Energetic electrons associated with magnetic reconnection in the sheath of interplanetary coronal mass ejection

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Magnetic reconnection is an important universal plasma dissipation process that converts magnetic energy into plasma thermal and kinetic energy, and simultaneously changes the magnetic field topology. In this paper, we report the first observation of energetic electrons associated with asymmetric reconnection in the sheath of an interplanetary coronal mass ejection. The magnetic field shear angle was about 151° , implying guide-field reconnection. The width of the exhaust was about 8×10^4 km. The reconnection rate was estimated as 0.044–0.08, which is consistent with fast reconnection theory and previous observations. We observed flux enhancements of energetic electrons with energy up to 400 keV in this reconnection exhaust. The region where energetic electron fluxes were enhanced is located at one pair of separatrices in the higher density hemisphere. We discuss these observation results, and compare with previous observations and recent kinetic simulations.

energetic electrons, magnetic reconnection, guide field, interplanetary coronal mass ejection

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Magnetic reconnection is an important universal process that changes the magnetic field topology and converts magnetic energy into plasma thermal and kinetic energy in experiment, astrophysical and space plasma. Magnetic reconnection in the terrestrial magnetosphere has been confirmed directly by *in situ* observations [1–5]. Recently, there were many observations of reconnection in the solar wind, which were often associated with interplanetary coronal mass ejection (ICME) [6–8]. Energetic electrons are important offspring of magnetic reconnection [9,10] and are observed in different magnetospheres [10–14]. Øieroset et al. [14] reported energetic electrons, with energy up to 300 keV, in the reconnection diffusion region of the Earth's magnetotail. In solar flares, observations showed that up to 50% of energy can be released to energetic electrons during reconnection

[15]. However, Gosling et al. [16] found the absence of energetic particles associated with reconnection exhausts in the solar wind. Recently, Wang et al. [17] presented the first evidence of energetic electrons associated with magnetic reconnection in the magnetic cloud boundary layer.

In this paper, we investigate whether energetic electrons associated with reconnection can be observed in other regions of solar wind besides the magnetic cloud boundary layer. We used data recorded by several instruments onboard the Cluster spacecraft, including data of the magnetic field recorded by the Fluxgate Magnetometer (FGM) [18], ion data recorded by the Hot Ion Analyser (HIA) of the Cluster Ion Spectrometry (CIS) experiment [19] and data of high-energy electrons and the pitch angle distribution of energetic electrons recorded by Research with Adaptive Particle Imaging Detectors (RAPID) [20]. We present the first observation of energetic electrons within the reconnection

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exhaust in the sheath of an ICME in this study.

1 Observations

The Cluster spacecraft encountered an ICME event on January 21, 2005. Foullon et al. [21] comprehensively examined this ICME event, and provided a coherent picture of the ICME geometry (see Figure 9 of [21]). Figure 1 displays the observations of the leading edge of the ICME measured by Cluster 1 between 16:45 and 20:45 UT for the identical observations of four Cluster spacecraft with small separation (~ 1000 km). All data in this figure are shown in geocentric solar ecliptic (GSE) coordinates. The spacecraft first measured the interplanetary shock, and then the sheath and the ICME. The region bounded between two vertical lines (i.e. SH1 and SH2) in Figure 1 is the sheath. The sheath of the ICME is a region of interaction between the ICME and the ambient solar wind, which is similar to the magnetosheath in the terrestrial magnetosphere and contains many substructures. There are two current sheet substructures in

the leading edge of the ICME; i.e. the sheath region [21]. We identify these two current sheets and find that the second one, which is highlighted grey in Figure 1, is an exhaust region of magnetic reconnection.

Figure 2 shows plasma and magnetic field data of the second current sheet from Cluster 1 in GSE coordinates between 18:42 and 18:48 UT when Cluster 1 was located at $(14.7, 10.7, -6.3)R_E$ (where R_E is the Earth's radius). The three components of the velocity of the solar wind are shifted by $(+900, -100, +50)$ km/s. Figure 2(a) exhibits a big drop, of about 70%, in the magnetic field strength and Figure 2(d) and (e) show enhancements in ion density and temperature from 18:44:15 to 18:45:55 UT. Changes in $\mathbf{V}$ and $\mathbf{B}$ were anticorrelated at the leading edge and correlated at the trailing edge (Figure 2(b) and (c)), implying that the region is a reconnection exhaust [6,7]. The field shear angle across the current sheet is 151° , which implies the reconnection region includes a non-negligible guide field. The ion density (Figure 2(d)) is not symmetric (having a big jump of a factor of 3) across the exhaust, indicating asymmetric reconnection.

Figure 1 Overview of observations made by Cluster 1 from 16:45 to 20:45 UT in GSE coordinates. (a) Three components, i.e. B_x (black dashed), B_y (grey dashed) and B_z (black), and magnitude (grey) of magnetic field; (b) three components of plasma bulk flow (V_x , V_y and V_z are black dashed, grey dashed and black lines, respectively); (c) ion density; (d) ion temperature.

Figure 2 Observations of the current sheet between 18:42 and 18:48 UT in GSE coordinates. (a) Magnetic field magnitude; (b) three components of the magnetic field; (c) three components of plasma flow; (d) ion density; (e) ion temperature. The velocity of plasma flow is shifted by (+900, -100, +50) km/s. The three components of magnetic field and plasma flow velocity, i.e. X, Y and Z components, are shown as the same in Figure 1.

To analyze the current sheet in more detail, we construct an LMN coordinate system where the N component is the normal of the current sheet, the M component is the X -line orientation and the L component is along the reconnection jets. We firstly calculate the normal direction of the current sheet (i.e. the N component) through minimum variance analysis of the magnetic field [22]. We then employ the relation $\mathbf{M} = \mathbf{N} \times (\mathbf{B}_A - \mathbf{B}_B) / |\mathbf{B}_A - \mathbf{B}_B|$, where $\mathbf{B}_A$ and $\mathbf{B}_B$ are the tangential magnetic field vectors on the two sides of the current sheet [8], to gain the X axis orientation. Finally, the L component forms the right-hand system with the M and N components; i.e., $\mathbf{L} = \mathbf{M} \times \mathbf{N}$. The three vectors of the LMN coordinates are $([0.5082, 0.3066, -0.8047], [-0.1593, 0.9517, 0.2620], [0.8464, -0.0050, 0.5326])$ in GSE coordinates. To identify Alfvén waves or rotational discontinuities for the exhaust, we compare the observation and “model”; i.e. the Walén relation [23]. The Walén relation can be described as $\mathbf{V}_{\text{pre}} = \mathbf{V}_{\text{ref}} \pm (1 - \alpha_{\text{ref}})^{1/2} (\mu_0 \rho_{\text{ref}})^{-1/2} [(\rho_{\text{ref}} / \rho) \mathbf{B} - \mathbf{B}_{\text{ref}}]$, where $\alpha = (P_{\parallel} - P_{\perp}) / m_0 |\mathbf{B}|^2$ is the pressure anisotropy factor (and $P_{\parallel}$ and $P_{\perp}$ are the plasma pressures parallel and perpendicular to the magnetic field, respectively). Here, the pressure anisotropy is assumed to be zero. The subscript “ref” denotes the reference time at the leading (trailing) edge of the exhaust and “pre” denotes the calculated velocity across the region. The projections of the magnetic field

and the velocity of the solar wind in the LMN coordinates are shown in Figure 3. Figure 3 also presents the amplitude of the magnetic field, velocity strength and energetic electron fluxes. B_N is approximately zero; B_M is large across the region, having an average value of -11 nT (i.e. $\sim 0.3B_0$, where B_0 is the upstream magnetic field strength); and B_L reverses from 40 to -40 nT, suggesting the field rotation occurs almost completely in the L direction. The observed ion velocities and the ion velocities predicted by the Walén test are shown in Figure 3(c) and (d). The predicted magnitude and three components of the ion velocity fit well with the observed ones. Since the HIA instrument of the CIS measurement cannot distinguish ion species, the predicted velocities may not fit well in some time intervals. The projection of solar wind in the normal direction of the current sheet is about 800 km/s. Thus, the spatial width of the exhaust is estimated as $\sim 8 \times 10^4$ km, which is less than other observations [8]. The N component of the velocity has an average shift (ΔV_N) of 22 km/s across the exhaust. Therefore, the speed of the reconnection inflow, V_{in} , is about $0.5\Delta V_N$; i.e. 11 km/s. The reconnection rate, V_{in}/V_A , is calculated to be about 0.044–0.08 according to the upstream Alfvén speed, where $V_A \approx 137$ –250 km/s. Thus, the reconnection rate in this event is higher than 0.044, which is in the range of fast reconnection and consistent with previous

Figure 3 Results of LMN analysis and the Walén test using Cluster 1 data. (a) Magnetic field magnitude; (b) three components of the magnetic field in LMN coordinates; (c) observed (black) and predicted (grey) velocity magnitudes; (d) observed and predicted velocities in LMN coordinates; (e) energetic electron differential fluxes (particles/(cm² sr s keV)). The black dashed, grey dashed and black lines in (d) are *L*, *M*, and *N* components of the observed velocities respectively, and the three grey lines are the predicted velocities for each component. The plasma velocity is shifted by (+300, −100, +500) km/s.

observations. According to the above analysis, we conclude that Cluster observed an asymmetric reconnection exhaust with a moderate guide field in the sheath of the ICME for the first time.

We are in fact more interested in energetic electrons within the reconnection exhaust region in the solar wind. Figure 3(e) shows the flux of energetic electrons in the range of 37.2–406.5 keV measured by the RAPID instrument onboard Cluster 1. Different colors represent different energy channels. We see that there are enhanced energetic electron fluxes between 18:45:25 and 18:45:50 UT with electrons accelerated up to 400 keV. However, the enhancement of the fluxes of energetic electrons is only detected at one pair of separatrices. There is no increase in energetic electron fluxes at the other pair of separatrices, where the plasma density is lower.

2 Discussion and conclusion

There are many direct observations of magnetic reconnection in the solar wind [6–8]. However, few observations have confirmed the presence of energetic electrons in the

reconnection exhaust of the magnetic cloud boundary layer [17]. In this paper, we report the first observation of energetic electrons within the exhaust in the sheath region of the ICME.

Various acceleration mechanisms have been proposed to interpret the origin of the energetic electrons during magnetic reconnection with or without guide field [9,24–26]. As the primary acceleration mechanism, electrons are accelerated by the reconnection electric field in the X-line region, and then may be further accelerated in the pileup region owing to curvature and gradient drifts along the electric field [9,26]. In addition, electrons can be accelerated by contracting magnetic islands via Fermi acceleration [24].

In guide-field reconnection, electrons are firstly accelerated by the parallel electric field that exists in low density cavities along one pair of the separatrices and form a cold electron beam [26]. This beam is funneled into the vicinity of the X-line and electrons are further accelerated by the reconnection electric field to form energetic electrons, which effuse along the higher density separatrices. In this paper, we report an increase in energetic electron fluxes, with energy up to 400 keV, associated with asymmetric guide field reconnection in the sheath of the ICME. The region where

the energetic electron fluxes increases is located at one pair of separatrices in the higher density hemisphere. Since B_L , B_M and V_L were negative when the Cluster detected the enhancement of energetic electron fluxes, we deduce that energetic electrons were observed at the separatrix with higher density than the opposite separatrix. Zhou et al. [27] comprehensively investigated the signatures of the density cavity (lower density) during reconnection in the presence of guide field. They found that there was no evident energetic electron acceleration in the cavity. In addition, the effects of the guide field on the structure of the density cavity have also been studied via simulation [28]. These observations show that, in the presence of the guide field, energetic electrons only exist at the higher density pair of separatrices, which is consistent with Pritchett's simulation [26].

Figure 4 shows the pitch angle distributions of 40.7 and 68.1 keV electrons. We see that the accelerated electrons are concentrated at a pitch angle below 60° , being primarily parallel to the magnetic field. Given that $B_L < 0$ and $V_L < 0$, it suggests that high energy electrons are ejecting from the X-line.

We should point out that the reconnection exhaust in our observation is asymmetric, whereas that having been simulated is symmetric [26]. In fact, a region of energetic electron enhancement was also observed at only one pair of

separatrices in the magnetic cloud boundary layer [17]. In addition, a kinetic simulation was conducted and a combined model (i.e. electric field acceleration and Fermi-type mechanism) put forward to explain the origin of energetic electrons during magnetic reconnection there [17]. We also consider that a single acceleration mechanism is not enough to produce such high energy and so many energetic electrons during magnetic reconnection. Such a phenomenon needs several acceleration processes with different mechanisms to gain energetic electrons. To our knowledge, there are no theories or simulations of electron acceleration during asymmetric reconnection. Therefore, the asymmetric signature of energetic electrons associated with reconnection needs to be further examined by numerical simulation and satellite observations.

In summary, using Cluster observations, we identified an asymmetric reconnection with a moderate guide field ($\sim 0.3B_0$) in the sheath of ICME. The spatial width of the exhaust region was about 8×10^4 km and the magnetic field shear angle was about 151° . The reconnection rate was higher than 0.044, consistent with fast reconnection predictions and previous observations. We only observed enhancement of energetic electron fluxes with energy up to 400 keV at one pair of separatrices in the higher density hemisphere. More observations and simulations are required to work on it.

Figure 4 Pitch angle distributions of energetic electrons: energetic electron differential fluxes (a), and pitch angle distributions of 40.7 keV (b) and 68.1 keV (c) electrons. The two vertical dashed lines mark the region of enhanced energetic electron fluxes.

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- 1 Deng X H, Matsumoto H. Rapid magnetic reconnection in the Earth's magnetosphere generated by whistler waves. *Nature*, 2001, 410: 557–560
- 2 Huang S Y, Zhou M, Sahraoui F, et al. Wave properties in the magnetic reconnection diffusion region with high β : Application of the k-filtering method to Cluster multispacecraft data. *J Geophys Res*, 2010, 115: A12211
- 3 Deng X H, Matsumoto H, Kojima H, et al. Geotail encounter with reconnection diffusion region in the Earth's magnetotail: Evidence of multiple X lines collisionless reconnection? *J Geophys Res*, 2004, 109: A05206
- 4 Øieroset M, Phan T D, Fujimoto M, et al. *In situ* detection of collisionless reconnection in the Earth's magnetotail. *Nature*, 2001, 412: 414–417
- 5 Vaivads A, Khotyaintsev Y, André M, et al. Structure of the magnetic reconnection diffusion region from four-spacecraft observations. *Phys Rev Lett*, 2004, 93: 105001
- 6 Gosling J T, Skoug R M, McComas D J, et al. Direct evidence for magnetic reconnection in the solar wind near 1 AU. *J Geophys Res*, 2005, 110: A01107
- 7 Gosling J T, Eriksson S, McComas D J, et al. Multiple magnetic reconnection sites associated with a coronal mass ejection in the solar wind. *J Geophys Res*, 2007, 112: A08106
- 8 Xu X, Wei F, Feng X. Observations of reconnection exhausts associated with large-scale current sheets within a complex ICME at 1 AU. *J Geophys Res*, 2011, 116: A05105
- 9 Hoshino H, Mukai T, Terasawa T, et al. Suprathermal electron acceleration in magnetic reconnection. *J Geophys Res*, 2001, 106: 25979–25997
- 10 Lu Q M, Wang R S, Xie J L, et al. Electron dynamics in collisionless magnetic reconnection. *Chin Sci Bull*, 2011, 56: 1174–1181
- 11 Zong Q G, Wang Y F, Yuan C J, et al. Fast acceleration of “killer” electrons and energetic ions by interplanetary shock stimulated ULF waves in the inner magnetosphere. *Chin Sci Bull*, 2011, 56: 1188–1201
- 12 Li L, Feng Y Y. Energetic electron flux distribution model in the inner and middle magnetosphere. *Sci China Tech Sci*, 2011, 54: 441–446
- 13 Xiao F L, Zong Q G, Su Z P, et al. Latest progress on interactions between VLF/ELF waves and energetic electrons in the inner magnetosphere. *Sci China Earth Sci*, 2010, 53: 317–326
- 14 Øieroset M, Lin R P, Phan T D, et al. Evidence for electron acceleration up to ~300 keV in the magnetic reconnection diffusion region of Earth's magnetotail. *Phys Rev Lett*, 2002, 89: 195001
- 15 Lin R P, Hudson H S. Non-thermal process in large solar flares. *Sol Phys*, 1976, 50: 153–178
- 16 Gosling J T, Skoug R M, Haggerty D K, et al. Absence of energetic particle effects associated with magnetic reconnection exhausts in the solar wind. *Geophys Res Lett*, 2005, 32: L14113
- 17 Wang Y, Wei F S, Feng X S, et al. Energetic electrons associated with magnetic reconnection in the magnetic cloud boundary layer. *Phys Rev Lett*, 2010, 105: 195007
- 18 Balogh A, Carr C M, Acuna M H, et al. The Cluster magnetic field investigation: Overview of in-flight performance and initial results. *Ann Geophys*, 2001, 19: 1207–1217
- 19 Rème H, Aoustin C, Bosqued M, et al. First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment. *Ann Geophys*, 2001, 19: 1303–1354
- 20 Wilke B, Daly P W, Mall U, et al. First results from the RAPID imaging energetic particle spectrometer on board Cluster. *Ann Geophys*, 2001, 19: 1355–1366
- 21 Foulon C, Owen C J, Dasso S, et al. Multi-spacecraft study of the 21 January 2005 ICME. *Solar Phys*, 2007, 244: 139–165
- 22 Sonnerup B U Ö, Cahill Jr L J. Magnetopause structure and attitude from Explorer 12 observations. *J Geophys Res*, 1967, 72: 171–183
- 23 Hudson P D. Discontinuities in an anisotropic plasma and their identification in the solar wind. *Planet Space Sci*, 1970, 18: 1611–1622
- 24 Drake J F, Swisdak M, Che H, et al. Electron acceleration from contracting magnetic islands during reconnection. *Nature*, 2006, 443: 553–556
- 25 Fu X R, Lu Q M, Wang S. The process of electron acceleration during collisionless magnetic reconnection. *Phys Plasmas*, 2006, 13: 012309
- 26 Pritchett P L. Relativistic electron production during guide field magnetic reconnection. *J Geophys Res*, 2006, 111: A10212
- 27 Zhou M, Pang Y, Deng X H, et al. Density cavity in magnetic reconnection diffusion region in the presence of guide field. *J Geophys Res*, 2011, 116: A06222
- 28 Lu S, Lu Q M, Cao Y, et al. The effects of the guide field on the structures of electron density depletions in collisionless magnetic reconnection. *Chin Sci Bull*, 2011, 56: 48–52

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