Structure of the Magnetic Reconnection Diffusion Region from Four-Spacecraft Observations

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Magnetic reconnection leads to energy conversion in large volumes in space but is initiated in small diffusion regions. Because of the small sizes of the diffusion regions, their crossings by spacecraft are rare. We report four-spacecraft observations of a diffusion region encounter at the Earth’s magnetopause that allow us to reliably distinguish spatial from temporal features. We find that the diffusion region is stable on ion time and length scales in agreement with numerical simulations. The electric field normal to the current sheet is balanced by the Hall term in the generalized Ohm’s law,

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\frac{E_n}{\mu_0 j/n_e} = B_n/v_n, \]

thus establishing that Hall physics is dominating inside the diffusion region. The reconnection rate is fast, \( \sim 0.1 \). We show that strong parallel currents flow along the separatrices; they are correlated with observations of high-frequency Langmuir/upper hybrid waves.

Magnetic reconnection in astrophysical plasma environments allows fast conversion of the magnetic field energy of two colliding magnetized plasmas into kinetic energy of ions and electrons. Energy and plasma from the solar wind can enter the Earth’s magnetosphere mainly due to magnetic reconnection between the magnetic fields of the solar wind and the Earth’s magnetosphere at the magnetopause \([1,2]\). The reconnection is initiated in small diffusion regions, where the magnetic flux is no longer frozen into the motion of the ions (ion diffusion region) and the electrons (electron diffusion region). The ion diffusion region (we refer to it simply as the diffusion region) is larger than the electron diffusion region. Single spacecraft observations have established the collisionless character of the diffusion region, particularly based on observations of an out-of-plane component of the magnetic field \([2–4]\). However, the single satellite measurements involve ambiguity in distinguishing spatial and temporal features of the diffusion region \([2]\). For a detailed description, and reliable comparison with numerical simulations and theories, it is important to use high quality multipoint observations of the diffusion region.

On 20 February 2002 around 13–14 UT the four Cluster spacecraft \([5]\) crossed the magnetopause many times tailward and duskward of the cusp (Fig. 1). We investigate one of the magnetopause crossings at 13:22 UT when the Cluster spacecraft cross the diffusion region. The separation between the spacecraft is about 100 km which is comparable to the ion inertial length \( \lambda_i \approx 75 \) km. All four-spacecraft observe a very similar structure of the current sheet thickness is about 300 km, \( \sim 4\lambda_i \). The current sheet.
thus, the current sheet has a planar structure on the scale of the spacecraft separation (0.0021), and is stable on the time scale of 1 s (approximately the ion gyroperiod). The current sheet is bifurcated, with the current (gradient in BL) being strongest along the outer edges. Such determination of the spatial structure of the diffusion region is only possible with multispacecraft measurements.

The out-of-plane magnetic field component BM [panel 2(b)] shows a bipolar variation with the highest amplitude being ~50% of BL outside the current sheet. According to numerical simulations, the bipolar variation in BM is an indication of the ion diffusion region in collisionless reconnection and has been used as one of the arguments for ongoing reconnection in previous studies [3,8]. The fact that all four-spacecraft, crossing the magnetopause consecutively, observed Hall fields of this large amplitude indicates that this is a stable spatial feature of the diffusion region rather than some brief temporal variation. There is no significant constant offset in BM, a so-called guide field. The presence of a nonzero normal component of the magnetic field BN ~ 3 nT [panel 2(c)] inside the current sheet also suggests ongoing reconnection. Inside the current sheet BN is a major fraction of the total magnetic field and the observed magnitudes agree with the simulation, while good agreement can not be expected when BN is a small fraction of the total field. The negative sign of BN, and the fact that a negative BM is followed by a positive, are both consistent with Cluster crossing the diffusion region south of the X line.

FIG. 1 (color online). Location of the four Cluster spacecraft (red circle) and the magnetic field lines of the Earth’s magnetosphere from the Tsyganenko 2001 model (interplanetary magnetic field IMF in GSE (BX, BY, BZ) = (0, 7, –2) nT, and solar wind pressure 3.5 nPa are observed averages from the ACE spacecraft). Assuming that reconnection occurs in regions with antiparallel magnetic fields, the varying IMF BZ (from +3 to –7 nT within 10 min) is consistent with a diffusion region occurring duskward and tailward of the cusp, as observed by Cluster.

FIG. 2 (color online). Left: The structure of the diffusion region from a numerical simulation. The magnetic field lines are shown, and the out-of-plane magnetic field is color coded (white is positive and black is negative). Also shown is the projection of the Cluster configuration and the approximate location relative to the diffusion region (C1: black square; C2: red diamond; C3: green circle; C4: blue triangle). Right: Cluster observations; simulation results are shown with gray thick lines. (a) Reconnecting magnetic field component. (b) Out-of-plane magnetic field component. (c) Normal magnetic field component. (d) Electric field normal to the magnetopause, directly observed En (solid lines), j x B/ne (dotted lines). (e) Tangential electric field; the average value is about –1 mV/m. (f) plasma density from the satellite potential. At the bottom the spatial scale obtained from the four-spacecraft magnetopause velocity estimate is given. The observations are consistent with fast collisionless reconnection.
The solid lines in panel 2(d) show the electric field component normal to the magnetopause, $E_n$ (the electric field is measured in the satellite spin plane and $E_n$ is along the direction in the spin plane closest to the magnetopause normal, here 5 degrees off from the nominal normal). $E_n$ changes sign from positive to negative in the center of the current sheet. The dotted lines show $\mathbf{j} \times \mathbf{B}/ne \cdot \mathbf{n}$, indicating how much of $E_n$ is balanced by the Hall term in the generalized Ohm’s law [9]. There is good agreement between $E_n$ and $\mathbf{j} \times \mathbf{B}/ne \cdot \mathbf{n}$ within the narrow region of strong $E_n$ at 13:22:04 UT. This observationally confirms the major role of the Hall term in the formation of the structure of the diffusion region. The cross-field potential drop across the region of strong electric field is $\sim 300$ V. A proton accelerating through 300 V would obtain a speed of $\sim 250$ km/s which is approximately the Alfvén velocity in the inflow region and comparable to the predicted outflow velocity of ions from the reconnection region.

If the magnetopause locally is a rotational discontinuity, then $B_0$, being $\sim 10\%$ of $B_L$ gives a reconnection rate of $\sim 0.1$. The reconnection rate is the ratio of plasma inflow velocity and the local Alfvén velocity in the inflow region. Such rates are typically observed in numerical simulations of fast collisionless reconnection [10]. A reconnection rate of 0.1 corresponds to an inflow velocity of $\sim 25$ km/s or a tangential electric field in the magnetopause reference frame, $E_{\text{tang}}$, of $\sim 1$ mV/m. The observed $E_{\text{tang}}$ is varying but on average $\sim 1$ mV/m [panel 2(e)]. This magnitude and sign of $E_{\text{tang}}$ are consistent with magnetic field observations, and simulations, of fast reconnection. Panel 2(f) shows that in the center of the current sheet (plasma outflow region) the density increases significantly by $\sim 50\%$, and there is a similarly large density dip when entering the current sheet, consistent with the simulations. Reference [4] attributed a density dip observed by Wind in the magnetotail to the density dip predicted by simulations near the separatrices, but the exact location and the stability of this dip could not be determined. Here, we can tell that it is a spatial structure and it is located at separatrices. There is no significant density gradient across the magnetopause, thus, reconnection is almost symmetric. The absence of a significant density gradient across the magnetopause during this event can be explained by reconnection occurring between the so called plasma mantle (solar wind plasma that has entered the magnetosphere at some very distant reconnection site) and the magnetosheath. The slight differences between the separatrices [e.g., panels 2(d) and 2(f)] may be due to different plasma flow velocities observed before entering and after exiting the current sheet; the velocity shear is $\sim 150$ km/s.

Simulations predict that a quadrupolar out-of-plane magnetic field structure in the diffusion region is caused by current loops that are mainly perpendicular to the ambient magnetic field in the center of the current sheet and mainly parallel near the separatrices, directed away from the X line. The evidence for Hall currents has been reported in the form of the detection of field-aligned electrons flowing toward the X line [4]. However, these observations do not allow the quantitative determination of the size of the current since the relative ion-electron motion is not known from these studies. Here we can do it by using four spacecraft to define the appropriate coordinate system and then using single spacecraft magnetic field perturbations to obtain the current. Panel 3(a) shows $B_M$ and Panel 3(b) shows the parallel current. As predicted by simulations, strong parallel currents occur along the outer edge of the bipolar $B_M$ structure. Panel 3(c) shows the electric field power integrated over a broad frequency range that includes the plasma frequency. The regions of strong emissions are clearly correlated with

![Image](3SEP004FP10V30100.png)
regions of strong parallel currents. Panel 3(d) shows the spectra of waves from C2 in one of the strong emission regions. There is a spectral peak near the plasma frequency, thus the waves are probably Langmuir or upper hybrid waves [11]. For the first time we can directly relate high-frequency waves in the vicinity of a reconnection region with the parallel currents of the separatrices.

In summary, using multispacecraft observations we can establish the spatial structure and stability of the current layer in the diffusion region of magnetic reconnection at the magnetopause. This allows us to resolve the spatial and temporal ambiguity that has always been present in the single spacecraft measurements. The diffusion region is stable on the ion time scale and its structure is consistent with theoretical predictions of fast reconnection that is governed by Hall physics. The reconnection rate is fast, $\sim 0.1$, and the bipolar out-of-plane and normal magnetic fields are quantitatively consistent with theoretical expectations. Such out-of-plane fields have been suggested as an indication of fast reconnection also by single spacecraft measurements with all the involved ambiguities. Here, in addition, we show that the large electric fields at the separatrices are balanced by the Hall term, $E_n \sim j \times B/\rho e n^\perp \hat{n}$, thus establishing the role of the Hall term in forming the structure and dynamics of the diffusion region. Other features are also consistent with predictions from numerical simulations: a bifurcated current sheet, density dips at the separatrices and a density increase in the center of current sheet. Multispacecraft measurements allow us to unambiguously resolve parallel currents along the separatrices and show that they are correlated with high-frequency Langmuir/upper hybrid waves. These waves can be involved in thermalization of electrons, formation of anomalous resistivity, and can be used as a diagnostics tool of reconnection sites. The good agreement between simulations and observations is a strong motivation to go further and study such important unanswered questions as whether reconnection at the magnetopause is always fast, whether the microphysics of the diffusion region affects the global processes, and what are the conditions for switch-on and switch-off of the reconnection process.

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