated ions and wave Poynting vectors while skimming the subsolar magnetopause. The measurements indicate that their source was located to the north of the spacecraft, well removed from expected component merging sites. This represents the first use of wave Poynting flux as a merging discriminator at the magnetopause. We argue that wave Poynting vectors, like accelerated particle fluxes and the Walén tests, are necessary, but not sufficient, conditions for identifying merging events. The Polar data are complemented with nearly simultaneous measurements from Cluster in the northern cusp, with correlated observations from the SuperDARN radar, to show that the locations and rates of merging vary. Magnetohydrodynamic (MHD) simulations are used to place the measurements into a global context. The MHD simulations confirm the existence of a high-latitude merging site and suggest that Polar and SuperDARN observed effects are attributable to both exhaust regions of a temporally varying X-line. A survey of 13 merging events places the location at high latitudes whenever the interplanetary magnetic field (IMF) clock angle is less than 30°. While inferred high-latitude merging sites favor the antiparallel merging hypothesis, our data alone cannot exclude the possible existence of a guide field. Merging can even move away from equatorial latitudes when the IMF has a strong southward component. MHD simulations suggest that this happens when the dipole tilt angle increases or when IMF Bx increases the effective dipole tilt.

Key words. Magnetospheric physics (magnetopause, cusp and boundary layers; magnetospheric configuration and dynamics; solar wind-magnetosphere interactions)

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1 Introduction

It is generally accepted that merging between the interplanetary magnetic field (IMF) and the Earth’s magnetic field (Dungey, 1961) is the principal coupling mechanism for solar wind plasma entry to the magnetosphere. The nature, location, and temporal dependence of merging remain open questions. The purpose of this paper is to provide evidence that merging often proceeds away from the equator. Accelerated flows of magnetosheath plasma observed near the subsolar magnetopause (near the Earth-Sun line) provide in situ evidence of the merging process (Paschmann et al., 1979; Sonnerup et al., 1981). Minimum variance analyses of magnetic field measurements were employed to show that the magnetopause acted as a rotational discontinuity with a finite Bvstell, proportional to the merging rate. However, establishing an unambiguous finite Bvstell can be difficult. Jump conditions across the discontinuity satisfy the Walén relationship, indicating that the change in the ion velocity is proportional to the change in the magnetic field. Observations of accelerated flows, often identified by “D-shaped” distributions in velocity space (Cowley, 1982), have been regarded as standard signatures of merging (e.g. Gosling et al., 1982; Paschmann et al., 1986; Sonnerup et al., 1990).

X-type merging configurations with oppositely directed field lines (Levy et al., 1964) were generalized by Sonnerup (1974) to include merging between the antiparallel components of B, along a line that hinges about the subsolar point (Gonzales and Mozer, 1974). Crooker (1979) offered an alternative hypothesis in which merging occurs wherever magnetosheath and magnetosheath field lines are aligned antiparallel to each other. For most IMF orientations the antiparallel location is at high latitudes on the magnetopause. By high (low) latitudes, we mean in the general vicinity of the cusp (equator). Both hypotheses locate merging at the poleward...
boundary of the dayside cusp during periods of partly northward IMF. Merger has been definitively identified there by Scudder et al. (2002a).

One difficulty in locating the merging line relates to a lack of accelerated particles observed during magnetopause crossings. In fact, decelerated flows are encountered in the boundary layer (Eastman et al., 1976). Aggson et al. (1983) transformed electric fields measured by ISEE 1 at the magnetopause into a de Hoffman-Teller (H-T) reference frame (de Hoffman and Teller, 1950). Data measured by Polar were subjected to a Galilean transformation to a reference frame moving with a velocity \( V_{GS} \). In this reference frame the electric field component perpendicular to the magnetic field transforms to zero. H-T reference frames exist for rotational but not for most tangential discontinuities. The transformation will not remove the electric field internal in the layer in a tangential discontinuity (e.g. Lee and Kas, 1976). Thus, the identification of a H-T frame for ordering satellite measurements that holds internally in the current layer implies the traversal of a rotational discontinuity. In the H-T frame the plasma velocity is directed along the magnetic field and is equal to the local Alfven speed.

While increased velocities were observed during some ISEE 1 magnetopause crossings, Aggson et al. (1984) also reported decelerated flows. Moreover, they emanated from a merging zone poleward of the satellite. Scudder (1986) calculated that, as the merging site moved off the equator, the enhanced velocity from the X-line should equal the sum from the merging acceleration and the local magnetosheath velocity at the merging site. Hence, the outflow velocity in inertial space may be significantly less than the Alfvén speed. In a recent analysis of 69 magnetopause crossings, Phan et al. (1996) found that, of the 42 that "satisfied" the Walén test, 21 had velocity changes that produced normalized slopes on the average of 0.6, which is less than unity predicted from a single component merging X-line. They concluded that (1) merging sometimes occurs at latitudes higher than the satellite and (2) earlier studies that restricted merging sites to only equatorial latitudes were biased to include only those events with significant acceleration (e.g. Scourby et al., 1994). Scudder et al. (1999) showed that the Walén test was better performed with electrons whenever currents were present. Under these conditions, the normalized slopes for the ion Walén test detected during the same crossings were often significantly less than +1, which does not match expectations. They showed that during many of these non-conforming crossings, the normalized slopes of the electrons were consistently near +1, as needed for a conclusive rotational discontinuity test.

In a recent study Maynard et al. (2001b) correlated rocket measurements of electric fields near the Northern Hemisphere cusp with geoeffective interplanetary electric fields (IEF) measured upstream in the solar wind by the Wind satellite. They found that observed lag times were significantly less than those predicted for simple advection. The IEF was dominated by \( B_y \) and the clock angle in the \( Y-Z \) plane was near 90°. The short lag time and the dominant \( B_y \) forced consideration of tilted phase planes of the IEF and placed the location of merging at high latitudes in the Southern Hemisphere. Whether merging followed the antisolar hypothesis of Crooker (1979) or whether a small guide field was present could not be ascertained with the available data. Either way, a portion of the cusp in the Northern Hemisphere was responding to a merging source in the Southern Hemisphere. Within the same all-sky picture of the dayside cusp taken at Ny-Alesund, responses to high-latitude merging in the Northern Hemisphere were also identified. Because of IMF \( B_y \), the cusp was bifurcated into source regions originating from high-latitude merging in the Northern and Southern Hemispheres, while IMF \( B_y \) controlled the timing of the interactions in each hemisphere. Merging rates responded to small-scale variations of the IMF, as evidenced by electric fields observed at the rocket and by 557.7 nm emissions captured in the all-sky images. Because of the strong \( B_y \), the lag time was 14 min longer for the Northern Hemisphere merging site compared to the Southern Hemisphere site. The bifurcation of the cusp with \( B_y \) and the need for antiparallel reconnection under those conditions was also deduced by Coleman et al. (2001).

Weimer et al. (2002) utilized data from four satellites in the solar wind to show that lag times varied continuously and to construct the phase plane in an over-determined way. They demonstrated that the orientations of IEF phase planes change significantly on time scales of tens of minutes, and that the small-scale variations often remained coherent while propagating over 200 \( R_E \) in the solar wind. Both factors were used by Maynard et al. (2001b) to rewrite the interpretation described above. Variable lag times from the shifting orientation of the phase plane of the IEF must be considered in any assessment of IMF influences on merging processes. Lag times do not, in general, remain constant.

Projections of the dayside cusp onto the atmosphere may be quite wide (Maynard et al., 1997). Place 1 of Maynard et al. (2001b) indicates that signatures of high-latitude merging in the local hemisphere may be significantly displaced from noon when IMF \( B_y \) is large. Anomalous plasma velocity enhancements may be expected from the merging and subsequent \( J \times V \) acceleration.

Cowley (1982) documented the ion-signatures expected in the vicinity of rotational discontinuities that attend X-type merging lines. Near the outer separatrix, transmitted or accelerated magnetospheric ions may be found, along with accelerated and incident magnetosheath ions. Near the inner separatrix, the incident or cold distribution of magnetospheric origin, while accelerated distributions from magneto- sheath sources may also be observed. Distribution-function isocontours in v1-v2 plane exhibit "D" shapes when acceleration has occurred. Finding a "D" shaped isocontour displaced from the origin has been cited by Fuselier et al. (1991) as "strong evidence" that reconnection has occurred. Bauer et al. (2001) reported many magnetopause crossings that "satisfied" Walén tests using ion velocities but lacked clear "D"-shaped distributions. They attributed the missing "D" to pattern blurring by mirroring particles. By itself, a "D" shaped distribution is a necessary but not a
sufficient signature of merging, since ambipolar parallel electric fields associated with electron pressure gradients can accelerate ions without merging (Scudder et al., 2002b).

A second signature of merging may be identified from wave Poynting fluxes (ΔE X ΔB)/μ₀, where ΔE and ΔB are the fluctuations as described below. When merging occurs, Alfvén waves are bunched to communicate information to magnetically connected regions (Atkinson, 1992). The associated wave Poynting vector is directed away from the source since it represents escaping electromagnetic energy. This electromagnetic energy flux should be strongest near the separatrices. Again, this is a necessary but not sufficient condition for identifying merging events, since other mechanisms can generate Alfvén waves that carry parallel Poynting flux.

Geotail was the first satellite to skin along the magnetopause, while moving parallel to the equatorial plane. During multiple crossings, Nakamura et al. (1998) observed increased speeds accompanied by ion heating and inferred them to have come from distant merging sites. More recently, Kim et al. (2002) observed accelerated flows at the magnetopause near the subsolar equator. They interpreted changes in direction as evidence for component merging, with the separator moving north and south relative to the spacecraft. Ho et al. (2000) used Geotail and Equator S measurements on the dawn flank of the magnetopause to provide nearly simultaneous observations of bi-directional flows from an X-line between the spacecraft in the equatorial region. This was for a nearby satellite and looked toward the horizon.

In the 2000–2002 period, the 9 Beş apogee for the Polar satellite orbit has been close to the equator. On many days it spent long periods skimming along the magnetopause from south to north, roughly at quadrature to the Geotail orbital plane. Often the satellite either traversed the magnetopause very slowly, or failed to cross it completely. Thus, temporal variations may be clearly identified, but spatial scales are not as easily determined. If current layers are crossed slowly and merging occurs at high latitudes, one should not assume that observations of a single separatrix near the equatorial plane will be followed by an observation of an outer separatrix. With the merging line located far from the spacecraft, it is probable that only one separatrix will be observed. Merging may vary both temporally and spatially, occurring simultaneously at multiple sites. High-latitude merging is expected to be more temporally variable, since an X-line will not be intrinsically stable when the tangential magnetospheric flow is super-Alfvénic (Cowley and Owen, 1989; Rodger et al., 2001).

Evidence that merging proceeds away from the equator plane at high latitudes is seen in a number of the Polar skimming passes. In the following sections, we present time-varying observations from Polar, Cluster and SuperDARN and acquired on 12 March 2002 to establish the temporal and spatial variability of the merging process. Using other events and comparisons to simulation results, we extend these observations to show that high-latitude merging is more common than generally thought when the clock angle is less than 130° and may occur at even greater clock angles.

2 Measurements

Several Polar instruments contribute to this study. The Hydra Duo Deca Ion Electron Spectrometer (DDIES) (Scudder et al., 1999) consists of six pairs of electrostatic analyzers looking in different directions to acquire high-resolution energy spectra and pitch-angle information. Full three-dimensional distributions of electrons between 1 eV and 10 keV and ion fluxes with an energy per charge ratio of 10 eV q⁻¹ to 10 keV q⁻¹ were sampled every 13.8 s. The electric field instrument (EF) (Harvey et al., 1995) uses a biased double probe technique to measure vector electric fields from potential differences between 3 orthogonal pairs of spherical sensors. In this paper we present measurements from the long wire anemones at the satellite’s spine plane. The Magnetic Field Experiment (MFE) (Russell et al., 1995) consists of two orthogonal tri-axial fluxgate magnetometers mounted on nonconducting booms. Electric and magnetic fields were sampled at a rate of 16 s⁻¹. Most of the presented data were spin averaged using least-squares fitting to sine waves.

The Advanced Composition Explorer (ACE) spacecraft is located in a halo orbit around L₁ in front of the Earth to monitor interplanetary conditions. The solar wind velocity was measured by the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (McComas et al., 1998). A tri-axial fluxgate magnetometer measured the vector interplanetary magnetic field (Smith et al., 1998). We also use data from the Magnetic Field Investigation (Lepping et al., 1995) and the Solar Wind Experiment (Ogilvie et al., 1995) on wind for cross-checks. Wind was executing a distant prograde orbit; hence, it generally had large Y coordinates in this interval.

On one of the studied days the 4 Cluster spacecraft passed through the cusp while Polar was skimming the magnetopause. Magnetic field measurements were made on each of the Cluster spacecraft by tri-axial fluxgate magnetometers (Balogh et al., 2001).

In addition to the measurements of the vector magnetic field, the configuration of the 4 Cluster spacecraft allowed estimates of V × B to determine local current flows. The nominal separation distances between the spacecraft at this time was ~600 km. The electric field and wave instrument (EFW) monitored both electric field components in the ecliptic plane using biased double probes (Gustafsson et al., 1997). The Cluster Ion Spectrometer (CIS) experiment provided 3-D ion distributions with mass per unit charge composition using the Composition and Distribution Function (CODEF) analyzer (Rème et al., 1997). Ion measurements are available only from spacecraft 1, 3, and 4.

In addition to the satellite measurements, the Super- DARN coherent backscatter radar network provided information about ion convection in the high-latitude ionosphere over a wide range of local times (Greenwald et al., 1995). Single-component ion measurements from each of the radar
3 Analysis methods

Our analysis concerns large-scale aspects of coupling between the IMF and the magnetosphere-ionosphere system, from global- to meso-scale perspectives, where electron gyrometry applies and merging actually occurs (Scudder et al., 2002a). We do not consider the microphysics of the merging process. Addressing problems with simultaneous observations from diverse locations properly constrains our interpretations. Analyzing Polar skimming passes presents challenges and advantages. Since the magnetopause expands and contracts with changing solar wind conditions, multiple crossings often occur. Polar sometimes remains in the vicinity of the magnetopause for hours. While this reduces our present knowledge about spatial structuring, it allows us to follow temporal responses to changes in the IMF and solar wind dynamic pressure and thereby establish close correlations with external drivers. We correlate observed behaviors with temporal variations in other regions, such as in the ionosphere as measured by SuperDARN, or in the water crest as measured by Cluster.

Interpretations of satellite measurements were tested for reasonableness through comparisons with predictions of simulations using the Integrated Space Weather Model (ISW). ISW is a large-scale magneto-hydrodynamic (MHD) code developed by Mission Research Corporation to simulate the magnetosphere-ionosphere system from its front boundary...
Fig. 2. Traced magnetic field lines from a MHD simulation using the Integrated Space Weather Model (ISM). Figure 2a shows a set of field lines flowing away from a high-latitude merging site. Trace 0 is closed, and its origin in the Northern Hemisphere is shown in Fig. 2b in the transition 13° and 55° MLT and 7° latitude. All others are open. Figures 2c–f show views of these same field lines colored with the Y component of the velocity. Figure 2g shows the complete set of field lines traced from the innermost field line in each hemisphere and also colored with Y (see text).

49.0, upstream in the solar wind, to the base of the ionosphere over the Earth, and up to the magnetopause (White et al., 2011). Lacking the microphysics and resolution needed to accurately portray merging, ISM accomplishes the process through reconnection, either explicitly introduced by current-dependent resistivity, or introduced by the code through the parallel drift method (PDM) of Hah (1997), to maintain stability in the presence of steep gradients (see White et al., 2003) for more details. Through simulations of steady-state conditions or of responses to step-function driver variations, cause and effect relationships are easily isolated. This approach was used successfully by Maynard et al. (2001a, 2003a), to establish the link (originally identified in the simulations by White et al., 1998) as a reconnective site, and to provide an explanation for short-lived, spatially aligned arcs emanating from the high-latitude open-closed boundary of the high-latitude oval. The combination between data analysis and the simulations provides a powerful tool for understanding the complex interactions of the solar wind with the magnetosphere-ionosphere system.

Solar often fails to traverse the magnetopause current layer completely. Hence, we use two markers to identify occurrences of merging. The first is to demonstrate the presence of accelerated parallel ion flows. Guidance comes from the interpretation of distribution functions given by Cowley (1982). Our second marker is the presence of parallel Poynting flux. Active merging must be communicated away from the site to other regions along the magnetic field lines by Alfvén waves. Parallel Poynting flux, carried by wave-propagating away from a source, can indicate where active merging is proceeding. Whereas the Alfvén Poynting flux specifies the transport of energy by convective flow, the wave Poynting flux, determined from $\mathbf{E} \times \mathbf{B}$, measures energy flow carried by Alfvén waves. To calculate the wave Poynting flux, we subtract the average magnetic field ($B_0$) and electric field ($E_0$), determined using a sliding boxaverages of 3 min, from the measured field quantities. The above cross product is then taken. When the sharp changes in $B$ occur as the magnetopause current layer is traversed, boxaverages can allow variations from large-scale changes to contaminate the results. To avoid this problem, we terminate the wave Poynting flux calculation at the edge of the current layer.
and resume the calculation when the major change in $B$ has been completed. Calculations using spin-averaged data have a resolution of 6 s on Polar and 4 s on Cluster. Since there are other ways to generate Alfven waves, we look for the temporal concurrence of accelerated ions and parallel point-fluxing, coming from the same direction, as the signatures of merging and indicators of its location with respect to the spacecraft.

To aid interpretation we establish the variable lag times for IMF features between ACE and Polar. The tilt of phase planes in the solar wind can change on short-term scales (Maynard et al., 2002; Werner et al., 2002). The proper lags from ACE to Polar are adjusted by requiring that the IMF clock angle in the $Y - Z$ plane be maintained across the bow shock (Song et al., 1992). Whenever Polar is in the magnetosheath, this technique can be used. When Polar is in the boundary layer or cusp, we must rely on the availability of at least two satellites in the solar wind to apply the technique described by Werner et al. (2002) and to determine how lag times change.

Whenever possible we look for corroborating data from diverse sites, such as SuperDARN or DMSP satellites in the ionosphere and/or Cluster in the cusp. An example in which data from all five sources can be utilized comes from the 11:00 to 13:00 UT interval on 12 March 2001.

4 Observations from 12 March 2001

4.1 Overview

On 12 March 2001, the Polar orbit sketched the subauroral magnetospheric cusp Cluster passed through the Northern Hemisphere cusp. Figures 1a and b show the $X - Z$ and $Y - Z$ solar magnetospheric (SM) projections of the Polar orbit. Arrows indicate the direction of spacecraft motion. The region of interest lies inside the red oval. Polar crossed it between 11:00 and 13:00 UT. At 12:00 UT the dipole was tilted outward 0.5°. Hence, the subauroral polars was very close to the $X = 0$ axis. Figures 1c and d present the $X - Z$ and $Y - Z$ projections of the Cluster orbits in GSM coordinates. Cluster crossed from the lobe to the magnetosheath above the cusp between 12:00 and 12:30 UT. Red ovals mark the period of interest. The inset in Fig. 1c depicts the nublous configuration of the Cluster satellites at 12:00 UT. Cluster 3 is in front, while Cluster 4 trails the other three. All spacecraft were located slightly post-nose. In addition, SuperDARN radar provided estimates of the ionospheric convection pattern. Thus, we can trace ionospheric responses to activity in the high altitude cusp and on the dayside magnetopause, and from there to its sources in the solar wind.

Figure 2 provides a conceptual context for measurements acquired in the various regions. Taced field lines come from the cusp region using an IMF clock angle of 115°, similar to the angle of 115° for the 12 March magnetopause cros-
Fig. 5. Comparisons of the component magnitude and clock angle of the magnetic fields measured at ACE (red and blue) and at Polar (black). The lag time is set at 36.5 min for the red ACE trace, which is appropriate for the magnetopause crossing observed at 11:40 UT and the wind 15 min. A lag time of 6.65 min (blue, ACE trace) was tried to bring into alignment the region around the directional discontinuities. The scale for ACE data is one unit of that marked.

ACE data - Red: lag keyed to magnetopause; Blue: lag keyed to directional discontinuity

The figures illustrate that closed field lines were found starting from the ionosphere in each hemisphere. By moving poleward 10 km in the ionosphere from the trace point of each closed field line, we define a set of "first" open field lines. The best-closed and free-open field lines are labeled 0 and 1 in Fig. 2(a). They map onto the black dot in the potential pattern in Fig. 2(b). Near 15 MLT and 70° magnetic latitude, and pass through the post-moon rays. Field-line 0 also traverses the low-latitude region of the post-moon magnetopause. The closed field line map onto the zero equipotential line between the two convection cells in the Southern Hemisphere.

To understand how the field lines change after merging, we have traced a number of field lines from a series of points along the Northern Hemisphere equipotential that passes through the origin of trace 0. The first of these, labeled 2-5 in Fig. 2(a), shows how a field line evolves as it is dragged back over the magnetopause. A similar set of field lines was mapped from the equipotential contour in the Southern Hemisphere at the end of trace 1 and is labeled 2-5. Line 2-5 probably pairs best with 2, although there is no way to trace the evolution of such pairs from a merging site. A high-latitude merging site can be inferred to be located close to where line 1 bends. Subsequent field lines show how they turn and curve back through the cusp, as they are dragged antisunward by the solar wind.

Figure 2c shows the complete set of first-open field lines traced from each hemisphere. The field lines are colored according to Vr. The Southern Hemisphere set of field lines in Fig. 2a are colored red in Fig. 2c to show their position relative to the first-open field lines. The arrow points to the approximate locations of merging. Sharp bends in open field lines from the Northern Hemisphere indicate general locations where merging is occurring. Most pre-moon (post-moon) field lines have a negative (positive) Vr. Exceptions to this are in the cusp, where J x B forces from the currents associated with the curves of newly merged field lines to drive the flow westward (eastward) in the Northern (Southern) Hemisphere (Siscoe et al., 2000). Note that the velocity separator is not the merging separator. The more vertical velocity separator results when the merging J x B forces overwhelm the normal hydrodynamic flow away from the nose. A faint line at about a 20° tilt from the equator separates open field lines traced from the Northern Hemisphere from those traced from the Southern Hemisphere. The curvature of the
Fig. 6. Ion spectrograms and the magnetic field measured by Polar and plotted for the interval between 11:00 and 13:00 UT on 12 March 2001. (a) $B_y$ is shaded red (blue) for positive (negative) values. (b) Parallel, perpendicular, and total ion energy spectra measured by the Hydros instruments. The colors highlight parallel and perpendicular ion flows associated with a contact and a crossing of the magnetopause.

Field lines in the upper left indicate that most are pulling away from high-latitude merging sites in the Southern Hemisphere. The fact that the velocity separator is so much different from the separation of traced field lines is further evidence that low-latitude component merging is not a dominant process in the simulation. Figures 3b-4 display the front, top, and side views of the Northern Hemisphere’s closed and open field lines in Fig. 2a, colored with $V_T$. Plasma flow in the boundary layer on the closed field line (b) is toward dusk. Flow above (left) the cusp on line 1 is toward dusk (down). Subsequently, the flow is toward dawn, both above and in the cusp, as the field line is dragged back through the mantle.

The primary flow direction near the magnetopause and in the outer portion of the boundary layer is determined by the diversion of flow from pressure gradients away from the stagnation region. Cowley and Owen (1989) have provided a model of the flow, which combines the effects of the hydrodynamic diversion of flow from stagnation point with the magnetic tension effects from merging. Scudder et al. (2002) argue that the stagnation point should, in fact, be a stagnation line along the magnetic field line that passes through the nominal stagnation point at the nose.

Thus, JSM suggests that with merging at high latitudes in the Northern Hemisphere, Polar should observe flow away from noon at its post-moon location. In the post-moon cusp, the open boundary layer can maintain movement toward dusk, corresponding to the flow in the magnetosheath. Due to merging, the outer separatrix should initially continue to move toward dusk (applicable to Cluster as it passes through the magnetopause above the cusp), while the inner separatrix (as well as the foot of the field line) is pulled toward dawn.
4.2 Interplanetary conditions

IMP measurements were made by the Wind and ACE spacecraft located near (-57, -165, 8) and (227, -38, 4), respectively. Figures 3a-c show the three IMP components observed at the locations of the two spacecraft. Data are referenced to the UT of ACE measurements. Wind data (green) were lagged according to the ionospheric time based on the solar wind velocities measured at ACE (plotted as the green trace in Fig. 3b). The agreement between the traces in Figs. 3a-c is only moderate. This is especially evident beyond 1000 U. However, Weimer et al. (2002) showed that agreement could be improved by allowing for the lag time that varies on a minute-to-minute basis. Figures 3d-g show the same data (Wind data is colored red) using the calculated variable lag, which is plotted as the red trace in Fig. 3d. The variable lag reflects constantly changing (in 1-3 phase planes).

Our analysis focuses on the interval 1000-1200 U. This interval is dominated by a large decrease in the magnetic field strength between 1112 and 1150 U (magnetic field, shown in Fig. 4). A directional discontinuity occurs, probably rotational, during which GSM By increases from positive to negative, and at 1138 U By becomes negative, preceding the sharp drop in B and reversal of By by a few minutes. The combined structure bears resemblance to a configuration observed in the interplanetary medium in front of a magnetic cloud on 24 December 1996, by Farrugia et al. (2001). The magnetic field decrease was interpreted as a slow shock, which, coupled with the preceding rotational discontinuity, could be the signature of an upstream reconnection layer. The structure at ACE is approximately planar. Maximum variance analysis of the 3-b interval found a well-defined maximum variance plane with a normal component of -1.44±0.06, consistent with the reconnection interpretation advanced by Farrugia et al. (2001) for the 24 December 1996 event. Figure 4 displays the three components and magnitude in principal axis coordinates. Polar observations at the magnetopause were acquired before and near the directional discontinuity passage.

4.3 Polar observations

Polar encountered the magnetopause current layer several times before crossing the magnetopause at 1148 U. Variable lags help us to establish the applicable solar wind conditions at that time. Figure 5 compares the three components and magnitude of B along with clock angle measurements at ACE and Polar during the interval from 1030 to 1500 U. (Plot scales were adjusted to reflect the factor of 6 increase after reentering the bow shock. The ACE data were lagged by 70.5 min before traces). The lag was determined by best matching the Polar and ACE clock angles between 1130 and 1205 U. Note that the lag is different from the lag between ACE and Wind, displayed in Fig. 3c, because of the different locations. This lag was good through 1208 U, when the first of the two directional discontinuities seen in the ACE and Wind data were sampled by Polar in the magnetosheath.

- The lag time decreased as the directional discontinuity structures approached. The variable lag time shown in Fig. 3d between ACE and Wind also decreased before the time of the structure, apparently due to the changed Bθ. In Fig. 5 the blue traces represent the ACE data with a 65.5-min delay, which is more appropriate for times at the arrival of the directional discontinuities. The decreased lag significantly improves the fit between 12:10 and 12:13 U. The fit in the center of the magnetic hole has further variations in lag. The directional discontinuities have similar profiles to those determined at ACE and at Wind, showing that they have maintained coherence while passing through the bow shock. Farrugia et al. (1991) found that the plasmasphere is maintained in the magnetosheath but the orientation may change somewhat.
on the passage through the bow-shock. Coherent passage through the magnetopause is important for establishing the relative timing and interpretation of Cluster measurements. Note the presence of a magnetic hole centered at ~12:30 UT, when the magnitude of $B$ measured at Polar is less than the expected shocked and lagged magnitude from ACE. We note in Fig. 3 that $B$ was also smaller at Wind in the middle of this structure, and suggest that ACE did not sample the minimum $B$ within the magnetic hole. The clock angle at the time of the magnetopause crossing was approximately $140^\circ$, similar to that of the EIM simulation discussed above relative to Fig. 2.

Figures 6b-d depict the energy spectra for the parallel, perpendicular, antiparallel, and total ion energy flux. To place these particle measurements in context, Fig. 6a shows Polar measurements of $B_x$ (red for positive and blue for negative) and $B_y$ (green trace). The first contact with the magnetopause occurred at 11:39 UT, as indicated by a burst of antiparallel ions (Fig. 6d). These fluxes occur while $B_x$ reversed to positive (Fig. 6a) and $B_y$ (as well as the magnitude of $B$) dipped. This is a good example of a partial entry into the magnetopause layer. Note too that bursts of parallel and antiparallel ion fluxes were seen during the magnetopause crossing at 11:48 UT. Both of these regions are highlighted by circles and are discussed in more detail below.

Two additional unique features of the spectrograms should be noted. First, there is a lack of plasma in the magnetosheath past the magnetopause. In a separate paper, Maynard et al. (2009b) establish that this is a depletions layer. It is one of the few regions forward IMF predicted by EIM simulations. Second, magnetosheath particles, including parallel and antiparallel fluxes, are also seen during the passage of the directional discontinuities. These fluxes are intense and have higher energies in the parallel component. Magnetosheath ions are often more biased toward perpendicular "parachute" distributions as the magnetopause is ap-
The dominance of the perpendicular fluxes is seen in low fluxes of the depletion layer region between 11:50 and 12:00 UT. The various regions are noted at the top of the plot.

Figure 7 shows 3 ion distribution plots accumulated between 11:39 and 11:44 UT, within the first circle of Fig. 6. The ion fluxes were shifted in velocity space by the perpendicular electron velocity, as the best proxy for the magnetic field line velocity. To create the distributions, symmetry was assumed around the parallel axis. Points of actual measurements are indicated by black dots (above parallel axis). No measurements exist between the white lines and the parallel axis, as this marks the closest approach of the particle detectors to the magnetic field direction in the analysis interval. For this time when Polar was on the magnetosphere side of the current layer, Fig. 7a shows a cold central core and an accelerated population, well displaced from zero, moving in the negative B direction, or arriving from north of the spacecraft.

From expectations for locations on the inner separation (Cowley, 1987), we interpret the accelerated population as being primarily of magnetosheath origin, but with a central core of reflected, accelerated, magnetosheath ions. Figures 7b and 7c also show similar distributions but with smaller displacements. These distributions indicate a merging-line vector to the north of Polar’s location.

Figure 8 displays 4 ion distribution plots at the time of the 11:40 UT magnetopause crossing. Figures 8a and b were taken at locations on the inside of the current layer, while Figs. 8c and d are from locations on the outside of the current layer. Figures 8c and d indicate enhanced-like magnetosheath distributions, centered about the origin. An accelerated, cold magnetosheath population is seen along B, coming from poleward of the spacecraft. Observed perpendicular energies are comparable to the unaccelerated magnetosheath distributions seen in Fig. 7. Figure 8a depicts an accelerated magnetosheath distribution with the cold magnetosheath background. Again, the acceleration is from north of the spacecraft, which was located at ~18° magnetic latitude and 13:10 MLT. In Figs. 8b the distinctions are birefringent; however, we suggest that the ion acceleration was weaker and parallel to the magnetic field, or comes from a location equator-ward of the spacecraft. How far from the spacecraft is not discernable.

To strengthen our interpretation that these two magnetosheath components reflect merging, events located poleward of the spacecraft, the three components of the wave Poynting vectors are plotted in Fig. 9. The background magnetic field components are provided as red lines for reference. Plots in Figs. 8d show the three GSM components and the
CLUSTER
Fluxgate Magnetometer (FGM)

Magnitude of the wave Pointing flux. Figure 9 shows the component of $N$ parallel to $B_s$. Between 11:19 and 11:24 UT, $S_y$ was negative (as expected), in agreement with the direction of the ion acceleration. In the traversal of the magnetopause current layer, the calculation was interrupted to avoid contamination. The negative $S_y$ on the outside of the ionosphere was again in agreement with the direction of particle acceleration. Thus, these two encounters pass our empirical tests for merging events at locations poleward of the spacecraft. In fact, we see enhancements in $N$ at 11:30, 11:43, and 11:48 UT, suggesting the occurrence of the merging rate at those times.

The normal direction for the full magnetopause crossing was found using the minimum variance technique of Sotirel and Leblanc (1984). The normal component was small, but directed outward from the magnetopause, consistent with the merging occurring at the north of the spacecraft. As a further check on the rotational nature of this crossing, a successful Weibel test across the full current layer using electrons (Seidel et al., 1994) resulted in a slope of nearly $-1$, indicating that the source of the rotation is above the spacecraft.

4.4 Cluster observations

Nearer to particle, Cluster crossed spatial regions more quickly than Polar. Figure 10 shows the fluxgate (FGM) component and the magnitude of the magnetic field measured by the 4 Cluster spacecraft between 12:00 and 12:35 UT. Cluster exited the mantle into the high-altitude cusp near 12:05 UT and crossed the magnetopause current layer out of the cusp into the magnetosphere between 12:13:50 and 12:15:00 UT. The magnitude of $B$ increased as the spacecraft exited the high-altitude cusp. The biggest change during this crossing event was in the $Y$ component. Each of the spacecraft saw the change at different times, with Cluster 3 (Cluster 4) observing the change first (last), indicating that the change is primarily of a spatial nature. The order of crossing (3, 1, 2, 4) is consistent with the spacecraft configuration shown in Fig. 1c, showing Cluster 3 (4) leading (trailing). The subsequent $B_y$ reversal between 12:15 and 12:31 UT did not result from Cluster crossing back into the cusp. Rather, it reflects the encounters with the first of two IMF directional discontinuities observed earlier by Polar. Note that all four spacecraft...
detected the negative shift in $B_y$ at nearly the same time, indicating that this change is temporal. For a magnetopause velocity of 100 km/s, it would take 60 s for a feature to cross the satellite configuration. In fact, with a 4-min lag, Cluster and Polar data are in excellent agreement after 12:15 UT. Figure 11 compares Cluster 3 and Polar magnetic field data with this lag applied to the Cluster measurements. $B_y$ subsequently also reversed polarity as it did at the location of Polar. At that time the magnitude of $B$ also decreased. Because Polar saw the same directional and magnitude changes in the magnetosphere, we can safely conclude that these exhibit magnetopause features rather than a reentry into the cusp. Key features of the combined data set are marked by arrows. As the constellation penetrated further into the magnetosphere, the lag between Polar and Cluster observations decreased slightly. This fits expectations, since the observations are made before the structure fully draped over the magnetopause. Minimum variance analysis of the magnetic field from each of the Cluster spacecraft at the magnetopause crossing and the directional discontinuities provided normals that were stable between the spacecraft. They were also stable between the magnetopause crossing and the $B_y$ reversal, indicating that the discontinuity was draped along the magnetopause orientation. All of the structure detected between 12:13 and 12:17 UT was present on the scale of the spacecraft separation and aligned parallel to the magnetopause boundary. The normal to the $B_y$ reversal near 12:20 UT was similar, but slightly tilted.

Figure 12 presents spectrograms of ion energy fluxes measured in the antiparallel (40°–130°) and perpendicular (0°–1°) directions by CIS on Cluster 3, Cluster 1 and Cluster 4. In all cases the parallel flux (not shown) was much weaker. Three distinct features, which occur at staggered times, are highlighted by dashed lines. The first is an increase in energy seen at 12:06 UT by Cluster 3, 12:06:10 by Cluster 1 and 12:06:50 UT by Cluster 4. The increase is more pronounced in the antiparallel fluxes. The second feature is similar, occurring between 12:10:50 and 12:11:30. The
third feature was seen in the perpendicular fluxes starting at 12:14 UT at Cluster 3. In this case the intensification starts at low-energies then spreads to higher energies. From Fig. 10, we see that this increase started in each spacecraft exited the current layer. After this time ion fluxes are more typical of magnetosheath flowing away from the subsolar stagnation region. Subsequently, the central energies were generally lower and the spectral width broader. Based on ion spectral characteristics, and the clear correlation of the magnetometer measurements with those from Parker, the features subsequent to 12:16 UT are of magnetosheath and solar wind origin. Between 12:14 and 12:15 UT the antiparallel fluxes are intense and higher in energy at Cluster 4, as expected from an active merging site located equatorward of the Cluster spacecraft.

Figures 13b–d show from Cluster 4 perpendicular H+ velocities ($V_\perp$ in blue) overlaid onto $E \times B$ velocities ($V_E$ in magenta) in GSM coordinates for the interval between 12:00 and 12:20 UT from Cluster 4. The velocities compare very cleanly. A 1.5 mV/m sunward electric field offset has been subtracted from the GSM $X$-axis EFW electric field data to make this comparison. The magnitude of the offset was selected to maximize the correlation. Sunward directed electric fields are related to asymmetries in the spacecraft sheath caused by photoemission (Galtfuss and Maynard, 1974).
Figure 14a-c present the GSM components of the wave Poynting flux in the same interval from the four Cluster spacecraft, calculated using the same method as with the Polar data. Figure 14d shows the parallel components. The wave Poynting flux is in the antiparallel direction, with peaks in the interval between 12:11 and 12:18 UT. This indicates that the satellite was above the source. Note the variability between the four spacecraft, which indicates that the structure had dimensions of the order of the spacecraft separation. Enhancements are also seen after 12:13:50 UT, but the proximity to the major current layer prevented the determination of the flux through the third region of velocity enhancement in Fig. 13. Smallest variations were also seen in the first interval of velocity enhancement. All three intervals have been highlighted by the black bar for comparison to Fig. 13. The variability in both time and space suggests that the merging process is not steady. Considering both the accelerated jets and the Poynting flux, we infer that Cluster is near the outer separatrix of an active merging site equatorward of the spacecraft.

The Cluster configuration was favorable for determining the currents from curl $B$ (Danilov et al., 2002). Figure 15 displays local currents derived using a GSM coordinate system centered on Cluster 2. Also plotted are the divergence of $B$ as a percentage of curl $B$ and the magnitude of $B$ at the locations of the four spacecraft. If the calculations were performed without error, Maxwell's equations demand that $\nabla \times B = 0$. Currents determined where the divergence-to-curl ratio exceed 90% should be treated with caution. In general, for this configuration, the expected error in $I_\lambda$ is at minimum 20%. Most of the large values of the divergence occur when the currents are small, highlighting their anisotropy. However, when the currents are large, the divergence ratio is, in general, small, indicating where the calculated currents are...
The calculations were performed using the computational model described in [Ref. 1]. The model allows for the simulation of the magnetic field evolution in the Earth's core, taking into account the electrical conductivity and the geomagnetic field. The results show a good agreement with observational data, particularly in the latitude belt of 30°-60°. The model predictions for the Earth's dipole moment and the secular variation match the observed values within the uncertainties.

Some of the key findings include:

- The model predicts a secular variation of the Earth's dipole moment that is consistent with the observed trend.
- The calculated field gradient at the Earth's surface is in agreement with satellite measurements.
- The model successfully reproduces the observed changes in the geomagnetic field over the past century.

The calculations were validated using a sensitivity analysis that included the effects of varying the electrical conductivity and the geodynamo parameters. The results indicate that the model is robust and can accurately predict the magnetic field evolution under different conditions.

In conclusion, the model provides a comprehensive framework for understanding the Earth's magnetic field dynamics, which is crucial for various applications, including navigation, space weather forecasting, and understanding the Earth's interior processes.
previous, the implications are that this also involves time-varying high-latitude merging. The next section relates these enhancements to intensification of ionospheric plasma velocities measured by SuperDARN radars.

4.5 SuperDARN measurements

Each SuperDARN radar measures the velocity component toward and away from the transmitter. To infer the large-scale flow pattern, the Roshonieni and Baker (1998) "map potential" technique was employed. Line-of-sight (I-o-s) velocity measurements from multiple radars are fitted to an expansion of the electrostatic potential in spherical harmonics, to yield large-scale global convection maps. First, the I-o-s data are filtered and mapped to a polar grid. These "gridded" measurements are then used to determine a solution for the electrostatic potential distribution that is most consistent with the available measurements. Velocities should fall along plasma streamlines in the modeled pattern. Backscatter targets within the radar field-of-view are not always available, and significant arcs exist outside the reach of the radar system. The statistical model of Roshonieni and Greenland (1996), parameterized by IMF conditions, is used to stabilize the solution in regions where no measurements are made. Figure 16 presents daytime Northern Hemisphere ionospheric convection patterns, each averaged over the interval given at the top. Dotted concentric semicircles indicate lines of constant magnetic latitude in 5° increments. Noon is located at the top of each pattern. During the period from 11:00 to 12:15 UT, SuperDARN was observing velocity enhancements in the 14 to 15 MLT region between 70° and 75°. Figures 16a and b show these enhancements by comparing two consecutive patterns near the 11:48 UT Polar magnetosphere crossing. The orange circle highlights the region of velocity enhancement, indicated by increased numbers of red drift vectors in the right pattern compared to the left. Note that the enhancement is localized, in the same region that the open-closed field line pair is mapped to in the simulation depicted in Fig. 2b, and occurs 1-2 min after the enhanced parallel fluxes were seen at Polar. We suggest that the delay is related to differences in Alfvén travel times. The signature in the ionosphere should lag that in the outer cusp by the order of a minute, due to Alfvén wave propagation time. The SuperDARN patterns show numerous increases in velocity in this general area over the hour-plus period.

To show the time variability, a search was made in the SuperDARN data for the largest velocity in the region and its location. The magnitude, the components, and the location are plotted in Fig. 17. The time of the three enhancements in merging observed at Polar are noted by the vertical red lines. The corresponding velocity peaks at SuperDARN are highlighted by the red dots. Within the interval that Polar was probing the magnetopause, these are the only peaks. Subsequent peaks starting at 12:06 UT correspond to the interval where Cluster observed evidence of merging. Figures 16c and d show SuperDARN potential patterns and vectors for intervals that contain the first 2 velocity and current enhancements at Cluster, depicted in velocities in Fig. 13 and currents in Fig. 15. Returning to Fig. 17, the velocity and current enhancements observed by Cluster and noted by the blue dots correspond to three velocity enhancements seen at SuperDARN. Those periods are noted by the blue oval in Fig. 15. Since Cluster observations come from above the cusp on the outer separatrix, while SuperDARN is looking at the response at the foot of the field line, we suggest that the difference in times from Alfvén wave propagation may be less than those observed by Polar. Note that no peaks above 800 m s⁻¹ occur after 12:15 UT. The velocity enhancements are in the region predicted by the simulation as being tied to high-latitude aerging. The correspondence with the Polar magnetopause merging criteria suggests that SuperDARN and Polar are observing the opposite exhaust regions of a time-varying active high-latitude merging line. Continuing the correlation withCluster, we are able to relate 3 more peaks in the SuperDARN velocities to time-varying merging. The implications from considering the 2-h period of SuperDARN velocities is that the rate of merging varies often and considerably. The location may be just as variable.

4.6 Summary of the 12 March observations

From the observations presented above we may conclude for this day when the IMF clock angle was about 140° that:

1. Polar, while skimming the nose of the magnetosphere, observed the effects of merging at high latitudes. Accelerated ions and wave Poynting flux were used as discriminators for the existence of merging. While the exact location of merging is not discernible from the data, it was above the spacecraft, which, in turn, was well above the component merging line location of Gonzalez and Mozer (1974).

2. The merging rate was temporally varying, as indicated by both Polar and Cluster measurements.

3. SuperDARN observed enhancements in the flow in the ionosphere associated with these time-dependent merging events observed at Polar. Polar, near the subsolar magnetopause and SuperDARN in the high-latitude ionosphere, monitored both exhaust regions. From SuperDARN observations we may also infer that variations in the merging rate occurred continuously for more than an hour.

4. Cluster continued the correlation, placing the merging location below the satellite, which was located above the cusp. Both SuperDARN and Cluster observed effects of time-varying merging.

5. Flow in the boundary layer and adjacent magnetosphere was generally away from the subsolar region unless specifically diverted by merging. In a time-dependent process, boundary layer flow varies continuously.

6. Two directional discontinuities and an associated magnetic hole were observed in the magnetosphere system.
from the solar wind. The effects of these were observed by both Polar and Cluster.

7. Adjacent to the magnetopause, Polar observed a depletion layer, implications of which are further discussed by Maynard et al. (2003b).

5 Other events

Table I summarizes all of the merging events investigated to date, using wave Poynting flux and accelerated ions as discriminators. The events are organized according to the applicable IMF clock angle (third column). The fourth column lists our best estimates of the merging locations. Note that the measurements provide information about whether the site is to the north or south of the spacecraft. For a number of events we calculated the difference between the spacecraft location and the component merging line of González and Moro (1974). The differences are listed in the last column. During periods when the ions and Poynting flux propagated from north of Polar and the differences are significant, we labeled the merging location as being at high latitudes. The last column also comments on special circumstances prevailing during each pass. If the ions and Poynting flux originated south of Polar, we were unable to discern from the measurements alone, whether the merging line is near the equator or at higher northern latitudes. Question marks indicate instances when assigned merging locations are ambiguous. The event of 05:48 UT on 1 April 2001 is labeled "close" because Moro et al. (2002) interpreted signatures obtained during this magnetic pulse crossing as indicating proximity to the separator. In some cases we relied on SuperDARN measurements and ISM predictions to identify merging locations. These are noted in column 5. The event at 05:05 UT on 16 April 2000 included episodic encounters with fluxes from the north and south of the spacecraft. We address this further in the discussion. During the two passes of 31 March 2000, Polar did not enter the dayside magnetosphere because of the high activity and very compressed conditions. In each case Polar crossed from the mantle to the magnetosheath above the cusp as noted in the comments.

For applicable clock angles of 120° or less in the events of Table I, merging generally occurred poleward of the spacecraft and was inferred to be at high latitudes. This conclusion should be substantiated in the analysis of more events; however, it is clear that one must consider high-latitude merg-
6 Discussion

We have used observations of accelerated particles and wave
breaking vectors as our primary indicators as to whether
merging has occurred and, if so, where. As demonstrated
above, both flux types provide necessary, but not sufficient,
conditions for identifying merging events. Establishing that
the boundary is a rotational discontinuity adds a third nec-
sessary indicator of merging. Since rotational discontinu-
ities may be found in any magnetohydrodynamic flow, in-
cluding those that do not involve reconnection, a success-
ful Watan test, by itself, is not a sufficient test to conclude
that merging geometries have been encountered. However,
the magnetopause-shear interface is generally thought to in-
clude such a structure to form a locally open boundary. In
this spirit a successful Watan test (with electrons) with slope
±3 is associated with a potential merging site, whose X-line
separator will, in general, be well removed from the space-
craft’s trajectory. Successful Watan tests to establish the ro-
tational discontinuities, in conjunction with observations of
accelerated particles, have been the primary empirical cri-
teria for identifying merging events. Recently, Socker et
al. (2005a) reported small-scale breaking of both ion and
electron protonos, as well as parallel electric fields within
merging regions poleward of the cusp during an interval of
northward IMF. In the events considered here, observations
were made away from the separatrix region. Thus, we rely
on signatures recognized as strong indicators, but not con-
clusive proof, that merging has occurred. With this caveat in
mind, we proceed by assuming that Polar detected signatures of actual merging events. We first comment on the use of Poynting flux as a discriminator. We next comment on some spatial-temporalscale implications of the observations.

6.1 Wave Poynting flux as a merging discriminator

When electron jetropy is broken and merging takes place along an X-line (Scaudder et al., 2002a), magnetic field energy is converted into particle kinetic energy, and the magnetic field configuration in the "diffusion" region changes. This information must be conveyed away from the separatrix along the merged field lines. Atkinson (1992), following earlier calculations by Soneaup and Wang (1987), showed that Alfven waves propagate away from the diffusion region, carrying the field-aligned currents (FACs) needed to discharge Hall electric fields that develop in the collisionless merging process. Thes FACs are carried by electrons (since the ions cannot respond in these thin layers) with relatively large drift speeds parallel to B, causing parallel electron Alfven Mach numbers as high as 4, as recently been reported by Scaudder et al. (2002a). These parallel currents can be seen to flow along the separatrices in the Hall MHD simulations of Ma and Bhattacharjee (2001). FACs are carried by obliquely propagating Alfven waves (Siscoe, 1983). We expect to detect Alfven waves propagating away from active merging sites along the separatrices.

Wave Poynting vectors were calculated using CRRES electric and magnetic field data by Maynard et al. (1996a), to determine locations of energy release at substorm onset. While most calculations were performed with spin-averaged measurements, Maynard et al. (1996b) were able to achieve higher time resolution using 10 second data retrieved during one CRRS pass. No significant power was found at frequencies above the P-2 range, covered by spin-averaged electromagnetic fields. A similar test was performed here. The power levels in both the high resolution F and B were significantly less at higher frequencies than at frequencies below the ion gyrofrequency. A check of the angle between S and B indicated that S was nearly field aligned during the enhancement at the magnetopause. Thus, the data are consistent with Alfven waves occurring at the magnetopause encounters where merging is claimed. The magnitudes of wave Poynting vectors generally peak below one-third to one-half of the total Poynting flux values. The peaks occurred at places where Polar encountered accelerated ions.

A further example of wave Poynting flux observations at a merging separatrix, from 31 March 2001, is given in Fig. 18. In this pass Polar crossed from the Southern Hemisphere mantle directly into the magnetosheath, without encountering the dayside magnetosphere. Figure 18a displays the parallel wave Poynting flux. The magnitude and F and Z components of B are shown in Figs. 18b and c. Figures 18d-f show the parallel, perpendicular and anti-parallel ions. Note that strong fluxes of accelerated parallel ions occurred in coincidence with the parallel wave Poynting flux. Three examples of ion distribution plots are given in Figs. 18g-i. Strong acceleration appears in each spectrum. After encountering these fluxes, Polar entered the magnetosheath, characterized by weak, perpendicular fluxes, identified as a depletion layer (Maynard et al., 2003b). The accelerated particles are in-

<table>
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<th>Date</th>
<th>Time (UT)</th>
<th>Angle</th>
<th>Merger Location</th>
<th>Discriminator</th>
<th>MER</th>
<th>MALT</th>
<th>Height (km)</th>
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<td>~90°</td>
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</table>
terpret as moving along the outer separatrices from a low-latitude merging site, that divides newly opened field lines being added to the mantle, from magnetosheath field lines tied to the IMF on both ends.

Fig. 16. Correlation of the wave Poynting flux measured by Polar above the cusp on 31 March 2001, with accelerated particles associated with the outer separatrix separating open magnetic field lines from IMF magnetic field lines in the magnetosheath.

We conclude that the wave Poynting flux provides a good discrimination to indicate when merging takes place and the direction of the merging site with respect to the measuring spacecraft. However, sources of Alfven waves other than merging may be available. Thus, their presence must be classified as necessary but not sufficient as a condition to establish that merging is occurring.

6.2 Location

The 12 March data indicate that Polar detected signatures of merging events, for removed from a near equatorial component merging line (Gonzalez and Mayer, 1994). This is true for many events listed in Table 1 with IMF clock angles < 150°. The measurements indicate that merging occurs at high latitudes under a variety of conditions. In other events the particle and Poynting fluxes were clearly propagating from south of the spacecraft. These signatures appear to be consistent with either component merging near the equator or anti-parallel merging at high latitudes in the conjugate hemisphere.
An intriguing event occurred on 16 April 2000, when the IMF clock angle was near 180°, but the inferred merging site was to the north of the Polar's location. The measurements were made at ~0520 UT, when Earth's dipole axis tilted toward midnight. We have conducted a series of SIM simulations with increasing dipole tilts to determine whether off-equatorial merging can occur with 180° clock angles. Figure 14 displays traces of magnetic field lines that are closed (black), have one foot in the Northern Hemisphere (red) or have both feet in the interplanetary medium (green), for 3 different dipole tilt angles. Simulation results are presented in both SIM and GSM coordinates. In both coordinate systems the red (open) field lines indicate that for dipole tilts ≥ 8°, merging moves away from the equator to higher latitudes. These are not extreme tilt angles. These conditions are met every day in the dipole rotations with UT. We note that ISM simulations incorporate current-dependent explicit resistivity, which typically rises near the equatorial magnetopause to force dissipation, to aid merging. The code can place dissipation wherever it chooses; via PDM to keep gradients in check. Thus, ISM predictions of merging away from the equator indicate a clear preference of the code for high-latitude merging. Recall too that $B_y$ serves to increase or decrease the effective dipole tilt (e.g. Crooker, 1992). Thus, over the course of the day at particular UTs merging may be preferred away from the equator, even with a nearly southward IMF. Thus, one should not automatically assume that merging must be confined to low latitudes. We have added question marks in Table 1 to events with particle and field signatures indicating merging sites south of the spacecraft. In some cases, when $B_y$ is significant, we suggest that merging locations may be southern high latitudes.
Two events on 31 March 2001 are called “shoulder” events in Table 1, one of which is discussed above relative to Fig. 18. The observations were near the outer separatrix, poleward of the cusp. Shoulders occur under strongly driven conditions, when the magnetic field poleward of the cusp is increased by currents flowing in the Region 1 separatrix. (Siscoe et al., 2002). These currents close across the polar cap and over the high-latitude magnetosphere. The fringing field of this solenoid depresses the magnetic field in the subauroral region, creating effective magnetic shoulders above the cusp. Other implications of these shoulders are presented in Maynard et al. (2003b). Certain dipole tilt angles accentuate these shoulders and, based on the results displayed in Fig. 19, could move the merging site away from the equator.

The ISM and observational results suggest that merging is possible at high latitudes in a common occurrence. Figure 2 illustrates high-latitude merging in simulations with a clock angle of 135°. Component merging exists in the same simulation near the equatorial magnetopause. It was aided by explicitly included equatorial resistivity in the simulation. Over the past two decades, component merging was assumed by many to be the rule, rather than the exception. A recent study by Moore et al. (2002) concluded that merging rates should be appreciable near the subauroral magnetopause for most IMF clock angles. To explain DMSP particle characteristics in the cusp, Wing and Newell (2002) argued that both subauroral and high-latitude sources simultaneously exist. Two high-latitude sources may also work. The results of Maynard et al. (2001b) require high-latitude sources in both hemispheres to reconcile the timing differences. Further work is needed to establish how the location of merging varies with IMF input.

6.3 Temporal characteristics

To date, the 12 March event is unique in that measurements from three separate locations were integrated to address the temporal aspects of the merging event. Whenever the merging rate increases, we expect that the magnetopause erodes inward slightly. This apparently was true at 11:39 and 11:48 UT, when Polar observed the effects of merging at northern high latitudes. The temporal nature of the process is further confirmed by the SuperDARN observations. Using Fig. 2 to understand the global context, we are able to correlate the velocity enhancements observed by SuperDARN near 13:00–15:00 MLT with the changes observed by Polar. These correlations continued in observations above the cusp by Cluster. We infer that SuperDARN observations primarily reflect temporal dependence of merging. Between 11:00 and 12:15 UT, multiple peaks in ion velocities observed by SuperDARN suggest that the merging rate and/or location varies on time scales of 2 min, to 8–10 min, commonly associated with flux transfer and pulse-reconnection events (e.g. Cowley and Lockwood, 1992). Maynard et al. (2003a) reported observations of temporal effects of merging processes on time scales of 1 to 3 minutes. The remote observations of 12 March show effects in both exhaust regions, with merging varying on similar short temporal scales.

7 Summary and conclusions

The location and temporal dependencies of dayside merging have been investigated from a global perspective. Measurements made in diverse regions of the Earth space constrain interpretations through demands for consistency between observed phenomena. Data acquired on 12 March 2001 near the subauroral magnetopause, in the high-altitude cusp, and in the ionosphere, indicate that merging occurred at high latitudes in a time-varying manner. We have used simultaneous detection of field-aligned wave Poynting flux and accelerated ions as the primary, remote discriminators of merging. For a period of time with the IMF clock angle at ~140° merging developed to the north of Polar, well removed from predicted locations of component-merging lines (Gonzalez and Mozer, 1974).

For more than an hour SuperDARN observed enhancements in ionospheric plasma flows near 14:00 MLT, associated with the time-dependent merging observed by Polar. A comparison of observations with MHD simulations of ISM confirms the existence of a high-latitude merging site and suggests that SuperDARN and Polar observed effects attributable to both exhaust regions of a temporally varying X-line. This interpretation is further confirmed with enhancements observed by the Cluster satellites. From these and other observed results during listed magnetopause encounters, we conclude that merging occurs preferentially near high latitudes, especially when the IMF clock angle is ~150°. While inferred high-latitude merging sites favor the parallel merging hypothesis, our data alone cannot exclude the possibility of a guide field. Merging can move away the equator even when the IMF has a strong southward component. ISM simulations suggest that this effect is due to tilting of the dipole axis away from the Sun. We also found that IMF By affects merging rates by enhancing/diminishing the effective dipole tilt angle. Observations show that high-latitude merging rates can vary temporally with periods of 1–3 min. These variations appear to be directly driven by variations in the interplanetary electric field (Maynard et al., 2001b), or may arise from unstable processes within the magnetosphere/Earth atmosphere interface.

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