Field-aligned electrons at the lobe/plasma sheet boundary in the mid-to-distant magnetotail and their association with reconnection

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[1] We have surveyed field-aligned electrons at the lobe/plasma sheet boundary and their association with reconnection in the distant magnetotail where reconnection is quasi-steady and large scale. Asymmetric (in energy) counterstreaming electrons are detected in ~30% of the boundary crossings when high-speed flows are present in the plasma sheet. In 98% of the electron beam cases the low-energy electrons are directed toward and the higher-energy electrons directed away from the X-line. The well-organized (by the signs of B_x and V_x) quadrupolar pattern of the electrons indicates that these electrons are associated with reconnection. The low-energy electrons could be the outer part of the Hall current loop, similar to previous reports in the near-Earth region. The mean electron energy in the distant tail is a factor of ten lower than in the near-Earth tail. Our observations suggest that the Hall effect can be detected even at large distances from the diffusion region. **Citation:** Manapat, M., M. Øieroset, T. D. Phan, R. P. Lin, and M. Fujimoto (2006), Field-aligned electrons at the lobe/plasma sheet boundary in the mid-to-distant magnetotail and their association with reconnection, *Geophys. Res. Lett.*, *33*, L05101, doi:10.1029/2005GL024971.

1. Introduction

[2] In collisionless magnetic reconnection, ions become decoupled from electrons in the ion-scale diffusion region. This decoupling of ions and electrons—a process known as the Hall effect—results in a system of quadrupolar Hall currents which in turn induces a quadrupolar Hall magnetic field [*Sonnerup*, 1979] (see Figure 1).

[3] The Hall magnetic field has been reported in the magnetotail in a number of studies [e.g., *Nagai et al.*, 2001; *Øieroset et al.*, 2001], but their detection requires good knowledge of the current sheet normal which often deviates substantially from the GSM-z direction, and the accuracy of the normal detection is often hindered by the dynamics of the current sheet.

[4] Another detectable signature of the Hall current are the current carriers - the electrons – themselves. It has been suggested that along the lobe/plasma sheet boundary one can observe the outer portion of the current loop in the form of low-energy field-aligned electrons flowing toward the diffusion region along the 4 separatrices [e.g., *Fujimoto et al.*, 1997, 2001; *Hoshino et al.*, 2001; *Nagai et al.*, 2001; *Øieroset et al.*, 2001; *Owen et al.*, 2005; *Alexeev et al.*, 2005]. On the same field lines, higher-energy electrons have also been reported which are directed away from the diffusion region [*Hoshino et al.*, 2001; *Nagai et al.*, 2001]. Such high-energy electrons have successfully been reproduced in simulations and they have been attributed to energization close to the X-line [*Hoshino et al.*, 2001].

[5] All the previous reports of electron behavior consistent with the Hall current direction have been case studies. And with the exception of a distant tail event [*Øieroset et al.*, 2001], all the previous reports by Geotail and Cluster are in the near-Earth tail associated with bursty reconnection. Because spacecraft are usually not at the right places (the lobe/plasma sheet boundary) during brief bursts of reconnection in the near-Earth plasma sheet, one does not know how common field-aligned electrons are in the lobe/plasma sheet boundary and whether they are always consistent with the Hall current loop.

[6] Here we present a survey of field-aligned electrons observed by the Wind spacecraft in a 5-year period at the lobe/plasma sheet boundary in the mid-to-distant tail (-235 R_E < X_{GSM} < -40 R_E) where reconnection is believed to be much more steady and extended than in the near-Earth tail [*Slavin et al.*, 1986; *Nishida et al.*, 1995; *Øieroset et al.*, 2000]. We do not impose any selection criteria other than the requirement that observations be made at the plasma sheet-lobe boundary. The purpose of this study is to investigate whether (1) field-aligned electrons are generally present at the this boundary during reconnection, and (2) whether these electrons are consistent with the Hall current loop.

2. Wind Orbit and Instrumentation

[7] We use data from Wind passes through the distant tail over the five-year period from 1999 to 2004. These passes were as close to the Earth as $X_{GSM} = -40$ R_E and as distant as $X_{GSM} = -235$ R_E. Plasma parameters were measured by Wind's 3D plasma and energetic particle detectors. Full 3-D electron distributions are sampled every three seconds (the spacecraft spin period), but are transmitted every 50 to 97 seconds. Magnetic field parameters, provided by the Wind magnetometer, are sampled 10.9 times per second, but here we use data averaged over three seconds.

3. Observations

3.1. Event Study

[8] Figures 2 and 3 show the time series and electron pitch angle distribution for one representative event to illustrate the selection criteria used in the statistical study in Section 3.2. On April 1, 1999, the Wind spacecraft was in the mid-tail at $X_{GSE} \sim -60$ R_E. Figure 2 plasma and

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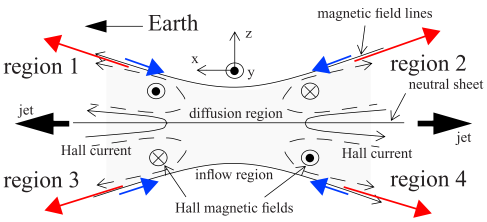

Figure 1. The magnetic reconnection ion diffusion region, emphasizing the electron behavior in the vicinity of the separatrices. Low energy electrons (short blue arrows) move toward the X-line, carrying the Hall current while electrons that emanate from the X-line (long red arrows) are energized near the X-line.

magnetic field data show that Wind was at first in the plasma mantle (where the ions are cold and the flow is steadily tailward at ~100 km s^{-1}). Wind remained in the mantle until ~16:23 UT when it went into the hot plasma sheet. The plasma flow in the plasma sheet is earthward and peaking at ~200 km s^{-1}. Wind reentered the mantle at 16:42 UT. During the excursion back and forth between the mantle and the plasma sheet, the spacecraft remained in the southern hemisphere ($B_x < 0$).

[9] Figure 3 shows an example of the presence of field-aligned counterstreaming electrons with different energies detected at the mantle/plasma sheet interface. The electron pitch angle (and energy) distribution was sampled at 16:22:29 UT, at the boundary between the mantle and the plasma sheet (where there are clear transitions in the ion temperature and magnetic field B_x). The low-energy electrons (with mean energy of ~70 eV) are field-aligned whereas the higher-energy electrons (with mean energy ~250 eV) are anti-field-aligned. Since the spacecraft was in the $V_x > 0$ and $B_x < 0$ region, the low-energy electrons are directed toward and the higher-energy electrons directed away from the X-line. This behavior of the electrons is similar to the previous Geotail and Cluster observations in the near-Earth plasma sheet boundary layer [*Fujimoto et al.*, 1997, 2001; *Hoshino et al.*, 2001; *Nagai et al.*, 2001; *Owen et al.*, 2005; *Alexeev et al.*, 2005].

[10] As the spacecraft penetrates deeper into the plasma sheet, the electron distributions are more complicated (not shown), with significant fluxes at all pitch angles [see also *Alexeev et al.*, 2005].

3.2. Statistical Study

[11] We now describe a statistical survey of all field-aligned electrons observed by Wind over a 5-year period at the lobe/mantle and plasma sheet interface (i.e., in the vicinity of the separatrices) when there are high-speed flows (presumably from reconnection) in the plasma sheet. This survey reveals how often field-aligned electrons are present at the lobe/plasma sheet boundary and whether their directions are generally consistent with the Hall pattern. By restricting the survey to the lobe/plasma sheet boundary, we are only investigating the outer part of the Hall current loop [*Hoshino et al.*, 2001]. The cross-field portion of the Hall current as well as the return current deeper inside the plasma sheet are not easily discernible in the data.

3.2.1. Data Selection

[12] We examined all times at which Wind moved from the plasma sheet to the lobe or mantle (or conversely). The plasma sheet is characterized by high density (around 0.1–0.3 cm^{-3}), low $|B_x|$ (less than 5–10 nT), and high ion temperature (generally at least 1 keV) while the lobe/mantle is characterized by high $|B_x|$ (at least 10 nT) and low ion temperature (less than 500 eV). In the distant tail, the plasma mantle has time to convect all the way down to the plasma sheet boundary, so the density in the distant tail lobe or mantle can in some cases exceed the plasma sheet density. However, the mantle is easily distinguished from the higher energy plasma sheet by the low-temperature and

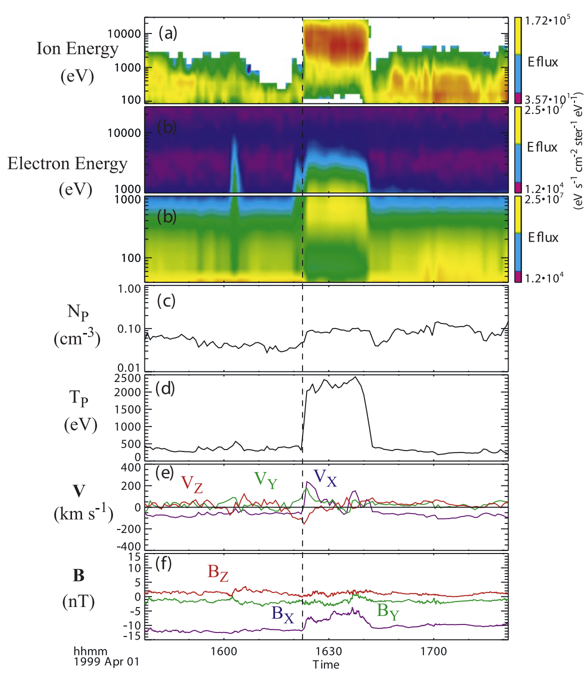

Figure 2. Wind observations from the distant tail (X_{GSM} = 60 R_E) on April 1 1999: (a) ion energy spectrogram, (b) electron energy spectrogram, (c) plasma density, (d) ion temperature, (e) x, y, and z (GSM) components of the velocity, and (f) x, y, and z (GSM) components of the magnetic field. The vertical dashed line marks the time of the electron distribution displayed in Figure 3.

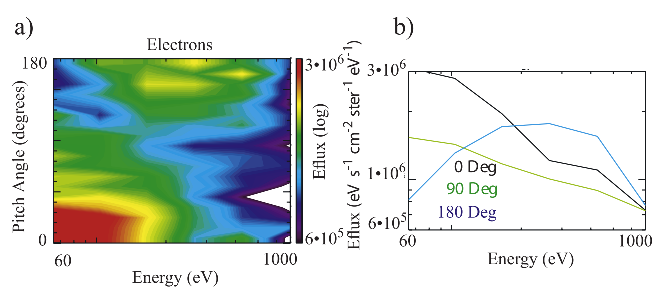

Figure 3. Electron distribution at the mantle/plasma sheet boundary at 16:22:29 UT on April 1, 1999. The time of the distribution is marked by the vertical dashed line in Figure 1. (a) Pitch angle distribution (pitch angle vs. energy) for the 60–1000 eV electrons. (b) Electron distributions at 0° (black line), 90° (green line), and 180° (blue line) pitch angle.

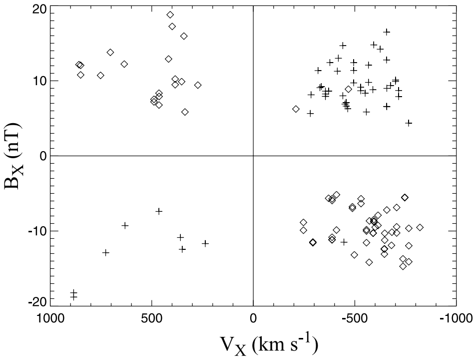

Figure 4. V_x vs. B_x for all the field-aligned electron events, where V_x is the x component of the ion velocity in the nearby plasma sheet. A plus indicates that the low energy electrons are moving parallel to the magnetic field while a diamond indicates that the low energy electrons are moving anti-parallel to the field.

steadily tailward flowing (at $\sim$100 km s^{-1}) ions and well as in the large B_x.

[13] In the case of a tailward-moving plasmoid caused by near-Earth reconnection, the observed field-aligned electrons can be associated with either the tailward flow from a near-Earth X-line or the earthward flow from a distant tail X-line. To ensure that only samples related to distant tail reconnection were included we excluded boundary crossings related to tailward-moving plasmoids. Tailward-moving plasmoids are recognizable in the data with their short (<5–10 minutes) duration, strong core (B_y) magnetic field, B_z reversal, and tailward high-speed flow. Hence in our survey we included only well-developed structures where the flows originate from a distant tail X-line.

[14] At each lobe/plasma sheet boundary crossing, we searched for field-aligned electrons. We then sorted the events by region: "region 1" is the quadrant north of the neutral sheet ($B_x > 0$) and earthward of the X-line ($V_x > 0$), "region 2" the quadrant north of the neutral sheet and tailward of the X-line, "region 3" the quadrant south of the neutral sheet and earthward of the X-line, and "region 4" the quadrant south of the neutral sheet and tailward of the X-line (see Figure 1). In determining whether the flow at a specific time was earthward or tailward, we used the direction of the flow in the adjacent plasma sheet.

[15] Samples where the direction of the plasma sheet flow was ambiguous, for example near a V_x reversal, were not included in the study.

3.2.2. Results

[16] Between March 31, 1999 and April 24, 2004, there were 355 plasma sheet/mantle (lobe) crossings. Of these, 330 crossings detected fast convective ion flows (presumably from reconnection) in the adjacent plasma sheet. The high percentage (93%) of high-speed flow occurrence rate is consistent with the distant tail reconnection being quasi-steady and that the reconnection X-line is extended across the tail, as opposed to the occurrence rate of $\sim$1% of high-speed flow in the near-Earth plasma sheet which indicates patchy and bursty reconnection [*Angelopoulos et al.*, 1994]. Field-aligned electrons were observed during 97 crossings (or $\sim$30% of the crossings with fast flows) on 34 different days. During these 97 boundary crossing we identified a total of 124 field-aligned electron distributions, 20 in region 1 (earthward of the X-line in the northern hemisphere), 45 in region 2 (tailward of the X-line in the northern hemisphere), 8 in region 3 (earthward of the X-line in the southern hemisphere), and 51 in region 4 (tailward of the X-line in the southern hemisphere). Figure 4 shows all 124 events as a function of B_x and V_x in the nearby plasma sheet. Figure 4 shows only the direction of the low-energy electrons relative to the magnetic field (with the high-energy electrons being in the opposite direction). A "plus" indicates that the low energy electrons are moving parallel to the magnetic field while a "diamond" indicates that the low energy electrons are moving anti-parallel to the field. In 121 of the 124 events (in all 4 quadrants) the low-energy electrons move toward the X-line along the lobe-plasma sheet boundary. Thus 98% of the events are in agreement with the Hall pattern in Figure 1.

[17] For the three events in which the low-energy electrons are directed away from the X-line, one event occurred in region 4 and two events occurred in region 2. Thus all three events were observed tailward of the X-line, at locations $X_{GSM} = -120\ R_E$, $X_{GSM} = -151\ R_E$, and $X_{GSM} = -198\ R_E$. The reason for these "inconsistent" cases is unclear. However, it is noted that the B_x values and ion temperatures associated with the inconsistent events are not much different than those for the consistent events (see Figure 4). Thus it is unlikely that the inconsistent events are a result of the spacecraft being located closer to the neutral sheet ($B_x = 0$), that is, not at the boundary. On the other hand all three inconsistent events were observed in the vicinity of the low-latitude magnetopause. It is thus possible that these 3 events are related to magnetopause processes, not to tail reconnection.

[18] Figure 5 shows the mean energy for the electrons directed away from the X-line vs. the electrons directed toward the X-line for all 124 events. Events consistent with the Hall pattern fall above the tilted (45°) straight line while the three events which do not fit this model fall below this line. The mean energy of the low energy electrons lies between a few tens of eV and 600 eV while the mean energy of the high energy electrons is in the $\sim$100–1200 eV range. The observed energy gain from the low energy electrons to the oppositely directed high energy electrons does not

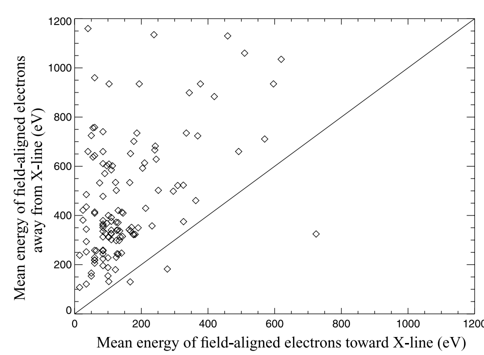

Figure 5. Mean energy of electrons moving away from the X-line vs. mean energy of electrons moving toward the X-line. Events consistent with the Hall current pattern fall above the tilted (45°) straight line while the three events which do not fit this pattern fall below this line.

follow a consistent pattern, but the average energy gain is a factor of 3.

4. Summary and Discussion

[19] We have surveyed the occurrence of field-aligned electrons in the distant tail lobe/plasma sheet boundary. We found that 93% of the Wind crossings from the lobe to the plasma sheet detected high-speed ion flows in the plasma sheet. Of the crossings with high-speed flows, 30% observed field-aligned electrons at the boundary. In 98% of the field-aligned electron events, low (high) energy electrons are directed toward (away from) the reconnection site. We now discuss implications of our findings.

4.1. Occurrence of Hall Electrons at the Plasma Sheet/Mantle (Lobe) Boundary

[20] The fact that in 98% of the cases (when field-aligned electrons are observed in the lobe/plasma sheet boundary during high-speed flows) the electron pitch-angle pattern is organized by the sign of B_x as well as the sense of the high speed flow V_x provides strong evidence that essentially all field-aligned electrons in this region are associated with reconnection. The 98% correlation also validates our initial assumption that the fast (V_x) flows in the plasma sheet, some of which may be as slow as 200 km/s, are generated by reconnection. The quadrupolar pattern of the low- and high-energy electrons and the lobe/plasma sheet boundary location where these electrons are observed are qualitatively similar to the electron distributions sampled by Geotail [*Hoshino et al.*, 2001; *Nagai et al.*, 2001]. According to the results of the simulations by *Hoshino et al.* [2001], the low-energy electrons (directed toward the X-line) are the Hall current carriers while the high-energy electrons (directed away from the X-line) are produced near the X-line.

[21] In Section 3.2.2., we found that each of the 97 crossings of the boundary where field-aligned electron distributions are observed has on average less than 2 such distributions. This is an indication that these electrons are confined to the boundary. Because the (3-s) 3-D electron distributions are transmitted only every 51–96 seconds, some of the field-aligned electron distributions may be missed. This could explain why Wind detected field-aligned electrons in only ∼30% of the lobe/plasma sheet boundary crossings (when high-speed flows are observed in the plasma sheet).

[22] If the low-energy electrons are indeed associated with the Hall current, the large number (121) of events not associated with flow reversals indicates that the majority are not detected in the proximity of the diffusion region. This, coupled with the fact that these electrons are observed in a large spatial range (from XGSM = −50 RE to XGSM = −235 RE), would allow the general conclusion that the signature of the Hall effect in terms of the field-aligned low-energy electrons can be observed at large distances from the diffusion region. Thus even though the Hall effect, by definition, is associated with the perpendicular current in the ion diffusion region, these electrons provide a way to deduce the presence of Hall effect in reconnection without actually sampling the diffusion region itself. Our findings also suggest that Hall electrons (similar to Figure 3) must be present and detectable at the dayside magnetopause as well.

4.2. Mean Electron Energies

[23] The observed mean field-aligned electron energies in the distant tail are lower (by about a factor of 10) than the corresponding energies observed in the near-Earth magnetotail where the low energies span 0.1 keV to a few keV [*Fujimoto et al.*, 2001; *Nagai et al.*, 2001] and the high energy electrons can reach tens of keV [*Nagai et al.*, 2001]. We suggest that since the Hall current loop is associated with ion scale dynamics, the energy of the low energy electrons carrying the Hall current scale with the ion Alfvén speed. Hence the difference in mean energies could be accounted for by the difference in the Alfvén speed in the near-Earth and the distant tail. In the near-Earth tail the lobe magnetic field and the lobe density is generally ∼20 nT and <0.01 cm s^{-1}, respectively, while the same parameters are typically ∼10 nT and ∼0.1 cm s^{-1} in the distant tail. Hence the Alfvén speed in the distant tail is generally lower than in the near-Earth tail by at least a factor of six, close to the observed difference.

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References

Alexeev, I. V., C. J. Owen, A. N. Fazakerley, A. Runov, J. P. Dewhurst, A. Balogh, H. Rème, B. Klecker, and L. Kistler (2005), Cluster observations of currents in the plasma sheet during reconnection, *Geophys. Res. Lett.*, *32*, L03101, doi:10.1029/2004GL021420.

Angelopoulos, V., C. F. Kennel, F. V. Coroniti, R. Pellat, M. G. Kivelson, R. J. Walker, C. T. Russell, W. Baumjohann, W. C. Feldman, and J. T. Gosling (1994), Statistical characteristics of bursty bulk flow events, *J. Geophys. Res.*, *99*, 21,257.

Fujimoto, M., M. S. Nakamura, I. Shinohara, T. Nagai, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun (1997), Observations of earthward streaming electrons at the trailing boundary of a plasmoid, *Geophys. Res. Lett.*, *24*, 2893.

Fujimoto, M., T. Nagai, N. Yokokawa, Y. Yamade, T. Mukai, Y. Saito, and S. Kokubun (2001), Tailward electrons at the lobe-plasma sheet interface detected upon dipolarizations, *J. Geophys. Res.*, *106*, 21,255.

Hoshino, M., T. Mukai, T. Terasawa, and I. Shinohara (2001), Suprathermal electron acceleration in magnetic reconnection, *J. Geophys. Res.*, *106*, 25,979.

Nagai, T., I. Shinohara, M. Fujimoto, M. Hoshino, Y. Saito, S. Machida, and T. Mukai (2001), Geotail observations of the Hall current system: Evidence of magnetic reconnection in the magnetotail, *J. Geophys. Res.*, *106*, 25,929.

Nishida, A., T. Mukai, T. Yamamoto, Y. Saito, and S. Kokubun (1995), GEOTAIL observations on the reconnection process in the distant tail in geomagnetically active times, *Geophys. Res. Lett.*, *22*, 2453.

Øieroset, M., T. D. Phan, R. P. Lin, and B. U.Ö Sonnerup (2000), Walén and variance analyses of high-speed flows observed by Wind in the midtail plasma sheet: Evidence for reconnection, *J. Geophys. Res.*, *105*, 25,247.

Øieroset, M., et al. (2001), In situ detection of collisionless reconnection in the Earth's magnetotail, *Nature*, *412*, 414.

Owen, C. J., J. A. Slavin, A. N. Fazakerley, M. W. Dunlop, and A. Balogh (2005), Cluster electron observations of the separatrix layer during traveling compression regions, *Geophys. Res. Lett.*, *32*, L03104, doi:10.1029/2004GL021767.

Slavin, J. A. et al (1986), Solar wind-magnetosphere coupling and the distant magnetotail–ISEE-3 observations, in *Space Wind-Magnetospheric Coupling: Proceedings of the Chapman Conference*, edited by Y. Kamide and J. A. Slavin, pp. 717–730, Terra Sci., Tokyo.

Sonnerup, B. U. Ö. (1979), Magnetic field reconnection, in *Solar System Plasma Physics*, vol. 3, edited by L. T. Lanzerott, C. F. Kennel, and E. N. Parker, pp. 45–108, Elsevier, New York.

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