



Reconnection Hall current system observed in the magnetotail and in the ionosphere

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[1] On 07 Sep 2001 around 21:40 UT, Cluster was located 19 R_E downtail, and observed earthward fast flows and strong perturbations in the dawn-dusk component of the magnetic field (B_Y). The perturbations corresponded to a sheet of tailward field aligned current close to the neutral sheet and another sheet of earthward field aligned current closer to the lobe. At Cluster footpoint, the ionospheric equivalent current density was monitored by the IMAGE magnetometer network. The observed equivalent current pattern is found to be consistent with a longitudinally extended current out of the ionosphere at 67° magnetic latitude and another sheet into the ionosphere 10 km further north. These observations provide evidence that the Hall current system generated in the ion diffusion region of a tail reconnection X-line, can close in the ionosphere.
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1. Introduction

[2] Historically, the idea of a meridional current system was proposed by *Boström* [1964] as part of a model for the auroral electrojet. Later, it has been called the Boström Case 2 current system. The system, reproduced in Figure 1, consists of a pair of earthward and tailward directed field-aligned current sheets, connected in the ionosphere by southward Pedersen current and in the equatorial plane by tailward current. Ground-based magnetic signatures related to the system are caused by the westward ionospheric Hall current, which is set up by the southward directed electric field associated with the Pedersen current. *Akasofu* [2003] has argued that the Boström Case 2 current system can explain several substorm related features. *Lui and Kamide* [2003] proposed a mechanism where the near-Earth magnetotail acts as a dynamo for this current system.

[3] A similar current system, further tailward and on a smaller scale, is believed to be set up during reconnection [*Sonnerup*, 1979]. *Treumann et al.* [2006] developed a theoretical framework for how the divergence of Hall currents in the ion diffusion region leads to the generation of two oppositely directed field aligned current (FAC) sheets. The scale of this current system in the north-south direction may be on the order of roughly 1000 km in the magnetotail and only a few tens of km in the ionosphere. The Hall currents,

which by definition are perpendicular to the magnetic field, and the FACs which close with them, were called the Hall current system by *Nagai et al.* [2001]. This terminology has also been adopted in our study. The current system has been observed close to the X-line [*Nagai and Machida*, 1998; *Nagai et al.*, 2001; *Runov et al.*, 2003; *Ueno et al.*, 2003], but also further away [*Fujimoto et al.*, 2001; *Nakamura et al.*, 2004a; *Runov et al.*, 2008; *Snekvik et al.*, 2008].

[4] Another FAC system is associated with the flow shear regions at the flanks of fast flows [e.g., *Takada et al.*, 2008]. As these currents are mainly organised azimuthally like a current wedge, they cannot explain the meridional current system reported in this paper. The following sections present observations from both the magnetotail and the ionosphere, which may be interpreted in terms of the Hall current system. To our knowledge, this is the first time evidence has been found that this current system can close in the ionosphere.

2. Observations

2.1. Magnetotail

[5] Figure 2a shows observations by Cluster on 07 Sep 2001. The three top panels contain the three components of the magnetic field, while the bottom panel contains the earthward velocity. The coordinate system is slightly modified by rotating XY_{GSM} 8.1 degrees anticlockwise around Z_{GSM} . This is done to ensure that the cross tail current is not included in the estimate of FACs due to tail flaring. The new coordinate system was found by a variance analysis of the magnetic field between 15:00 UT and 23:00 UT, which was the time Cluster spent in the plasma sheet. The maximum variance direction normal to the Z_{GSM} axis was chosen as the X -axis. A long time interval for the variance analysis was used so that temporary FACs would not affect the result.

[6] During the first 17 minutes in Figure 2a, the B_X signature shows that C1 (black), C2 (red), and C4 (blue) were in the northern hemisphere, while C3 (green) crossed the neutral sheet several times. Just before 21:50 UT, all spacecraft moved southward relative to the current sheet. C1, C2 and C4 remained close to the center of the current sheet until the end of the time interval. C3 first moved towards the southern lobe and then back to the neutral sheet. When the satellites were close to the center of the current sheet ($B_X \approx 0$), they measured fast earthward flows of 200–600 km/s. There were also strong perturbations of B_Y by more than 10 nT. In comparison, B_Z was relatively stable around a few nT most of the time.

[7] In order to check whether the perturbations in B_Y were caused by FACs, five one minute time intervals, marked with I–V, were chosen. Each time interval was selected such that the combined measurements of Cluster covered as much of the northern or southern plasma sheet as possible. A scatter

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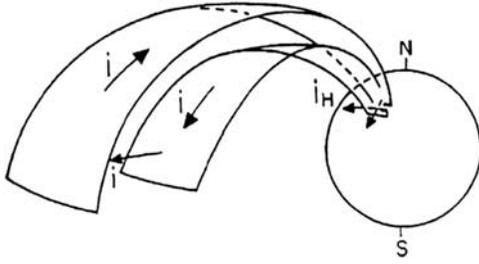


Figure 1. Boström's Case 2 current system [Boström, 1964].

plot of B_Y versus B_X/B_L is shown for each time interval (Figures 2b–2f). The lobe magnetic field, B_L , was calculated by assuming that the sum of the plasma and magnetic pressures in the plasma sheet equals the magnetic pressure in the lobe. $B_X/B_L = 0$ corresponds to the neutral sheet while $B_X/B_L = \pm 1$ corresponds to the lobes.

[8] Although there is considerable temporal variance in the scatter plots, a spatial pattern emerges. The fitted line in each scatter plot, clearly shows this. In Figures 2b–2e, there is an increase of B_Y from the neutral sheet out to $B_X/B_L \approx 0.5$.

Then it decreases towards the northern lobe. This corresponds to a tailward current in the center of the current sheet and an earthward current closer to the lobe. In Figure 2f, which is from the southern hemisphere, B_Y decreases from the lobe to a minimum value of about -7 nT and then increases again towards the neutral sheet. By also checking scatter plots from other time intervals (not shown), the pattern seemed to be persistent between 21:35 and 21:51 UT, but absent before 21:35 UT.

[9] By assuming that the variation of the fitted lines was due to field aligned current sheets, it is possible to estimate the currents. If the dawn dusk width of the sheets is much larger than their thickness (as in Figure 1), Ampère's law gives

$$j[\text{A/m}] = \frac{\Delta B_Y}{\mu_0}, \quad (1)$$

except near the flanks of the field aligned current sheets. Equation (1) is justified in interval II–V where the variation of B_Z is small compared to the variation of B_Y but is more uncertain in interval I where the variations are of comparable magnitude. The maximum difference of B_Y along the fitted lines, was 5–8 nT in the northern hemisphere

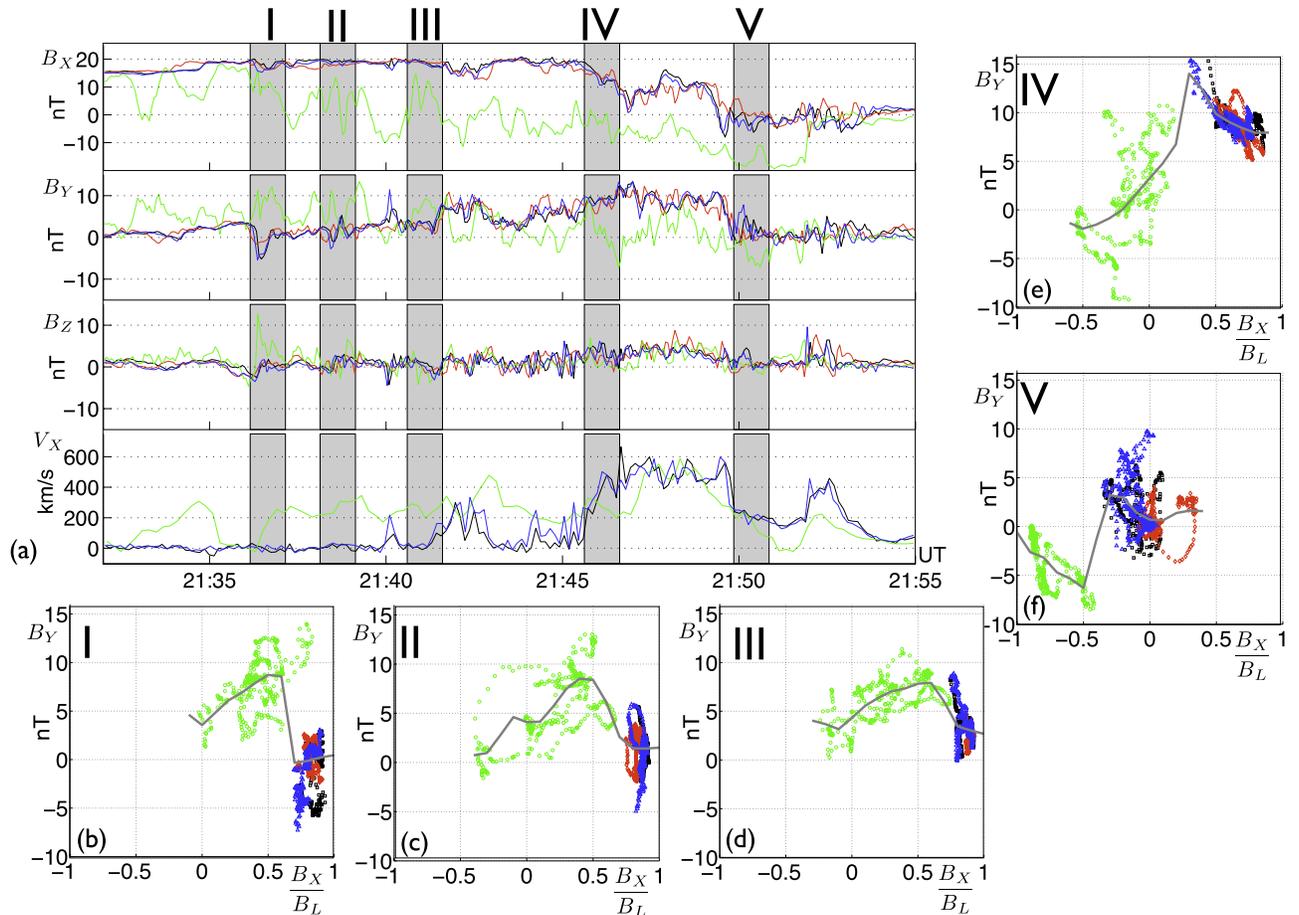


Figure 2. Observations by Cluster on 07 Sep 2001 in a coordinate system modified for tail flaring. (a) The earthward, duskward and northward components of the magnetic field (B_X , B_Y and B_Z), and the earthward component of the velocity (V_X). C1, C2, C3 and C4 are shown with black, red, green and blue colors, respectively. Cluster is located at $XYZ_{\text{GSM}} = (-19, 1, 1) R_E$. (b–f) Scatter plots of B_Y versus B_X normalised with the lobe magnetic field, B_L , are shown for each of the shaded intervals in Figure 2a.

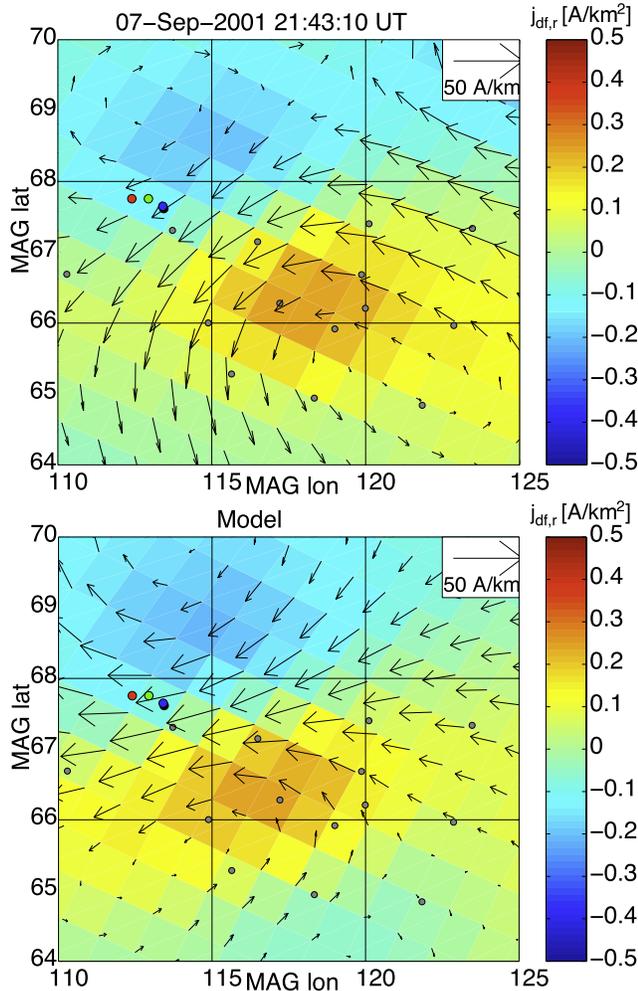


Figure 3. (top) The measured ionospheric equivalent current density, displayed by the black arrows, and its curl, displayed by the color palette, on 07 Sep 2001 at 21:43:10 UT. The gray dots mark the locations of the IMAGE magnetometers, and Cluster footprints are denoted by the black, red, green, and blue dots. (bottom) The modelled ionospheric equivalent current density, caused by a longitudinally extended sheet of tailward field-aligned current at 67° magnetic latitude and a similar sheet of earthward field-aligned current 10 km north.

(Figures 2b–2e) and about 5 nT in the southern hemisphere (Figure 2f). A representative value seems to be $\Delta B_Y \approx 6$ nT. This gives a current of 90 kA for a $3 R_E$ wide sheet, which is similar to the typical width of high speed flow channels in the magnetotail [Nakamura *et al.*, 2004b].

2.2. Ionosphere

[10] During the event, the ionospheric footprint of Cluster was within the same region as the International Monitor for Auroral Geomagnetic Effects (IMAGE) magnetometer network. According to both the local IMAGE measurements and the global Auroral Activity Index (*AE*), the ionospheric conditions were very quiet. A substorm was observed several hours later. Normally during substorms, the presumably weak magnetic signatures related to the Hall current system would be obscured by the strong activity, and therefore the

quiet conditions offered a rare opportunity for observing these signatures.

[11] Figure 3 (top) shows the ionospheric equivalent current density at 21:43:10 UT, obtained with the 2-D SECS method [Amm, 1997; Amm and Viljanen, 1999; Pulkkinen *et al.*, 2003]. The currents were derived from the difference between the IMAGE magnetometer data and the background magnetic field. Since the ionospheric conditions were so quiet, particular care was taken when estimating the background magnetic field. It was computed as the average magnetic field during a very quiet time interval between 21:30 and 22:00 UT on 09 Sep 2001. The equivalent current density is displayed by the black arrows, and its curl by the color palette, in Figure 3. Assuming uniform conductances, which is reasonable for quiet conditions, the equivalent current would correspond to ionospheric Hall current, positive curl to upward FAC and negative curl to downward FAC. The gray dots mark the locations of the magnetometers. Cluster footprints, mapped from the magnetosphere using the T89 [Tsyganenko, 1989] model with $K_p = 2$, are denoted by the black, red, green, and blue dots.

[12] Since the expected width of the signature in the north-south direction is only a few tens of km [Tremann *et al.*, 2006], which is lower than the resolution of IMAGE (~ 50 km at best), the observed signature would be smeared out. Therefore, a simple model was made to check if the observed pattern could actually be produced by the narrow field-aligned current sheets. In the model, there was a longitudinally extended sheet of upward field-aligned current at 67° magnetic latitude with a downward current sheet 10 km further north. The field-aligned current was closed by southward flow between the sheets. The intensity of one current sheet corresponded to $3 R_E \times 30 \text{ kA}/R_E/10^\circ$. A $3 R_E$ long line in the Y_{GSM} direction at the Cluster location, corresponding to the assumed dawn-dusk extent of the current sheet, would map to an approximately 10° long line in the ionosphere. Net current into the ionosphere was zero. Assuming uniform conductances (with the Hall-to-Pedersen conductance ratio $\alpha = 1$, which is suitable for such quiet conditions [Juusola *et al.*, 2007]), the magnetic field measured by IMAGE due to the current system was then computed, and from that the equivalent current density and its curl. The resulting pattern is displayed in Figure 3 (bottom).

[13] Approximately during 21:38:30–21:46:00 and 21:50:30–21:51:30 UT, the measured pattern and amplitude resembled those of the model, showing westward equivalent current with negative curl north of it and positive curl south of it close to the Cluster footprint. At other times, the pattern was clearly different, displaying either southward or northward equivalent current density.

3. Summary and Conclusion

[14] In the diffusion region around the X-line, particles become demagnetized, because their gyro-radii exceeded the scale of the current sheet. Since ions have a much larger gyro-radius than electrons, the diffusion region of the ions is also much larger. The Hall current system is set up in the ion diffusion region outside the electron diffusion region, where electrons are still magnetized, while the ions are decoupled.

[15] The FACs out of the diffusion region consist of currents away from the X-line close to the lobes and towards

the X-line deeper inside the plasma sheet. The scatter plots in Figure 2 are consistent with such currents both in the northern and southern hemisphere. Combined with the observations of fast earthward flows in the central plasma sheet, it is quite likely that Cluster observed the Hall current system from an X-line. By using the reconstruction technique for the current sheet described by Runov *et al.* [2005], we have estimated the distance between the outward and inward currents to be approximately 1500 km, which agrees with the predictions of Treumann *et al.* [2006].

[16] Although there is a clear pattern in Figures 2b–2f, there is some scatter around the fitted lines. This can be caused by fast variations of the FACs or by other sources. The former possibility can only be sorted out by using the curlometer method [Robert *et al.*, 1998] when the separation between the Cluster spacecraft is much smaller than it was in this event. Another likely source to the scatter is the currents created in the flow shear regions at the flanks of the flow channel.

[17] In the conjugate ionosphere, the equivalent current pattern observed by the IMAGE magnetometer network was consistent with that produced by a pair of tailward and earthward field-aligned current sheets. The amplitudes of the sheets corresponded to those measured by Cluster in the magnetosphere. These observations strongly suggest that the Hall current system closes in the ionosphere at the earthward side of the X-line. This current system is similar to the Boström Case 2 current system, but with a scale in the north-south direction of only 1500 km in the magnetotail and 10 km in the ionosphere.

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References

- Akasofu, S.-I. (2003), A source of auroral electrons and the magnetospheric substorm current systems, *J. Geophys. Res.*, *108*(A4), 8006, doi:10.1029/2002JA009547.
- Amm, O. (1997), Ionospheric elementary current systems in spherical coordinates and their application, *J. Geomagn. Geoelectr.*, *49*, 947–955.
- Amm, O., and A. Viljanen (1999), Ionospheric disturbance magnetic field continuation from the ground to ionosphere using spherical elementary current systems, *Earth Planets Space*, *51*, 431–440.
- Boström, R. (1964), A model of the auroral electrojets, *J. Geophys. Res.*, *69*, 4983–4999.
- Fujimoto, M., T. Nagai, N. Yokokawa, Y. Yamada, T. Mukai, Y. Saito, and S. Kokubun (2001), Tailward electrons at the lobe-plasma sheet interface detected upon dipolarizations, *J. Geophys. Res.*, *106*, 21,255–21,262.
- Juusola, L., O. Amm, K. Kauristie, and A. Viljanen (2007), A model for estimating the relation between the hall to pedersen conductance ratio and ground magnetic data derived from champ satellite statistics, *Ann. Geophys.*, *25*, 721–736.
- Lui, A. T. Y., and Y. Kamide (2003), A fresh perspective of the substorm current system and its dynamo, *Geophys. Res. Lett.*, *30*(18), 1958, doi:10.1029/2003GL017835.
- Nagai, T., and S. Machida (1998), Magnetic reconnection in the near-Earth magnetotail, in *New Perspectives on the Earth's Magnetotail*, *Geophys. Monogr. Ser.*, vol. 105, edited by A. Nishida, D. N. Baker, and S. W. H. Cowley, pp. 211–224, AGU, Washington, D. C.
- 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*, 25,929–25,949.
- Nakamura, R., et al. (2004a), Flow shear near the boundary of the plasma sheet observed by Cluster and Geotail, *J. Geophys. Res.*, *109*, A05204, doi:10.1029/2003JA010174.
- Nakamura, R., et al. (2004b), Spatial scale of high-speed flows in the plasma sheet observed by Cluster, *Geophys. Res. Lett.*, *31*, L09804, doi:10.1029/2004GL019558.
- Pulkkinen, A., O. Amm, and A. Viljanen (2003), Ionospheric equivalent current distributions determined with the method of spherical elementary current systems, *J. Geophys. Res.*, *108*(A2), 1053, doi:10.1029/2001JA005085.
- Robert, P., M. W. Dunlop, A. Roux, and G. Chanteur (1998), Accuracy of current density determination, in *Analysis Methods for Multi-Spacecraft Data*, edited by G. Paschmann and P. W. Daly, pp. 395–418, Int. Space Sci. Inst., Bern.
- Runov, A., et al. (2003), Current sheet structure near magnetic X-line observed by Cluster, *Geophys. Res. Lett.*, *30*(11), 1579, doi:10.1029/2002GL016730.
- Runov, A., et al. (2005), Reconstruction of the magnetotail current sheet structure using multi-point cluster measurements, *Planet. Space Sci.*, *53*, 237–243, doi:10.1016/j.pss.2004.09.049.
- Runov, A., et al. (2008), Structure of the near-earth plasma sheet during tailward flows, *Ann. Geophys.*, *26*, 709–724.
- Snekvik, K., R. Nakamura, N. Østgaard, S. Haaland, and A. Retinò (2008), The Hall current system revealed as a statistical significant pattern during fast flows, *Ann. Geophys.*, *26*, 3429–3437.
- Sonnerup, B. U. Ö. (1979), Magnetic field reconnection, *Sol. Syst. Plasma Phys.*, *3*, 45–108.
- Takada, T., et al. (2008), Local field-aligned currents in the magnetotail and ionosphere as observed by a Cluster, Double Star, and MIRACLE conjunction, *J. Geophys. Res.*, *113*, A07S20, doi:10.1029/2007JA012759.
- Treumann, R. A., C. H. Jaroschek, R. Nakamura, A. Runov, and M. Scholer (2006), The role of the Hall effect in collisionless magnetic reconnection, *Adv. Space Res.*, *38*, 101–111, doi:10.1016/j.asr.2004.11.045.
- Tsyganenko, N. A. (1989), A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, *37*, 5–20.
- Ueno, G., S. Ohtani, T. Mukai, Y. Saito, and H. Hayakawa (2003), Hall current system around the magnetic neutral line in the magnetotail: Statistical study, *J. Geophys. Res.*, *108*(A9), 1347, doi:10.1029/2002JA009733.

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