Asymmetry of the Ion Diffusion Region Hall Electric and Magnetic Fields during Guide Field Reconnection: Observations and Comparison with Simulations

J. P. Eastwood,[1,*] M. A. Shay,[2] T. D. Phan,[3] and M. Øieroset[3]
[1]*The Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*
[2]*Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*
[3]*Space Sciences Laboratory, University of California, Berkeley, California 94720, USA*
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In situ measurements of magnetic reconnection in the Earth's magnetotail are presented showing that even a moderate guide field (20% of the reconnecting field) considerably distorts ion diffusion region structure. The Hall magnetic and electric fields are asymmetric and shunted away from the current sheet; an appropriately scaled particle-in-cell simulation is found to be in excellent agreement with the data. The results show the importance of correctly accounting for the effects of the magnetic shear when attempting to identify and study magnetic reconnection diffusion regions in nature.

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Collisionless magnetic reconnection plays an important role in many plasma phenomena. Of particular interest is the central diffusion region, where the plasma decouples from the magnetic field and the magnetic field "reconnects" [1]. In a proton-electron plasma, the protons demagnetize on larger scales than the electrons, leading to the creation of Hall electric and magnetic fields [2–5]. Both these simulations and observations [6–9] of symmetric, antiparallel reconnection show that a characteristic quadrupole pattern is created in the out of plane magnetic field, and a bipolar pattern is created in the normal electric field.

Although this basic structure is well established, it is important to understand how it might be altered by a guide field (i.e., when the shear between the reconnecting fields is less than 180°), since in many laboratory, space, and astrophysical contexts the guide field cannot be neglected. Simulations of guide field reconnection with symmetric boundary conditions suggest that the Hall magnetic field pattern is distorted, and may disappear entirely for large guide fields [10–15]. Such predictions are important because most experimental studies of the ion diffusion region have concentrated on searching for the existence of the Hall fields and using this evidence to thus establish the existence of diffusion region encounters in the data [16]. If in certain geometries the pattern of Hall fields is so distorted that the quadrupole signature is absent, it is necessary to identify other signatures of the diffusion region in order to identify and probe guide field reconnection experimentally. Furthermore, knowledge of this distortion can itself be used to develop our understanding of reconnection.

Observations of reconnection, and in particular satellite observations of reconnection in space plasmas, are crucial to constraining existing models and providing ground truth. However, because relatively few diffusion region encounters have been reported in the literature, very little is known experimentally about the structure of the diffusion region in the presence of a guide field. Here we present new measurements of a diffusion region in the presence of a moderate guide field ($B_g \sim 20\%$ of the reconnecting field B_R), made by the four Cluster spacecraft [17] in the Earth's near magnetotail. In this region the guide field is usually small, unlike the magnetopause, solar wind, or corona, but the advantage of the magnetotail is that the effects of the guide field can be studied in isolation, since the boundary conditions are otherwise largely symmetric and the geometry is largely two dimensional. This event was found in the course of surveying five years (2001–2005) of Cluster magnetotail observations for diffusion region encounters, and is, thus far, the only example we have identified of a guide field reconnection diffusion region encounter where the spacecraft simultaneously observed both sides of the magnetotail current sheet, demonstrating that the observed signatures were spatial and not temporal in nature. Through appropriate scaling, the observations are directly compared to simulations of guide field reconnection performed using the particle-in-cell code P3D [18] and are found to be in excellent agreement. This result shows experimentally that the structure of the diffusion region is indeed altered by the guide field, and that this is qualitatively and quantitatively consistent with theory.

The observations, made on 1 October 2001 from 0935 UT–0943 UT, are shown in Fig. 1 when the spacecraft were near the magnetotail current sheet [at $(-16.1, 7.9, 1.1)$ Re (Earth radii) in geocentric solar magnetospheric (GSM) coordinates], and formed a regular tetrahedron approximately 2000 km in size. Note that this interval is different from the one studied in [19]. Figures 1(a)–1(d) show magnetic field data [20] at 4 s resolution. Figure 1(e) shows the electric field normal to the current sheet [21], and Figs. 1(f)–1(h) show the ion density, outflow speed, and temperature [22].

The data have been rotated into a current sheet coordinate system. Since the four spacecraft were too far apart to use multispacecraft timing techniques, and minimum variance analysis [23] was found to perform poorly, the co-

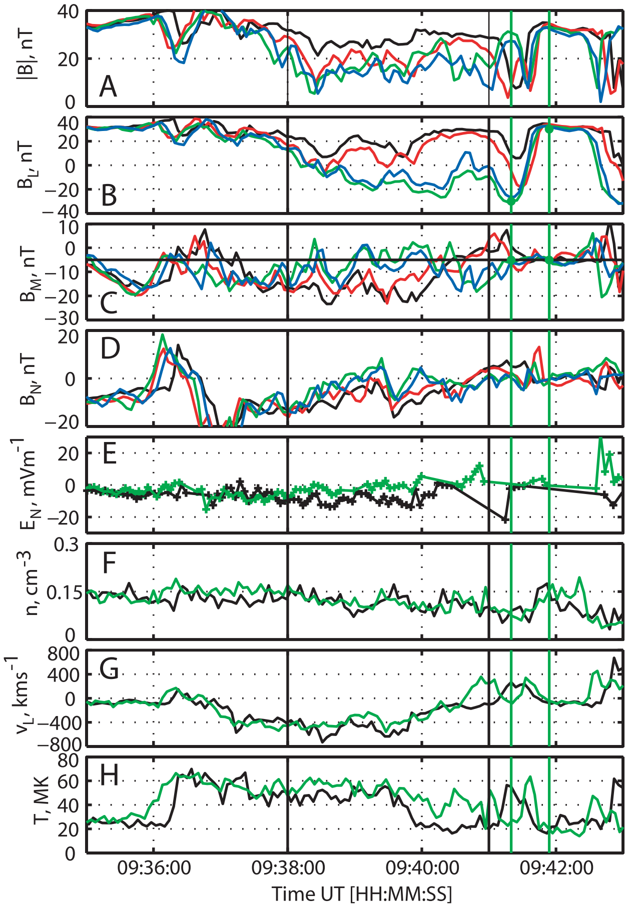

FIG. 1 (color). Data from Cluster 1–4 (shown in black, red, green and blue, respectively) from 1 October 2001. (a)–(d) Magnetic field at 4 s resolution. The green dots in (b) and (c) show the data from Cluster 3 used to determine the coordinate system used in the analysis.

ordinate system was constructed using measurements of the magnetic field above and below the current sheet outside of the flow by Cluster 3. At 0941:20 UT (marked by a vertical green line and green dots in the B_L and B_M time series), Cluster 3 was located below the current sheet [$\mathbf{B_1} = (-30.7, 0.4, 4.7)$ nT GSM]; shortly after, at 0941:54 UT (marked by a second green line and dots), Cluster 3 had moved to above the current sheet [$\mathbf{B_2} = (30.7, -10.7, 0.64)$ nT GSM]. This was due to the motion of the current sheet relative to the spacecraft. The magnetic field measured at these two times was used to construct the coordinate system: $\mathbf{N} = \mathbf{B_1} \times \mathbf{B_2}/|\mathbf{B_1} \times \mathbf{B_2}|$, $\mathbf{L} = \mathbf{B_2} - \mathbf{B_1}/|\mathbf{B_2} - \mathbf{B_1}|$, and $\mathbf{M} = \mathbf{N} \times \mathbf{L}$. From this, the magnetic shear is found to be ~159°, the guide field $B_g \sim -5.8$ nT, and the reconnecting field (measured at the edge of the outflow jet) $B_R \sim 31$ nT, consistent with a normalized guide field $B_g/B_R \sim -0.2$. Relative to the GSM coordinate system, $\mathbf{L} = (0.9820, -0.1774, -0.0649)$ points earthward and contains the reconnecting field, $\mathbf{M} = (0.1263, 0.8720, -0.4728)$ contains the guide field, and $\mathbf{N} = (0.1405, 0.4561, 0.8788)$ points along the current sheet normal, with a current sheet tilt of 28° (Fig. 2). Cluster 1 and Cluster 3 were mainly separated in the N direction, with Cluster 3 below and earthward of Cluster 1.

Finally, it should be noted that the electric field is obtained by the electric field and wave (EFW) experiment which measures the components of the dc electric field in the spacecraft spin plane [approximately the geocentric solar ecliptic x-y plane]. The third component has been reconstructed using the assumption that $\mathbf{E} \cdot \mathbf{B} \sim \mathbf{0}$, i.e., $E_\parallel = 0$, which is expected to be valid in the ion scale region that is the subject of this Letter (in the simulations presented below, $E_\parallel$ is an order of magnitude smaller than the reconnection electric field in the outflow region of reconnection where the satellites pass). The reconstruction requires that $\mathbf{B}$ is not too weak and does not lie near the spin plane; as a result, the time series of E_N is irregularly sampled. Complete ion plasma data were only available on Cluster 1 and Cluster 3, and so our analysis is restricted to these two spacecraft.

Referring to Fig. 1, the tailward flow starts at ~0936:30 UT, marked by the ejection of a tailward moving island, as indicated by the characteristic positive then negative perturbation in B_N [24]. Tailward flow continued to be observed until 0940:30 UT, whereupon earthward flow was observed by Cluster 3 (V_L positive). The reversal in the flow is accompanied by a reversal in B_N from negative to positive values during this interval. (This pattern is somewhat disturbed by a secondary island that occurs during this interval at ~0939:30 UT.) Furthermore, Cluster 3 observes earthward flow before Cluster 1. Recalling that Cluster 3 is earthward of Cluster 1, this indicates that a single X line moved tailward across the tetrahedron.

We now examine the properties of the interval 0938 UT–0941 UT, marked by the two black vertical lines, in more detail. During the majority of this interval Cluster 1 and Cluster 3 encountered fast tailward jets. Referring to the B_L time series in Fig. 1, during this interval Cluster 1 was located above the current sheet ($B_L > 0$) and Cluster 3 was below the current sheet ($B_L < 0$). However, they both observed similar plasma density and temperature, indicat-

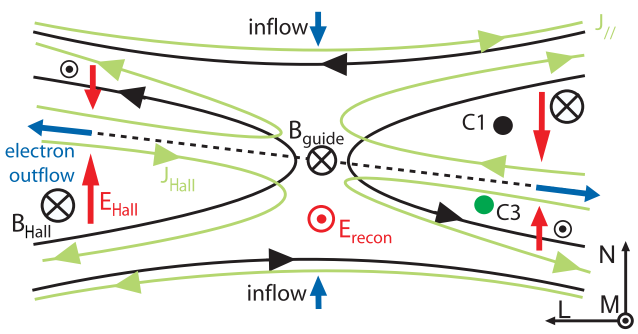

FIG. 2 (color). Sketch of the overall configuration of the ion diffusion region encounter. The guide field points in the $-M$ direction. Cluster 1 and Cluster 3 are shown at 9:38 UT when they are embedded in tailward (V_L negative) flow and Cluster 1 is above the current sheet and Cluster 3 below.

ing that the inflow conditions on both sides were essentially symmetric, as is expected for reconnection in the Earth's magnetotail.

The signatures of the electric and magnetic field associated with Hall physics in the ion diffusion region are expected to be observed in the E_N and B_M components, respectively. Figure 3 shows the out of plane magnetic field and the normal electric field as a function of the reconnecting magnetic field B_L, for those points where $v_L < -50\ \mathrm{km\,s^{-1}}$ and $|B_L| < 30$ nT. This ensures that only data points near the current sheet and within the tailward reconnection jet are included. Furthermore, the data have been normalized. We plot $b_M = B_M/B_{L,\max}$ and $e_N = E_N/(B_{L,\max}V_{\mathrm{out}})$, where $B_{L,\max} = 30$ nT and $V_{\mathrm{out}} = 600\ \mathrm{km\,s^{-1}}$ as a function of $b_L = B_L/B_{L,\max}$. During this interval, Cluster 1 (black crosses) was located above ($b_L > 0$) and Cluster 3 (green crosses) below ($b_L < 0$) the current sheet. Therefore, the difference between the two sides is due to real spatial structure, and not simply due to temporal variations.

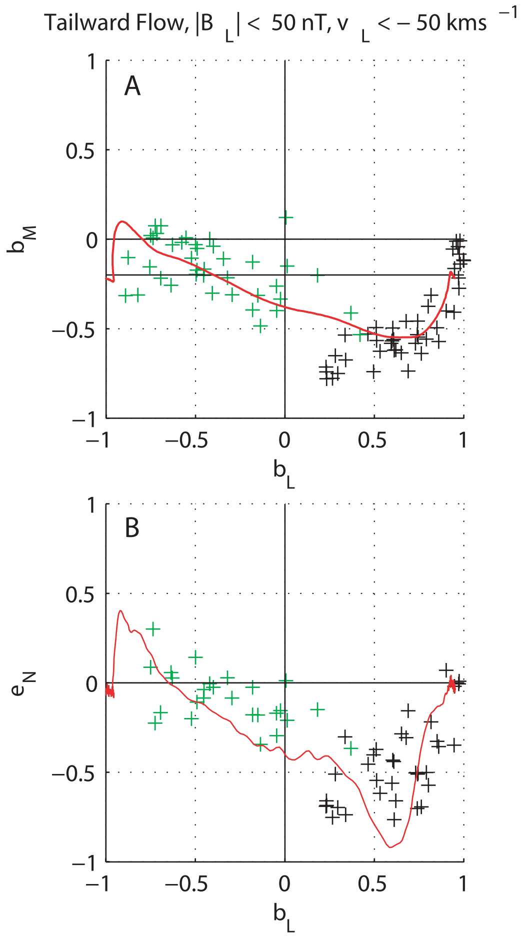

FIG. 3 (color). Top: Normalized out of plane magnetic field b_M as a function of b_L. Bottom: Normalized normal electric field e_N as a function of b_L. In both cases data from Cluster 1 and Cluster 3 are shown as black and green crosses. The red curves show the predicted signatures from the particle-in-cell simulation shown in Fig. 4.

From Fig. 2, we expect that in $-V_L$ flow, b_M and e_N should both be anticorrelated with b_L. Although this basic pattern is observed, an asymmetry, particularly in e_N, is immediately obvious; $e_N \neq 0$ where $b_L = 0$. Evidently the b_M pattern is superimposed on a guide field. However, we have established that the normalized guide field is -0.2, and it is clear that at the midplane, b_M on average is less than -0.2 (and closer to -0.5). Therefore, this indicates that while for symmetric, antiparallel reconnection we would expect these patterns to be symmetric, here they are not.

To further understand this, a full particle simulation of guide field reconnection was performed using the code P3D [18]. While the code is three dimensional, here the simulations are performed in two dimensions such that $\partial/\partial M = 0$. The system was initialized with two Harris current sheets superimposed on an ambient population [25], with a guide field of 0.2 and $m_i/m_e = 25$. The simulation was run until steady reconnection was observed, but before the boundary conditions could significantly affect the dynamics. Figure 4 shows a portion of the

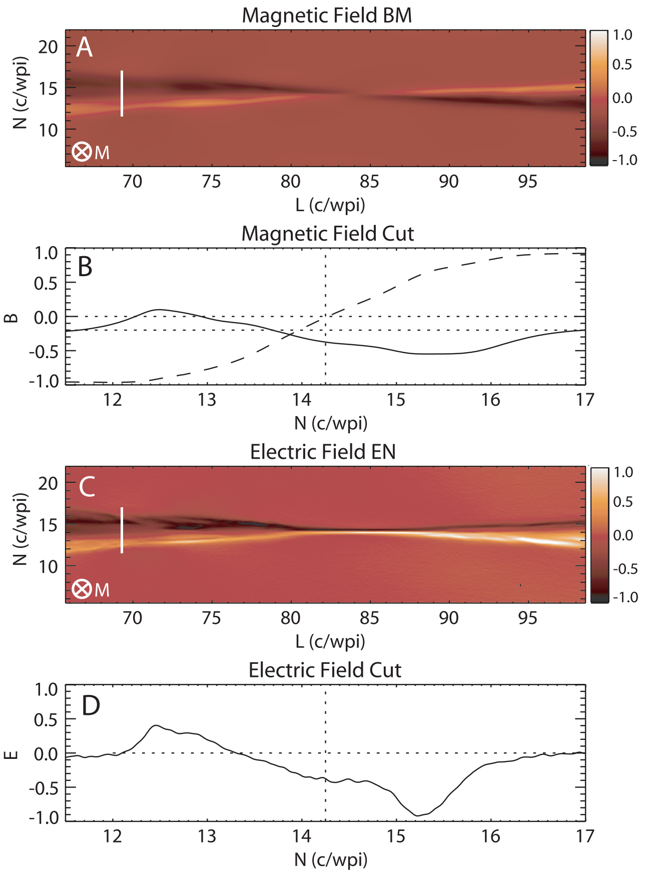

FIG. 4 (color). Particle-in-cell simulation of reconnection. The top panel shows the two-dimensional structure of the out of plane magnetic field B_M. The second panel shows cuts through the magnetic field along the white line in the top panel (solid line, B_M; dashed line, B_L). The bottom two panels show the normal electric field E_N in the same format as the top two panels. In magnetotail geometry, the Earth is to the right.

simulation domain, centered on a reconnection X line that formed in one of the current sheets. The data have been renormalized to the central current sheet density and the inflow magnetic field, and averaged over two ion gyroperiods to smooth the data. Using this renormalization the system size is $112.2 \times 56.1c/\omega_{pi}$. The simulation coordinate system is the same as that used in the experimental data; above the current sheet, the reconnecting field points in the positive L direction. Figure 4(a) shows the out of plane magnetic field B_M. Figure 4(b) shows the magnetic field as a function of N across the reconnection exhaust, corresponding to the white line in the top panel. The reconnecting field B_L is shown as a dashed line, and the out of plane field B_M is shown as a solid line. The vertical dotted line shows where the reconnecting field $B_L = 0$, i.e., the location of the center of the current sheet, at $N = 14.25c/\omega_{pi}$. It can be seen that the reversal in the B_M perturbation relative to the guide field does not occur at the center of the current sheet, but is shunted such that $B_M = 0.2$ at $N = 13.7c/\omega_{pi}$. The width of the positive Hall field region is $2.2c/\omega_{pi}$ and the width of the negative Hall field region is $3.3c/\omega_{pi}$. As such, the negative Hall perturbation is ~50% wider than the positive Hall region. Figures 4(c) and 4(d) show the normal electric field E_N in the same format; again the Hall electric field is not centered on the current sheet reversal; E_N and B_M both reverse in sign at approximately the same location, which is consistent with $E_N \sim -v_L B_M$. The presence of the guide field alters the pattern of the Hall currents by enabling the reconnection electric field to induce electron motion and currents along the magnetic field (shown in Fig. 2), and displaces the electron outflow in the N direction due to $\mathbf{j}_{\mathrm{Hall}} \times \mathbf{B}_{\mathbf{g}}$ forces [13,15,26]. It should be noted that the asymmetry is introduced across the current sheet in the N direction, and not in the L direction. In the previous analysis of a diffusion region with a 50% guide field [6], the encounter occurred below the current sheet and so the Hall fields were observed as being symmetrically overlaid on the guide field across the flow reversal.

To make a quantitative comparison between the observed data and the simulation, the simulation data are also shown in Fig. 3 in red. The observed asymmetry in the Hall fields is reproduced by the simulation and there is good agreement between the simulated and observed data, particularly in the shape and magnitude of the perturbation in b_M and e_N as a function of b_L. Cuts at other locations in the L direction show similar agreement with the data. Based on studies of electron outflow without a guide field, increasing the mass ratio is expected to result in a thinner central electron jet but similar current sheet tilting.

In summary, Cluster observations of guide field reconnection in the Earth's magnetotail provide clear experimental data showing that the guide field distorts the pattern of the observed Hall fields. This example of guide field reconnection is thus far unique (to our knowledge) because it was observed by two spacecraft on opposite sides of the reconnecting current sheet simultaneously. The Hall magnetic field perturbation was not simply superimposed on the guide field, but was asymmetric and shunted away from the current sheet. What is particularly remarkable is that even though the guide field is moderate, it introduces considerable asymmetry into the Hall pattern. In the many applications of reconnection where the guide field is non-negligible, even in moderate cases such as the one studied here, one should be careful to properly account for the guide field when attempting to identify and study diffusion regions in experimental data.

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*Previous address: Space Sciences Laboratory, University of California, Berkeley, California 94720, USA.
jonathan.eastwood@imperial.ac.uk

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