In situ detection of the electron diffusion region of collisionless magnetic reconnection at the high-latitude magnetopause

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Abstract: Magnetic reconnection is the most fundamental energy-transfer mechanism in the universe that converts magnetic energy into heat and kinetic energy of charged particles. For reconnection to occur, the frozen-in condition must break down in a localized region, commonly called the ‘diffusion region’. In Earth’s magnetosphere, ion diffusion regions have already been observed, while electron diffusion regions have not been detected due to their small scales (of the order of a few km) (Paschmann, 2008). In this paper we report, for the first time, in situ observations of an active electron diffusion region by the four Cluster spacecraft at the Earth’s high-latitude magnetopause. The electron diffusion region is characterized by nongyrotropic electron distribution, strong field-aligned currents carried by electrons and bi-directional super-Alfvénic electron jets. Also observed were multiple micro-scale flux ropes, with a scale size of about $5c/\omega_{pe}$ (12 km, with $c/\omega_{pe}$ the electron inertial length), that are crucial for electron acceleration in the guide-field reconnection process (Drake et al., 2006a). The data demonstrate the existence of the electron diffusion region in collisionless guide-field reconnection at the magnetopause.

Keywords: electron diffusion region; magnetic reconnection; high-latitude magnetopause

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1. Introduction

The conversion of magnetic energy to charged particle kinetic energy plays an important role in our solar system and throughout other astrophysical systems. Reconnection was first proposed by Giovanelli (1947) as a possible mechanism for converting magnetic energy stored in the magnetic field into kinetic energy of charged particles.

Magnetic reconnection occurs in a small (diffusion) region where the plasma frozen-in condition has broken down and the terms in general Ohm’s law must be considered. There are two mechanisms of reconnection: resistive reconnection, which requires anomalous resistivity within the diffusion region, and collisionless reconnection, which is based on the inertial effects of ions and electrons. In collisionless reconnection, ions demagnetize in a small volume of space (of the order of ion inertial length, $c/\omega_{pi}$), which is called the ion diffusion region, while electrons demagnetize in a much smaller region (of the order of electron inertial length), which is called the electron diffusion region. The decoupling of ions and electrons produces the Hall magnetic field, which is quadrupolar in the magnetotail symmetric reconnection (e.g., Fu XR et al., 2006; Huang C et al., 2010; Lu S et al., 2011) and bipolar at the magnetopause asymmetric reconnection. Signatures of the Hall effect have been observed in the magnetotail (Øieroset et al., 2001; Wang RS et al., 2010a), the subsolar region (Mozer et al., 2002; Peng FZ et al., 2017; Zhang YC et al., 2017) and the high latitude magnetopause (Zhang H et al., 2008; Lu Q et al., 2010). The presence of a guide field will have a significant effect on the magnetic reconnection region. Particle simulations showed that a strong field-aligned current is present near the X-line (Drake et al., 2003). Quadrupolar plasma density structure is an important observational signature of Hall reconnection with a strong guide field (Kleva et al., 1995; Tanaka, 1996). Plasma electrons flowing parallel along newly reconnected field lines lead to a plasma density asymmetry across the dissipation region rather than the symmetric structure that occurs in the absence of a guide field. Plasma ions polarization drift across the magnetic field to charge neutralize the parallel-flowing electrons (Drake and Shay, 2007). Ion diffusion regions have been observed, and until recently electron diffusion regions have been extensively reported and studied (Mozer et al., 2005; Oka et al., 2016; Burch et al., 2016; Eriksson et al., 2016; Argall et al., 2018), mostly using MMS observations near the equatorial magnetopause. In the following we report, for the first time, in situ detection of an active electron diffusion region by the four Cluster spacecraft at the Earth’s high-latitude magnetopause on 23 April 2002.

2. Observation and Interpretation

Firstly, we show evidence that Cluster crossed the reconnection site. On 23 April 2002, bi-directional plasma jets (Figure 1h) were...
detected by the Cluster as it crossed the magnetopause from the cusp region into the magnetosheath in the northern hemisphere at ~ 08:18:20 UT (GSE [4.0, -0.4, 7.6] R\(_\oplus\); 10 Magnetic Local Time). The magnetopause is clearly associated with sharp transitions of the magnetic field and plasma moments. From 08:08 to 08:28 UT, the \(B_1\) component (component of maximum variance, Figure 1f) of the magnetic field in an LMN coordinate system (the N component is normal to the boundary) changed from negative (\(-100\) nT) to positive (\(+100\) nT), indicating a geometry in favor of magnetic reconnection. To establish quantitatively that the observed bi-directional jets (Figure 1h) are the result of reconnection between magnetosheath and magnetospheric cusp magnetic fields, we performed the Walén test to examine the relationship between the flow velocity in the deHoffmann-Teller frame and the Alfvén velocity. Figure 2a and Figure 2b show that the Walén test for bi-directional jets from 08:17 UT to 08:20 UT is very well satisfied. The high correlation coefficients, 0.99 and 0.97, between the plasma flow velocity and the Alfvén velocity, and their identical slopes of 0.93, indicate that the Walén test is satisfied. Also, the normal component of the magnetic field (\(B_n\), Figure 3e) changed its sign (seen more clearly in the spin-averaged data) when the plasma bulk flow jet reversed at around 08:18:25. Walén test results are strong evidence (Paschmann et al., 1979) which, together with other evidence presented here, is consistent with the interpretation that a guide-field reconnection site was observed at the high latitude magnetopause (between the cusp and the magnetosheath), as illustrated in Figure 4. The detection of the uninterrupted bi-directional reconnection jets implies that the spacecraft moved from the magnetospheric side to the magnetosheath side of an active reconnection X-line (Figure 4b) and crossed the ion diffusion region (Øieroset et al., 2001). Note that in the case of guide field reconnection, the Hall magnetic signatures would be distorted or even disappear (Eastwood et al., 2010; Wang RS et al., 2012). In addition to the bi-directional ion jets, bi-directional (parallel and antiparallel) electrons (Figure 1d and Figure 1e), ions that peak at 90° pitch angle (Figure 1c), and the electron density profile in the dissipation region (Figure 1b) are consistent with the guide-field reconnection scenario (Drake and Shay, 2007) as illus-

Figure 1. Overview of the guide-field reconnection. (a) Energetic electron flux; (b) Plasma electron density; (c) Plasma ion pitch angle; (d) Plasma electron pitch angle (98 eV); (e) Plasma electron pitch angle (70 eV); (f–g) Magnetic field components (\(B_1\) and \(B_n\)) in the LMN coordinate system (in nT); (h) Plasma velocity \(V_i\) component. Time intervals from 08:17:20 UT to 08:18:20 UT (\(W_1\)) and 08:19:00 UT to 08:20:00 UT (\(W_2\)) are marked with purple dashed lines, for which Walén test are done and shown in Figure 2.

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trated in Figure 4. Similar bi-directional electron pitch angle distributions are also observed in magnetotail reconnection (Wang RS et al., 2010a).

The scale size of the electron current sheet and reconnection rate can be estimated based on magnetic field measurements by the four spacecraft. The timing differences of the magnetopause crossing as measured by the four spacecraft give the normal direction ([$-0.63, 0.47, -0.62$] GSE) of the magnetopause current sheet with a speed of $V_{ce} = 8.01$ km/s. The half thickness of the electron current layer is about 80 km ($\sim 36 \, c/\omega_{pe}$). In contrast to observations in previous studies (Eastwood et al., 2010; Vaivads et al., 2004), there exists a significant constant offset (as high as 80 nT) in $B_M$—a so-called guide field throughout the reconnection region (Figure 2g). More interestingly, we find that the guide field is strongly compressed, to 110 nT (37% enhancement), in the field-reversal region (Figure 3d). The presence of a non-zero normal component $B_N$ in the reconnected field-reversal ($B_{r}$) reversal region (Figure 3e) (of about 7.5 nT) suggests ongoing reconnection; $B_N$ being about 7.5% of $B_r$ suggests a reconnection rate of 0.075. This is in agreement with simulation results that suggest that Hall reconnection with a guide field can still be a fast process (Fu XR et al., 2006; Tanaka, 1996; Hesse et al., 1999, 2002; Huba, 2005; Pritchett, 2001; Rogers et al., 2001) and independent of, or weakly dependent on, the dissipation mechanism (Pritchett, 2001; Ricci et al., 2004).

We now show evidence that the Cluster spacecraft 1 (C1) and 2 (C2) detected the electron diffusion region. According to numerical simulations, the electron diffusion region is a very thin current sheet with a width on the order of the electron inertial length, whose edge is defined by bi-directional super-Alfvénic electron jets (Shay et al., 2001). Both C1 and C2 detected bi-directional super-Alfvénic electron jets (with 10 seconds time shift, see Figure 3a). The duration of the electron jets is only 20 seconds which is much shorter than that of the ion jets (about 4 minutes), indicating the scale length of this region is 70 $c/\omega_{pe}$ (76 km). Bi-directional electron jets were observed only by C1 and C2, indicating that the thickness of this electron diffusion region is less than 35 $c/\omega_{pe}$ (76 km). To our knowledge, this is the first in situ detection of bi-directional super-Alfvénic electron jets in an electron diffusion region. Phan et al. (2007) deduced from the magnetic field measurement that there should be a super-Alfvénic electron jet (uni-directional) when C1 crossed one of the reconnection exhausts on Jan. 14, 2003. In addition to the bi-directional super-Alfvénic electron jets, a non-gyrotropic electron distribution was detected by C2. Figure 3g shows 16 slices (one per sector) of perpendicular distributions (pitch angle between 75° and 105°) which were calculated based on rebinning of magnetic fields to the same sampling rate. The non-circular shapes of the contours indicate a thin electron gyroradius scale current sheet, which has been predicted for the electron diffusion region by particle-in-cell simulations (Hesse et al., 2002; Scudder and Daughton, 2008). Fi-
nally, a strong field-aligned current was observed at the same time that the bi-directional super-Alfvénic electron jets were detected. Figure 3b presents the evolution of the field-aligned current density \( J \), which is calculated by linear interpolation (Robert et al., 1998) for the time period of interest. It can be seen clearly that the field-aligned current in the electron diffusion region of the reconnection site is enhanced greatly (Drake et al., 2003). The maximum current reaches a remarkable \( \sim 1.5 \mu \text{A/m}^2 \), which is about 15 times stronger than the current found in antiparallel reconnection (Bale et al., 2002). (c)–(e) the high-resolution (0.04 s) magnetic field data from four Cluster spacecraft: (c) The L component of the magnetic field; (d) Guide magnetic field component \( B_M \); (e) Normal magnetic field component \( B_N \) over-plotted with spin-averaged data (red), 8 flux-rope-like structures are identified (marked by arrows); (f) Electron density from spacecraft potential; vertical dashed lines (black) mark the dissipation region with multiple flux ropes, yellow shaded area marks the compression guide field region where multiple flux ropes are located. (g) Nongyrotropic electron distribution detected by C2 during one spin (08:18:24.8 UT to 08:18:28.8 UT). It shows 16 slices (one per sector) of perpendicular distributions (pitch angle between 75° and 105°), which were calculated based on rebinning of magnetic fields to the same sampling rate. The non-circular shapes of the contours indicate a thin electron gyroradius scale boundary layer.

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guide field direction. These flux ropes have a strong core field as 
$c/\omega_{pe} (12 \text{ km})$, and the axis of the flux ropes is roughly in the 
magnetic flux rope. The average size of eight flux ropes is about 
minimum eigenvalues (Sonnerup and Cahill, 1967) indicate it is a 
gram for this structure and the ratio (5.3) of the intermediate to 
B_y x B_y hodo-
versus the maximum variance 
conspicuous bipolar perturbations in 
tures rather than brief temporal phenomena. One of the most 
polar signatures in the reconnection region are stable spatial fea-
quite large, usually larger than 20 nT. C1 and C2 observed such 
fields consecutively, indicating that magnetic structures with bi-
polar signatures in the reconnection region are stable spatial features rather than brief temporal phenomena. One of the most 
 conspicuous bipolar perturbations in $B_y$ is illustrated in the hodo-
gram in Figure 2c. The nearly circular shape of the corresponding 
medium variance $B_y^*$ versus the maximum variance $B_x^*$ hodo-
gram for this structure and the ratio (5.3) of the intermediate to 
minimum eigenvalues (Sonnerup and Cahill, 1967) indicate it is a 
magnetic flux rope. The average size of eight flux ropes is about 
$5 c/\omega_{pe} (12 \text{ km})$, and the axis of the flux ropes is roughly in the 
guide field direction. These flux ropes have a strong core field as 
illustrated in Figure 3d. Electron density depletions (Drake et al., 
2003) with about 20% less electron density (Figure 3f) derived 
from the spacecraft potential (available with high time resolution, 
5 samples/sec) are embedded in the flux ropes.

Drake et al. (2003) found that, with the presence of a guide field, 
the reconnection region would become strongly turbulent to form 
small magnetic islands (Drake et al., 2006a, 2006b) rather than lamellar-like structures formed in anti-parallel cases in three 
dimensional reconnection simulations. However, it should be 
noted that the observations shown in this study suggest that the "magnetic islands" formed by the reconnection are flux ropes with 
their axis in the guide field direction rather than plasmoids with a 
weak core field as suggested by Drake et al. (2006a, 2006b) and Fu 
XR et al. (2006). These eight magnetic field structures can be inter-
preted as flux ropes in agreement with the morphology of a flux 
rope (Zong QG et al., 2003) or plasmoid (Zong QG et al., 2004, 
2005; Wilken et al., 1995) in the cusp region or in the magnetotail.
The flux ropes are essential in trapping and accelerating electrons in 
the reconnection process (Drake et al., 2006a; Wang RS et al., 
2010b, 2016).

The energetic electrons are substantially accelerated in the diffusion 
region. Figure 2d shows the energetic electron spectra for the 
background (08:14–08:15 UT, cusp region and 08:26–08:27 UT, 
magnetosheath) and during the guide-field reconnection time period (08:18–08:19 UT). The electron energy distributions can be fit to straight lines in the energy range from 30 to 300 keV, indicating the electron spectra to be a typical power law distribution, 
with the spectral indices of 1.20 (background) and 1.92 (reconnec-
tion) and correlation coefficients of 0.98 and 0.98, respectively. 
The spectral index ($\gamma = 1.92$) with the plasma $\beta_e = 0.043$ is remark-
ably in agreement with the theoretical prediction of the spectral 
index ($\gamma = 1.95$) by Drake et al. (2006a) who suggests that elec-
trons gain kinetic energy when reflected by multiple "magnetic is-
lands" that form during the reconnection process (the Fermi 
mechanism).

These multiple flux ropes in the electron diffusion region provide a set of narrow channels of open flux tubes that connect the mag-
etosheath to the magnetosphere and allow the solar wind popu-
lation moving along the reconnect IMF and magnetospheric 
magnetic field lines, thus facilitating the overall plasma and en-
ergy transport from the solar wind into the magnetosphere. In-
vestigating the electron diffusion region is crucial for a thorough 
understanding of the fundamental physics of the magnetic recon-
nection process, which is a universal energy transfer mechanism.

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