Simultaneous Geotail and Wind observations of reconnection at the subsolar and tail flank magnetopause

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[1] We report a fortuitous two-spacecraft conjunction when Geotail and Wind observed the occurrence of reconnection simultaneously at the subsolar and dawn tail flank magnetopause during stable B_y dominated IMF. Furthermore, bi-directional jets were observed by Geotail which indicate the presence of an X-line in the subsolar region. These observations are consistent with the presence of a tilted X-line hinged near the subsolar point and spanning the entire dayside (from subsolar to $X_{GSE} = -10$ R_E) magnetopause, as expected from component reconnection. In addition, our observations do not reveal any thickening of the boundary layer down the flanks, the plasma boundary layer being confined to the reconnecting magnetopause current layer. This suggests that reconnection dominates over diffusive entry or Kelvin-Helmholtz instability at the low latitude magnetopause even when the IMF clock angle is 90°. **Citation:** Phan, T. D., H. Hasegawa, M. Fujimoto, M. Oieroset, T. Mukai, R. P. Lin, and W. R. Paterson (2006), Simultaneous Geotail and Wind observations of reconnection at the subsolar and tail flank magnetopause, *Geophys. Res. Lett.*, *33*, L09104, doi:10.1029/2006GL025756.

1. Introduction

[2] The occurrence of reconnection at the subsolar [e.g., *Paschmann et al.*, 1979; *Sonnerup et al.*, 1981] and flank [e.g., *Gosling et al.*, 1986; *Phan et al.*, 2001] magnetopause has been well established by single spacecraft in-situ observations. Remote sensing methods have indicated the presence of an X-line spanning a large portion of the dayside magnetopause during southward IMF [*Fuselier et al.*, 2002; *Pinnock et al.*, 2003], but this has not been confirmed by in-situ measurements. Establishing the presence of extended X-lines in the magnetosphere by in-situ measurements requires the presence of widely separated multi-spacecraft detecting the same reconnection events. The chances for such conjunctions are exceedingly small because the boundary conditions (determined by the solar wind magnetic field) are highly varying. The only event ever reported where 2 spacecraft detected the same reconnection event at the magnetopause only allowed the deduction of a short X-line of 3 R_E(the separation distance between the spacecraft) [*Phan et al.*, 2000].

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[3] Here we report a fortuitous event where the Geotail and Wind spacecraft detected reconnection flow signatures simultaneously at the subsolar and tail flank magnetopause, indicating that reconnection occurs along the entire dayside (subsolar to tail flank) magnetopause even for B_y dominated IMF.

[4] In Section 2 we describe the orbit and instrumentations of Geotail and Wind during this event. Section 3 presents the observations. We summarize and discuss the implications of the observations in Section 4.

2. Orbit and Instrumentations

[5] Figure 1 shows that between 19:00–22:00 UT on Jan 13, 1996, the Geotail spacecraft skimmed the low-latitude ($z_{GSM} \sim 2$ R_E) magnetopause near, but slightly dawnward of the subsolar point. At the same time, Wind crossed the tail flank magnetopause at $x_{GSM} \sim -10$ R_E, and 6.6 R_E below the magnetic equator. Magnetosheath measurements were made by the IMP-8 at the dusk flank during the Geotail and Wind encounters of the magnetopause. Because the magnetic field clock angle is preserved across the bow shock, the magnetosheath clock angle ($\tan^{-1}[B_y/B_z]$) can be used as proxy for the IMF clock angle. Thus IMP-8 is the "solar wind monitor" for this event.

[6] The present study uses Wind plasma data obtained by the 3DP instrument [*Lin et al.*, 1995] with a temporal resolution of 49s except during one magnetopause crossing (20:29:56–20:35:55 UT) when 3s resolution data (collected in the burst memory mode) were available. Geotail plasma data are taken from the Low Energy Particle instrument [*Mukai et al.*, 1994] (also at 3 s resolution) for the magnetosphere and magnetopause intervals, and from the Comprehensive Plasma Instrument [*Frank*, 1994] (at 20 s resolution) for the magnetosheath intervals adjacent to the magnetopause. The magnetic field temporal resolution is much higher but for the present analysis the magnetic field data from Wind [*Lepping et al.*, 1995] and Geotail [*Kokubun et al.*, 1994] are averaged over 3 seconds.

[7] The boundary normal (LMN) coordinate system is used in this paper. It is defined such that the N axis points outward along the magnetopause normal and the (L, M) plane is tangential to the magnetopause with L oriented approximately due north and M due west (see Figure 2).

3. Observations and Analyses

3.1. Overview of Observations

[8] Figure 3 shows the Wind and Geotail crossings of the tail flank and subsolar magnetopause, respectively. Both

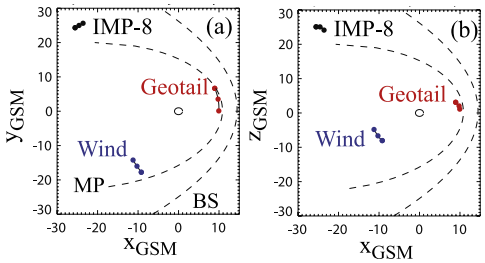

Figure 1. Wind, Geotail and IMP-8 spacecraft orbits at 19:00–23:00 UT on 1996-01-13. Geotail was near the subsolar magnetopause while Wind sampled the dawn flank magnetopause (x_{GSE} = −10 R_E). IMP-8 was in the dusk magnetosheath providing solar wind clock angle information.

spacecraft were at first in the magnetosphere. Wind crossed the tail flank magnetopause (3.8 hours MLT, −20° MLAT) fully at ∼20:30 UT into the magnetosheath, followed by multiple partial crossings back into the current layer until 21:00 UT (Figure 3c). The plasma flow in the magnetopause is nearly twice as fast as the magnetosheath flow. The Geotail spacecraft encountered the low-latitude boundary layer (LLBL) and the magnetopause multiple times near the subsolar region (13.3 hours MLT, 5° MLAT) from just before 20:00 UT to just after 21:00 UT. Plasma jets were also observed at the multiple crossings (Figures 3e and 3f). Several jets encountered by Geotail and Wind at the magnetopause occurred at precisely the same times (indicated by the red bars in Figures 3b and 3e) during this interval.

[9] During the 4 hours around the magnetopause crossings, the magnetosheath magnetic field measured by IMP-8 (Figure 3g) on the dusk side was remarkably steady, with the y component (∼15 nT) being the dominant field component (B_z∼ 0). Because the IMF clock angle is preserved across the dayside bow shock, we inferred from the IMP-8 measurements that the IMF clock angle (tan-1[B_y/B_z]) was ∼90°. The dominance of IMF B_y over B_z is

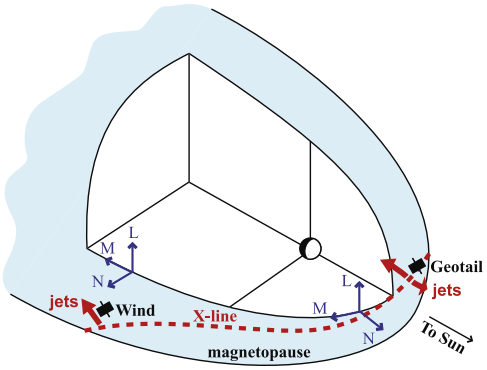

Figure 2. Schematic of a tilted X-line extending from the subsolar region to the high-latitude dawn flank. Observations at Wind indicate the presence of a stable and tilted X-line far below the magnetic equator. Bi-directional jets detected by Geotail suggest an X-line hinged near the subsolar point.

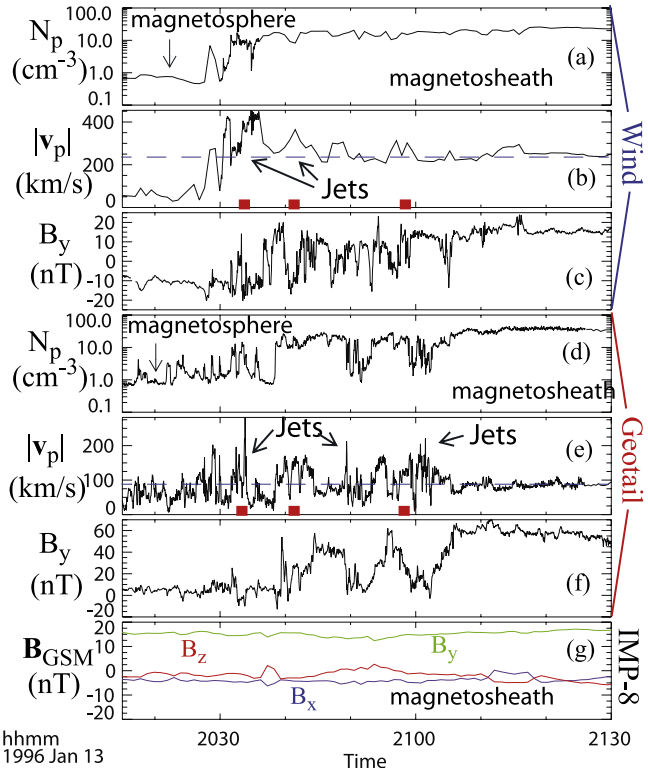

Figure 3. Overview of subsolar and dawn flank magnetopause crossings by Geotail and Wind, respectively, during steady and B_y dominated magnetosheath magnetic field condition. (a–c) Wind plasma density, flow speed and GSM-y component of the magnetic field. (d–f) Geotail plasma density, flow speed and GSM-y component of the magnetic field. (g) Magnetic field in GSM in the dusk magnetosheath sampled by IMP-8. The magnetopause current layers are easily recognized by changes in B_y at Wind and Geotail. Red bars in Figures 3b and 3e indicate intervals when Geotail and Wind detected jets simultaneously.

confirmed by the dominant B_M magnetosheath field (and B_L ∼ 0) measured by Geotail near the subsolar region (Figure 4h) and Wind at the dawn flank (Figure 4d).

3.2. Analyses of Wind Observations at the Tail Flank

[10] *Phan et al.* [2001] studied the present Wind crossing in great details. It was shown that the plasma jets seen by Wind were consistent with them being caused by reconnection. For one of the MP crossings (at 20:31:10–20:31:42 UT) when 3-s resolution Wind plasma data were available, the plasma flow in the deHoffmann-Teller frame is 98% of the predicted Alfven speed. The sense of the accelerated flows, being in the positive L and positive M direction (see Figures 4b–4c and the schematic in Figure 2), is consistent with the X-line being below the spacecraft. Phan et al. deduced based on the value of the normal magnetic field (∼−5 nT) that the X-line was situated ∼1 R_E from the spacecraft. Taking into account the position of Wind at Z_{GSM} = −6.6 R_E, this implies that the X-line was close to 8 R_E below the magnetic equator. The tilt of the X-line was inferred from the reconnection (accelerated) flow direction to be ∼60° from the equatorial plane.

[11] Flow enhancements (in V_L and V_M) were detected at all (complete and partial) crossings of the magnetopause in the 20:30–21:00 interval (Figure 4b–4c). This indicates that reconnection at the tail flank magnetopause was occurring continuously during this 30-min interval. The persistence of the flow jet direction also indicates that the X-line was always below and sunward of Wind the entire time. Thus the observations are consistent with a stable X-line rather than one that is formed closer to the subsolar region and simply convects past Wind on the flanks.

[12] Finally, Figures 3 and 4 show that there was no plasma (density) boundary layer beyond (earthward of) the magnetopause current layer. The density gradient across the magnetopause is confined to the reconnecting magnetopause current layer.

3.3. Analyses of Geotail Observations Slightly Duskward and Northward of the Subsolar Point

[13] In the 20:28–21:02 UT interval, that is, during the times when Wind detected dawnward and northward reconnection flows at the dawn flank, Geotail detected plasma jets near the subsolar region that were enhanced (relative to the magnetosheath flow) mostly in the duskward (negative **M**) and slightly southward (negative **L**) direction. Figure 5a displays the Walen analysis for a representative magnetopause crossings (at 20:55:25–20:56:00). It shows good agreement with the reconnection prediction. The flow velocity in the deHoffmann-Teller frame was well correlated with the Alfven velocity, with flow speed at 90% of the Alfven speed. The sense of the flow enhancement as well as the negative Walen slope are consistent with the reconnection site being dawnward and northward of Geotail at this time. However, at the next magnetopause crossings (at 20:56:25–20:56:38 UT), the flow was enhanced in the opposite (dawnward and northward) direction. The flow velocity in the deHoffmann-Teller frame for this interval was also well correlated with the Alfven velocity, with flow speed at 83% of the Alfven speed. But the slope is now positive (Figure 5b). The sense of the flow enhancement and the positive Walen slope indicate that the reconnection site was duskward and southward of the spacecraft during this brief interval. Finally, the deHoffmann-Teller velocities for the two consecutive magnetopause crossings are 173° to each other, consistent with Geotail being on opposite sides of the same X-line.

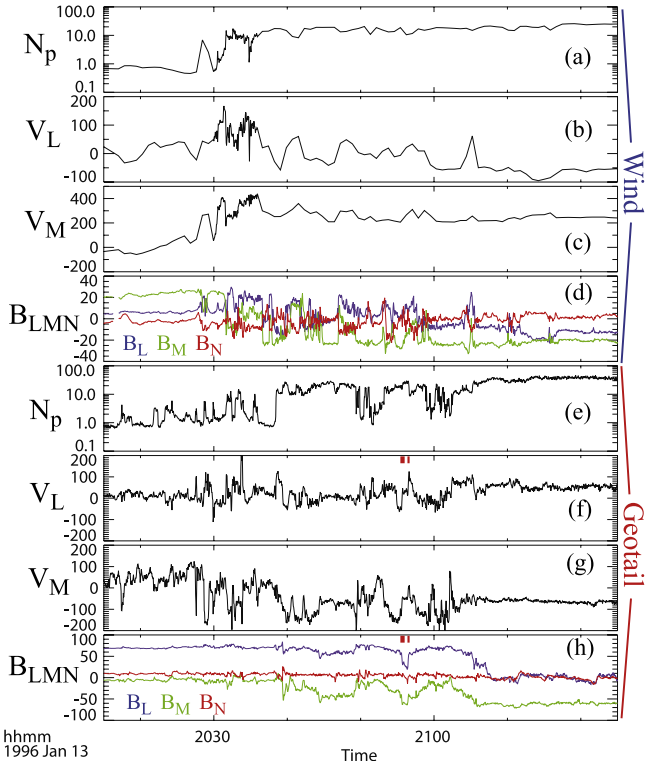

Figure 4. Zoom-in of Figure 3 showing the components of the velocity and magnetic field in the LMN boundary normal coordinate system. (a–d) Wind density, velocity and magnetic field. (e–h) Wind density, velocity and magnetic field. The horizontal red bars in Figures 4f and 4h indicate the intervals used in the Walen analysis in Figure 5.

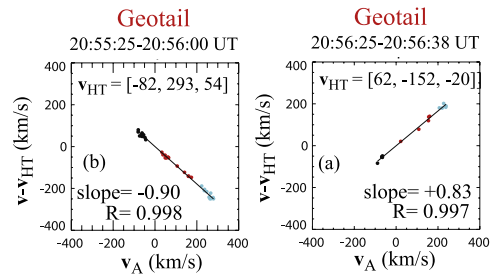

Figure 5. The Walen analysis at Geotail at consecutive magnetopause crossings at (a) 20:55:25–20:56:00 UT, and (b) 20:56:25–20:56:38 UT. These are scatter plots of the GSE components of flow velocity in the deHoffmann-Teller frame versus the Alfven velocity. The black, blue and red dots denote the x, y, and z components, respectively. The Walen slopes at the 2 consecutive magnetopause crossings have opposite signs and the two deHoffmann-Teller velocities (in km/s) are 173° to each other, consistent with the spacecraft being on the opposite sides of the same X-line during these 2 intervals.

4. Discussions

[14] We have presented, to the best of our knowledge, the first report based on in-situ measurements of simultaneous reconnection at the subsolar and tail flank magnetopause. We now discuss the implications of our observations for (1) component merging, (2) the extent of the X-line, and (3) the dominance of the reconnection process even when the IMF clock angle is 90°.

4.1. Component Merging and the Extent of the X-line

[15] The detection by Geotail in the subsolar region of bi-directional jets (with significant dawn-dusk component) at consecutive magnetopause crossings suggests the presence of a tilted X-line in the vicinity of the subsolar point, consistent with component reconnection [*Sonnerup*, 1974; *Gonzales and Mozer*, 1974]. This finding is similar to the previous reports of bi-directional jets in the subsolar region

(for a B_y dominated IMF) by *Kim et al.* [2002] and *Pu et al.* [2005]. The large dawn-dusk (M) component of the Geotail plasma jets provides further evidence for component merging [*Gosling et al.*, 1990].

[16] The observations of reconnection at the subsolar and tail flank occurring simultaneously and lasting at least half an hour at each location suggest that the two spacecraft detected a tilted X-line that spans the entire dayside magnetopause. The persistence of the reconnection flow direction observed at Wind indicates the presence of a stable X-line, rather than patches of reconnection X-lines that form and convect tailward. If we assume symmetry on the dusk side, such an X-line would be at least 50 R_E long. In a previous study, under purely southward IMF conditions, *Phan et al.* [2000] had interpreted the repeated detection of reconnection jets emanating from an equatorial X-line by Equator-S and Geotail at the dawn flank magnetopause to signify the presence of a 40 Re X-line spanning the entire dayside equator. Although no in-situ measurements were made at other magnetopause locations (including the subsolar region), radar observations for the same event suggested the presence of such an extended X-line [*Pinnock et al.*, 2003].

[17] It is interesting that the X-line in the present case of B_y dominated IMF (clock angle ~90 degrees) appears to be at least as long as for the purely southward IMF case. Since according to the empirical model of *Burke et al.* [1999], the cross polar cap potential drop for 90° IMF clock angle is only ~50% of the value for purely southward IMF (clock angle = 180°), this would imply that the reconnection rate must also be reduced by ~50% compared to the southward IMF case. Such a dependence of the reconnection rate on the magnetic shear would be consistent with some theoretical predictions [e.g., *Pritchett*, 2001].

[18] The finding of an extended X-line at the magnetopause is somewhat similar to our recent finding of a 390 R_E X-line in a solar wind current sheet [*Phan et al.*, 2006] which suggests that reconnection can operate in a large-scale and continuous mode.

4.2. Dominance of Reconnection for 90° IMF Clock Angle

[19] The thickness of the LLBL at the flank magnetopause can reveal the processes that lead to solar wind entry across the magnetopause. Thick flank LLBLs that have been reported to-date tend to be associated with northward IMF conditions [*Mitchell et al.*, 1987; *Phan et al.*, 1997, 2005; *Fairfield et al.*, 2000; *Hasegawa et al.*, 2004]. Diffusive entry or nonlinear Kelvin-Helmholtz Instability (KHI) have been suggested as the entry mechanisms in those studies. For southward IMF, the flank LLBL tends to be significantly thinner [*Mitchell et al.*, 1987] and in one event, *Gosling et al.* [1986] showed that there was no plasma boundary layer beyond the reconnecting magnetopause current layer. *Newell and Meng* [1998] and *Phan et al.* [2005] suggested that for southward IMF, the reconnection rate at the low-latitude magnetopause may exceed the rate of plasma entry from non-reconnection processes, to the extent that reconnection may destroy any pre-existing boundary layer. The open question is the state of the LLBL (hence the dominant process) when the IMF clock angle is 90°, that is, neither southward nor northward.

[20] In the present case of 90° clock angle, there was no boundary layer beyond the magnetopause current layer (or the reconnection layer) at the tail flank. There was no evidence for large KHI vortices since such large vortices would have deformed (and displaced) the magnetopause significantly and undoubtedly would have been detected by Wind during the hours when the spacecraft was in the vicinity of the magnetopause. It is also unlikely that the absence of a thick boundary layer is a latitude effect since the thick LLBL associated with KHI reported by *Hasegawa et al.* [2004] was observed by Cluster over a large range of magnetic latitudes. Our finding thus suggests that for 90° IMF clock angle, reconnection still dominates over other processes at the dayside magnetopause. However, low-latitude reconnection no longer dominates at the low-latitude magnetopause when the IMF turns northward [*Phan et al.*, 2005].

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