

Chapter 2

Magnetic Reconnection and the Associated Energetic Particles in the Boundary Layer

2.1 Introduction

Previous studies have shown that BL is a turbulent layer formed by the interaction of the MC and the ambient solar wind (Wei et al. 2003a, b, c). Compared with those in the nearby upstream solar wind, the magnetic field in the BL is decreased and the plasma is compressed and heated. These features indicate that magnetic reconnection could prevail in the BL, but the ‘direct evidence,’ the Alfvénic reconnection jets, has not been found (Wei et al. 2006). In addition, although energetic electrons associated with magnetic reconnection in the solar flares and magnetotail have been reported (Imada et al. 2007; Lin and Hudson 1971; Øieroset et al. 2002), no such energetic electrons have so far been found in the solar wind reconnection. After analyzing 7 reconnection exhausts observed by ACE spacecraft (Fig. 2.1), Gosling et al. (2005a) found that no evidence for any substantial increase in energetic particle intensity associated with these events. So they suggest that local reconnection is not a significant source of energetic particles in the solar wind and reconnection itself may not be a particularly effective process for populating other space and astrophysical environments with energetic particles (Gosling et al. 2005a).

In this chapter, we report a Petschek-like reconnection with roughly Alfvénic reconnection jets inside a BL and present the first observation of energetic particles accelerated by magnetic reconnection in the solar wind.

2.2 Analyzing Methods

Compared with the magnetic reconnection in the magnetotail, where the reconnection X-line and reconnection jets generally point to the Z and X directions in geocentric solar ecliptic (GSE) coordinate (Fig. 1.7), in most cases, it is not very easy to discriminate the reconnection in the solar wind from the unambiguous

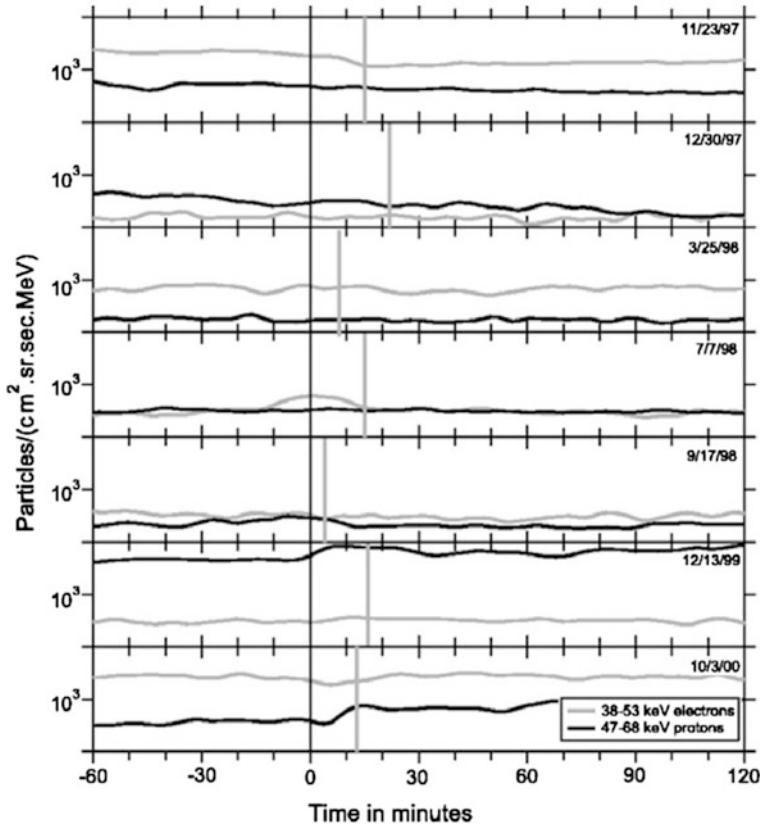


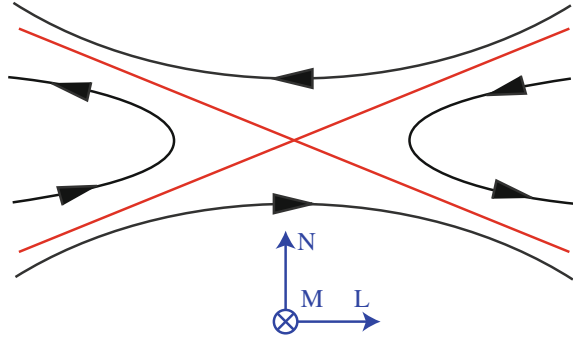
Fig. 2.1 Ion and electron fluxes observed by ACE spacecraft. The beginning of exhausts are shifted to $t = 0$ (black vertical line) and the end of the exhausts are marked by gray vertical line. Reproduced from (Gosling et al. 2005a), by permission of John Wiley and Sons Ltd

signatures in GSE coordinates. So it is necessary to construct a new coordinate based on the reconnection current sheet.

2.2.1 LMN Coordinate

To facilitate analyzing magnetic reconnection, we try to construct the LMN coordinate (Hudson 1970; Sonnerup and Cahill 1967) based on the reconnection current sheet (Fig. 2.2). In this coordinate, L points along the antiparallel magnetic field direction, N points along the overall current sheet normal and M points along the X-line direction. Practically, each direction could be deduced by the minimum variance analysis of magnetic field (MVAB) (Paschmann and Daly 1998).

Fig. 2.2 Magnetic reconnection shown in LMN coordinate



2.2.2 Walen Relation

When a spacecraft crosses a reconnection exhaust, the Alfvénic reconnection jets could be described by the Walen relation in the form of:

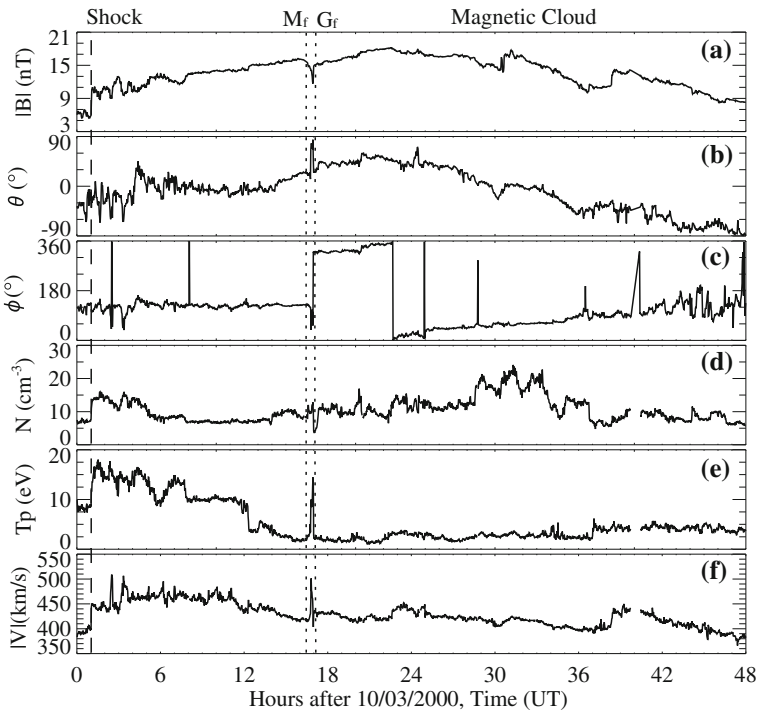


Fig. 2.3 a–f WIND measurements of the magnetic field strength, latitude angle, azimuth angle, proton density, temperature, and velocity. The left dashed line shows a shock driven by the MC. The BL is bounded by the dot lines (marked by Mf and Gf)

$$\mathbf{V}_{pre} = \mathbf{V}_{ref} \pm \sqrt{\frac{\rho_{ref}(1 - \alpha_{ref})}{\mu_0}} \left(\frac{\mathbf{B}}{\rho} - \frac{\mathbf{B}_{ref}}{\rho_{ref}} \right). \quad (2.1)$$

Here ρ , $\mathbf{V}$, and $\mathbf{B}$ represent plasma density, velocity vector, and magnetic field vector, while $\alpha = (p_{//} - p_{\perp})\mu_0/B^2$ is the pressure anisotropy factor. 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 positive (negative) sign is chosen for the trailing (leading) edge of the exhaust.

2.3 Magnetic Reconnection in the BL

Figure 2.3 provides an overview of solar wind conditions measured at (32.6, -251.7, -3.8)Re in GSE coordinate on 3rd October 2000 by the Wind spacecraft. The MC’s leading edge, marked between Mf and Gf, reveals a decreased field

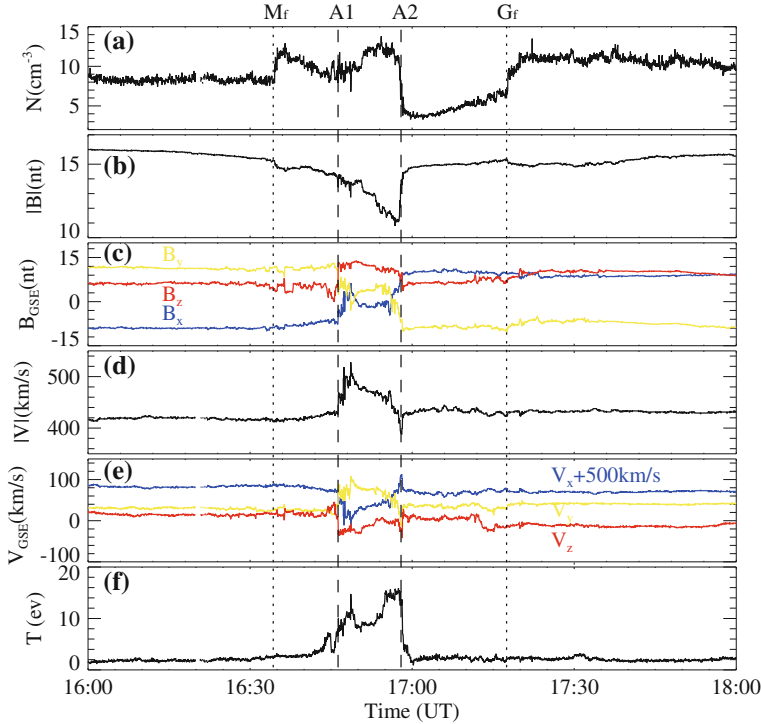


Fig. 2.4 a–f WIND measurements of density, magnetic field, velocity (V_x has been shifted by 500 km/s), and temperature between 16:00 and 18:00 UT on October 3, 2000 with a cadence of 3 s. The MCBL is shown by the dotted lines; the dashed lines marked by A1 and A2 inside the BL represent the reconnection exhaust boundaries at 16:46 UT and 16:58 UT, respectively. Reprinted with permission from (Wang et al. 2010), Copyright 2010 by American Physical Society

strength, sudden change in field orientations, increased flow velocity and proton temperature.

Figure 2.4 shows more detailed information between 16:00 and 18:00 UT. According to further analysis, it is found that the area between 16:46 and 16:58 UT (marked by A1 and A2) exhibits the general characteristics of magnetic reconnection. In particular, the magnetic field in the X and Y directions are almost reversed, and the total magnitude of magnetic field declines $\sim 4\text{nT}$ and rotates $\sim 143^\circ$. Moreover, the plasma velocity increases $\sim 100\text{ km/s}$ and the proton temperature increases $\sim 10\text{ eV}$. All these features indicate that WIND spacecraft may encounter a reconnection exhaust.

To see the reconnection exhaust more clearly, the LMN current sheet coordinate system is constructed and shown in Fig. 2.5. The current sheet normal N , $(0.76, 0.64, 0.06)$ in GSE, is calculated by minimum variance analysis of the magnetic field (MVAB) across the exhaust (Paschmann and Daly 1998). So is the X-line direction M , $(-0.02, -0.06, 0.99)$ in GSE, nearly perpendicular to the ecliptic plane. We assume that the associated MC has a flux-rope-like structure (Burlaga 1995) and get its axis pointing to $(-0.84, 0.23, 0.49)$ in GSE. Figure 2.3a reconstructs the geometric configuration of the reconnection event.

Fortunately, this reconnection exhaust is also observed by the ACE spacecraft located at $(255.2, -29.2, -7.5)\text{Re}$. Since ACE is farther away from the X-line than WIND, it takes ACE 14 min, which is 2 min longer than WIND, to cross the exhaust. Detailed magnetic field and velocity conditions projected in the LMN coordinate

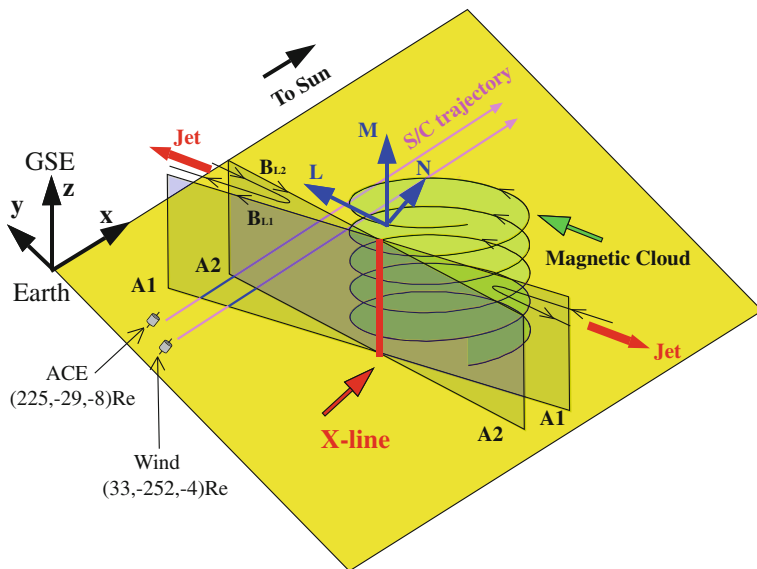


Fig. 2.5 Geometric configuration of the reconnection exhaust; the reconnection jets and X lines are shown in red; the following MC is sketched in green. Reprinted with permission from (Wang et al. 2010), Copyright 2010 by American Physical Society

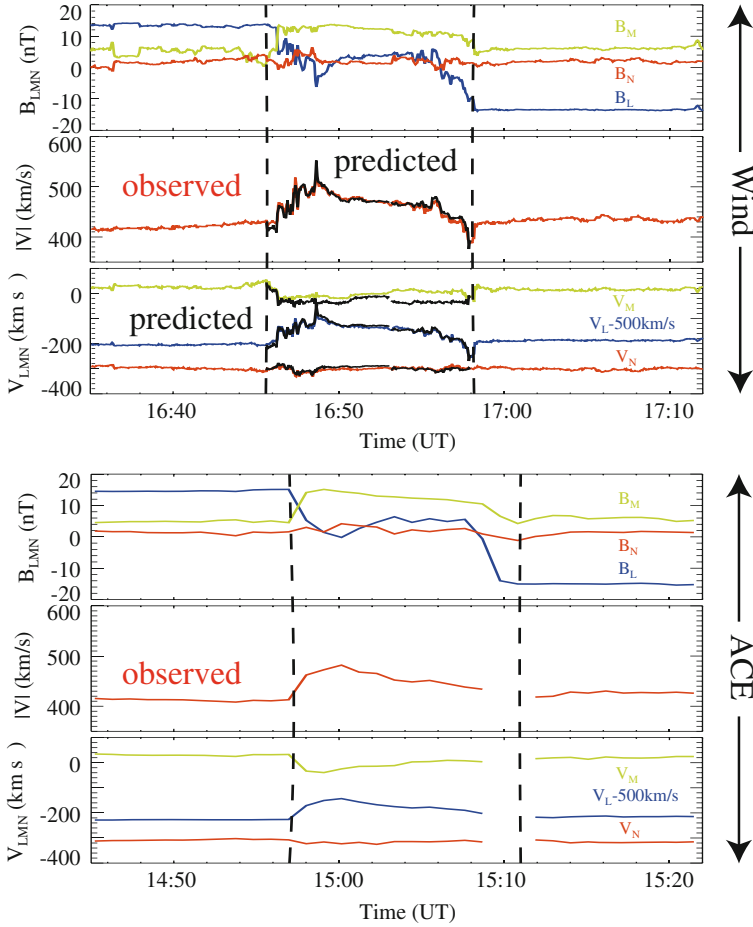


Fig. 2.6 measurements of magnetic field and velocity in the LMN coordinate system (V_L has been shifted by -500 km/s). The *dashed lines* denote the exhaust boundaries and the *black lines* stand for the reconnection jets calculated by Walen relation. The pressure anisotropy factor is set to zero in this calculation

are shown in Fig. 2.6. It could be found that the normal magnetic field B_N is almost constant and near zero, while the antiparallel magnetic field B_L component changes from $+14$ nT to -14 nT, entirely reversed all over the exhaust. In addition, V_N is roughly steady while V_L increases ~ 100 km/s in the exhaust. Moreover, we use WIND data¹ to compare the observed plasma velocity in the exhaust with the prediction given by Walen relation (Eq. 2.1). As seen in Fig. 2.6, both magnitude

¹The data provided by the ACE spacecraft is not used to calculate the predicated velocity since there is a data gap near the trailing edge of the exhaust.

and components of the predicted velocity agree well with the observations. The increased velocity is mainly in the L direction and the increment is close to the Alfvén speed. The observed plasma flows exhibit primary features of reconnection jets. All these evidences indicate that WIND and ACE spacecraft detected a reconnection exhaust in the BL.

2.4 Energetic Particles Associated with Magnetic Reconnection

In this event, we fortunately observed energetic particles associated with magnetic reconnection that has not been so far reported in the solar wind. As shown in Fig. 2.7, the increments of particle fluxes display strong energy selectivity and pitch angle dependency. Particularly, (1) low-energy electrons were mainly heated

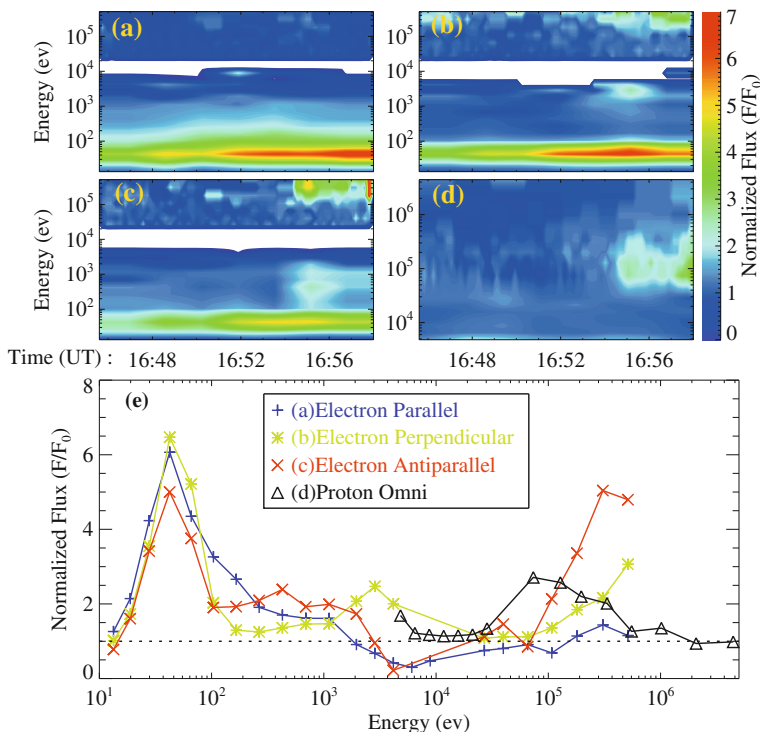


Fig. 2.7 Wind measurements of 10 eV–500 keV electrons normalized fluxes in parallel (a), perpendicular (b) and antiparallel (c) directions, respectively. d 5–5000 keV protons normalized omni flux. All the fluxes are divided by the mean background flux F_0 at every energy band for normalizing. The background flux F_0 is chosen by the mean flux of a nearby quiet period (between 16:00 and 16:3 UT) for each energy band. The missing data is shown by blank. e Combined normalized fluxes at 16:55 UT for a typical show. Reprinted with permission from (Wang et al. 2010), Copyright 2010 by American Physical Society

around 10–200 eV with an intense enhancement near 50 eV which resembles the observations of Huttunen (Huttunen et al. 2008). (2) 1–100 keV electrons do not show such enhancement, while 100–500 keV electron fluxes mainly increase at pitch angle between 90 and 180° (perpendicular and antiparallel to the field line). (3) The protons are accelerated around 100 keV, but no remarkable increments are found in other energy bands.

In the high-energy range (100–500 keV) where our greatest concern exists, the electron has a burst increase near 16:55 UT. As shown in Fig. 2.8, the least square fits of the electrons and protons, measured by WIND (SST-Foil), also show power law distributions ($f(v) \propto E^{-k}$) with a smaller power index k inside the exhaust and larger ones outside. Although the spacecraft does not cross the reconnection diffusion region, where the energetic electrons were thought to be initially produced, we can still rule out the possibility that such irregular flux enhancements are merely

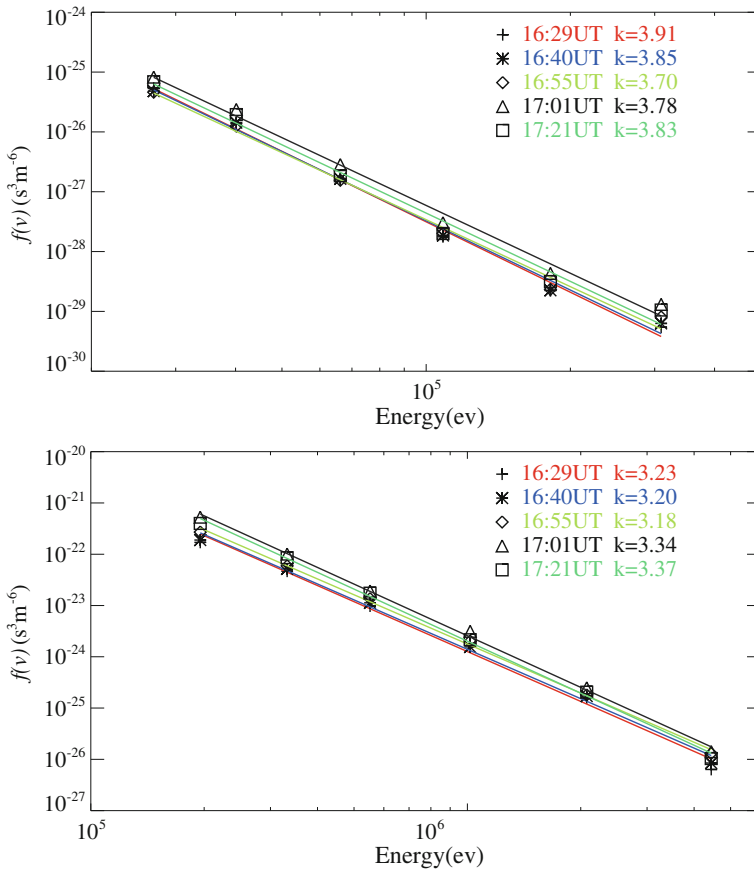


Fig. 2.8 Energy spectrum of electron (*up*) and proton (*down*) fitted by a power law distribution near the reconnection exhaust

caused by the variation of background electron temperature or density (see the isotropic low-energy electrons around 40 eV for example). Instead, both the reconnection topological structure and the harder spectrum in the exhaust suggest that they are most probably accelerated by magnetic reconnection and then expelled through the long reconnection separatrixes (Egedal et al. 2009; Pritchett 2006). Since the local magnetic field at 16:55 UT just points to the reconnection region and the expelled energetic electrons are mainly concentrated near the specified two of the four reconnection separatrixes by the modulation of the guide field (Egedal et al. 2009; Pritchett 2006), the Wind spacecraft would naturally measure enhanced field-aligned energetic electrons in the antiparallel direction (Fig. 2.7).

2.5 Discussion and Conclusion

The small normal velocity shear ($\Delta V_N = 12$ km/s) across bifurcated current sheet could be considered as a $V_{in} = 6$ km/s reconnection inflow. Correspondingly, the reconnection electric field is calculated to be $E = 0.084$ mV/m ($E = B \times V_{in}$) and the dimensionless reconnection rate could be estimated by $V_{in}/V_A = 5.3\%$ ($V_A = 113$ km/s is the external Alfvén speed). These signatures are consistent with the Petschek-like model of fast reconnection and they also resemble the previous observations.

In this event, it takes ACE spacecraft 14 min to cross the exhaust with a 300 km/s velocity (V_N). So the width of the exhaust could be calculated to be $\sim 2.5 \times 10^5$ km (or 40 Re) and the distance to the X-line is $\sim 2.4 \times 10^6$ km (or 374 Re). The observational location of ACE is so far away from the X-line ($\sim 32308d_i$), and no hall signatures are observed in this area.

Nevertheless, it is difficult to calculate the real length of the X-line since its direction (M) is nearly perpendicular to the ecliptic plane ($M = [-0.02nx, -0.06ny, 0.99nz]$ in GSE), while both spacecrafts are almost in that plane. However, the observed similar characteristics make it reasonable to believe that this Petschek-like reconnection with quasi-steady and large-scale properties also has a long reconnection X-line extending several hundreds of earth radius as those previously reported observations (Gosling et al. 2007; Phan et al. 2006). If the X-line could extend to ~ 668 Re as is observed in previous event (Gosling et al. 2007), the reconnection potential energy is ~ 358 keV, and this energy might play an important role in the acceleration of energetic particles.

To sum up, we observed a magnetic reconnection exhaust in a BL. After the detailed analyses, it is found that the reconnection jets meet the Walen relation, and this event belongs to Petschek-like fast reconnection which has large-scale and quasi-steady properties as previous observations (Davis et al. 2006; Gosling 2011; Gosling et al. 2005b, 2007; Phan et al. 2006). In addition, the first observation of energetic particles (100–500 keV electrons and ~ 100 keV protons) associated with magnetic reconnection in the solar wind is reported.

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