Cluster survey of cusp reconnection and its IMF dependence

C. Twitty,[1] T. D. Phan,[1] G. Paschmann,[2] B. Lavraud,[3] H. Rème,[4] and M. Dunlop[5]

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[1] We have surveyed the occurrence of tailward-of-the-cusp reconnection detected by Cluster as a function of the interplanetary magnetic field (IMF) clock angle. The survey covers 3 years (2001–2003) of cusp and magnetopause (MP) crossings and is restricted to periods of relatively stable IMF. Our survey indicates that the reconnection associated plasma flows occur almost exclusively when the IMF has a northward component (or the clock angle is within ~90° of the GSM +z direction). This finding at first seems inconsistent with the component merging model which should allow reconnection to occur for larger than 90° clock angle (or less than 90° in magnetic shear angle). However, it is possible that this is a geophysical effect. When the IMF has a southward component, reconnection equatorward of the cusp could prevent tailward-of-the-cusp reconnection by (1) creating low-shear condition behind the cusp, and (2) preventing the formation of a plasma depletion layer adjacent to dayside MP, resulting in super-Alfvenic magnetosheath flows at high latitude. No reconnection flows can be detected sunward of the X-line in this regime. Finally, the occurrence rate of tailward-of-the-cusp reconnection flows is ~90% when the IMF has a northward component, indicating that simultaneous reconnection in the northern and southern cusps is common during northward IMF. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 7835 Space Plasma Physics: Magnetic reconnection. **Citation:** Twitty, C., T. D. Phan, G. Paschmann, B. Lavraud, H. Rème, and M. Dunlop (2004), Cluster survey of cusp reconnection and its IMF dependence, *Geophys. Res. Lett.*, *31*, L19808, doi:10.1029/2004GL020646.

1. Introduction

[2] In-situ observations have established the occurrence of reconnection jets at the low-latitude MP [e.g., *Paschmann et al.*, 1979] as well as the high-latitude MP tailward-of-the-cusp [e.g., *Gosling et al.*, 1991].

[3] At the low-latitude MP, reconnection signatures have been detected for a large range of IMF orientation [e.g., *Scurry et al.*, 1994] and local magnetic shear angle [e.g., *Paschmann et al.*, 1986; *Fuselier et al.*, 2000]. The Scurry et al. study found nearly equal occurrence of low-latitude enhanced flows for the IMF clock angle range of 60°–180°. Similarly, *Phan et al.* [1996] found nearly equal probability of detecting reconnection flows for the local shear range of 60°–180°.

[4] At the high-latitude MP tailward of the cusp, reconnection signatures have been reported when the IMF is northward [e.g., *Kessel et al.*, 1996]. However the occurrence of cusp reconnection for the full range of IMF clock angle is not known from in-situ observations. Here we report the results of a systematic survey of cusp and MP crossings by the Cluster spacecraft in 2001–2003 to investigate the IMF range in which reconnection flows originating from tailward-of-the-cusp reconnection are detected either at the MP or in the high-altitude cusp.

2. Individual Events

[5] We present 2 examples of tailward-of-the-cusp reconnection events, one detected at the MP and the other in the high-altitude cusp (see Figure 1). These examples help illustrate the selection criteria used in the statistical survey in Section 3.

2.1. 2002-03-18: Tailward-of-Cusp Magnetopause

[6] Figures 2a–2d show Cluster observations of reconnection associated accelerated (or decelerated) flows at the MP tailward of the cusp [see also *Phan et al.*, 2003]. These flows are seen between the 2 dashed lines in Figure 2b. The GSM flow components show that between 14:56:10 (dotted line) and 15:03:52 UT (right dashed line), the flow deflection (relative to magnetosheath flow) was sunward ($\Delta v_x > 0$). However, $\Delta v_x < 0$ between 14:54:52 (left dashed line) and 14:56:10 UT. The flow reversal is indicative of the passage of an X-line. The observed flow change across the MP in the sunward-of-the-X-line interval agrees with the reconnection predicted flow change $\Delta \mathbf{v}_{pred} \sim \pm \Delta \mathbf{B}(\mu_0 \rho_{sheath})^{-1/2}$ [*Paschmann et al.*, 1979] to within 87% in magnitude and 9° in angle (see Table 1). During the MP crossing, the IMF was northward with variable duskward B_y. The clock angle (=$\tan^{-1}[B_y/B_z]$) varied between 35° and 40°. In this event, the magnetosheath β is 1.1 and the flow next to the MP is sub-Alfvenic ($M_A \sim 0.8$).

2.2. 2001-02-04: Northward IMF High-Altitude Cusp

[7] Figure 3 shows plasma jets detected at the tailward edge of the high-altitude cusp [see also *Lavraud et al.*, 2002]. On its outbound pass at ~13 MLT from the lobe (before 19:50 UT) to the magnetosheath (after 22:00 UT), the Cluster spacecraft crossed the high-altitude cusp (19:50–22:00 UT). At the tailward edge of the cusp, adjacent to the lobe, jets were detected in the 19:56:50–20:26:40 UT interval (between the two dashed lines). These jets are downward (earthward) directed and have a significant negative y component. The IMF was persistently northward ($B_z > 0$) and

[1]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[2]Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany.
[3]Los Alamos National Laboratory, Los Alamos, New Mexico, USA.
[4]Centre d'Etude Spatiale des Rayonnements, Centre National de la Recherche Scientifique, Toulouse, France.
[5]Rutherford Appleton Laboratory, Oxford, UK.

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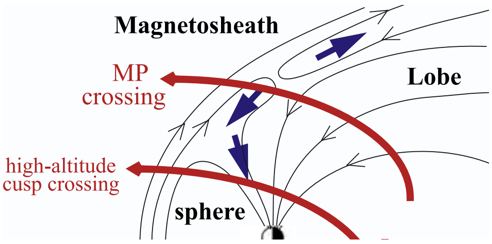

Figure 1. The effective trajectories of Cluster (from January to June of 2001–2003) through tailward-of-the-cusp MP or high-altitude cusp. Reconnection flows originating from tailward-of-cusp reconnection can be detected sunward of the X-line by both types of crossings.

duskward ($B_y > 0$) and the IMF clock angle varied between 0° and 60° in the jet encounter interval.

[8] The jet detection at the tailward edge of the cusp indicates a tailward-of-the-cusp source. The negative y component of the perpendicular flow (Figure 3c) is consistent with tailward-of-the-cusp reconnection with a positive IMF B_y. Also consistent with the tailward-of-the-cusp reconnection interpretation is the presence of "reversed energy-latitude ion dispersion," where low-energy cutoff declines with increasing x_{GSE} due to time-of-flight effect associated with sunward field line convection [e.g., *Reiff*, 1984].

3. Statistics

3.1. Selection Criteria and Reconnection Evidence

[9] We survey the IMF dependence of all reconnection events detected by Cluster (as in Section 3) in January–June of 2001–2003 at either (1) the MP tailward of the cusp or (2) the high-altitude cusp. Mid- and low-altitude reconnection flows are not surveyed here because they have lower speeds and the inclusion of such cases could introduce selection biases where only the high-shear (small clock-angle) cases are identifiable. We restrict the survey to those crossings for which the IMF has consistent (northward or southward) direction during and around the crossings. This restriction minimizes errors resulting from incorrectly propagating the IMF structures from ACE (~210 Re upstream) to the high-latitude reconnection site. With this restriction, 12 MP and 19 high-altitude cusp jet encounters were found (Tables 1 and 2).

[10] For all tailward-of-the-cusp MP crossings during stable IMF we identify reconnection events based on the agreement between the observed and predicted flow change. Events where the flow velocity change agrees with prediction to better than 50% are deemed reconnection events [*Phan et al.*, 1996]. This selection criterion would include low-shear as well as high-shear events. To combine reconnection events detected at the MP with those in the high-altitude cusp (Section 3.2) in the same survey (Section 4) we restrict our survey to the sunward of the X-line portion of the reconnection flow and record the time-shifted IMF in that interval. Note that we do not require the MP flow to be sunward. It only needs to be sunward accelerated relative to the magnetosheath flow. Table 1 provides information on the 12 MP crossings in terms of the reconnection flow interval, the boundary conditions around the current sheet and the shear-stress balance test. In all 12 cases the rotational discontinuity jump condition is well satisfied. The velocity change agrees with prediction to better than 88% on average in magnitude and 7° in angle. Furthermore, even though not required by our selection criteria, all 12 MP events have reversals in the x and z components of the velocity, i.e., jets in the MP are sunward and equatorward directed, opposite to sheath flow. The flow reversals in all events, together with good agreement with flow prediction, are consistent with the jets being the result of reconnection.

[11] For each high-altitude cusp crossing we identify jets at the tailward edge of the cusp. Because the jets are easily discernable (e.g., see Figure 3) from their surroundings, the interval can be picked without imposing a velocity threshold for event selection. Although the shear-stress balance test cannot be performed on the jets detected in the cusp because this test has to be done across the MP, the flow behavior is consistent with reconnection. Figure 4 shows $v_{\perp_y}$ averaged over the jet interval as a function of the average clock angle over the same interval (blue points). The positive (negative) correlation between the two quantities in the southern (northern) hemisphere for nearly all events is consistent with the jets being the result of tailward-of-the-cusp reconnection when detected sunward of the X-line. Note that $v_{\perp_y}$ of the MP jets (green points) also shows the expected correlation. Table 2 contains a list of all high-altitude cusp jet events. The "reversed ion dispersion" is clearly observed in all 19 cases, further supporting the reconnection interpretation.

3.2. Dependence on IMF Clock Angle

[12] The top panel of Figure 5 shows the occurrence of tailward-of-the-cusp reconnection (as detected at the MP

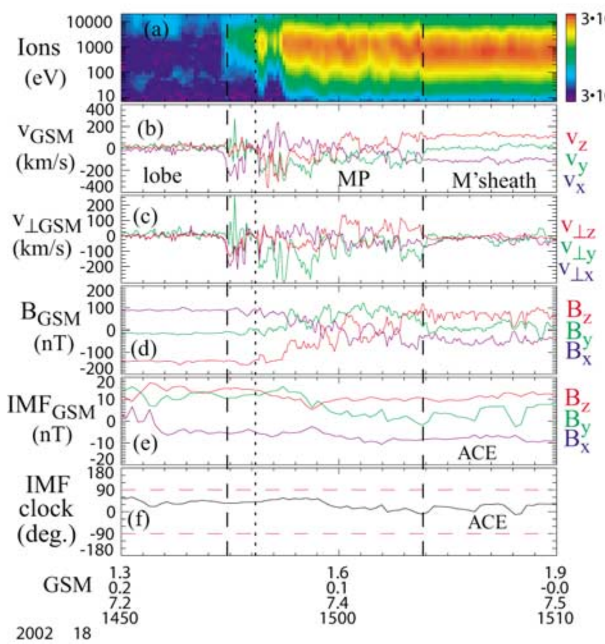

Figure 2. Cluster crossing of tailward-of-cusp MP. (a–d) Cluster ion spectrogram (in eVs^{-1} cm^{-2} ster^{-1} eV^{-1}), velocity, perpendicular velocity and magnetic field, respectively. (e–f) IMF and clock angle, $\tan^{-1}(B_y/B_z)$. Sunward-of-the-X-line jets are between the dotted line and the right dashed line.

Table 1. Tailward-of-Cusp Magnetopause Crossings With Reconnection Jets

Jet Interval	MP Time[a]	Sheath Time[a]	$\lvert\Delta v\rvert/\lvert\Delta v_A\rvert$[b]	Angle[c] (deg.)	$\lvert B_{Sh}\rvert/\lvert B_{lobe}\rvert$[d]	Allowed Shear[e]	Obs. Shear[e]	$v_{x,MP}$	$v_{z,MP}$	$v_{x,sh}$	$v_{z,sh}$	$M_{A,sh}$	β_{sh}	Cl. Ang.[f]	MLT	Lat.
01-03-05/0807:00–0811:10	0810:03	0814:31	0.85	1	0.78	39	92	171	−275	−51	42	0.2	0.4	81	13.6	72
01-03-31/1138:20–1142:38	1141:39	1143:04	1.08	9	0.64	50	161	266	−476	−123	46	0.5	1.2	−5	12.7	72
01-04-12/1009:50–1013:10	1013:33	1015:18	0.84	3	0.88	28	61	273	−311	−104	88	0.2	0.1	−70	11.2	63
01-04-21/2142:20–2146:32	2146:26	2148:38	0.82	1	0.62	52	161	66	−118	−52	38	0.5	2.3	−85	8.9	57
02-01-05/1954:32–2011:40	1954:48	1950:59	0.88	5	0.80	36	160	38	49	−32	−13	0.3	0.2	−65	14.7	−45
02-02-03/0914:40–0915:15	0914:50	0914:02	0.92	12	0.45	63	136	64	116	−20	−26	0.3	2.7	−45	11.8	−58
02-03-18/1456:10–1457:30	1457:29	1500:21	1.13	9	0.75	41	134	156	−254	−106	136	0.8	1.1	38	12.4	78
02-03-25/0733:48–0741:40	0734:04	0728:06	1.01	12	0.90	26	77	101	90	−132	−129	0.4	0.1	−57	9.4	−68
02-04-10/2311:03–2313:21	2313:08	2310:07	0.71	13	0.85	32	153	146	126	−72	−49	0.6	0.3	26	12.7	−81
03-01-28/1556:46–1556:46	1557:36	1555:48	1.15	3	0.68	47	154	240	395	−75	−95	0.6	0.9	8	11.7	−69
03-03-07/1626:55–1642:00	1627:20	1549:01	1.06	5	0.91	25	115	43	323	−149	−75	0.7	0.5	−49	11.6	−73
03-04-09/2316:10–2320:30	2319:46	2311:20	1.03	9	0.76	41	169	198	204	−109	−168	0.9	0.9	−13	14.1	−83

[a]MP and magnetosheath times used in the shear stress balance test.
[b]Ratio of observed to reconnection predicted flow change.
[c]Angle between observed and predicted flow change.
[d]Ratio of magnetosheath to lobe magnetic field strengths.
[e]Allowed ($\cos^{-1}[\lvert B_{sheath}\rvert/\lvert B_{lobe}\rvert]$) and observed magnetic shear (in degrees).
[f]IMF clock angle.

and in the high-altitude cusp) as a function of the IMF clock angle. The IMF clock angle corresponding to each (12-s time-shifted) ACE magnetic field measurement in the jet interval is counted in this statistics. These flows occur nearly precisely when the IMF clock angle is within 90° of the GSM +z direction. We have also normalized the occurrence distribution by the distribution of IMF clock angle (gathered in January–June of 2001–2003) to remove the IMF clock angle occurrence biases. The normalized distribution remains essentially the same (not shown).

4. Summary and Discussions

4.1. IMF Dependence

[13] The key finding of our statistical survey is that tailward-of-the-cusp reconnection seems to occur almost exclusively when the IMF has a northward component. When the IMF has a southward component, the high-altitude cusp typically reveals ion dispersion consistent with dayside reconnection instead of reversed dispersion, the transition from the cusp to the mantle/lobe is gradual (with no sharp boundaries or magnetic shear), and no reconnection flow signatures are seen near the lobe/mantle or at tailward-of-the-cusp MP.

[14] The finding of cusp reconnection being confined to northward IMF seems inconsistent with the component merging model which should allow reconnection to occur for larger than 90° clock angle (or less than 90° in magnetic shear as seen at the low-latitude MP). But first one needs to establish that this is the correct expectation from component merging behind the cusp. If the magnetic field strength is vastly different on the two sides of the high-latitude MP, the minimum allowable shear angle $\cos^{-1}(\lvert B_{sheath}\rvert/\lvert B_{lobe}\rvert)$ [*Sonnerup*, 1974] for component merging would be smaller than but close to 90°, which would not be significantly different from our result. We examined the field strength asymmetry in the 12 MP cases (Table 1). The field ratio varies between 0.45 and 0.91, with an average of 0.75. Thus the minimum shear for component merging varies between 63° and 23°. One therefore should have observed

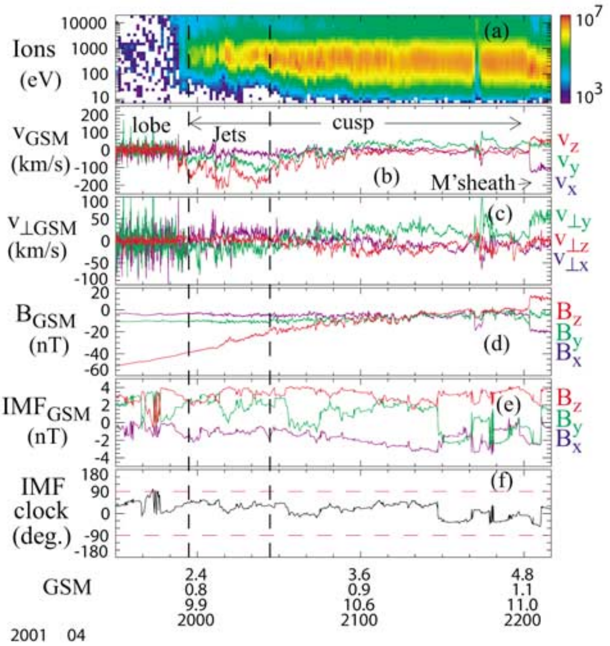

Figure 3. Cluster crossing of the high-altitude cusp. The parameters are the same as in Figure 2. Reconnection flows are between the dashed lines.

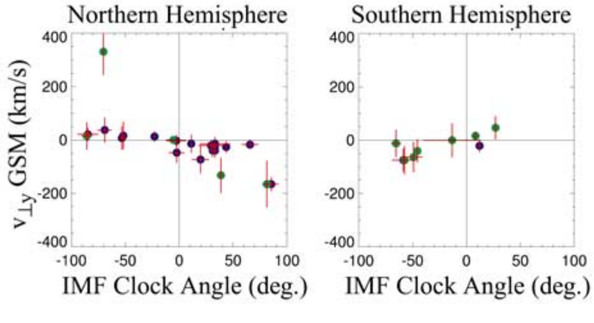

Figure 4. Y component of the perpendicular velocity versus the IMF clock angle for MP (green) and high-altitude (blue) jet events. Each point represents the average over the jet interval and the vertical and horizontal bars represent the standard deviations.

reconnection events for clock angle ≫ 90°, whereas all 12 jet events have clock angle < 90°.

[15] However it is possible that our finding indicates a geophysical effect rather than the failure of the component merging model. When the IMF has a southward component (clock angle > 90°), reconnection occurs equatorward of the cusp and may prevent cusp reconnection. This can happen as follows. First, equatorward-of-the-cusp reconnection and subsequent convection of the field lines into the lobe could result in very low magnetic shear (and consequently no reconnection) at tailward-of-the-cusp MP. Furthermore, dayside reconnection could prevent the formation of a plasma depletion layer (PDL) adjacent to the low- and high-latitude MP, resulting in super-Alfvenic magnetosheath flows at high latitudes. No accelerated reconnection jets can be detected sunward of the X-line in this regime. It is noted that the magnetosheath flows in all 12 MP cases are sub-Alfvenic (Table 1). It is unclear if the flows are indeed super-Alfvenic immediately tailward of the cusp when the IMF has a southward component.

[16] The finding of cusp reconnection being confined to northward IMF suggests that reconnection rarely occurs simultaneously equatorward and tailward of the cusp when the IMF has a southward component. On the other hand, the previous finding of equatorward-of-the-cusp reconnection for shear of 60°–180°, coupled with the present survey, would suggest that simultaneous equatorward and tailward-of-the-cusp reconnection could occur for northward IMF. These conclusions would be consistent with the ground based observations by *Sandholt et al.* [1998] where such simultaneous reconnection occurs for northward but not for southward IMF.

[17] It should be emphasized that our survey of reconnection flows detected sunward of the X-line indicates that reconnection does not occur in the sub-Alfvenic regime when the IMF is southward. This survey would not find signatures of reconnection sites formed further tailward in the super-Alfvenic regime. Whether such cases would affect our conclusion is unclear.

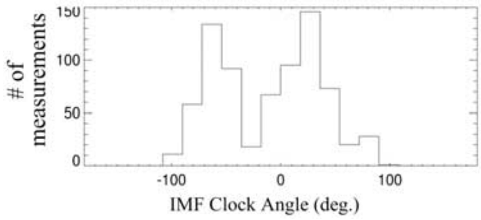

Figure 5. Occurrence of tailward-of-the-cusp reconnection. The occurrence is found to be confined almost exclusively to positive IMF B_z.

Table 2. High-Altitude Crossings With and Without Jets

Jet Interval	Rev Disp?[a]	Cl. Ang.[b] (deg.)	MLT (hrs)	Lat. (deg.)	Alt. (R_E)
High-Altitude Cusp Crossings With Jets					
01-02-04/1956:50–2026:40	y	33	13.1	75	10.4
01-03-09/1644:40–1648:20	y	12	11.6	−71	8.0
01-03-17/0509:30–0512:44	y	33	11.2	74	8.3
01-04-02/0104:02–2110:10	y	−52	9.2	60	8.4
02-01-25/0750:20–0752:46	y	−22	18.1	69	8.5
02-02-06/0643:30–0648:20	y	−51	15.3	66	9.9
02-02-25/0523:16–0525:08	y	66	13.3	83	7.8
02-02-27/1544:30–1553:20	y	−84	12.7	69	9.1
02-03-04/0856:05–0858:10	y	75	14.4	75	8.1
02-03-09/0256:05–0259:00	y	33	9.9	75	7.9
02-03-16/0203:16–0602:25	y	31	11.9	76	7.8
02-03-23/0602:25–0613:05	y	−1	12.3	66	8.6
03-02-12/0846:50–0852:00	y	−2	16.9	72	8.0
03-02-17/0300:00–0310:50	y	20	12.1	82	8.0
03-02-24/0601:40–0608:00	y	30	14.9	80	7.7
03-03-15/0738:50–0740:30	y	85	12.7	67	8.3
03-03-20/0050:40–0053:40	y	11	9.0	72	7.3
03-03-22/1108:10–1110:50	y	−68	12.5	63	8.5
03-04-08/0138:00–0142:40	y	44	9.4	66	7.2
High-Altitude Cusp Crossings Without Jets					
01-03-21/2306–2311	n	54	8.8	68	7.9
01-03-24/0834–0839	n	−85	12.6	72	8.3
02-04-08/1435–1445	n	64	7.6	−75	9.6

[a]Is "reversed ion dispersion" clearly present?
[b]IMF clock angle.

4.2. Occurrence Rate of Tailward-of-Cusp Reconnection

[18] The analysis in Section 3 in terms of IMF dependence involves only cases where reconnection flows are detected. It was found that these flows only occurred when the IMF has a northward component. Now we turn the question around and ask how often tailward-of-the-cusp reconnection occurs when the IMF does have a northward component. We found that the 12 MP crossings in Table 1 are all the MP crossings that occurred when the IMF was northward and relatively stable. Thus for the MP, the occurrence rate is 100%. For the high-altitude crossings during stable northward IMF, in addition to the 19 cases with jets, we found 3 cases without clear jet signatures (Table 2). Thus the overall reconnection occurrence rate (combining the MP and the cusp cases) is better than 90%.

[19] This occurrence rate is substantially higher than the 50% occurrence rate of reconnection flow signatures observed equatorward of the cusp for southward IMF [*Phan et al.*, 1996]. This difference at first seems surprising since the reconnection occurrence rate is often thought to be highest at the dayside MP where the solar wind compression is strongest. The reason may be related to the dependence on the IMF of magnetosheath plasma β adjacent to the MP. Previous studies found that reconnection events tend to correspond to low magnetosheath β (<2) [e.g., *Paschmann et al.*, 1986]. The plasma β in all the MP cases here is indeed low, varying between 0.1 and 2.7, with an average of 0.9 (Table 1). The occurrence of low β, which favors reconnection, could be related to the presence of the PDL under northward IMF which extends to high latitudes [*Avanov et al.*, 2001]. Indeed, the PDL is clearly present in at least half of the MP events here. For southward IMF, the magnetosheath β next to the low-latitude MP tends to be higher because of the weaker or absence of a PDL.

[20] Finally, the high occurrence rate implies that simultaneous reconnection in the northern and southern cusps is common during northward IMF, but they may or may not involve the same flux tubes to create a boundary layer on closed field lines.

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References

Avanov, L. A., et al. (1996), High-latitude magnetic reconnection in sub-Alfvénic flow: Interball tail observations on May 29, 1996, *J. Geophys. Res.*, *106*, 29,491.

Fuselier, S. A., et al. (2000), Cusp observations of high- and low-latitude reconnection for northward IMF, *J. Geophys. Res.*, *105*, 253.

Gosling, J. T., et al. (1991), Observations of reconnection of interplanetary and lobe magnetic field lines at the high-latitude magnetopause, *J. Geophys. Res.*, *96*, 14,097.

Kessel, R. L., et al. (1996), Evidence for high-latitude reconnection during northward IMF, *Geophys. Res. Lett.*, *23*, 583.

Lavraud, B., et al. (2002), Cluster observations of the exterior cusp and its surrounding boundaries under northward IMF, *Geophys. Res. Lett.*, *29*(20), 1995, doi:10.1029/2002GL015464.

Paschmann, G., et al. (1979), Plasma acceleration at the Earth's magnetopause: Evidence for magnetic reconnection, *Nature*, *282*, 243.

Paschmann, G., et al. (1986), The magnetopause for large magnetic shear: AMPTE/IRM observations, *J. Geophys. Res.*, *91*, 11,099.

Phan, T. D., et al. (1996), Low-latitude magnetopause and boundary layer for high magnetic shear: 2. Occurrence of magnetic reconnection, *J. Geophys. Res.*, *101*, 7817.

Phan, T. D., et al. (2003), Simultaneous Cluster and IMAGE observations of cusp reconnection and auroral proton spot for northward IMF, *Geophys. Res. Lett.*, *30*(10), 1509, doi:10.1029/2003GL016885.

Reiff, P. (1984), Evidence of magnetic merging from low-altitude spacecraft and ground-based experiments, in *Magnetic Reconnection in Space and Laboratory Plasmas*, *Geophys. Monogr. Ser.*, vol. 30, edited by E. W. Hones, p. 103, AGU, Washington, D. C.

Sandholt, P. E., C. Farrugia, J. Moen, Ø. Noraberg, B. Lybekk, T. Sten, and T. Hansen (1998), A classification of dayside auroral forms and activities as a function of interplanetary magnetic field orientation, *J. Geophys. Res.*, *103*, 23,325.

Scurry, L., et al. (1994), A statistical study of accelerated flow events at the dayside magnetopause, *J. Geophys. Res.*, *99*, 14,815.

Sonnerup, B. U. Ö. (1974), Magnetopause reconnection rate, *J. Geophys. Res.*, *79*, 1546.

M. Dunlop, Rutherford Appleton Laboratory, Oxford, UK.

B. Lavraud, Los Alamos National Laboratory, Los Alamos, NM, USA.

G. Paschmann, Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany.

T. D. Phan and C. Twitty, SSL, University of California, Berkeley, CA 94720, USA. (phan@ssl.berkeley.edu)

H. Rème, Centre d'Etude Spatiale des Rayonnements, Centre National de la Recherche Scientifique, Toulouse, France.