In Situ Observations of a Secondary Magnetic Island in an Ion Diffusion Region and Associated Energetic Electrons

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Numerical simulations have predicted that an extended current sheet may be unstable to secondary magnetic islands in the vicinity of the X line, and these islands can dramatically influence the reconnection rate. In this Letter, we present the first evidence of such a secondary island near the center of an ion diffusion region, which is consistent with the action of the secondary island instability occurring in the vicinity of the X line. The island is squashed in the z direction with a strong core magnetic field. Energetic electrons with anisotropic or field-aligned bidirectional fluxes are found in the ion diffusion region, and the enhancement of energetic electron fluxes is more obvious inside the secondary island.

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Magnetic reconnection is a fundamental plasma process during which magnetic energy is converted into kinetic energy, and it is always accompanied with changes of magnetic topological structures. It is an important issue of understanding the structures of the diffusion region and energetic electrons in the process of magnetic reconnection. The characteristics of the ion diffusion region, where the interconnection of flux tubes from two different plasma regions occurs, have been extensively studied [1–4]. Numerical studies indicate that the diffusion region displaying a single X line structure is stable once the reconnection is established [5–8]. However, recent numerical simulations predicted that an extended current layer may be unstable to second magnetic islands in the vicinity of the X line [9–13]. In two-dimensional (2D) particle-in-cell simulations with open boundary conditions, Daughton *et al.* [10] found that secondary islands can be formed near the center of the ion diffusion region. Once a secondary island is formed, the flux within the secondary island grows until the island is ejected out from the center of the diffusion region, and a new secondary island may be formed and then ejected out periodically. Employing fully kinetic simulations with Monte Carlo treatment of the Fokker Planck collisional operator, Daughton *et al.* [12] further demonstrated that an extended reconnection layer is unstable to large amplitude secondary islands for sufficiently large Lundquist numbers, and the reconnection rate may be dramatically enhanced.

In this Letter, we report the first direct evidence of a secondary magnetic island near the center of an ion diffusion region during a magnetic reconnection detected by Cluster in the near Earth magnetotail ($\sim 16 R_E$) on 4 October 2003. The secondary island is considered to be the result of an unstable extended current sheet in the vicinity of the X line, which is consistent with the predictions of numerical simulations. The energetic electrons associated with the secondary magnetic island are also discussed.

We use observation data from several different instruments on board Cluster. Magnetic field measurements are obtained from the fluxgate magnetometer (FGM) [14], and the ion plasma data are taken from the Cluster ion spectrometer (CIS) experiment [15]. Furthermore, the middle- and high-energy electrons data are obtained from the plasma electron and current experiment (PEACE) instruments [16] and the research with adaptive particle imaging detectors (RAPID) [17], respectively. The electron density is derived from the spacecraft potential measurements [18]. The electric field is measured by the electric field and waves (EFW) instrument [19]. The two components of the electric field in the spin plane are measured, and the third component is calculated by assuming $\mathbf{E} \cdot \mathbf{B} = 0$. This assumption is valid except in the electron diffusion region, where electrons are not frozen in the magnetic field lines.

During the interval 06:19–06:21 UT on 4 October 2003, when Cluster was located at $[-16.1, 7.4, -2.6]$ R_E (the geocentric solar magnetospheric coordinate system), a reconnection event was observed by Cluster in the Earth's magnetotail. During the time of interest, the spacecraft separation is only about 300 km, which is about $0.4c/\omega_{pi}$. In this Letter, the data are shown in a current sheet coordinate system: the L direction points towards earthward, and the N direction is normal to the plane of the neutral sheet. $[L, M, N]$ is a right-handed triple [20]. Because the time series of the magnetic field are well correlated among the satellites in this reconnection event, multispacecraft time analysis can be used to determine the N direction in this Letter [21]. Relative to the geocentric solar magnetospheric coordinate system, $L = [0.9999, -0.0010, 0.0170]$, $M = [0.0002, 0.9991, 0.0500]$, and $N = [-0.017, -0.0500, 0.9990]$. Figure 1 shows Cluster measurements in the current sheet coordinate system by the C4 satellite. From the sign of B_L, we can know that Cluster crosses the neutral sheet twice: first from south to north, and then return to south of the neutral sheet. The moving speed of the neutral sheet in the normal direction can also be calculated with multispacecraft time analysis, which is about 52.4 and 248.5 km/s for the first and the second crossing, respectively.

For convenience, we divide the whole interval into three short subintervals: L_1, L_2, and L_3 according to the sign of B_N, as shown in both Figs. 1 and 3. During subinterval L_1, Cluster stays at the south part of the neutral sheet due to the observed negative B_L, while positive B_N and an earthward high-speed flow with velocity up to 1000 km/s are observed. At the same time, a negative out-of-plane magnetic field B_M and a positive E_N with an average value about 20 mV/m are also observed. In this Letter, we do not Lorentz transform the electric field data into the current sheet frame, because the difference between the two frames is negligible. During the subinterval L_3, a tailward high-speed flow with velocity up to 800 km/s and negative B_N are observed. During most of the subinterval (from 06:20:35 UT), B_L has a negative value and Cluster is at the south part of the neutral sheet. Correspondingly, the out-of-plane magnetic field B_M has positive values, while E_N has positive values. Prior to 06:20:35 UT during the subinterval L_3, Cluster is at the north part of the neutral sheet due to positive B_L, and B_M has negative values. From the above observations, during subintervals L_1 and L_3 we can find the reversal of the high-speed flow, and that B_N changes sign from positive to negative values. Simultaneously, the Hall electric field E_N directed to the center of the neutral sheet, and the out-of-plane magnetic field B_M consistent with a Hall current system are also observed. The Hall electric field E_N directed to the center of the neutral sheet has already been studied in both numerical simulations [5,7]. According to numerical simulations, $B_M \sim 0.2B_0$ and $E_N \sim V_A B_0$ (where V_A is the Alfven speed, and B_0 is the magnetic field outside the current sheet), which can be estimated to be about 5 nT and 20 mV/m based on the parameters measured in this reconnection event. They are consistent with the measured B_M and E_N in Figs. 1(d) and 1(k). Therefore, we can conclude that Cluster passed through an ion diffusion region from earthward to tailward. At the beginning of this reconnection event (around 06:19:00UT), there is no obvious out-of-plane magnetic field B_M, and this reconnection event is thus an almost antiparallel reconnection without appreciable overall guide field.

Now let us analyze the detailed structures of the reconnection event during subinterval L_2. During this subinterval, B_L changes sign from negative to positive values, and thus Cluster enters the north part of the current sheet from its south part. Correspondingly, E_N changes sign from positive to negative values, while both E_L and B_N change sign from negative to positive values. Furthermore, an

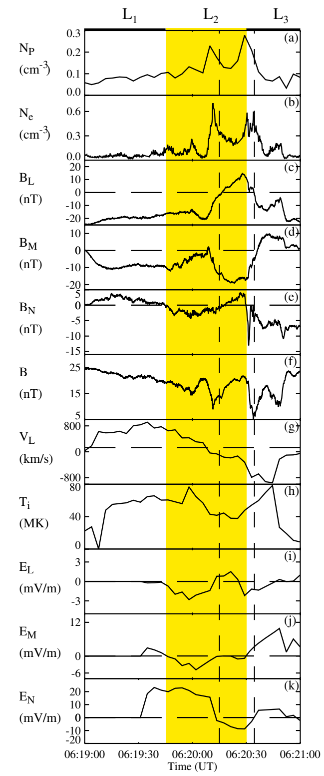

FIG. 1 (color online). Cluster measurements during the interval 06:19–06:21 UT on 4 October 2003. From the top to bottom panels the proton (at 4 s resolution) and electron (at 0.2 s resolution) densities, the three components and magnitude of the magnetic field (0.045 s resolution), the L component of proton bulk flows (4 s resolution), the proton temperature and three components of the electric field (at 4 s resolution), are shown. The data are obtained from the C4 satellite. The whole interval is divided into three short subintervals: L_1 (0619:00–0619:44UT), L_2 (0619:44–0620:30UT), and L_3 (0620:30–0621:00 UT) according to the sign of B_z. The dashed lines in the figure denote the points of $B_x = 0$.

enhancement of the out-of-plane magnetic field B_M is found near the point where B_N changes its sign. The observational signatures described above indicate the existence of a magnetic island [22–24]. Because the magnetic island is near the center of the diffusion region, we conclude that it is a secondary magnetic island, which is consistent with the secondary island instability predicted in [10–12]. At the same time, there exists a strong out-of-plane magnetic field B_M (up to -20 nT) near the center of the magnetic island. Therefore, the island corresponds to a flux rope with a strong core field, which is also caused by Hall effects. Compared with B_M measured just outside the magnetic island, the amplitude of the core field is enhanced about 1.8 times, which is consistent with numerical simulations [7,11,25]. In the magnetic island, E_N is directed to the center of the neutral sheet, while E_L is directed to the center of the island. Such structures of the electric field have also been predicted in numerical simulations [7], and their values are $E_N \sim V_A B_0$, $E_L \sim 0.3 V_A B_0$. Based on the parameters in this reconnection event, they are $E_N \sim 20$ mV/m, $E_L \sim 6$ mV/m, respectively.

In summary, Cluster passed through an ion diffusion region from earthward to tailward, and this event is an almost antiparallel reconnection without appreciable overall guide field. In the center of the diffusion region, there exists a secondary magnetic island (flux rope). Such an island is consistent with numerical simulations [10–12], which predicted the formation of secondary islands near the center of the ion diffusion region when the current sheet is sufficiently long and unstable to secondary islands in the vicinity of the X line. Based on these measurements, the approximate path of Cluster through the diffusion region is reconstructed as shown in Fig. 2.

In the secondary island, the amplitude of B_L is significantly larger than that of B_N, which indicates that the island is squashed in the N direction. Using multi-spacecraft time analysis, we can know that the moving speed of the neutral sheet in the normal direction is ~52.4 km/s. Thus, according to the time delay (~23 s) which Cluster detects the negative and positive peaks of B_L inside the magnetic island, the size of the island in the N direction is estimated to be about 1205 km $\sim 1.7c/\omega_{pi}$. According to the time delay (~4 s) which C1 and C2 detect the same point of $B_N = 0$ and the separation in the L direction (~176.9 km) between C1 and C2, the moving speed of the island in the L direction is calculated to be about 44.3 km/s. Using the time width (~50 s) for B_N pulse (the time delay which Cluster detects the negative and positive peaks of B_N in the island), the size of the island in the L direction is estimated to be about 2215 km $\sim 3.1c/\omega_{pi}$. Therefore, the scale ratio of the island in the L and N directions is about 2:1.

Figure 3 displays the parallel and perpendicular electron temperatures, the electron temperature anisotropy $T_{e\text{-paral}}/T_{e\text{-perp}}$, and the differential fluxes of energetic electrons measured by the C4 satellite. The enhancement of energetic electron fluxes, as well as the parallel and perpendicular temperatures, can be obviously measured in the ion diffusion region by all the four Cluster satellites.

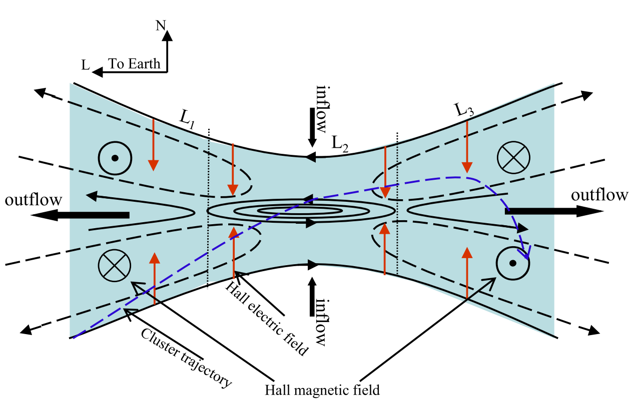

FIG. 2 (color online). Illustration of the magnetic geometry and the trajectory of Cluster.

The parallel temperature is larger than the perpendicular temperature, and the electron distributions are anisotropic with an average anisotropy $T_{e\text{-paral}}/T_{e\text{-perp}} = 1.3$. Simultaneously, a further enhancement of energetic electron fluxes is found in the secondary magnetic island. This is consistent with the simulation results [7,26] and observations [25], where electrons can be accelerated in magnetic islands.

Figure 4 shows the pitch-angle distributions of energetic electron fluxes measured by the C4 satellite, and the similar results can also be obtained by the other satellites (not shown). The measured pitch-angle distributions display high anisotropy in the ion diffusion region, including in the secondary magnetic island. In general, the distributions of the energetic electrons are field-aligned bidirectional, which have peaks at 0° (parallel to the magnetic field) and 180° (antiparallel to the magnetic field), and minima at 90° (perpendicular to the magnetic field). Therefore, there are more electrons streaming in the parallel and antiparallel directions, and it is consistent with the electron temperature anisotropy described in Fig. 3. The energetic electrons are accelerated by the reconnect electric field near the center of the diffusion region with a weak magnetic field. After they leave the vicinity of the X line, the energetic electrons stream in the direction parallel or antiparallel to the magnetic field when they enter the region with a strong magnetic field (the outflow region) [7,27,28].

In conclusion, we present the first *in situ* observations of a secondary magnetic island near the center of an ion diffusion region during a reconnection event in the Earth's magnetotail. The observations are consistent with the secondary instability occurring in the vicinity of the X line as predicted in numerical simulations [10–12]. The scale sizes of the magnetic island are about $3.1c/\omega_{pi}$ and $1.7c/\omega_{pi}$ in the L and N directions, respectively, which are in the ion inertial length scale. The island is squashed in the N direction. A strong core magnetic field exists in the

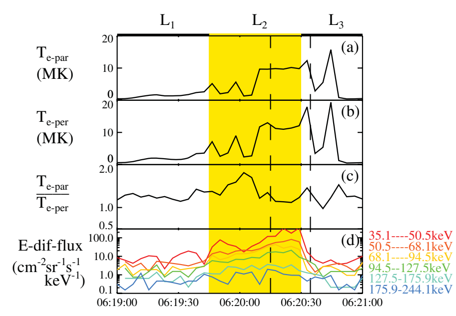

FIG. 3 (color). The parallel and perpendicular electron temperatures, the electron temperature anisotropy, and the differential fluxes of energetic electrons with energies from 35.1 to 244.1 keV, are displayed from the top to bottom panels. All data are at 4 s resolution, and are obtained from the C4 satellite. As in Fig. 1, the whole interval is divided into three short subintervals: L_1, L_2, and L_3. The dashed lines in the figure denote the point of $B_L = 0$.

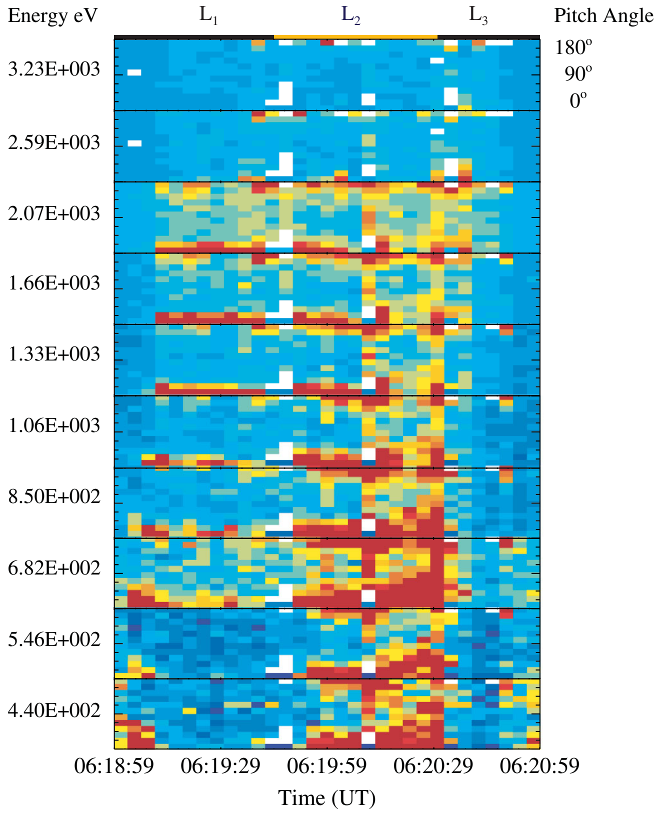

FIG. 4 (color). The electron pitch-angle distributions measured by the C4 satellite from 06:18:05 to 06:21:58 UT.

secondary magnetic island. At the same time, enhancement of energetic electron fluxes is found in the ion diffusion region, and the electron distributions are anisotropic or field-aligned bidirectional. The enhancement of energetic electron fluxes is more obvious inside the secondary magnetic island than in other regions, and it means that electrons can still be acceleration inside magnetic islands.

Numerical simulations have predicted the process of the secondary island instability [10–12], which can be described as follows: a single X line is firstly formed, and then secondary islands are formed in the vicinity of the X line. Therefore, there is only one current sheet when the secondary island instability occurs. In this Letter, a secondary magnetic island is observed near the center of the diffusion region, which is consistent with the above theoretical predication. Secondary magnetic islands have also been observed by other Cluster observations [29,30]. Eastwood *et al.* [29] presented a secondary island entrained in the outflow plasma during magnetic reconnection. Chen *et al.* [30] also observed a secondary island in the outflow region between two current sheets.

The formation of secondary magnetic islands near the center of the ion diffusion region is probably related to a tearing mode in an elongated current sheet [10,12]. The existence of a secondary magnetic island inside an ion diffusion region can dramatically change the reconnection rate and the production of energetic electrons during magnetic reconnection. However, to understand the physical consequences of these results, future work on both observations and simulations is needed to be done.

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[1] M. Yan, L. C. Lee, and E. R. Priest, J. Geophys. Res. **97**, 8277 (1992).
[2] M. Øieroset *et al.*, Nature (London) **412**, 414 (2001).
[3] Z. W. Ma and A. Bhattacharjee, J. Geophys. Res. **106**, 3773 (2001).
[4] P. L. Pritchett and F. V. Coroniti, J. Geophys. Res. **109**, A01220 (2004).
[5] P. L. Pritchett, J. Geophys. Res. **106**, 3783 (2001).
[6] M. A. Shay *et al.*, Phys. Plasmas **11**, 2199 (2004).
[7] X. R. Fu, Q. M. Lu, and S. Wang, Phys. Plasmas **13**, 012309 (2006).
[8] M. A. Shay, J. F. Drake, and M. Swisdak, Phys. Rev. Lett. **99**, 155002 (2007).
[9] D. Biskamp, Phys. Fluids **29**, 1520 (1986).
[10] W. Daughton, J. D. Scudder, and H. Karimabadi, Phys. Plasmas **13**, 072101 (2006).
[11] J. F. Drake *et al.*, Geophys. Res. Lett. **33**, L13105 (2006).
[12] W. Daughton *et al.*, Phys. Rev. Lett. **103**, 065004 (2009).
[13] R. Samtaney *et al.*, Phys. Rev. Lett. **103**, 105004 (2009).
[14] A. Balogh *et al.*, Ann. Geophys. **19**, 1207 (2001).
[15] H. Rème *et al.*, Ann. Geophys. **19**, 1303 (2001).
[16] A. D. Johnstone *et al.*, Space Sci. Rev. **79**, 351 (1997).
[17] B. Wilken *et al.*, Space Sci. Rev. **79**, 399 (1997).
[18] A. Pedersen *et al.*, J. Geophys. Res. **113**, A07S33 (2008).
[19] G. Gustafsson *et al.*, Ann. Geophys. **19**, 1219 (2001).
[20] J. P. Eastwood, T. D. Phan, S. D. Bale, and A. Tjulin, Phys. Rev. Lett. **102**, 035001 (2009).
[21] S. J. Schwartz, *Shock and Discontinuity Normals, Mach Numbers and Related Parameters, in Analysis Methods for Multi-spacecraft Data*, edited by G. Paschmann and P. W. Daly (International Space Science Institute, Bern, 1998), p. 249.
[22] J. A. Slavin *et al.*, J. Geophys. Res. **108**, 1015 (2003).
[23] Q. G. Zong *et al.*, Geophys. Res. Lett. **31**, L18803 (2004).
[24] P. D. Henderson *et al.*, Ann. Geophys. **24**, 651 (2006).
[25] L. J. Chen *et al.*, Nature Phys. **4**, 19 (2008).
[26] J. F. Drake *et al.*, Nature (London) **443**, 553 (2006).
[27] P. L. Pritchett, Geophys. Res. Lett. **33**, L13104 (2006).
[28] R. S. Wang, Q. M. Lu, C. Huang, and S. Wang, J. Geophys. Res. **115**, A01209 (2010).
[29] J. P. Eastwood, T. D. Phan, and F. S. Mozer *et al.*, J. Geophys. Res. **112**, A06235 (2007).
[30] L. J. Chen *et al.*, Phys. Plasmas **16**, 056501 (2009).