Spatial Distribution of Energetic Electrons during Magnetic Reconnection *

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Electron acceleration by the inductive electric field near the X point in magnetic reconnection is an important generation mechanism for energetic electrons. Particle simulations have revealed that most of energetic electrons reside in the magnetic field line pileup region, and a depletion of energetic electrons can be found near the centre of the diffusion region [Phys. Plasmas, 13 (2006) 012309]. We report direct measurement of energetic electron in and around the ion diffusion region in near-Earth tail by the cluster, and our observations confirm the above predictions: a depletion of the high-energy electron fluxes is detected near the centre of the diffusion region. At the same time, the plasma temperature has a similar profile in the diffusion region.

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Magnetic reconnection is a fundamental plasma process which converts stored magnetic energy into high speed flows and energetic particles, and it has been used to successfully explain many explosive phenomena in space, laboratory and astrophysical plasma.[1] There are mounting observation evidences that a significant portion of the magnetic energy during reconnection is released in the form of energetic electrons. In the solar flares, x-rays are thought to be associated with energetic electrons generated in magnetic reconnection.[2,3] In the Earth's magnetotail, energetic electrons produced by magnetic reconnection are observed directly by Wind spacecraft.[4] However, until now how and where energetic electrons are accelerated during reconnection is still an open question.

Recently, considerable efforts have been devoted to understanding the generation mechanism of energetic electrons in reconnection.[5−7] Hoshino *et al.* studied the process of electron acceleration in reconnection without the initial guide field using Particle-in-cell (PIC) simulations.[5] They found that electrons are accelerated not only around the X point but also in the magnetic field pileup region due to ∇B and curvature drifts. Fu *et al.* compared electron acceleration between reconnection with the initial guild field and without the initial guild field using two-dimensional PIC simulations.[7] They found that electrons can be accelerated in both the X- and O-type regions in reconnection without initial guide field. If the initial guide field exists, electrons can only be accelerated in the X-type region and there is no obvious acceleration in the O-type region. The inductive electric field is considered to play a key role for energetic electrons during magnetic reconnection. They also found that most of the energetic electrons reside in the magnetic field line pileup region, and there is a depletion of energetic electrons near the X point in magnetic reconnection without an initial guide field.[7] In this Letter, for the first time, the above predictions are compared with the spatial distribution of energetic electrons measured by the Cluster, which fortuitously cross a diffusion region in the near magnetotail.

Figure 1 shows the cluster tetrahedron configuration at about 07:50 Universal Time (UT) on 10 September 2001 in GSM coordinates (used throughout this study). Such a Cluster configuration does not change for a sufficiently long time, and they can be thought to be stationary in our study. Cluster was located in the magnetotail plasma sheet, approximately $19R_E$ (the radius of Earth) from the centre of the Earth during this time period.

Figure 2 shows the spin-resolution ($4s$) data obtained from a flux-gate magnetometer[8] and a Cluster ion spectrometry[9] on broad of the four satellites. Note that there is no data of plasma density and high-speed flow from Cluster 2, i.e. C_2. In Fig. 2(a), we can find that although the density occasionally drops to below the average values of the plasma sheet it never reaches the values associated with the lobe. Hence during the interval presented in Fig. 2, the Cluster remains inside the plasma sheet and do not encounter the lobe. The Cluster detects a tailward (negative V_x) high speed flow (up to 500 km/s) followed by an earthward (positive V_x) high speed flow (up to 500 km/s) around 7:58 UT. At the same time, the z component of the magnetic field B_z changes from negative values to

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positive values. The coincidence of V_x and B_z reversals indicates that the Cluster flies from the tailward side of an active diffusion region to the earthward side,

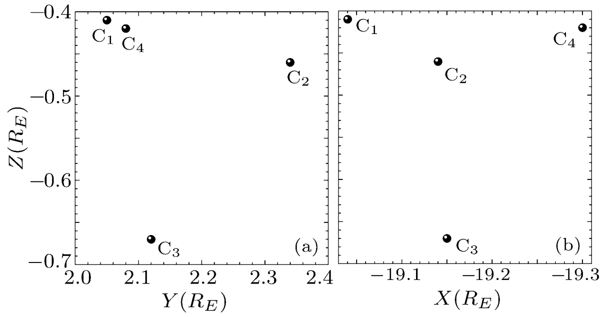

Fig. 1. Positions of the four satellites on 10 September 2001 in GSM coordinates.

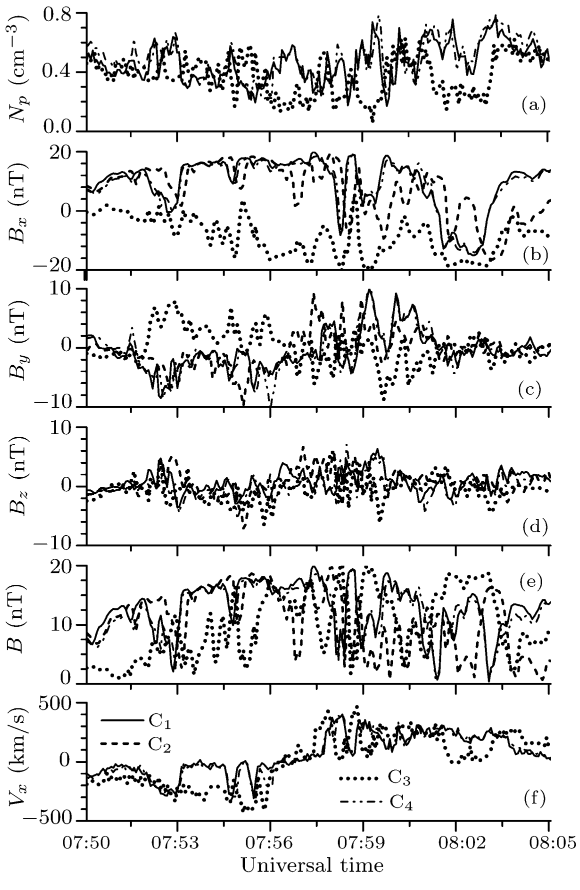

Fig. 2. (a) Plasma density, (b)–(e) three components and magnitude of magnetic field, and $(f)x$ component of high-speed flow.

as shown in Fig. 3. The signatures of the Hall magnetic field can also be clearly found in Fig. 2. During the interval between 07:51:55 UT and 08:01:16 UT, the Hall signatures are detected by the four satellites all the time. This implies that all the four satellites are in the ion diffusion region. At the same time, the x component of magnetic field B_x measured by C_3 (C_1, C_2 and C_4) remains mostly negative (positive) means that C_3 (C_1, C_2 and C_4) stays predominantly in the southward (northward) side of the current sheet. When the Cluster stays in the tailward of the X line, the C_3 satellite (the C_1, C_2 and C_4 satellites) observes positive (negative) values of B_y. However, when the Cluster enters the earthward of the X line, the C_3 satellite (C_1,C_2 and C_4 satellites) observes mainly negative (positive) values of B_y. This is in agreement with the quadrupolar out-of-plane Hall magnetic field configuration. The amplitude of the observed Hall magnetic field is about 5–8 nT, which corresponds to about 37–50% of the total magnetic field magnitude (about 16 nT).

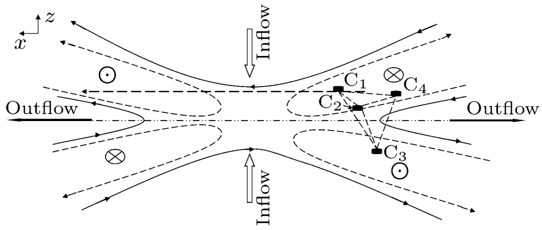

Fig. 3. Schematic diagram of the ion diffusion region in the magnetotail.

Figure 4 shows the plasma temperature, magnetic field vector, high-speed flows and energetic electron differential fluxes. The bottom four panels denote electron differential fluxes obtained from the RAPID[10] on the four satellites (C_1, C_2, C_3, C_4) from 35.1 to 244.1 keV. A depletion in the energetic electron fluxes in the diffusion region is detected by all the four satellites. The depletion of C_1, C_2 and C_4 occurs at the same time, and the duration is about 162 s. It is noted that the first two low energy channels of C_3 is not well calibrated (private communication with Q. G. Zong), while the other energy channels have the same depletion as other satellites. From the four bottom panels of the figure, the energetic electron fluxes peak in the magnetic field line pileup region, and then they decrease monotonically away from the region. Therefore, we can conclude that the diffusion region is only region to accelerate the electrons, and the maximum energy reaches in the magnetic field line pileup region. There is no secondary acceleration in the magnetic field line pileup region, otherwise we should find that the peak of the energetic electrons will continue to increase when the satellites leave this region. Similarly, a local minimum of the plasma temperature can also be found near the centre of diffusion region. From Fig. 4, we can also find that the energetic fluxes in the earthward of the active X-line are larger than those in the tailward, which is consistent with the statistical analysis using the Geotail by Imada *et al.*[11] This phenomena can not be found in the simulations,[7] where the structures of the reconnection is symmetrical in the earthward and tailward of the X line.

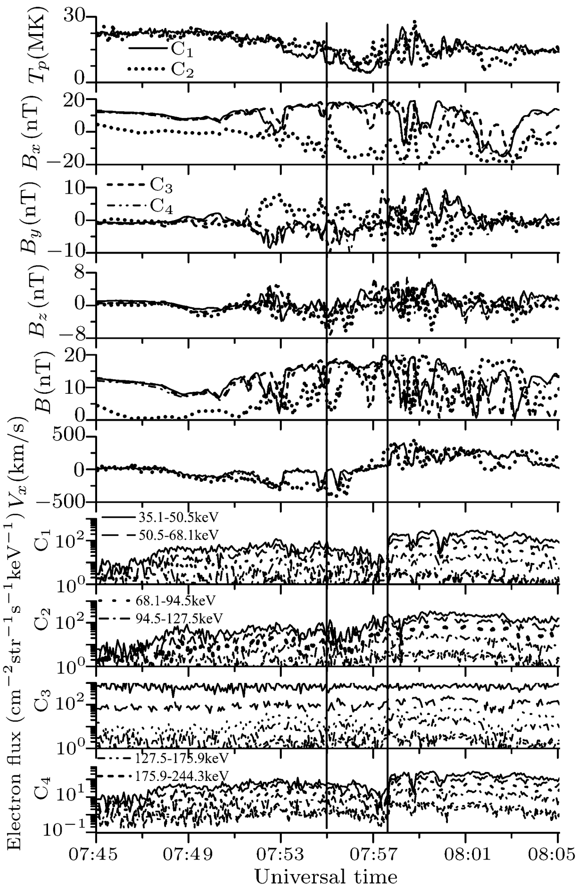

Fig. 4. From top to bottom: plasma density, plasma temperature, three components of magnetic field (B_x, B_y, B_z), the x component of the high-speed flow and energetic electron flux of four satellites (C_1,C_2,C_3,C_4) from 35.1 keV to 244.1 keV.

The observation is inconsistent with Wind observation in deep magnetotail where no dip in fluxes is detected. The difference between the two observations may be attributed to the initial guild field B_y. In this study, the initial guild field is zero unlike the Wind observation where the initial guild field is about 6 nT (50% of the total field).

In this summary, we have presented Cluster plasma and field observations which establish one of the clearest encounters with a diffusion region reported to date. The key observation characteristics are: (1) A reversal of high-speed flow V_x (from negative to positive) coincides with a reversal of B_z (from negative to positive). (2) Out-of-plane Hall magnetic field B_y is observed by the four satellites of the Cluster.

We also analyse the energetic electron fluxes during the magnetic reconnection. Consistent with the particle simulations,[7] we find a depletion near the centre of diffusion region. This is the signature that electrons can be highly accelerated by the inductive electric field near the X-point, and then the peak of the electron flux can be found in the magnetic field line pileup region.

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