Cluster PEACE observations of electron pressure tensor divergence in the magnetotail

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[1] Cluster crossed the magnetotail neutral sheet on four occasions between 16:38 and 16:43 UT on 08/17/2003. The four-spacecraft capabilities of Cluster are used to determine spatial gradients from the magnetic field vectors and, for the first time, full electron pressure tensors. We find that the contribution to the electric field from the Hall term (max of ~6 mV/m) pointed towards the neutral sheet, whereas that from the electron pressure divergence (max of ~1 mV/m) pointed away from the neutral sheet. The electric field contributions in this direction were closely anti-correlated. During this period Clusters 1 and 4 were sometimes above and below the neutral sheet respectively. This allowed the simultaneous observation of magnetic fields that are interpreted as two quadrants of the Hall magnetic field system. An associated field-aligned current system was detected using the curlometer and moments of the particle distributions. **Citation:** Henderson, P. D., C. J. Owen, A. D. Lahiff, I. V. Alexeev, A. N. Fazakerley, E. Lucek, and H. Rème (2006), Cluster PEACE observations of electron pressure tensor divergence in the magnetotail, *Geophys. Res. Lett.*, *33*, L22106, doi:10.1029/2006GL027868.

1. Introduction

[2] The large and small scale behavior of the magnetosphere is in some way governed by electric fields. The flow of magnetic field and plasma from the solar wind gives rise to the convection electric field that can permeate the magnetosphere. On smaller scales, electric fields are thought to play a vital role in the microphysics of reconnection.

[3] Electric fields are governed by the generalized Ohm's law:

$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{en_e} - \frac{\nabla . \mathsf{P}_e}{en_e} - \frac{m_e}{e}\frac{d\mathbf{v}_e}{dt} + \eta \mathbf{j} \qquad (1)$$

Here, $\mathbf{E}$, $\mathbf{v}$, n and P are electric field, velocity, density and pressure tensor respectively (subscripts e and i denote the species). $\mathbf{B}$, $\mathbf{j}$ and η are the magnetic field, current density and the resistivity respectively and e is the electronic charge.

[4] The first term on the RHS is the ideal MHD term expressing frozen-in convection of magnetic field and plasma. The second term is the Hall term and becomes important when the scale size of the system approaches the ion inertial length. At this scale size the ions become demagnetized and no longer move with the magnetic field. The electrons remain magnetized until the electron inertial length where they too become demagnetized. The third and fourth terms are the divergence of the electron pressure tensor ($\nabla . \mathsf{P}_e$) and electron inertia terms. Attempts have been made to estimate the $\nabla . \mathsf{P}_e$ term [e.g., *André et al.*, 2004] and empirically argue its role in parallel electric field generation [e.g., *Scudder et al.*, 2002]. However, neither the $\nabla . \mathsf{P}_e$ or the electron inertia terms have, to date, been properly determined in previous observational studies. In the absence of anomalous resistivity caused by, for example, wave-particle interactions, the last term can be normally considered negligible in collisionless space plasmas.

[5] This equation can be used to investigate the general electric field properties of the plasma sheet. The charge separation that exists when the scale of the system reduces to the ion inertial length creates a Hall electric field that points towards the neutral sheet on both sides [*Nagai et al.*, 2001; *Borg et al.*, 2005; *Wygant et al.*, 2005]. Kinetic simulations [*Pritchett and Coroniti*, 1995] suggest that an electric field directed towards the neutral sheet can arise from a negatively charged thin current sheet. Additionally, the electron pressure would be expected to be larger towards the center than the edges. This simple effect will lead to an electric field pointing away from the neutral sheet from the $\nabla . \mathsf{P}_e$ term.

[6] The plasma sheet is also a prime location for magnetic reconnection [*Vasyliunas*, 1975] to occur and create one or more X-lines. The reconnection itself is believed to occur within an extremely localized region of the magnetotail called the diffusion region. This surrounds the X-line and comprises two distinct parts, the ion and electron diffusion regions [*Sonnerup*, 1979]. These regions are on the scales of the ion and electron inertial lengths, which, in the plasma sheet, are on scales of hundreds and a few km respectively.

[7] The 'reconnection electric field' would be in the same direction (dawn to dusk) as the cross tail current ($\mathbf{j} . \mathbf{E} > 0$) and cause an $\mathbf{E} \times \mathbf{B}$ drift of plasma and magnetic field towards the X-line from above and below the neutral sheet. Assuming there is no guide magnetic field in the cross tail direction, the magnetic field at the X-line vanishes. Thus, the Hall and ideal MHD terms cannot support the reconnection electric field at this point. The electron terms must therefore play a significant role at the X-line. Simulations [e.g., *Hesse et al.*, 1999] suggest that the spatial derivatives

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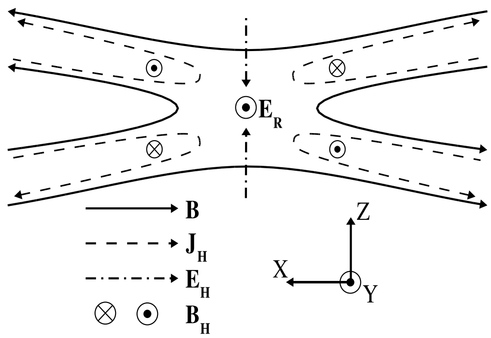

Figure 1. Magnetic field, electric field and current topology around an X-line. The field-aligned current system (J_H) associated with the Hall current system and quadrupolar magnetic field system (B_H) are marked. Previous observations and simulations show that the Hall electric field normal to the current sheet (E_H) points towards the current sheet. The reconnection electric field (E_R) points across the magnetotail.

of the off-diagonal components of P_e support the reconnection electric field in a small region around, and at, the X-line. Outside this small region, the reconnection electric field is supported by the Hall term, then the ideal MHD term at larger distances.

[8] The measurement of the $\nabla \cdot \mathsf{P}_e$ term is therefore very important for both the understanding of the general properties of the plasma sheet and the reconnection process.

[9] Hall-MHD simulations by *Yin et al.* [2001], which include the full electron pressure tensor to initiate reconnection, find that in the other direction parallel to the neutral sheet (up or down the tail) the contributions are generally towards (away from) the X-line for the $\nabla \cdot \mathsf{P}_e$ (Hall) term. The electric field normal to the neutral sheet from the Hall ($\nabla \cdot \mathsf{P}_e$) term points towards (away from) the neutral sheet and is largest at the X-line. The contributions normal to the neutral sheet were found to be more spatially extensive and larger than those in the plane of the neutral sheet.

[10] As well as the creation of a neutral sheet directed electric field, the differential motion of ions and electrons within the ion diffusion region creates Hall currents directly related to reconnection. These in turn drive a system of field aligned currents outside the ion diffusion region, which act to close the Hall currents and also create the quadrupolar magnetic field structure previously reported [*Nagai et al.*, 2001; *Runov et al.*, 2003; *Asano et al.*, 2004; *Borg et al.*, 2005; *Alexeev et al.*, 2005]. These systems are illustrated in Figure 1.

[11] The four-spacecraft nature of the Cluster mission makes it possible for the first time to directly determine both the Hall and $\nabla \cdot \mathsf{P}_e$ terms using the multi-point observations. In this letter we discuss signatures of reconnection near an active X-line and investigate the Hall and $\nabla \cdot \mathsf{P}_e$ terms in the generalized Ohm's law in this context. These are the first calculations of the full $\nabla \cdot \mathsf{P}_e$ term calculated from 3D electron phase space distributions.

2. Data Overview

[12] We use data from the PEACE [*Johnstone et al.*, 1997], FGM [*Balogh et al.*, 2001] and CIS [*Rème et al.*, 2001] instruments on the 4 Cluster spacecraft. At 16:40 UT on 17 August 2003, Cluster was located at (−16.7, −5.5, 3.5) R_E GSM, near apogee in the tail (GSM will be used throughout this letter unless otherwise stated). At this time the average separation of the Cluster spacecraft was only 200 km, which is ideal for the use of multi-spacecraft methods in the investigation of current sheets. The spacecraft were in a mode that enabled full 3D spin resolution data from the PEACE instruments on all four spacecraft and from CIS on Cluster 4 to be sent to the ground (a relatively rare situation). Great care and effort has been made to verify the calibration of the four PEACE data sets in order to support differencing of the data from different spacecraft to produce valid gradients for presentation here. Note that all the plasma data were interpolated onto the time stamps of Cluster 4 PEACE, while high time resolution FGM data, and the current density derived from these data using the curlometer method [*Dunlop et al.*, 2002], were averaged onto these time stamps. See *Dunlop et al.* [2002, and references therein] for caveats relating to the use of the curlometer method when observing small scale structures. The same linear estimator technique used in the curlometer was used in the derivation of electron pressure tensor gradients here. In this way the $\nabla \cdot \mathsf{P}_e$ term could be effectively compared to the Hall term. These two derived quantities are averages through the tetrahedron.

3. Data Analysis

[13] Throughout the period 15:00 to 18:00 UT the spacecraft were close to or in the plasma sheet. The plasma was initially relatively cold (electron energy ~300 eV). At approximately 16:30 UT the Cluster spacecraft entered a region containing hotter plasma, the electrons reaching ~6 keV at approximately 17:00 UT. Cluster crossed the neutral sheet a number of times during this period. We note that the speeds at which the spacecraft crossed the neutral sheet (determined from multi-spacecraft timing of the passage of the $B_X = 0$ surface through the Cluster tetrahedron) became faster towards 17:00 UT. The current density, compared at constant B_X, also increased during successive encounters of the current sheet which suggests that the current sheet was thinning during this time. A reversal of the ion flow (from ~1000 km s^{-1} tailwards to ~1000 km s^{-1} Earthwards) was observed at around 16:55 UT, which suggests that an active X-line moved past the spacecraft location in the tailwards direction. The AE index was ~750 nT at 17:00 UT, suggesting that a large substorm occurred during this interval.

[14] Figure 2 shows observations from a 5-minute period between 16:38 and 16:43 UT, containing a number of neutral sheet crossings. The first to fourth panels show the magnetic field measured on each spacecraft (Cluster 1 - black, Cluster 2 - red, Cluster 3 - green, Cluster 4 - blue). All B_X were initially negative, indicating that all spacecraft were nominally below the neutral sheet, but became positive as the spacecraft crossed the neutral sheet at approximately 16:39:20 UT. After several more crossings between 16:41 and 16:42 UT the spacecraft moved below the neutral sheet at approximately 16:42:30 UT. B_Y was negative throughout most of this time and B_Z was small. The magnitude of the magnetic field observed at high resolution (10 vectors per

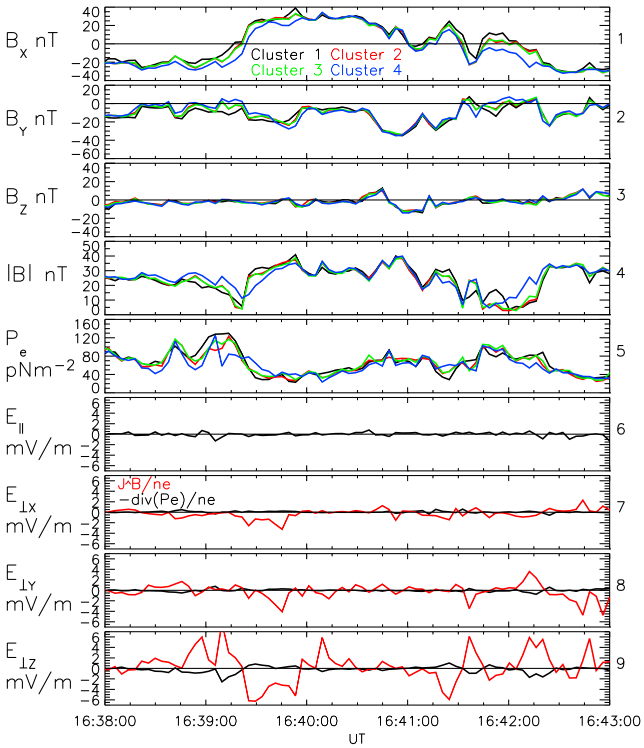

Figure 2. The first to fourth panels show the B_X, B_Y and B_Z components and |B| from all spacecraft (Cluster 1 - black, Cluster 2 - red, Cluster 3 - green, Cluster 4 - blue). The fifth panel shows $\frac{1}{3}Tr\mathsf{P}_e$. The sixth panel shows the parallel component of the electric field from $\nabla \cdot \mathsf{P}_e$ at the barycenter. The seventh to ninth panels show the perpendicular components of the electric field from the Hall term (red) and $\nabla \cdot \mathsf{P}_e$ (black).

second, not shown) is small (∼2 nT) at all spacecraft when $B_X = 0$, suggesting there was little or no guide field. Minimum variance analysis over this period suggests the neutral sheet normal was in the (−0.037, 0.088, −0.995) direction, with a minimum-intermediate eigenvalue ratio of 3.7. The GSM system should therefore satisfactorily represent a natural neutral sheet frame, with GSM Z corresponding to the neutral sheet normal direction.

[15] Between 16:41:45 and 16:42:00 UT the 4 second averaged magnetic field data shows that Cluster 1 was above the neutral sheet ($B_X \sim +10$ nT), whereas Cluster 4 was below the neutral sheet ($B_X \sim -10$ nT). The same data suggest that the spacecraft concurrently observed significantly different B_Y (Cluster 1 observed $B_Y \sim -5$ nT, Cluster 4 observed $B_Y \sim +5$ nT). The high time resolution magnetic field data (not shown) show some high frequency fluctuations, but generally reflect the behavior seen in the 4 second averaged data. For example, at 16:41:49 UT Cluster 1 observed $B_X = +10$ nT and $B_Y = -6$ nT, whereas Cluster 4 observed $B_X = -8$ nT and $B_Y = +6$ nT. At 16:41:55 UT Cluster 1 observed $B_X = +11$ nT and $B_Y = -8$ nT, whereas Cluster 4 observed $B_X = -12$ nT and $B_Y = +4$ nT. Note that these spacecraft were separated by only ∼220 km in the Z direction. At the crossing location (16:39:49 UT) the plasma density was ∼0.8 cm^{-3}, giving a proton (electron) inertial length ∼255 km (∼6 km), which defines the scale length of any proton (electron) diffusion region. The flows in the period shown here were in the tailward direction, which suggests that an active X-line may have been located Earthwards of the spacecraft. Plasma β (not shown) remained >1 and confirms that the spacecraft remained in the plasma sheet during this period. The fifth panel shows the magnitude of the electron pressure ($\frac{1}{3}Tr\mathsf{P}_e$) from each spacecraft. The pressure was generally higher when the spacecraft were closer to the neutral sheet.

[16] The sixth to ninth panels in Figure 2 show the full components of the electric field arising from the $\nabla \cdot \mathsf{P}_e$ term (black) and the Hall term (red) in the generalized Ohm's law (equation (1)). These are derived from the gradients between each of the 4 Cluster spacecraft, and in the former case we believe this to be the first such calculation performed. The four panels respectively show the electric field components parallel to the barycentric magnetic field and the projections of the perpendicular component onto the 3 GSM axes. At 16:39:30 UT, the X and Y components of the perpendicular electric field from the Hall term (red trace) are both negative. As at this time $B_X \sim B_Y$, this electric field would seem to the directed across the tail, but could in some part be associated with the Hall term pointing away from the X-line in agreement with *Yin et al.* [2001]. However, no clear signature of the $\nabla \cdot \mathsf{P}_e$ term occurred in the X component. No clear sustained signature of a reconnection electric field in the (positive) Y direction from the $\nabla \cdot \mathsf{P}_e$ term can be seen (eighth panel). A number of peaks in the (positive) Y direction can be seen in the contribution from the Hall term and these could be supporting (part of) the reconnection electric field away from the X-line. The ninth panel shows the Z component of the perpendicular electric field (i.e. the component normal to the nominal neutral sheet). Where the spacecraft were close to the neutral sheet (i.e. around the $B_X = 0$ crossings) it can be seen that the Hall term pointed towards the neutral sheet while the $\nabla \cdot \mathsf{P}_e$ term pointed away from it. The bipolar signatures in this component are thus caused by the spacecraft barycenter crossing the neutral sheet. The electric field contributions in this direction are an order of magnitude larger during this period than those observed at a previous crossing (∼16:00 UT, not shown), during which Cluster observed no fast flows.

[17] The contributions from the spatial gradients of the off-diagonal components of the electron pressure tensor to the $\nabla \cdot \mathsf{P}_e$ term are generally smaller than those of the diagonal terms. However, this is not always the case. For example, during the enhanced $\nabla \cdot \mathsf{P}_e$ observed at 16:39:06 UT, some of the contributions from the spatial derivatives of the off-diagonal components are clearly significant and comparable in size to those from the diagonal components.

[18] Figure 3 shows a scatter-plot of the Hall and $\nabla \cdot \mathsf{P}_e$ contributions to the perpendicular Z electric field measured between 16:38:30 and 16:42:30 UT. A best fit straight-line shows that the Hall term was well anti-correlated (correlation coefficient = −0.9, statistical significance >99%) with the $\nabla \cdot \mathsf{P}_e$ term and is on average ∼5.3 times stronger during this period. The PEACE and FGM instruments, used to derive the $\nabla \cdot \mathsf{P}_e$ and Hall terms respectively, are independent, measure physically different parameters and are non-cross-calibrated. The high correlation coefficient gives confidence that the data is not instrument error

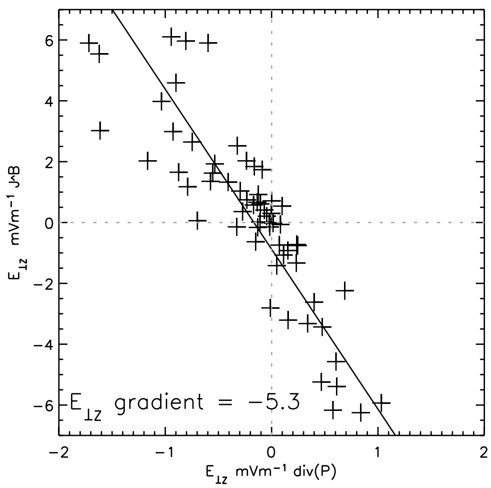

Figure 3. Scatter-plot showing the contributions to the Z component of the perpendicular electric field from the Hall term and $\nabla \cdot \mathsf{P}_e$ terms in Ohm's law.

dominated. A large dispersion of these points might be expected if the errors were large.

[19] The first to fourth panels (fifth to eighth) of Figure 4 show the parallel and perpendicular components of the curlometer current derived from FGM data in the barycenter (electron and proton velocity moments derived from PEACE and CIS CODIF data on Cluster 4 respectively). It is important to note that the first to fourth panels use the barycentric magnetic field whereas the data in fifth to eighth panels are derived using the magnetic field measured from Cluster 4. The ninth panel shows a comparison between the barycentric and Cluster 4 B_X for reference. The first panel shows that the majority of the curlometer-derived current was aligned to the magnetic field. The main perpendicular component was in the Y direction and can be identified with the cross tail current. Three enhanced current contributions parallel to the magnetic field are highlighted A to C. On the basis of concurrent magnetic field strength, A is observed when the spacecraft were located close to, but below, the neutral sheet whereas B and C were related to currents nearer the boundaries of the plasma sheet. Current A was directed anti-parallel (i.e. in the +X direction, towards the X-line), B was in the anti-parallel direction (in the -X direction, away from the X-line) whereas current C was in the parallel direction (again in the -X direction). The fifth to eighth panels suggest that the electrons generally carry the current. The highlighted curlometer current signatures are consistent with enhancements of electron velocity during periods of constant proton velocity at Cluster 4. Signature B (C) is consistent with the movement of protons (electrons) anti-parallel to the magnetic field and electrons (protons) parallel to the magnetic field.

[20] During current enhancement A, all spacecraft see similar parallel electron flows to those observed on Cluster 4 (not shown). However, as Cluster 1 approaches the neutral sheet and B_X is close to zero, its local magnetic field becomes almost perpendicular to the mainly -X directed barycentric magnetic field. At this point (16:39:15 UT) Cluster 1 sees large negative perpendicular X directed electron flows (not shown).

4. Discussion

[21] The electric field contributions normal to the neutral sheet arising from the $\nabla \cdot \mathsf{P}_e$ and Hall terms are observed to have opposite sign. The electric field from the Hall term points towards the neutral sheet whilst the electric field from the $\nabla \cdot \mathsf{P}_e$ term points away from the neutral sheet. Thus during a traversal of the neutral sheet these are observed as bipolar signatures. This is consistent with the observation that the electron pressure is largest at the neutral sheet, however, a quantitative result has been achieved by directly calculating the divergence of the full electron pressure tensor using multi-spacecraft methods.

[22] Between 16:41:45 and 16:42:00 UT Clusters 1 and 4 were either side of the neutral sheet (Cluster 1–4 B_X separation ~20 nT). These spacecraft simultaneously detect B_Y with opposing signs (Cluster 1–4 B_Y separation ~12 nT). This behavior can be observed in both the high time resolution and 4 second averaged magnetic field data. This could be interpreted as an observation of tailward half of the Hall quadrupolar system (Figure 1). Current density derived from the curlometer technique showed a number of enhancements in the component parallel to the magnetic field. Towards the center of the current sheet, the current is directed towards the X-line, whereas towards the boundary

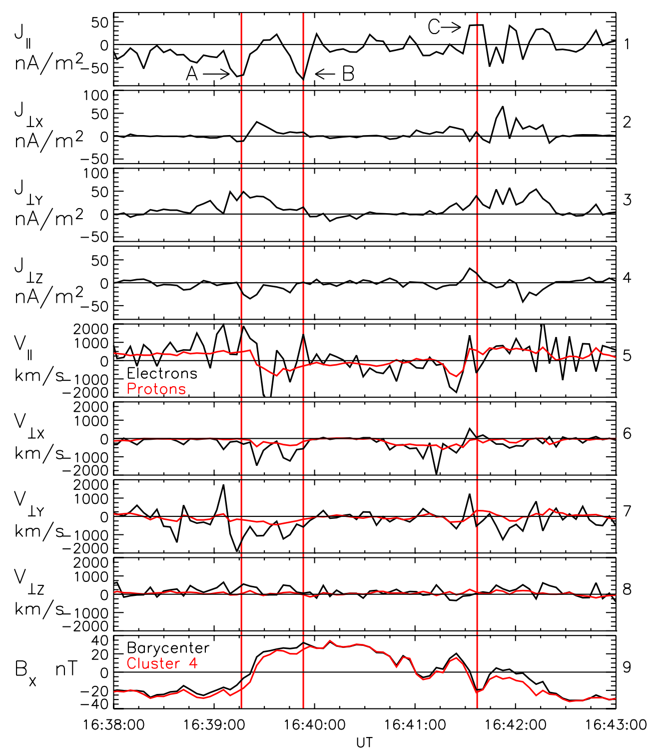

Figure 4. The first to fourth panels show the parallel and three perpendicular components of the current density derived from the curlometer technique (at barycenter). The fifth to eighth panels show the parallel and three perpendicular components of velocity from electrons (black) and protons (red). The particle measurements are from Cluster 4. The ninth panel shows B_X at the barycenter and at Cluster 4.

of the plasma sheet the currents are directed away from the X-line. These currents are consistent with the field-aligned current system acting to close the Hall current system (Figure 1). When these current enhancements are compared with particle velocity moments it can be seen that electrons dominate the currents.

[23] It is found that in the event detailed here, the perpendicular Z component of the electric field from the Hall term is a factor of $\sim$5.3 larger than that of the $\nabla \cdot \mathsf{P}_e$ term and is well anti-correlated. There are no clear anti-correlations in the electric field components transverse to the neutral sheet. However, we note that the electric field in these directions in the simulations of *Yin et al.* [2001] are smaller, more complex and spatially less extended. The electric field contributions in the direction normal to the neutral sheet are an order of magnitude larger during this period than at a previous encounter with the neutral sheet. This previous crossing, at $\sim$16:00 UT (not shown), did not display any characteristic reconnection signatures. The contributions to the $\nabla \cdot \mathsf{P}_e$ term mainly originated from the spatial gradients of the diagonal components of the electron pressure tensor, with the contribution of the off-diagonal components sometimes being non-negligible.

[24] Simulations predict that the region in which the reconnection electric field is supported by the $\nabla \cdot \mathsf{P}_e$ term alone, although extended across the tail, is very localized around the X-line. It is unlikely that Cluster could sample this region as the electron inertial length is on the order of a few km. The reconnection electric field from the Hall term is more spatially extended (the ion diffusion region, which is on the order of the ion inertial length). As no strong reconnection electric field contribution from the Hall or $\nabla \cdot \mathsf{P}_e$ term was seen, we suggest that the spacecraft do not sample directly either diffusion region. The electric field system normal to the neutral sheet as well as the system of field aligned currents that close the Hall currents and the associated magnetic field deflections exist in regions extending away from the diffusion regions. The observation of a B_X separation of $\sim$20 nT in spacecraft separated by $\sim$220 km (Clusters 1 and 4) suggests that the current sheet was thin at this time. This, along with the field-aligned current system associated with the Hall current system observation, suggests that the Cluster spacecraft were at least magnetically connected to an ion diffusion region, i.e. on magnetic field lines that map to the vicinity of the diffusion region.

[25] It is noted that the velocities from Cluster 4 are point measurements and are therefore not expected to observe all the current signatures measured by the curlometer, which in some sense is an average current density through the tetrahedron. For example, at 16:42 UT the parallel current derived from the curlometer is enhanced. However, no anti-parallel electron or parallel proton flows that could cause this signature are observed at Cluster 4. We note that at this time Clusters 1, 2 and 3 do observe fast ($\sim$1000 kms^{-1}) anti-parallel electron flows (not shown) giving confidence in the particle moments. This result also suggests that the parallel current signatures are spatially thin.

5. Conclusions

[26] On 17 August 2003 an active X-line passed by Cluster. On a number of occasions between 16:38 and 16:43 UT the spacecraft crossed the neutral sheet and observed a field-aligned current system (with both particle and field experiments) consistent with the system that would act to close the Hall currents in the diffusion region. The spacecraft also made a simultaneous observation of a magnetic field system that is interpreted as two branches of the associated quadrupolar magnetic field system. During this time the particle instruments recorded phase space density distributions from which spin resolution moments were derived.

[27] After considerable efforts by the PEACE team to perfect the PEACE calibration, the multi-spacecraft nature of the Cluster mission was used to derive the first measurements of the divergence of the full electron pressure tensor.

[28] We have shown that the electric fields normal to the neutral sheet from the Hall and electron pressure divergence have opposite sign, with the Hall term pointing towards the neutral sheet and the divergence of the electron pressure term pointing away. In this example these fields are closely anti-correlated with the Hall term being approximately 5.3 times larger.

[29] **Acknowledgments.** The work of the PEACE operations team in the calibration of data is gratefully acknowledged. The authors wish to thank the World Data Center for Geomagnetism, Kyoto, for AE index plots for 2003. PDH acknowledges UK PPARC studentship funding. IVA was supported by the MSSL PPARC funded rolling grant and benefited from travel funds associated with an INTAS grant (03-51-3738).

References

Alexeev, I. V., C. J. Owen, A. N. Fazakerley, A. Runov, J. P. Dewhurst, A. Balogh, H. Rme, 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.

André, M., A. Vaivads, S. C. Buchert, A. N. Fazakerley, and A. Lahiff (2004), Thin electron-scale layers at the magnetopause, *Geophys. Res. Lett.*, *31*, L03803, doi:10.1029/2003GL018137.

Asano, Y., T. Mukai, M. Hoshino, Y. Saito, H. Hayakawa, and T. Nagai (2004), Current sheet structure around the near-Earth neutral line observed by Geotail, *J. Geophys. Res.*, *109*, A02212, doi:10.1029/2003JA010114.

Balogh, A., et al. (2001), The Cluster Magnetic Field Investigation: Overview of in-flight performance and initial results, *Ann. Geophys.*, *19*, 1207–1217.

Borg, A. L., M. Øieroset, T. D. Phan, F. S. Mozer, A. Pedersen, C. Mouikis, J. P. McFadden, C. Twitty, A. Balogh, and H. Rème (2005), Cluster encounter of a magnetic reconnection diffusion region in the near-Earth magnetotail on September 19, 2003, *Geophys. Res. Lett.*, *32*, L19105, doi:10.1029/2005GL023794.

Dunlop, M. W., A. Balogh, K.-H. Glassmeier, and P. Robert (2002), Four-point Cluster application of magnetic field analysis tools: The Curlometer, *J. Geophys. Res.*, *107*(A11), 1384, doi:10.1029/2001JA005088.

Hesse, M., K. Schindler, J. Birn, and M. Kuznetsova (1999), The diffusion region in collisionless magnetic reconnection, *Phys. Plasmas*, *6*, 1781–1795.

Johnstone, A. D., et al. (1997), PEACE, A Plasma Electron And Current Experiment, *Space Sci. Rev*, *79*, 351–398.

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*(A11), 25,929–25,950.

Pritchett, P. L., and F. V. Coroniti (1995), Formation of thin current sheets during plasma sheet convection, *J. Geophys. Res.*, *100*(A12), 23,551–23,566.

Rème, H., et al. (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment, *Ann. Geophys.*, *19*, 1303–1354.

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.

Scudder, J. D., F. S. Mozer, N. C. Maynard, and C. T. Russell (2002), Fingerprints of collisionless reconnection at the separator: 1. Ambipolar-Hall signatures, *J. Geophys. Res.*, *107*(A10), 1294, doi:10.1029/2001JA000126.

Sonnerup, U. O. (1979), Magnetic field reconnection, in *Solar System Plasma Physics*, vol. 3, pp. 45–108, Elsevier, New York.

Vasyliunas, V. M. (1975), Theoretical models of magnetic line merging, *Rev. Geophys.*, *13*, 303.

Wygant, J. R., et al. (2005), Cluster observations of an intense normal component of the electric field at a thin reconnecting current sheet in the tail and its role in the shock-like acceleration of the ion fluid into the separatrix region, *J. Geophys. Res.*, *110*, A09206, doi:10.1029/2004JA010708.

Yin, L., D. Winske, S. P. Gary, and J. Birn (2001), Hybrid and Hall-MHD simulations of collisionless reconnection: Dynamics of the electron pressure tensor, *J. Geophys. Res.*, *106*(A6), 10,761–10,776.

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