# Reconnection at the dayside low-latitude magnetopause and its nonrole in low-latitude boundary layer formation during northward interplanetary magnetic field

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[1] On 2001-12-02 Wind crossed the dayside magnetopause (MP) at ~15 MLT and traversed the adjacent low-latitude boundary layer (LLBL) over a period of 2 hours. The IMF was steady (northward and dawnward) during the MP/LLBL encounter. Reconnection flows were observed in the MP that were directed 130° away from the magnetosheath flow direction. In contrast, the LLBL flow was aligned with the magnetosheath flow. The counterstreaming field-aligned and anti-field-aligned electrons have different energies and their fluxes are unbalanced in the open MP whereas they are precisely balanced throughout most of the LLBL indicative of a closed LLBL. These observations indicate that reconnection occurs at the low-latitude MP during northward IMF (with a significant $B_y$), but low-latitude reconnection is not responsible for the creation of the LLBL. Instead, reconnection appears to be in the process of eroding a pre-existing LLBL that was created either by diffusive entry or by non-simultaneous double-cusp reconnection.
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## 1. Introduction

[2] The existence of the low-latitude boundary layer (LLBL) earthward of the magnetopause (MP) that contains magnetosheath plasma provides evidence for the transfer of plasma across the MP [*Eastman et al.*, 1976]. How the magnetosheath plasma crosses the MP has been a subject of debate. Candidate mechanisms include magnetic reconnection, diffusive entry, and Kelvin-Helmholtz instability and the dominance of these processes may be dependent on the IMF orientation.

[3] During southward IMF, reconnection is commonly observed at the low-latitude MP. A density and velocity boundary layer often exists beyond the magnetopause current layer. However, there are cases where the only plasma boundary layer is embedded in the current layer itself [*Gosling et al.*, 1986; *Eastman et al.*, 1996]. If reconnection occurs at the MP in such cases, one would naturally conclude that the plasma boundary layer (which is confined to the MP) is simply the reconnection layer itself. In other cases where a plasma boundary layer exists beyond the current layer, several studies have indicated that the outer part of the LLBL (which includes the magnetopause current layer) is usually on open field lines but the inner part may be on closed field lines [e.g., *Mitchell et al.*, 1987; *Fujimoto et al.*, 1996]. The origin of the closed inner LLBL is presently not known.

[4] When the IMF is strongly northward, reconnection at the low-latitude MP is less efficient or absent. The entire LLBL may be on closed field lines [*Mitchell et al.*, 1987; *Phan et al.*, 1997]. Processes such as Kelvin-Helmholtz instability (KHI) [e.g., *Miura*, 1984] or diffusive entry [e.g., *Sonnerup*, 1980; *Johnson and Cheng*, 1997] have been suggested to play a dominant role in the formation of the LLBL. *Phan et al.* [1997] pointed out that the tangential LLBL flow next to the low-magnetic-shear MP is well-aligned with the magnetosheath flow while the flow and density profiles are smooth and gradual across the LLBL, consistent with diffusive entry. On the other hand, evidence for LLBL formed by reconnection in both northern and southern cusps as suggested by *Song and Russell* [1992] has also been reported [e.g., *Le et al.*, 1996; *Fuselier et al.*, 2002].

[5] In this letter we report a case study of a dayside magnetopause and an extended LLBL under steady northward (and dawnward) IMF, with the IMF clock angle ~45°. In this event, reconnection signatures were detected at the local MP, but low-latitude reconnection does not appear to be responsible for the formation of the adjacent LLBL; it might be in the process of eroding a pre-existing LLBL instead.

## 2. Observations and Analyses

### 2.1. Overview of Observations

[6] On 2001-12-02 Wind crossed the dawnside MP and LLBL at ~ 15 MLT, −15 degrees magnetic latitude, and 11 $R_E$ in radial distance. Figure 1 shows the Wind encounter with the magnetosheath proper (before 05:35 UT), the plasma depletion layer (PDL) (05:35–06:34 UT), the MP (06:34–06:52 UT), the LLBL (06:52–08:31 UT), and the low-latitude plasma sheet. A schematic of the event and the LMN boundary normal coordinate system are shown in Figure 2. The PDL is characterized by magnetic field pile-up (Figure 1l), density (Figure 1d) and parallel temperature (Figure 1e) decrease on approach to the MP. The tangential flow ($V_M$) acceleration on approach to the MP in the PDL is associated with magnetosheath field draping [*Chen et al.*, 1993]. The MP is recognized by a magnetic field rotation (Figure 1n) of ~80°, from $\Phi_B$ = 30° in the PDL to $\Phi_B$ =

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$-50°$ in the magnetosphere. The LLBL is earthward of the MP, with gradually decreasing density and flow speed and increasing ion and electron temperatures. In the LLBL, the ion distributions consist of mixed magnetosheath and magnetospheric populations (Figure 1c), while the electrons are single population with energy between magnetosheath and magnetospheric energies (Figure 1j), i.e., keV magnetospheric electron population is absent. Furthermore, Figure 1o shows that large magnetic field fluctuations, $\delta B$, are observed at the MP, magnetosheath and the LLBL but the level of fluctuations diminishes abruptly at the entry into the magnetosphere at 08:31 UT.

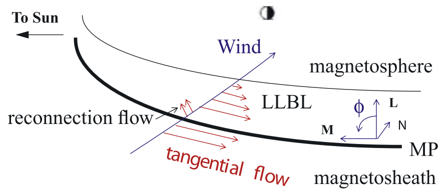


**Figure 2.** Schematics of the Wind crossing of the dayside (15 MLT) MP and LLBL. The tangential flow in the LLBL is well aligned with the magnetosheath flow whereas the magnetopause reconnection flow direction is drastically different (and has a sunward component). The LMN coordinate system is derived from GSM, with **N** normal to the magnetopause and pointing outward, **L** points approximately in the $z_{GSM}$ direction and **M** points west (and sunward), i.e., $\sim -y_{GSM}$.

[7] During the 2-hour MP/LLBL crossing, the IMF (Figure 1b) was steady and northward ($B_z \sim 5$ nT) and dawnward ($B_y \sim -5$ nT). The resulting IMF clock angle($=\tan^{-1}[B_y/B_z]$) is $\sim 45°$. Note that even though the clock angle is small, the magnetic shear across the MP at 15 MLT was 80°. This moderate shear is due partly to the inclined magnetic field in the magnetosphere at this local time and latitude. The solar wind ram pressure varied between 5 and 8 nPa (Figure 1a), but there are no systematic variations to account for the MP crossing, nor the extended residence time of the spacecraft in the LLBL. In fact, the gradual variations of the density, temperature and velocity in the LLBL interval indicate that the spacecraft steadily traversed the MP/LLBL. With single spacecraft one cannot reliably deduce the thickness of the LLBL, but it is noted that the radial distance along the spacecraft trajectory during the LLBL interval is $\sim 1$ $R_E$.

## 2.2. Reconnection Flow at the MP

[8] Figures 1h–1i show the presence of reconnection flows at the MP. As expected, the main component of the magnetosheath flows on the duskside at low latitudes points in the $-M$ direction (i.e., tailward) with $V_M$ reaching $-170$ km/s in the PDL right next to the MP. In the MP interval (06:34–06:52 UT), there are two instances when the flows were directed in the +M (sunward) direction. The flow reversal across the MP is indicative of reconnection. More quantitatively, if we take the first positive $V_M$ flow (right

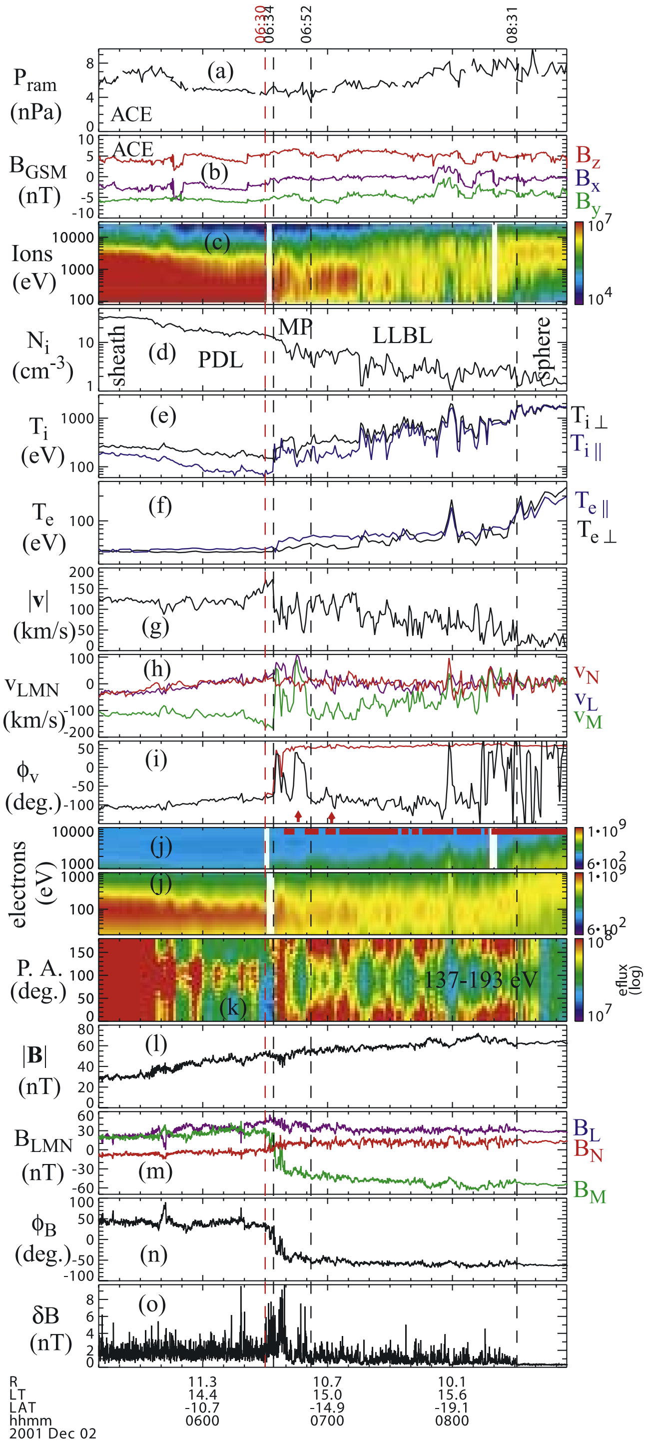


**Figure 1.** Solar wind (a) ram pressure and (b) magnetic field from ACE. Wind data: (c) ion energy-time spectrogram (in $eVs^{-1}cm^{-2}ster^{-1}eV^{-1}$), (d)–(e) ion density and temperatures, (f) electron temperatures, (g)–(i) ion flow speed, flow velocity in LMN coordinate system, flow angle in the (L-M) plane tangential to the MP, (j) electron energy-time spectrograms from 3DP instruments, (k) pitch-angle spectrogram of 137–193 eV electrons, (l)–(o) magnetic field strength, field components in LMN, field direction in L-M plane, and field fluctuations. The red dashed line indicates the reference time for the shear-stress balance test. The left 2 black dashed lines border the MP. The right most dashed line marks the inner edge of the LLBL. The red arrows in panel i mark the times of the electron distributions in Figure 3.

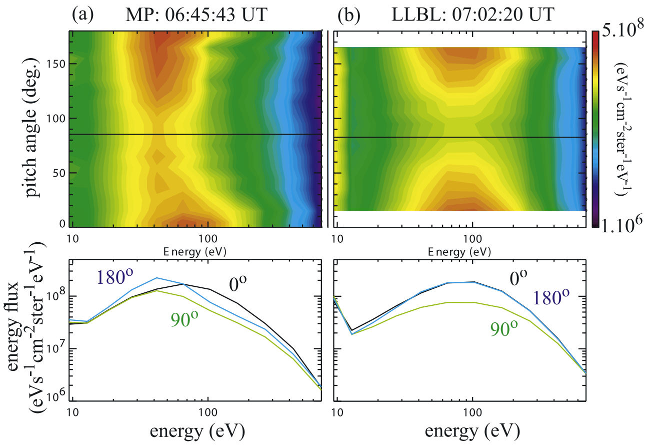


**Figure 3.** Electron energy flux as functions of electron pitch angle and energy in (a) MP reconnection layer, (b) LLBL. The times of the distributions are marked by red arrows in Figure 1i.

across 06:34 UT), the $\Delta B_M$ across the MP is $\sim$ 58 nT (28 nT in the magnetosheath and $-20$ nT in the magnetosphere). With a magnetosheath density of $\sim$15 cm$^{-3}$, the predicted change of the M component of the Alfvén velocity across a reconnecting MP, $\Delta V_{M,predicted} \sim -\Delta B_{L,M}(\mu_0\rho_{sheath})^{-1/2}$, is $\sim$250 km/s. The observed $V_M$ change was 220 km/s ($-170$ km/s in magnetosheath and 50 km/s in the MP). Thus the observed flow change agrees with the rotational discontinuity (RD) condition to $\sim$80%. To further illustrate the agreement with the reconnection prediction, Figure 1i shows the observed (black) and predicted (red) flow direction in the LM plane where the $\sim$120° flow rotation across the MP was well predicted (to within $\sim$10°) by the RD relation $\Delta V_{L,M} \sim -\Delta B_{L,M}\ (\mu_0\rho_{sheath})^{-1/2}$ based on a single reference point in the magnetosheath (taken at the red vertical dashed line). The predicted flow direction is valid not only across a RD but also across the slow expansion fan region earthward of the RD [*Lin and Lee*, 1994]. The negative sign in the RD relation was chosen based on the observed negative correlation between $\mathbf{\Delta v}$ and $\mathbf{\Delta B}$ at the MP and indicates that the X-line was tailward of Wind. This is consistent with the observed deceleration instead of the acceleration of the flow across the MP. The second positive $V_M$ flow (in the middle of the MP) agrees with the predicted direction to within 20°. The reconnection flows are observed on field lines that have low-latitude plasma sheet orientation, indicating that the reconnection site is equatorward of the cusp, and ruling out poleward-of-the-cusp reconnection as the source of these flows.

[9] Between the two positive $V_M$ flows in the MP the flow is tailward (similar to the magnetosheath and LLBL flow direction). This brief tailward flow interval coincides with a larger $T_i$ (panel e) at a level close to that of the LLBL. This suggests that the spacecraft had gone briefly into the LLBL during this interval before reentering the MP where reconnection flow was again detected.

### 2.3. LLBL Flow Properties

[10] While the flow in the MP is consistent with reconnection and is 130° away from the magnetosheath flow, the flow direction in the adjacent LLBL is substantially different from what would be expected (the red line in Figure 1i) if the LLBL were the slow expansion fan portion of the reconnection layer. Instead, the LLBL flow is well aligned with the magnetosheath flow. The LLBL flow speed fluctuates but on average decreases gradually as the spacecraft moved inward toward the magnetosphere.

[11] Toward the inner part of the LLBL and in the magnetosphere the flow speed is much lower and the flow direction is highly variable. Some of the variable flow directions may be caused by uncertainties in the velocity determination at low (<50 km/s) flow speeds.

### 2.4. Electron Pitch Angle Behavior

[12] In addition to the stark contrast between the LLBL and MP flow behavior, Figure 3 shows the contrast between electron pitch angle distributions detected in the reconnection flow region versus those sampled in the LLBL.

[13] Figure 3a shows an example of electron pitch-angle distributions (in energy flux) sampled in the reconnection flow at the MP (at 06:45:43 UT). The field-aligned (0°) and anti-field-aligned (180°) electrons have different mean energies and their fluxes are not balanced. The 0° population has higher energy (i.e., hotter) than the 180° population. The unbalanced fluxes is consistent with this region being on open field lines due to reconnection [see also *Phan et al.*, 2001].

[14] In contrast, the parallel and anti-parallel electron fluxes in the LLBL (Figure 3b), taken at 07:02:20 UT, are precisely balanced at all energies. This balanced flux feature (marked by red bars in Figure 1j) is present in most of the LLBL samples. The few unbalanced electron distributions in the LLBL have the same mean energy but different flux levels at 0° and 180° and do not resemble the open-field distributions in Figure 3a.

[15] If the pitch-angle information were displayed in a spectrogram representation (Figure 1k) instead, the parallel and antiparallel fluxes would appear balanced not only in the LLBL, but also in the MP reconnection flow region. The slight imbalance of flux in Figure 3a would not be discernable in the spectrogram representation. Thus it is important that the deduction of magnetic topology be made using the appropriate data representation.

## 3. Summary and Discussions

[16] We have studied a Wind crossing of the dayside (15 MLT) low-latitude MP and LLBL when the IMF was northward and dawnward (clock angle $\sim$45°) and the magnetic shear at the local MP was $\sim$80°. The large local magnetic shear, coupled with the small IMF clock angle, provides a rather unique opportunity to study the relationship between reconnection and LLBL formation. We now discuss the key observations.

### 3.1. LLBL Formation

[17] Earthward of the MP, an extended (1.5-hour crossing time) LLBL was observed where the density and flow speed gradually decreased and the ion and electron temperature increased on approach to the magnetosphere. The LLBL flow was not aligned with the MP reconnection flow but was instead aligned with the magnetosheath flow. Also in contrast to the MP, the field-aligned and anti-field-aligned electron fluxes are well balanced at all energies in most of

the LLBL, suggesting that this region is almost entirely on closed field lines. These properties indicate that the LLBL was not created by reconnection at the low-latitude MP. Furthermore, as reconnection at the MP implies plasma inflows from both sides of the MP current layer, reconnection at the low-latitude MP must be in the process of eroding the pre-existing LLBL. We note that *Newell and Meng* [1998] arrived at a similar conclusion based on low-altitude DMSP observations.

[18] The next question is the origin of the pre-existing LLBL. The combination of (1) the alignment of the tangential LLBL flow with the external magnetosheath flow, (2) the gradual variations of the LLBL plasma parameters with distance from the MP, and (3) the closed field topology are all consistent with the LLBL being formed by magnetosheath plasma diffusing across the MP. The question is the absence of magnetospheric electrons in the LLBL. One possible explanation is that since the inner edge of the LLBL marks the convection reversal, it would also mark the boundary between regions with and without high-energy (keV) electrons. The plasma sheet contains keV electrons because of the sunward convection, whereas the LLBL is absent of high-energy electrons because there is no energization associated with anti-sunward flows [*Newell and Meng*, 1998]. Another possibility is that the magnetospheric electrons are scattered into the loss cone in the closed LLBL by the *Kennel and Petscheck* [1966] mechanism.

[19] An alternative scenario is that the existing LLBL was created by reconnection in both northern and southern cusps [*Song and Russell*, 1992; *Fuselier et al.*, 2002]. This scenario could naturally explain the absence of high-energy magnetospheric electrons because the lobes do not have these electrons. It is however unclear whether this model could account for the observed LLBL-magnetosheath flow alignment and the plasma profiles across the LLBL.

[20] The smoothness of the magnetic field in the LLBL rules out the nonlinear KHI as the process that creates the observed LLBL (at 15 MLT).

[21] Finally, if reconnection and diffusive entry occur at the same time and are competing with each other, the fact that a LLBL exists in the presence of reconnection indicates that the reconnection rate is slower than the rate at which the LLBL was created. One would thus expect that for southward IMF, when the reconnection rate is expected to be higher at the low-latitude MP, reconnection could erode the LLBL at a faster rate which would result in a much thinner LLBL or even no LLBL. This scenario could explain the findings of *Mitchell et al.* [1987] of a thinner LLBL (of mixed open and closed topology) during southward IMF.

### 3.2. Electrons at the Reconnecting MP and in the LLBL

[22] Counterstreaming electrons observed in the MP and LLBL could be the result of mirroring off the ionosphere [*Fuselier et al.*, 1997]. However, our observations indicate that here is a systematic difference between the MP and LLBL electron distributions. In the reconnecting MP where one knows for certainty that the field lines are open, there is a mismatch (of $\sim$60 eV) in 0° and 180° electron energies and their fluxes are unbalanced at most energies. Such ''counterstreaming'' electrons should not be misinterpreted as evidence for closed field lines. The asymmetric pitch angle distributions are similar to those observed in the magnetotail which have previously been interpreted as due to Hall effects and energization near the X-line [*Fujimoto et al.*, 1997].

[23] By contrast, within most of the LLBL the counterstreaming populations are precisely matched. This drastic difference with the open-field distributions strongly suggests that the LLBL is on closed field lines.

### 3.3. Concluding Remarks

[24] The present event suggests that for northward IMF, reconnection at the low-latitude MP does not lead to the formation of the adjacent LLBL, but it is in the process of eroding the LLBL instead. The question remains whether the pre-existing LLBL was formed by diffusive entry or by double-cusp reconnection. One may be able to distinguish between these two processes in future studies by examining southward IMF situations. If a closed LLBL also exists earthward of the open MP/outer LLBL as reported by *Mitchell et al.* [1987] and *Fujimoto et al.* [1996], the closed LLBL in such a case is unlikely to be created by cusp reconnection because cusp reconnection ceases when the IMF has a southward component [*Twitty et al.*, 2004]. Furthermore, if the flow in the closed LLBL is aligned with the magnetosheath flow (and drastically different from the MP reconnection flow direction), it would make a strong case for diffusive entry.

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