Coupling the solar-wind/IMF to the ionosphere through the high latitude cusps

Nelson C. Maynard,
Mission Research Corporation

Abstract

Magnetic merging is a primary means for coupling energy from the solar wind into the magnetosphere-ionosphere system. The location and nature of the process remain as open questions. By correlating measurements from diverse locations and using large-scale MHD models to put the measurements in context, it is possible to constrain our interpretations of the global and meso-scale dynamics of magnetic merging. Recent evidence demonstrates that merging often occurs at high latitudes in the vicinity of the cusps. The location is in part controlled by the clock angle in the interplanetary magnetic field (IMF) YZ plane. In fact, B_Y bifurcates the cusp relative to source regions. The newly opened field lines may couple to the ionosphere at MLT locations of as much as 3 hr away from local noon. On the other side of noon the cusp may be connected to merging sites in the opposite hemisphere. In fact, the small convection cell is generally driven by opposite hemisphere merging. B_X controls the timing of the interaction and merging sites in each hemisphere may respond to planar features in the IMF at temporally different times. Correlation times are variable and are controlled by the dynamics of the tilt of the interplanetary electric field phase plane. The orientation of the phase plane may change significantly on time scales of tens of minutes. Merging is temporally variable and may be occurring at multiple sites simultaneously. Accelerated electrons from the merging process excite optical signatures at the foot of the newly opened field lines. All-sky photometer observations of 557.7 nm emissions in the cusp region provide a "television picture" of the merging process and infer the temporal and spatial variability of merging, tied to variations in the IMF.

1. Introduction

The cusp and dayside boundary layers that form the magnetopause mediate how energy from the solar wind couples into the magnetosphere-ionosphere system. Magnetic merging at the magnetopause between magnetic fields of opposite polarity was proposed by *Dungey* [1961] to interconnect the interplanetary magnetic field (IMF) with the Earth's magnetic field, breaking an IMF field line into two open field lines tied through the cusps to each ionosphere. As these open field lines are dragged anti-sunward by their tie to the solar wind, they drive convection in the northern and southern polar caps. Merging is now generally accepted as the primary mechanism for coupling. Questions remain as to (1) *where* merging takes place, (2) *when*, or on what time scale, is merging actively happening, and (3) even *how* the process is accomplished. High resolution electric and magnetic field and energetic particle measurements provide new tools for investigating these basic questions. Over the last several years, a number of new insights have been gained from combining and/or correlating remote measurements in the ionosphere (both ground- and space-based), in situ measurements at the magnetopause with Polar and Cluster, measurements upstream in the solar wind to monitor the input from the solar wind, and simulations using magnetohydrodynamic (MHD) models of the whole solar-wind/magnetosphere/ionosphere system. Addressing problems with simultaneous data from multiple satellites and diverse locations within the context of the large-scale picture from the simulations constrains our interpretations. In this paper we will apply these new insights to each of these basic "reporter" questions, after first providing a quick overview on methods that have been used to experimentally establish the existence and location of magnetic merging. The paper is meant to be a synopsis and a synthesis of recent results, details of which are in the referenced papers, and not a comprehensive review.

2. Merging Primer

Magnetic merging is a local reconfiguration of the magnetic field in which fields of opposite polarity merge, resulting in a new configuration, and magnetic energy converted to kinetic energy. At the magnetopause, interplanetary magnetic field lines connect to closed magnetospheric field lines to create two open magnetic field lines that have one foot in each hemisphere's ionosphere and extend out into the solar wind. 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 [e. g., *Gonzales and Mozer* 1974]. The remaining parallel component is usually referred to as a guide field.

What happens at the separator at the center of the X configuration, some times referred to as within the "black box", to provide parallel electric fields and dissipation necessary for merging is an open question. Both ion and electron gyrotropy must be broken. The questions revolve around "how". A recent review of the physics involved has been done by *Scudder* [1997]. Hall and pressure gradient terms must be considered in the generalized Ohm's law. Other terms involve anomalous resistivity and electron inertia. Simulations using both MHD and particle-in-cell (PIC) codes have been compared in the Geospace Environmental Modeling (GEM) magnetic reconnection challenge [see *Birn et al.*, 2001 and associated papers in the same issue]. Simulations which included the Hall effect, bringing the dynamics of whistler waves into the system, all produced similar rates of reconnection or merging [*Birn, et al.*, 2001]. Observationally, the breaking of gyrotropy of both ions and electrons at a merging site above the cusp for northward IMF has been definitively identified by *Scudder et al.* [2002a].

Since most measurements are away from the merging separator, proxies in the data for identifying that merging has taken place have been developed. Minimum variance analyses [*Sonnerup and Ledley*, 1974] of magnetic field measurements (often combined with maximum variance of electric fields [e. g. *Kawano and Higuchi*, 1995]) have been employed to show that the magnetopause was a rotational discontinuity with a finite B_{normal} and $E_{tangential}$, which are proportional to the merging rate. The existence of a rotational discontinuity is a necessary, but not sufficient, condition for merging. However, establishing an unambiguous finite B_{normal} can be difficult. Rotational discontinuities satisfy the Walén relationship, which specifies that the change in the ion velocity is proportional to the change in the magnetic field. Often the proportionality constant found in the data is different from $\pm$ 1. *Scudder et al.* [1999] showed that the Walén test is better done with electrons. More recently *Ma et al.* [2002] have shown that, depending on how the merging topology is crossed, minimum variance may provide an erroneous normal direction and even the Walén test may be compromised.

Another commonly used proxy for merging is the identification of accelerated flows of magnetosheath plasma observed near the subsolar magnetopause [*Paschmann et al.* 1979; *Sonnerup et al.* 1981]. 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]. This is a necessary, but not sufficient, condition for merging to have occurred. While accelerated plasmas were observed during some ISEE-1 magnetopause crossings, *Aggson et al.* [1984] also reported decelerated flows. Moreover, they emanated from a merging site poleward of the satellite. *Scudder* [1984] calculated that, as the merging site moved off the equator, the exhaust velocity from the X-line should equal the sum from the merging acceleration and the local magnetosheath velocity at the merging site. This becomes especially significant for X-lines located at high latitude where the open field lines from the backside of the separator are draped over the nose to the opposite hemisphere cusp and may have decelerated flows.

Recently, *Maynard et al.* [2002b] have used wave Poynting flux as an additional discriminator for merging. The magnetic reconfiguration in the merging process must be communicated away from the X along the separatrices via Alfvén waves carrying field aligned currents [see *Atkinson*, 1992; *Ma and Bhattachargee*, 2001]. These waves will have a parallel Poynting flux. Its direction, like the accelerated particles, will be away from the source. Again, this is another necessary, but not sufficient, proxy.

Crooker [1979] offered an alternative hypothesis in which merging occurs wherever magnetospheric and magnetosheath field lines are aligned antiparallel to each other. For most IMF orientations antiparallel merging proceeds at high latitudes on the magnetopause. It is of particular interest to note that on the basis of the first high-altitude magnetopause and cusp measurements by the Heos-2 satellite, *Haerendel et al.* [1978] concluded that the merging process is intermittent, of small scale, and located predominantly in the cusp region. *Sibeck and Newell* [1994] have also argued for continuous and patchy, sporadic merging in the vicinity of the cusps. Both the antiparallel and component merging hypotheses locate merging at the equator for periods of southward IMF and at the poleward boundary of the dayside cusp during periods of purely northward IMF. Differences occur for the intermediate clock angles, which are the most common situations. We will address this when we answer the question “where”.

In a series of papers in the early 1990s Cowley and Lockwood developed the concept of pulsed reconnection or merging [see *Cowley and Lockwood*, 1992]. It was a component-merging based hypothesis that merging happened in bursts, separated by gaps when no merging was taking place at a particular location. The typical repetition rate was 8 min, similar to the typical repetition rate for flux transfer events, which were originally discovered in the ISEE-1 and -2 data taken near the nose by *Russell and Elphic* [1979]. In these pulses of merging open flux was added to the dayside ionosphere, which stimulated convective flow and the ionospheric convection pattern. Others have argued that merging was more continuous, varying in rate and location [see *Newell and Sibeck*, 1994]. In fact, most of the theory of the process has been developed around steady state merging. Considering the variability of the magnetic field in the solar wind and the magnetosheath, the process is unlikely to be steady, although it may be occurring somewhere continuously. We will address this when we attempt to answer the question “when”.

3. A New Perspective on Solar Wind Coupling to the Magnetosphere

Results from two sounding rockets, launched into the ionospheric extension of the cusp from Ny-Ålesund in the Svalbard archipelago north of Norway, compelled consideration of a new view of the propagation of structures in the interplanetary magnetic field (IMF) in the solar wind and their effects on the merging process. The most startling result of *Maynard et al.* [2000, 2001c] was the correlation, in each case, of electric field variations seen in the ionosphere by the sounding rocket with small-scale variations in the effective interplanetary electric field nearly 200 R_E upstream. The variations in both data sets had scales of minutes. Remarkably, the lag time was less than the advection time (the time that a feature would take to transit the intervening distance using the measured solar wind velocity). The observed correlations indicated that surfaces of constant phase in the interplanetary electric field (IEF) must be tilted with respect to the Sun-Earth line. The sense of tilt was such that first interactions with the magnetosphere occurred on the Southern Hemisphere magnetopause. This forced the conclusion that the interaction with the magnetosphere that was causing the variations seen at the rocket in the Northern Hemisphere ionosphere had to be in the Southern Hemisphere.

Two additional assumptions were made by *Maynard et al.* [2001c] to harmonize these observed correlations of interplanetary and ionospheric dynamics. First, merging locations are determined using the antiparallel criterion of *Crooker* [1979]. The data are insufficient to specify whether field lines at the merging site are exactly antiparallel or have a small guide field; however, the results are more easily explained if merging proceeds near the two cusps rather than at low magnetospheric latitudes. Second, an optical signal in the ionosphere marks every merging event. In the dayside cusp, poleward moving 630.0 nm auroral forms associated with flux transfer events [*Sandholt et al.*, 1986] reflect prolonged access of magnetosheath plasma to the ionosphere. We suggest that a prompt optical responses also occurs in the ionosphere following small-scale variations in the merging rate/location. In following effects of such small-scale IEF variations it is necessary to examine variations of 557.7 nm, rather than 630.0 nm auroral emissions, because of the long lifetime of the $O(^1D)$ state.

To illustrate some of the concepts involved when tilted phase planes in the solar wind interact with the magnetosphere ionosphere system, we use the cartoon of *Maynard et al.* [2001c; 2002a] for conditions when the IMF was dominated by $B_Y > 0$ and $B_X < 0$ (with slightly negative B_Z). The two top plots of Figure 1 show the last closed field line surface generated by the T96 magnetic field model [*Tsyganenko and Stern*, 1996]. To give the magnetosphere its normal shape, mantle field lines were added poleward of the cusp. The basic indentation of the cusp with emanating field lines is shown along with the connected sash [*White et al.*, 1998; *Maynard et al.*, 2001a]. For $B_Y > 0$ the separator passes through the dawn (dusk) side of the cusp in the Southern (Northern) Hemisphere. The yellow planes in the top two plots of Plate 1 represent surfaces of constant IEF phase. The tilt angle is comparable to estimated values during the two rocket studies. The upper left plot shows the phase plane impacting the separator first on the Southern Hemisphere dawn side, equatorward of the cusp. The yellow dashed line represents a conceptual mapping of recently opened field lines near the northern cusp as a result of merging in the Southern Hemisphere. Newly merged field lines are pulled tailward and toward dawn by $\mathbf{J} \times \mathbf{B}$ (magnetic tension) forces at the magnetopause [*Siscoe et al.*, 2000] as the solar wind flows past the Earth. The top right plot shows the same phase plane at a later time as it interacts with the Northern Hemisphere antiparallel merging site. In the case of $B_Y > 0$, the Northern Hemisphere antiparallel merging site is located near the dusk side of the cusp for $\theta > 90°$, in the sash for $\theta \approx 90°$, and on the poleward edge of the cusp with northward B_Z. The orange line designates potential Northern Hemisphere merging sites. Note that when the phase plane reaches the orange line, it has already passed the time and location associated with component merging.

Figures 1a and 1b are simplified to emphasize the timing of the interactions in each hemisphere. Phase planes that are coplanar in the solar wind are distorted by the decreasing velocity in the magnetosheath and drape over and around the magnetopause before the IMF merges with the Earth's magnetic field. For the sake of illustration, Figure 1 ignores delays and associated field-line draping occurring as the solar wind slows in the magnetosheath [*Shepherd et al.*, 1999]. Of importance here is the fact that, because of the tilt and the negative B_X, merging occurs *first* in the Southern Hemisphere and *later* in the Northern Hemisphere. When B_X is involved, the two hemispheres may respond to the same feature at different times as a consequence of high latitude merging.

The convection pattern shown in the lower left quadrant of Figure 1 is placed on a magnetic latitude versus magnetic local time (MLT) grid. It was derived using the *Weimer* [2001] (W2K) convection model, represented in inertial coordinates. *Maynard et al.* [1995] showed that cusp potential patterns are well ordered in the inertial reference frame in which the throat between the two cells resides near noon for both polarities of B_Y, in agreement with the statistical position of cusp particle precipitation. Estimated projections of the Northern and Southern Hemisphere merging lines are represented by the orange and yellow dashed lines, respectively.

For the correlations found by *Maynard et al.* [2000; 2001c] to exist, logic demanded consideration of phase plane tilt and high latitude locations of the merging sites. The concept of tilted phase planes was then explored extensively by *Weimer et al.* [2002] using simultaneous data from four satellites in the solar wind. They allowed the lag time between any two satellites to vary and found a method of calculating that lag on a minute by minute basis. A simple variable lag shift harmonized all three components of the IMF, correlating the data where in some cases no obvious correlation existed. When the positions of the other three satellites were adjusted by the variable lags relative to ACE, all four became located in the same plane. Moreover, that plane underwent significant orientation shifts with scales of tens of minutes. The significance of this is that more phenomena, observed in the cusp, may have direct ties to the solar wind than we previously have been able to identify. It is important to get the timing for the interaction correct and to remember that the hemispheres may respond at different times, especially when B_X becomes dominant.

4. Where?

The previous section introduced the necessity, at least in some cases, for high latitude merging, which favors the anti-parallel merging hypothesis of *Crooker* [1979]. This is in contrast to the more prevalent view that whenever B_Z is negative, component merging occurs nearer the equatorial plane along a separator passing through the nose, but tilted somewhat by B_Y [following *Sonnerup*, 1974; *Gonzalez and Mozer*, 1974]. However, it is consistent with the conclusions of *Haerendel et al.* [1978] that merging is predominently in the cusp region.

The high latitude location illustrated conceptually by Figure 1 would be around the rim of the cusp, with the location dependent on the strength and direction of IMF B_Z relative to B_Y. The merging site is post-noon (pre-noon) in the Northern Hemisphere if B_Y is positive (negative). The opposite is true for the Southern Hemisphere. The rim around the indentation of the cusp is in part from the Chapman-Ferrero currents, whose closure above the cusp depresses the magnetic field inside the loop [see *Siscoe et al.*, 2000]. Figure 3 of *Siscoe et al.* [2002c] shows how the indentation moves post-noon as the clock angle increases through 90° and back to being centered about noon as the clock angle approaches 180°.

Maynard et al. [2002b] utilized data from Polar, Cluster and SuperDARN to conclude that merging is often at high latitudes for clock angles less than 150°. In their featured example from March 12, 2001, Polar was skimming the magnetopause above the nose, Cluster was passing through the Northern Hemisphere cusp post-noon, while SuperDARN monitored the convective flow patterns in the ionosphere. Figure 2 shows the satellite locations and an expanded insert with the configuration of the four Cluster spacecraft. Spacecraft separations was of the order of 600 km at this time. At the magnetopause crossing Polar observed accelerated particles and parallel wave Poynting flux from above the spacecraft, which was poleward of the nominal component merging line, indicating that the source was at high latitude. The minimum variance normal and an electron Walén test confirmed the location above the spacecraft. None of these tests are sufficient in themselves, but as a group, the tests point to a conclusion that Polar was monitoring the back exhaust region of a high latitude merging line. *Maynard et al.* [2002b] present evidence that SuperDARN and Cluster monitored the forward exhaust effects of the high-latitude X-line.

Interpretations of satellite measurements can be tested for reasonableness through comparisons with predictions of simulations using the Integrated Space Weather Model (ISM). ISM is a large-scale magneto-hydrodynamic (MHD) code developed by Mission Research Corporation to simulate the magnetosphere-ionosphere system from 40 R_E upstream in the solar wind, to the base of the ionosphere near the Earth, and to -300 R_E in the magnetotail [see *White et al.*, 2001]. To conceptually illustrate the connectivity between diverse regions that Polar, Cluster and SuperDARN were monitoring, Figure 3 [from *Maynard et al.*, 2002b] identifies a high latitude merging site in an ISM run with an IMF input clock angle of 135°. Last 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. A last-closed and first-open field line pair, traced from the Northern Hemisphere ionosphere, are shown in Figure 3a and labeled 0 and 1. They map from the black dot in the potential pattern in Figure 3b, near 15 MLT and 71° magnetic latitude, and pass through the post-noon cusp. Field-line 0 also traverses the low latitude region of the post-noon magnetopause. This closed field line maps to near the zero equipotential line between the two convection cells in the Southern Hemisphere.

A number of field lines have been traced from a series of points along the Northern Hemisphere equipotential that passes through the origin of trace 0 to understand how the field lines change after merging. The first 4 of these, labeled 2-5 in Figure 3a, demonstrate the evolution of a field line above the separator, 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 0 and is labeled 2' - 5'. Although there is no way to trace the evolution of exact pairs from a merging site, these file lines illustrate the evolution below the separator and how the newly opened field lines drape over the dayside magnetopause. Line 2' probably pairs best with 2. We infer a high-latitude merging site to be located close to where line 1 bends. The open field lines below a high latitude merging site from an open boundary layer over the dayside magnetopause [see also *Maynard et al.*, 2002a].

Figure 3c shows the complete set of first open field lines traced from each hemisphere. The field lines are colored according to V_Y. The Northern Hemisphere set of field lines in Figure 3a are colored red in Figure 3c to show their position relative to the first open field lines. Most prenoon (postnoon) field lines have a negative (positive) V_Y. Exceptions to this are in the cusp where $\mathbf{J} \times \mathbf{B}$ forces from the currents associated with the curvature of newly merged field lines drive flow westward (eastward) in the Northern (Southern) Hemisphere [*Siscoe et al.*, 2000]. Figures 3d - 3f display the front, top, and side views of Northern Hemisphere closed and open field lines in Figure 3a colored with V_Y. Flow in the boundary layer on the closed field line (0) is toward dusk. Flow above (in) the cusp on line 1 is toward dusk (dawn). Subsequently the flow is toward dawn, both above and in the cusp, as the field line is dragged back through the mantle.

With this conceptual picture, *Maynard et al.* [2002b] connected velocity enhancements measured between 1400 and 1500 MLT in the ionosphere by SuperDARN with enhancements in the merging rate measured above the nose postnoon by Polar, as it was skimming the magnetopause. Polar observed accelerated ions and wave Poynting flux originating above the satellite, which was located 10° above the component merging line of *Gonzalez and Mozer* [1974]. Minimum variance analysis and an electron Walén test also placed the X above the spacecraft. They concluded that the merging was at high latitudes. Based on Figures 1 and 3, the location was probably near the postnoon side of the cusp.

Figure 4 shows the temporal response of the maximum velocity measured by SuperDARN in the 1400 to 1500 MLT region where the field lines in Figure 4 mapped. Three enhancements are marked with the corresponding times of enhancements at Polar. The connectivity between ground-based and satellite measurements continued as Cluster passed outward through the cusp 20 minutes later. The effects of temporally varying merging were observed at Cluster, which correlated with enhancements at SuperDARN shown in Figure 4. Following the conceptual picture in Figure 3, Cluster, as it crossed into the magnetosheath, would have observed effects near the outer separatrix from merging below the spacecraft, while SuperDARN measurements would be more connected to the inner separatrix, or the open-closed field line boundary.

Cluster, with the four spacecraft in an approximate tetrahedral configuration, provided an additional test on the location conclusions. The current inside the configuration was estimated by determining the curl **B** [*Dunlop et al.*, 2002]. Figure 5 displays local currents derived using a GSM coordinate system centered on Cluster 2. Also plotted are the divergence of **B** as a percentage of the curl **B** and the magnitude of **B** at the locations of the four spacecraft. Maxwell's equations demand that $\nabla \cdot \mathbf{B} = \mathbf{0}$, if the calculations were performed without error. Currents determined where the divergence-to-curl ratio exceeds 50% should be treated with caution. In general, for this configuration, the expected error in J is at minimum 20%. Most of the large values of the divergence occur when the currents are small, highlighting their uncertainty. However, when the currents are large, the divergence ratio is in general small indicating where the calculated currents are reasonably valid. The curl **B** calculation integrates the currents over the scale size of the tetrahedron (600 km). The largest current was detected between 1214 and 1215 UT, as the spacecraft passed from the depressed magnetic field region of the cusp out into the magnetosheath, and is primarily in the $+Z$ and $-X$ directions, noted by the green bars. It takes the four spacecraft over a minute to cross the main current layer, indicating its temporal stability. Thus, the center of this current should be well resolved. Counterclockwise Chapman-Ferraro currents on the dusk edge of the cusp have the anticipated direction. This places Cluster near the sidewall of the cusp. The observed wave Poynting flux and particle accelerations were from below the spacecraft. This infers that the high-latitude merging location was consistent with Figure 3 and close to the conceptual orange hook in Figure 1. Cluster was above the merging site.

When we consider that Polar and SuperDARN were showing temporally varying merging at high latitudes 20 min previous, and that the variations in the accelerated particles and Poynting flux at Cluster also connect to the SuperDARN variations, currents related to time varying merging also may be expected signatures at Cluster. J_Y is the most variable component showing both polarities, although the strongest are currents in the $-Y$ direction. Some of the variability could occur if the current scale size was less than that of the Cluster configuration. Currents from structures of scale size less than 600 km may suffer from this error. Attention is directed to negative J_Y excursions observed between 1206 and 1207, 1211 and 1211:40, and 1214:30 and 1215 UT marked by red bars. There is also an associated smaller $-J_X$ excursion. These correspond to times when negative velocity enhancements in the negative Y direction were observed both in the particle moments and ExB. This suggests that the variations in J_Y are related to temporally varying merging.

Thus *Maynard et al.* [2002b] have connected ionospheric signatures in the 1400 to 1500 MLT region with high latitude merging on the afternoon side of the cusp. Connecting merging to the 1400+ MLT region implies a wide cusp in the ionosphere. A width of the order of 4 hours was in fact found by *Maynard et al.*, [1997]. The picture from the simulations provided by Siscoe et al. [2002c] shows that the cusp itself is shifted toward dusk (dawn) for positive (negative) B_Y. The merging location may not generally be symmetric about noon. The high latitude merging location was confirmed by Polar measurements above the nose. In fact, in 13 merging events reported by *Maynard et al.* [2002b], a high-latitude merging site was inferred whenever the IMF clock angle was less than 150°. Based on both Polar data and ISM simulation results, the merging site can move off the equator even for 180° clock angles when the dipole is tilted or there is a large IMF B_X. These results favor antiparallel locations, but do not exclude a small guide field. Nor can we exclude component merging at a location remote from the measurements. However, *Maynard et al.* [2002b] pointed out that high latitude merging in the MHD simulations was remarkable in itself. The MHD code accomplishes merging through dissipation, either explicitly introduced through current dependent resistivity, or introduced by the numerics of the partial donnar method (PDM) of *Hain* et al. [1987] where ever large gradients need to be mediated in the code. Even in the presence of dissipation explicitly introduced to aid merging, which is keyed to where the current exceeds a threshhold (primarily located at the nose in the subsolar region and in the plasma sheet in the magnetotail), the code adds dissipation, and therefore merging, at high latitudes to satisfy the externally applied boundary conditions.

Returning to the rocket results, *Maynard et al.* [2001c] found that B_X, and the resulting tilted phase planes, forced consideration of merging in the opposite hemisphere driving a portion of the cusp in the local hemisphere near local noon. While B_Y bifurcated the cusp relative to source location, B_X controlled the timing of the interaction at each location. These results and recent work of *Coleman et al.* [2001] point toward not only high latitude merging, but also the split merging separator hypothesized in the antiparallel scenario of *Crooker* [1979] and further defined by *Luhman et al.* [1984]. Whenever B_Y is dominant, the principal merging locations are at high latitudes on opposite sides of noon in the opposite hemispheres, the ends of which are loosely connected by a velocity separator across the nose at noon. Note that *Wing et al.* [2001] have put forward a different scenario for a bifurcated cusp suggesting that a high latitude merging source be combined with a near equator component merging source.

5. When and on what time scales does merging occur?

The influence of B_X on the timing of interactions leads naturally to the next question of when and on what time scales does merging occur. The *Cowley and Lockwood* [1994] picture of temporally dependent merging implies that all flux transfer occurs in short episodic merging events of component merging in the near equatorial regions followed by periods where no merging takes place. Repetition time for these events is typically six to ten minutes. Many have tied these episodic events to flux transfer events (originally discovered by *Russell and Elphic*, [1989]) and ionospheric signatures such as poleward moving auroral forms of *Fasel et al.* [1992]. However, these episodic events seem to have larger scales than those previously inferred from the measurements associated with flux transfer events. The merits of pulsed merging versus more continuous, but time-dependent, merging have been debated at a recent conference in articles by *Lockwood* [1994], *Sibeck and Newell* [1994], and *Maynard, et al.* [1994].

In placing merging at high latitudes *Maynard et al.* [2001c] also concluded that the rate was varying on time scales of 1-2 minutes, driven by variations in the IMF. In addition to the correlation between the solar wind electric field and the electric fields measured by the rocket, *Maynard et al.* [2001c] also found optical responses in all-sky images at 557.7 nm which peaked at every enhancement in the effective solar wind electric field. The variations in the green line were harmonized with the IMF measurements over more than 20 minutes, implying time varying, but nearly continuous, directly-driven merging. The location was closer to the implied open-closed field line boundary. 557.7 nm emissions generally imply more energetic electrons than those typically found in the cusp away from the open-closed boundary, probably 500 eV or greater in energy. *Maynard* [2002] suggested that these could be generated during active merging, which makes localized 557.7 nm emissions a signature, in fact a "television" record, of the spatial and temporal variability of the merging process on the magnetopause. These localized 557.7 nm emissions are separate from the larger-scale and more diffuse background aurora from higher-energy plasma-sheet electrons found in the closed field line region, and identified as "type 5" dayside aurora by *Sandholt et al.* [1998].

Figures 6, 7, and 8 show sequences of 557.7 nm all-sky images, taken every 30 s and projected to 150 km [*Maynard* 2002]. Referring back to the cartoon of Figure 1 for positive B_Y, the expected merging locations in the local hemisphere would be on the orange hook pattern on the dusk side of the high-altitude cusp and projecting down to the dusk side of the cusp in the ionosphere. The location on the hook depends on the relative strength and polarity of B_Z. For negative B_Y the hook would be on the morning side of the cusp. In Figures 6, 7, and 8 an orange hook has been overlaid to guide the eye. Magnetic north is toward Greenland in the upper left of the images. In the sequence in Figures 6 and 7 in which B_Y dominates, localized emissions appear and disappear on time scales of 90 s to a few minutes. Multiple sites are active simultaneously, often initiating at different times. The emissions roughly follow the hook with activity present in all images. Note that the emissions are elongated and point toward the center of the image, which indicates that these structures are rays with the length tied to their vertical extent. The sequence in Figure 8 occurred 15 minutes later when a significant negative B_Z was also present. Note that the emissions have moved to the front side of the hook as hypothesized. They are still temporally varying, but have continuity over larger spatial scales.

Placing these results back into the context of the high altitude cusp, merging would be expected to be occurring in short temporal bursts of time scales of a few minutes or less at multiple locations simultaneously on the rim of the cusp. The locations would shift from the dusk edge of the rim toward the frontside and noon as the clock angle increases, as shown in the cusp configuration from Figure 3 of *Siscoe et al.* [2002c]. This is a much different temporal response than would be expected from the pulsed reconnection model of *Cowley and Lockwood* [1992], which is based on near equatorial component merging and which may exist under other IMF conditions. The temporal variations are consistent with the observations from *Maynard et al.* [2002b], discussed above in the context of Figures 3, 4, and 5, and the earlier conclusions of *Haerendel et al.* [1978]. These results favor observations of small spatial-scale, temporally-variable merging at high latitudes around the cusp with time scales of a few minutes of less. High-latitude merging is expected to be more temporally variable, since an X-line will not be intrinsically stable when the tangential magnetosheath flow is super-Alfvénic [*Cowley and Owen*, 1989; Rodger et al., 2001]. The temporal variability observed by *Maynard et al* [2001c] has its source in the opposite hemisphere. One may expect that temporal variations will be seen in the optical responses from both near and remote hemisphere merging sites as the cusp is bifurcated by B_Y.

6. How?

All of the above observations and conclusions have involved data taken well away from the merging separator. The question of how merging is in fact accomplished, or the microphysics of the process, can therefore not be addressed by those events. One recent experimental investigation does, however, address how and has bearing on the previous conclusions. *Scudder et al.* [2002a] used Polar observations above the cusp with northward IMF to discern that the spacecraft stayed in close proximity to the merging separator for over 25 minutes on May 29, 1996. In addition to the usual tests described above, they were able to confirm that both ion and electron gyrotropy were broken. Parallel electric fields are a necessary condition for merging. The first direct measurement of parallel electric fields at the separator was made, and it was shown that they are derived from the electon pressure gradient force, rather than from anomalous resistivity. The magnetic field reached machine zero at the separator indicating antiparallel merging with no guide field in this northward IMF case. These results provide strong evidence that the ambipolar and Hall terms provide the necessary physics in the Ohm's Law for accomplishing merging at the separator. In fact, ambipolar electric fields may occur in other situations in addition to merging in the vicinity of the magnetopause such as depletion layers [*Scudder et al.*, 2002b].

The long duration of the satellite in the vicinity of the separator indicates a steady state process, albeit with possible rate variations. This is in contrast to the temporally and spatially varying properties of high latitude merging discussed above. The *Scudder et al.* [2002a] event was for northward IMF and was located above and behind the cusp. The other merging events described above were deduced to be located on the side and front walls of the cusp. All locations would not intrinsically support steady reconnection because of the super-Alfvénic tangential magnetosheath flow [e. g., *Rodger et al.*, 2001]. Two factors deserve consideration to resolve this issue. First, in the *Scudder et al.* [2002a] event the nominal magnetosheath flow would be through the X. *Siscoe et al.* [2002] have pointed out that in their MHD simulations an active merging site above the cusp remains stationary in the presence of fast flowing magnetosheath plasma. They refer to this as flow-through reconnection (FTR). In the simulation a tongue of weak magnetic field extends sunward from the null point. The tongue is also characterized by strong electric current, and it has a part where the velocity is sub-Alfvénic. Whether FTR can in reality provide a means for steady state reconnection above the cusp remains to be checked experimentally. Secondly, the back wall of the cusp may serve as a barier to mediate the flow. The Interball satellite has found non-linear turbulence in a boundary layer at the indentation of the cusp [e. g., *Savin et al.*, 2002a, 2002b]. They postulate that the turbulence is indicative of patchy merging. The role of this turbulent boundary layer relative to merging needs further study.

7. Implications

These results point to commonly-occurring, high-latitude merging. The optical results and the event of March 12, 2001 depict the process also as temporally varying on scales of a few minutes or less, of small spatial scale, and may be occurring at multiple sites at any particular time. Cluster, with its ability to separate spatial from temporal and to measure currents is an ideal mission to verify these implications.

A consequence of high latitude merging is an open boundary layer draped over the nose [*Maynard et al.*, 2002a]. Whenever B_Y is comparable or greater than the other components, the cusp is bifurcated relative to its source region. The newly opened field lines on the backside of the X connect to the opposite hemisphere cusp. As a result, the small convection cell is in fact driven from merging in the opposite hemisphere [*Maynard et al.*, 2001b, 2001c]. Also the open boundary layer may be quite thick back along the flank of the magnetopause [*Maynard et al.*, 2001a].

Perhaps the broadest and most far-reaching implications come from the consideration of B_X and the resulting tilted phase planes [*Maynard et al.*, 2001c; *Weimer et al.*, 2002]. The tilt can greatly change the lag time from an upstream solar wind monitor, and that lag time, as well as the phase plane tilt, can vary significantly on scales of 10s of minutes. Tilted phase planes and B_X lead to merging at high latitudes and timing differences between merging in each hemisphere. *Maynard et al.* [2001c] found a difference in interaction times of 14 min. Care must be taken in determining the variable lag to assess possible correlation of magnetosphere and ionosphere phenomena with the IMF system inputs. The correlations found by *Maynard et al.* [2000, 2001c] and the coherence of small scale variations between 4 spacecraft in the solar wind found by *Weimer et al.* [2002] show that many small scale phenomena in the magnetosphere-ionosphere system may be directly driven.

B_X serves to enhance or diminish the effective dipole tilt [*Crooker*, 1992]. In the MHD simulations, increasing the dipole tilt can push the merging site off the equator, even for purely southward IMF [*Maynard et al.*, 2002b]. Remember that the dipole tilt varies $\pm$ 12° each day from the Earth's rotation and $\pm$ 23.5° with season. Adding to or subtracting from these changes with B_X means that merging may shift to or away from the equatorial or high latitude regions with UT, season, and sector structure.

Identifying an optical response from active merging provides a new tool for understanding solar wind coupling to the magnetosphere-ionosphere system. High resolution 557.7 nm all-sky observations have been made now for the second winter at Ny-Ålesund in Svalbard (J. Moen, private communication), and their analysis should improve our understanding of the temporal and spatial behavior of magnetospheric merging, especially at high latitudes.

Acknowledgements. I am grateful to my co-authors on the papers that this work synopsizes. Special thanks go to W. J. Burke, D. M. Ober, and D. R. Weimer, who have been the closest to these efforts. F. S. Mozer, J. D. Scudder and M. Dunlop contributed ideas and analysis techniques. We thank the instrument PIs on Polar and Cluster, F. S. Mozer, J. D. Scudder, C. T. Russell, M. Andre, A Balogh, and H. Rème, and to R. Pfaff, PI for one of the rockets, for access to the data. S. W. H. Cowley and G. L. Siscoe also provided helpful comments. We are grateful to C. W. Smith and D. J. McComas for use of the ACE magnetic field and plasma data, and to R. P. Lepping and K. W. Ogilvie for use of the Wind data. The work at MRC was supported by NASA contract NASW-02017, NASA grant NAG5-3182 (subcontract to the University of California, Berkeley) and by the NASA Sun-Earth Connections Theory Program Grant NAG5-8135 (subcontract to Boston University). The ISM was developed under sponsorship of the Defense Threat Reduction Agency, 45045 Aviation Drive, Dulles, VA 20166-7517. Cluster is a mission of the European Space Agency and its member countries.

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N. C. Maynard, Mission Research Corporation, 589 West Hollis Street, Suite 201, Nashua, NH 03062 (e-mail: nmaynard@mrcnh.com)

Received 2002; revised 2002; accepted 2002.

Figure 1. Cartoon illustrating the various merging sites in the magnetosphere and ionosphere and their relationship to the aurora [*Maynard et al.*, 2001c]. The top two plots show a 3-D representation of the magnetopause defined by the last closed field line surface from the Tsyganenko 96 model with mantle field lines added. The yellow phase plane is shown abutting the Southern Hemisphere merging site in the left plot and encountering the Northern hemisphere cusp region in the right plot. Newly opened field lines in the Southern Hemisphere would pass by the dotted yellow region in the Northern Hemisphere in the top left. The orange line in the top right schematically delineates possible Northern Hemisphere merging sites, applying the antiparallel criterion. The bottom two plots depict the ionospheric configuration. Mapped onto a W2K convection pattern and an all-sky image are the field of view of the optics, the approximate rocket and DMSP trajectories, and the projections of the merging sites color coded for comparison with the top plots. Note that the all-sky image is inverted from the potential pattern, with both shown in their most commonly displayed orientation. (see text)[from *Maynard et al.*, 2001b, 2002a]

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Figure 2. Plots of the Polar orbit in the XZ and YZ solar magnetospheric (SM)coordinate planes and of the Cluster orbit in the XZ and XY geocentric solar ecliptic (GSE) planes. The regions of interest are highlighted by the red ovals. Nominal magnetopause and bow shock configurations are indicted in panels a, c and d as appropriate. The circles at the origin represent the Earth. In panel c the insert shows the configuration of the 4 Cluster spacecraft with Cluster 3 leading and Cluster 4 trailing. The tetrahedron configuration is maintained quite well during the interval of interest. Spacecraft separation is of the order of 600 km [from *Maynard et al.*, 2002b].

Figure 3. Traced magnetic field lines from a MHD simulation using the Integrated Space Weather Model (ISM). Figure 3a 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 Figure 3b to be between 15 and 16 MLT and 71° latitude. All others are open. Figures 3d-3f show three views of these same field lines colored with the Y component of the velocity. Figure 3c shows the complete set of first open field lines traced from the ionosphere in each hemisphere and also colored with V_Y (see text)[from *Maynard et al.*, 2002b].

Figure 4. The maximum velocities and their locations determined by SuperDARN for the interval between 1100 and 1300 UT [from *Maynard et al.*, 2002b].

Figure 5. (a-c) Currents in GSM coordinates determined by the Curl B calculation. The calculation is centered on Cluster 2. (d) The ratio of the divergence of B to the curl of B expressed in per cent. The ratio provides an indication of where the calculation is reliable (see text). The magnitude of B is given in the bottom panel for context [from *Maynard et al.*, 2002b].

Figure 6. All-sky images of 557.7 nm emissions taken every 30 s, starting at 0700:15 UT on December 16, 1998. The orange hook is an approximation of the mapping locus of the Northern Hemisphere merging line for IMF BY negative, following the conceptual cartoon of Figure 1 (see text). Its placement is approximate and meant to guide the eye only. Note that features appear and disappear at various positions on the hook on time scales of 1 to 2 min [from *Maynard et al.*, 2002].

Figure 7. All-sky images of 557.7 nm emissions taken every 30 s, starting at 0703:15 UT on December 16, 1998. The orange hook is an approximation of the mapping locus of the Northern Hemisphere merging line for IMF BY negative, following the conceptual cartoon of Figure 1 (see text). Its placement is approximate and meant to guide the eye only. Note that features appear and disappear at various positions on the hook on time scales of 1 to 2 min.

Figure 8. All-sky images of 557.7 nm emissions taken every 30 s, starting at 0715:45 UT on December 16, 1998. The orange hook is an approximation of the mapping locus of the Northern Hemisphere merging line for IMF BY negative, following the conceptual cartoon of Figure 1 (see text). Its placement is approximate and meant to guide the eye only. Note that 15 minutes later than the observations in Figure 6, the emissions are all on the equatorward portion of the hook [from *Maynard et al.*, 2002].