Quasi-continuous reconnection accompanied by FTEs during IMF B_z≈0 nT observed by Double Star TC-1 at the dawnside magnetopause

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Abstract: During a one-hour interval of interplanetary magnetic field (IMF) B_z≈0 nT, the equatorial spacecraft Double Star TC-1 encountered the dawn flank magnetopause many times at the magnetic local time (MLT) of about 08:00 and the latitude of about -27°. During each encounter, reconnection jets were observed with their velocities up to more than 500 km/s, significantly higher than the background flow in the magnetosheath. The fast flows match the theoretical prediction of Alfvénic acceleration well. The medium temperature and density of ions in the boundary layer indicate the open magnetic field topology inside this layer. The mainly southward and tailward flows of the plasma jets alongside with the negative slopes of the Walén test indicate that the spacecraft was located south of the reconnection site, consistent with both anti-parallel and component reconnection models. The accelerated flows were observed lasting for about one hour, with some modulations by the oscillations of the magnetopause, but no reversals in the direction of V_z were found during the interval. The significantly enhanced flows in the boundary layer compared to the adjacent magnetosheath indicate that the reconnection was quasi-continuously active at the magnetopause northward of the spacecraft under such IMF conditions. At the same time, the bipolar signatures in B_N with enhancements of the magnetic field indicate the occurrence of the Flux Transfer Events (FTEs). The observed reconnection was quasi-continuous, whereas the simultaneously accompanied FTEs were time-dependent under the IMF B_z≈0 nT. For this event, however, it is not possible to identify whether the reconnection was anti-parallel or component because the TC-1 was far away from the reconnection site.

Key words: continuous reconnection; flank magnetopause; Flux Transfer Event

1 Introduction

Magnetic reconnection is one of the most important processes of the solar wind-magnetosphere interaction, and plays a crucial role in the solar wind plasma transport into the magnetosphere. Dungey (1961, 1963) was the first to introduce the concept of reconnection into the solar wind-magnetosphere interaction and he developed models for reconnection at low latitude on the dayside magnetopause under southward IMF, and at high latitude on the magnetopause behind one or both cusps under northward IMF, respectively.

Reconnection may often happen when the field lines across the magnetopause are anti-parallel because of the short growth time of the tearing instability in the anti-parallel direction (Quest and Coronity, 1978).The reconnection site could be deduced by the geometrical criteria of anti-parallel configuration (Crooker et al, 1979, Luhmann et al, 1984). Zong et al (2005) reported Cluster observations of reconnection at multiple X-lines at the edge of the northern cusp which were similar to the anti-parallel type. Dunlop et al (2009) investigated anti-parallel reconnection observed on the dayside closed field lines at the high latitude magnetopause.

On the other hand, both theoretical and observational analyses indicated that reconnection could still take place when the magnetic fields across the magnetopause are not anti-parallel, with the shear angle being much smaller than 180° (Cowley et al, 1973; Sonnerup et al, 1974). In this case the position of the reconnection line could be deduced by the geometrical criteria of the component reconnection model (Gonzales and Mozer, 1974). Chandler et al (1999) reported the component reconnection observed by Polar equatorward of southern cusp during northward IMF. Pu et al (2005, 2007) analyzed several events of component reconnection observed by TC-1 and Cluster near the sub-solar magnetopause. Kim et al (2002) also found evidence of component reconnection near the sub-solar point.

As a significant process that converts magnetic field energy into plasma energy, reconnection can be considered to be either steady (Paschmann et al, 1979; Gosling et al, 1982; Frey et al, 2003) or time-dependent, creating Flux Transfer Events, FTEs (Russell and Elphic, 1978, 1979), or quasi-periodic with some intermittency (Kan et al, 1988; Nishida et al, 1989). It is difficult to conclude whether steady or transient reconnection is more probable at the magnetopause. Phan et al (2000, 2001, and 2006) reported Equator-Geotail and Wind-Geotail observations of the extended reconnection at the flank magnetopause. Zheng et al (2005) investigated Cluster observations of continuous reconnection at the dayside magnetopause in the vicinity of the cusp. The global magneto-hydrodynamic (MHD) simulation by Raeder (2006) presented a generation mechanism of the intermittent FTEs in the form of repeated plasmoids that are independent of the external trigger.

Many observations of reconnection processes under northward IMF (Song et al, 1992; Chandler et al, 1999; Petrinec et al, 2000; Phan et al, 2003; Pu et al, 2005; Lavraud et al, 2002, 2005, 2006; Bogdanova et al., 2005, 2008; Øieroset et al, 2005; Yan et al, 2008) and southward IMF (Dunlop et al, 2005; Trattner et al, 2007; Yan et al, 2009) have been previously reported. The reconnection at the magnetopause was understood to be either stable or transient. Phan et al (2004) investigated observations of continuous reconnection by three Cluster spacecraft under steady IMF conditions, where the inner spacecraft observed the slowing of the accelerated flows while the outer one observed them more continuously. Rosenqvist et al (2008) analyzed the same event with the conclusion of continuous reconnection, but the reconnection rate could be modulated even under steady IMF. Hasegawa et al (2008) reported a quasi-continuous reconnection at the tailward of the cusp under northward IMF. However, there have been much fewer reports of continuous reconnection when IMF B_z was close to 0 nT.

In our observations, when IMF B_z was around 0 nT, the reconnection can be identified as a quasi-continuous process, as illustrated in Figure 6, whereas a series of the time-dependent FTEs were observed at the same time, showing the features of quasi-steadiness and time-dependence simultaneously.

The paper is organized as follows: Section 2 presents the details of the observation and its analysis. Section 3 gives a discussion of the event, and section 4 gives the summary of the presented work.

2 **Observations**

The Double Star Program (DSP) includes equatorial and polar orbiting spacecraft (Liu, 2005). The Equatorial spacecraft TC-1 covered the dayside magnetopause region during spring, 2004. The instruments onboard TC-1 measured magnetic field vectors, the ion temperature, bulk velocity and density, and the electron temperature, bulk velocity and density. The data used in this work include the TC-1 magnetic field measurements by the Flux Gate Magnetometer (FGM) (Carr et al., 2005), the ion parameters by the Hot Ion Analyzer (HIA) (Rème et al., 2005), and the Flux Gate Magnetometer (FGM) (Balogh et al, 2001) on Cluster SC1, as the IMF monitor in the upstream magnetosheath (Panel 1 in Figure 1). The time resolution used in this work is the spin-resolution of 4 seconds, and the vectors are presented in the geocentric solar magnetospheric (GSM) coordinates.

On May 2, 2004, TC-1 encountered the magnetopause many times at an MLT of about 8:00 and latitude of about 27 ° (Figure 1), and crossed the magnetopause into the magnetosheath at about 18:47 UT, as identified by the abrupt change in the observed B_z (Figure 2). The orbit of TC-1 was nearly tangential to the magnetopause for several hours, as shown in Figure 1, which provided a good opportunity to observe the magnetopause boundary layer and the processes at the magnetopause, such as reconnection. The northward IMF lasted for about eight hours before the interval of interest, until it showed IMF $B_z \approx 0$ nT for about 2 hours. Panel 1 in Figure 2 presents the IMF observed by SC1 of the Cluster in the upstream magnetosheath, at the similar MLT as TC1. The time lag of 2 minutes has been counted in from the SC1 to TC1, because SC1 is located 4 Re upstream of TC-1 in the X direction (Panel 1 in Figure 1). It can be seen that the draped IMF B_z is very close to 0 nT, and the draped IMF B_y is the dominant component. The draped IMF B_x (green line in Panel 1 of Figure 2) is smaller than the B_y (blue line in Panel 1 of Figure 2). The draped IMF orientation observed by Cluster SC1 in the magnetosheath during this interval was found to be consistent with the ACE observation, which is not shown. Because of the location at the flanks, the draping of the magnetic field against the magnetopause plays a critical role in the orientation of the magnetosheath field. At the location of SC1, about 4 Re upstream of TC-1, the observed draped IMF has significantly larger B_y than B_x (both are negative). At the location of TC-1, the draped IMF observed in the magnetosheath has the similar B_x (green line in Panel 5 of Figure 2) and B_y (blue line in Panel 5 of Figure 2), adjacent to the magnetopause, shown in Panel 5 of Figure 2 (see 18:47 UT-19:06 UT). This rotation from dawnward at SC1 to tailward at TC-1 is consistent with the draping effect in the magnetosheath at dawnside.

Under IMF $B_z \approx 0$ nT, during the nearly one-hour interval 17:55 UT-18:47 UT, the spacecraft observed accelerated flows every time it encountered the magnetopause (Panel 4 in Figure 2). The velocity of the fast flows, up to more than 500 km/s, was significantly higher than the background flow in the magnetosheath. Such acceleration could likely be generated by reconnection, rather than from possible Kelvin-Helmholtz (K-H) waves due to velocity shear or small penetrations at such a flank side of the magnetopause. The directions of the flows were steadily southward ($-V_z$) and tailward ($-V_x$), also negative in the L-direction of the boundary coordinates (the dominant and negative V_L in panel 7 of figure 2), implying the spacecraft was located southward of the reconnection site. The accelerated flows were quite continuous, with some modulations by the magnetopause motion.

During the interval 17:55 UT-18:47 UT, the observed fast flows were always southward and tailward, without any reversal. In fact, the fast flows were quite continuous during this interval because nearly 80% of the time was filled by the high speed flows. It will also be discussed that the reconnection was quasi-continuously active as shown in Figure 6. On the other hand, some bipolar signatures could be seen in B_N with enhancements of the magnetic field (panel 5 and 6 of Figure 2), at 17:54 UT,17:55 UT, 17:57 UT, 18:01 UT, 18:04 UT, 18:17 UT, 18:25 UT, 18:32 UT, 18:34 UT, 18:43 UT, 18:51 UT, and 18:54 UT, marked by the vertical lines. The enhancements in the magnetic field occurred at every bipolar signature, indicating the existence of the FTEs (e. g., Zhang, et al, 2010). The ion density increased at the FTEs (at 17:54 UT, 17:55 UT, 17:57 UT, 18:01 UT, 18:04 UT, 18:17 UT, 18:25 UT, 18:32 UT, 18:34 UT and 18:43 UT) inside the

magnetosphere while it decreased at the FTEs (at 18:51 UT and 18:54 UT) in the magnetosheath. This can be understood in terms of the flux tubes that opened at the magnetopause between the magnetosheath and the magnetosphere. Each FTE happened when the observed velocity increased or decreased which was caused by the motion of the magnetopause.

In order to verify the occurrence of reconnection, the Walén tests have been carried out at the crossings of the magnetopause current sheet. As illustrated in figure 3 (a~e, with the time intervals, correlations coefficients (cc) and the relationships between v_A and $v\text{-}V_{HT}$ in each panel), five Walén tests resulted in very high correlation coefficients with negative and nearly unity slopes, except for the failure at UT 19:06, possibly because of the decrease in the ion density, as shown in Figure 2 panel 1. The time intervals and the results of the Walén tests are listed in table 1. The negative slopes indicate that the spacecraft was located south of the reconnection site. This is consistent with the observed southward and tailward directions of the accelerated flows. The near unity values of the slopes indicate the agreement of the observed velocity with the Alfvénic acceleration during the reconnection processes.

Furthermore, with accounting of the anisotropic pressure, the prediction of Alfvénic acceleration during the reconnection was calculated and compared to the observed velocity. Based on a single point reference in the magnetosheath and local magnetic field measurements, the flow prediction could be calculated as: $\Delta\mathbf{v}_{predicted}=\mathbf{v}_{2t}-\mathbf{v}_{1t}=-(1-\alpha)^{1/2}(\mu_0\rho_1)^{-1/2}\,[\mathbf{B}_{2t}(1-\alpha_2)/(1-\alpha_1)]$ (Hudson, 1970; Paschmann et al, 1986). The negative sign was chosen from the observed negative correlation between $\Delta\mathbf{v}$ and $\Delta\mathbf{B}$ at the magnetopause**.** Subscript "1" denotes the reference time at 19:07 UT and "2" denotes the prediction for every other time. The pressure anisotropy factor is $\alpha=(p_{\parallel}-p_{\perp})\mu_0/B^2$. As illustrated in figure 4 panels 2 and 3, the predicted tangential V_x and V_z were marked by red points only when the ion density was higher than 6 cm^{-3} (the black line in Panel 2 of Figure 2). At the magnetopause current sheet crossings, the predicted V_x and V_z agree with observations quite well. The observed low ion density at 19:06 UT could explain why the Walén test failed there. In the boundary layer, there are still several predictions of the accelerated flows close to the observed velocity, with the ion density higher than 6 cm^{-3}. The agreement of the predicted V_x and V_z with the observations in the magnetopause current sheets is consistent with the results of the Walén tests. Both results indicate that the observed fast flows were generated by reconnection which might be continuously active somewhere north of the spacecraft. The medium ion density (1 cm^{-3} ~ 6 cm^{-3}) and temperature in the boundary layer and even inside the magnetosphere (for a few hours not shown before 17:35 UT) indicate the mixture of the cold and dense plasma from the magnetosheath with the hot and diluted plasma from the magnetosphere via the open magnetic field line generated by reconnection.

3 Discussion

In the presented observations, there is no evidence for the spacecraft crossing the vicinity of the reconnection site. In fact, the draped IMF observed by Cluster in the upstream magnetosheath in this event was mainly dawnward ($-B_y$) and anti-sunward ($-B_x$), with $B_z\approx0$ nT. According to the anti-parallel reconnection model, when the IMF is dominantly dawnward, the reconnection site could be located at the northern high latitude region at the dawnside and the southern high latitude at the duskside, as illustrated in Figure 5 (a). On the other hand, the component reconnection site should be located as a tilted X-line from north-dawn quadrant to south-dusk quadrant under dawnward IMF ($-B_y$) (Sonnerup et al, 1974, Gonzales and Mozer, 1974), as illustrated in Figure 5(b). The reconnection site can be predicted to be north of the TC-1 position, whether the reconnection was anti-parallel or component. This implies that the observed tailward ($-V_x$) and southward ($-V_z$) fast flows should come from the reconnection site in the other hemisphere, far away from the spacecraft. The direction of the accelerated flows is consistent with the expected location of either anti-parallel or component reconnection. The magnetic shear angle across the magnetopause at TC-1 was about 62°, far from 180°.

However, we could not tell whether the reconnection was anti-parallel or component because the spacecraft was far away from the reconnection site, but this event could be considered as supporting either of them.

Reconnection at the magnetopause can be quasi-steady (Paschmann et al 1979) or time-dependent (Russell and Elphic, 1978). In Panel 4 of Figure 2, the fast flows lasted about one hour with some modulation of the magnetopause motion. In the quasi-steady scenario, due to the motion of the magnetopause, the TC-1 encounters the reconnected fast flows at different distances from the magnetopause: when the magnetopause moves inward, the TC-1 is closer to the magnetopause and encounters the more accelerated flows. On the other hand, when the magnetopause moves outward, the TC-1 is located deeper inside the boundary layer, and slower flows are observed. The repeated encounters of reconnection jets at multiple magnetopause crossings could be considered as evidence for continuous reconnection (Gosling et al, 1982). During the one-hour interval, nearly 80% of the time was filled by the fast flows, quite continuously even in the single spacecraft observation. It implies that the reconnection might be active continuously during the interval. Figure 6 gives the plot of $|V_i|$ as a function of N_i, which is a good illustration that the reconnection was quasi-continuous because the velocity in the multiple magnetopause/boundary layer crossings was mostly enhanced compared to the magnetosheath velocity (Phan et al, 2004; Hasegawa et al, 2008). The acceleration was observed in the boundary layer quite continuously, with only few low points between the ion density of 1-6 cm^{-3} in the boundary layer.

On the other hand, a series of FTEs can be seen during the quasi-continuous reconnection, marked by the vertical lines in panels 5 and 6 of Figure 2. As mentioned above, these FTEs correspond to the intervals with increases or decreases in the flow speed, indicating the passage of the reconnected flux tubes over the spacecraft. However, the series of FTEs also showed some intermittency in themselves, implying that they might also be caused by repeated plasmoids as suggested by Raeder (2006). If so, the intermittent FTEs can be driven by quasi-continuous reconnection. There seems to be somehow mixed features in the observation. The medium density (1 cm^{-3}-6 cm^{-3}) and temperature of the ions in the boundary layer and even deeper inside the magnetosphere could indicate the entry of the cold and dense plasma from the magnetosheath. There was little difference in the plasma β between the magnetosphere and magnetosheath, which also implies the entry of the magnetosheath plasma into the magnetosphere. The presented observations show the quasi-continuous reconnection accompanied by time-dependent FTEs when the draped IMF B_z was close to 0 nT, and can support the existence of the extended reconnection process (Phan et al, 2000, 2001) that drives the plasma transport into the magnetosphere at the dawnside magnetopause.

4 Summary

The reconnection at the magnetopause can be either steady or time-dependent. The TC-1 observed quasi-continuous reconnection accompanied by FTEs when the draped IMF B_z was close to 0 nT in the event presented in this paper. The conclusions of the analysis are summarized as follows:

(1) During the one-hour interval of IMF $B_z \approx 0$, reconnection jets were observed by TC-1 with velocities up to more than 500 km/s at the south-dawn flank magnetopause, significantly higher than the background flows in the magnetosheath.

(2) Walén tests at the magnetopause crossings indicate that the fast flows satisfied the Walén relation quite well, and the observed velocity of the fast flows matched the theoretical prediction for Alfvénic acceleration very well, indicating that the accelerated flows were generated by reconnection.

(3) The negative slopes of the Walén test showed that the spacecraft was located south of the reconnection site, consistent with the observed southward and tailward flows, but the event could not be used to identify whether the reconnection was anti-parallel or component.

(4) The reconnection was indicated to be quasi-continuously active at the magnetopause north of the spacecraft, and it was simultaneously accompanied by a series of time-dependent FTEs, showing the features of quasi-steadiness and time-dependence simultaneously.

(5) The presented observation could support the extension of the reconnection process to the flank magnetopause; this process converts magnetic energy into plasma energy and causes solar wind transport into the magnetosphere.

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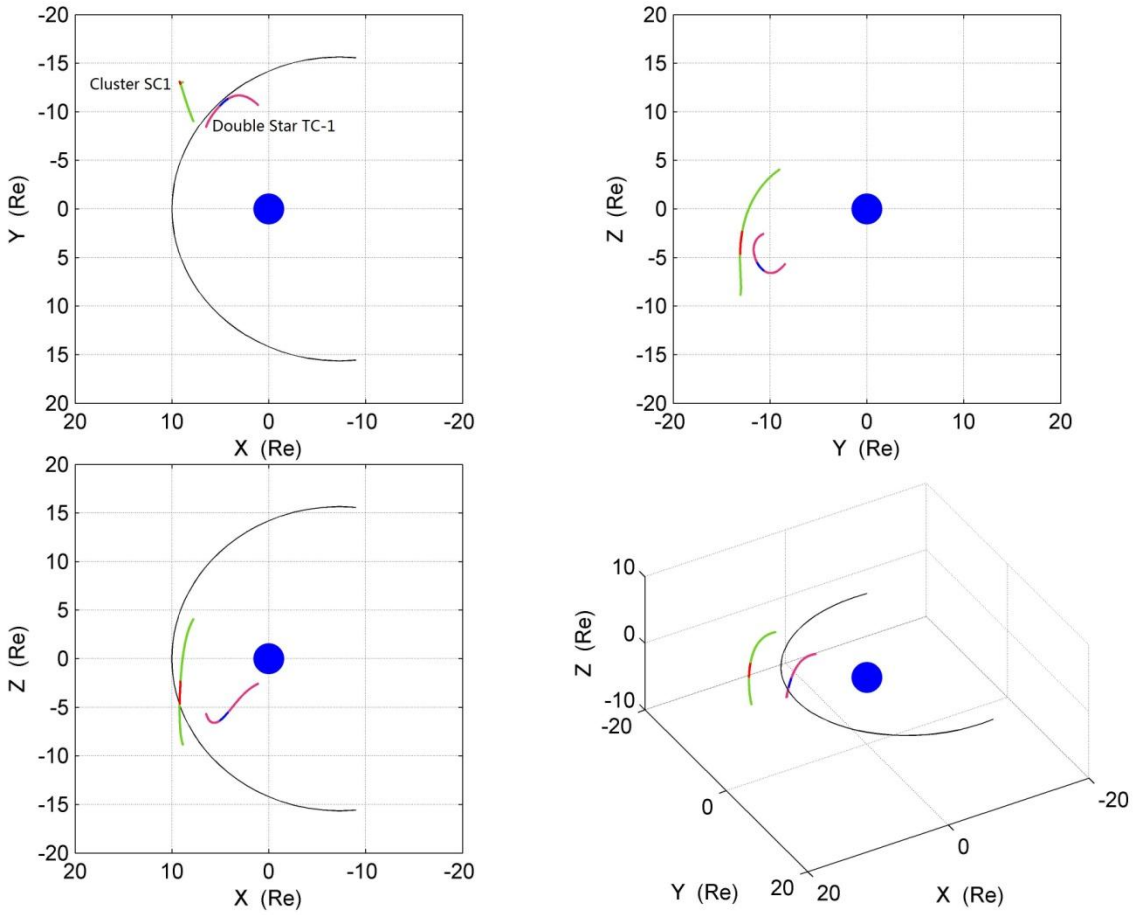

Figure 1.Orbits of the Double Star TC-1 near the magnetopause and Cluster SC1 in the upstream magnetosheath, with similar magnetic local time during the interval of interest. The relative position of the TC-1 and SC1 orbits and the magnetopause are shown in the X-Y plane (top left panel), the X-Z plane (bottom left panel), and the Y-Z plane (top right panel) and in 3D (bottom right panel). The investigated interval is marked by the blue color for TC1 and by the red for SC1. The position vectors are presented in GSM coordinates.

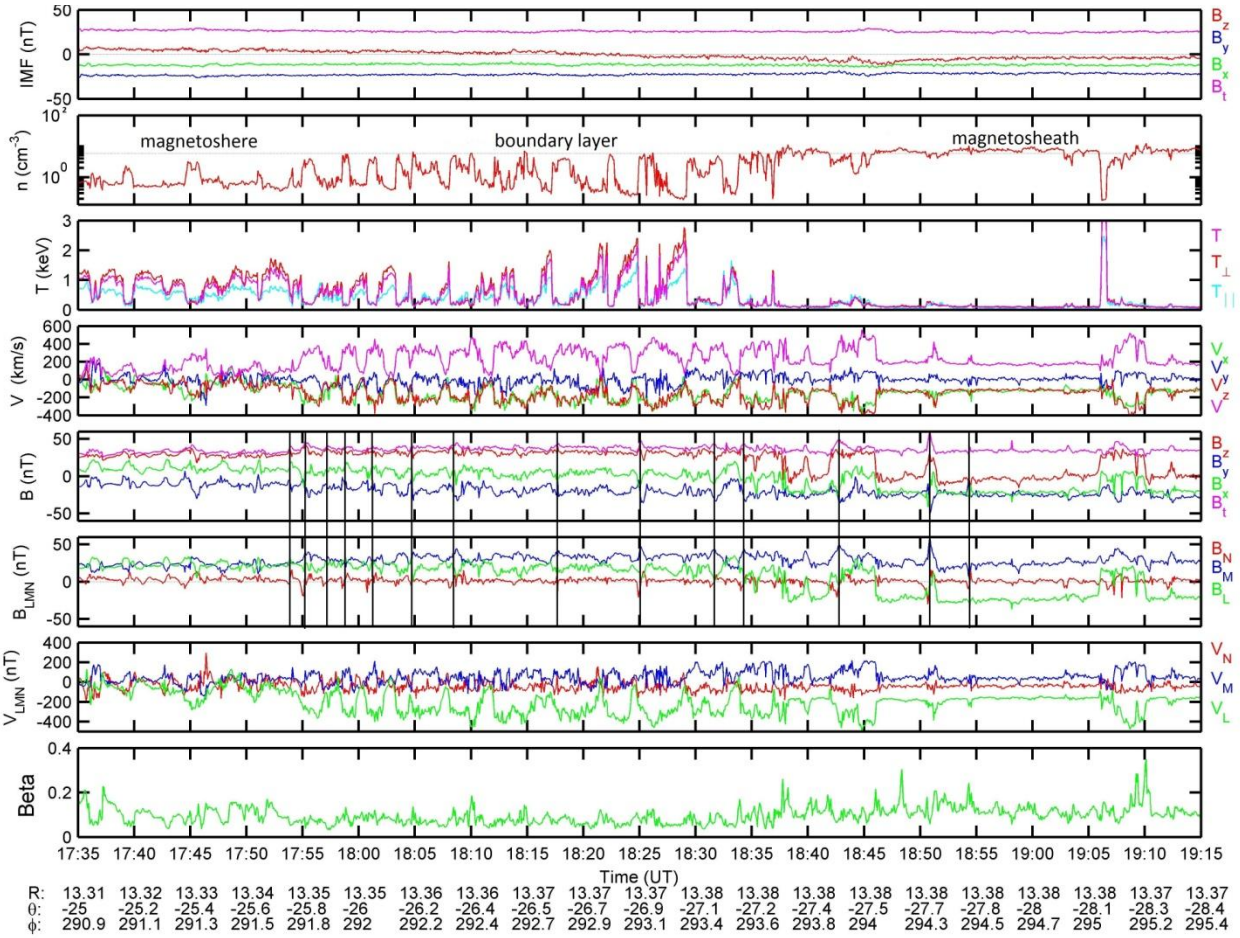

Figure 2. TC-1 observations at the south-dawn flank of the magnetopause and the IMF monitored by the Cluster SC1 in the upstream magnetosheath. Panel 1 indicates the IMF in GSM coordinates observed by Cluster SC1 in the upstream magnetosheath, with the time lag of 2 minutes from SC1 to TC1 counted. Panel 2 shows the ion density in logarithmic coordinate; panel 3 presents the ion temperature; panel 4 and 7 show the ion bulk velocity in GSM coordinates and in boundary coordinates, respectively; panel 5 and 6 present the magnetic field in GSM coordinates and in boundary coordinates, respectively; and panel 8 shows the plasma β. The boundary coordinates were calculated by the minimum variation analysis (MVA) method at the magnetopause crossing, L was northward and tailward, M was dawnward, and N outward normal to the magnetopause.

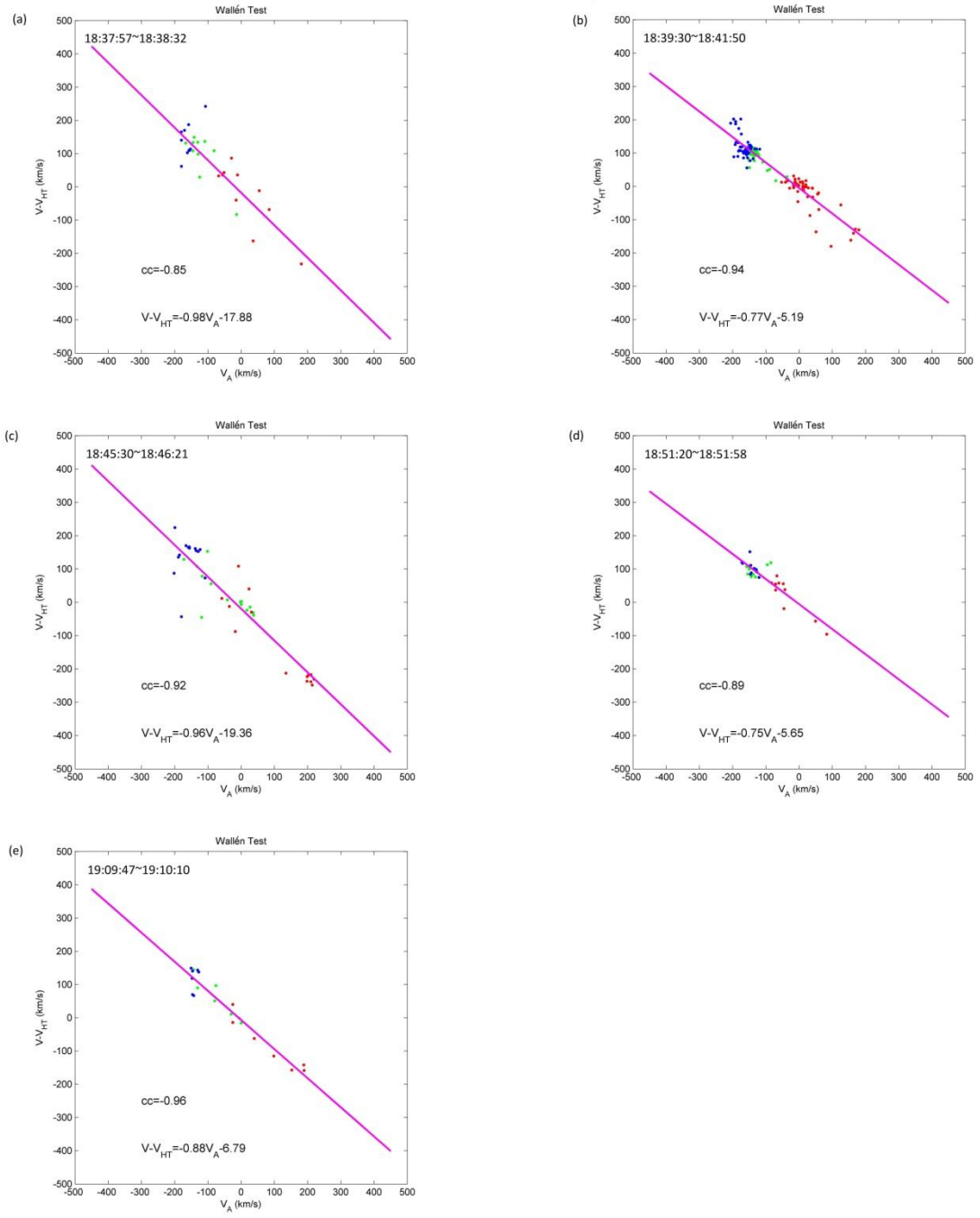

Figure 3. Walén test plots of $V\text{-}V_{HT}$ vs V_A at the magnetopause current sheet crossings. The time intervals, correlations coefficients (cc) and the relationships between v_A and $v\text{-}V_{HT}$ were presented in each panel. Five tests result in high correlation coefficients, negative and nearly unity slopes of the Walén relations. The V_x, V_y, V_z were plotted as data points in green, blue and red, respectively. The panel a~e correspond to the intervals number 1, 2, 3, 4, and 6 in Table 1.

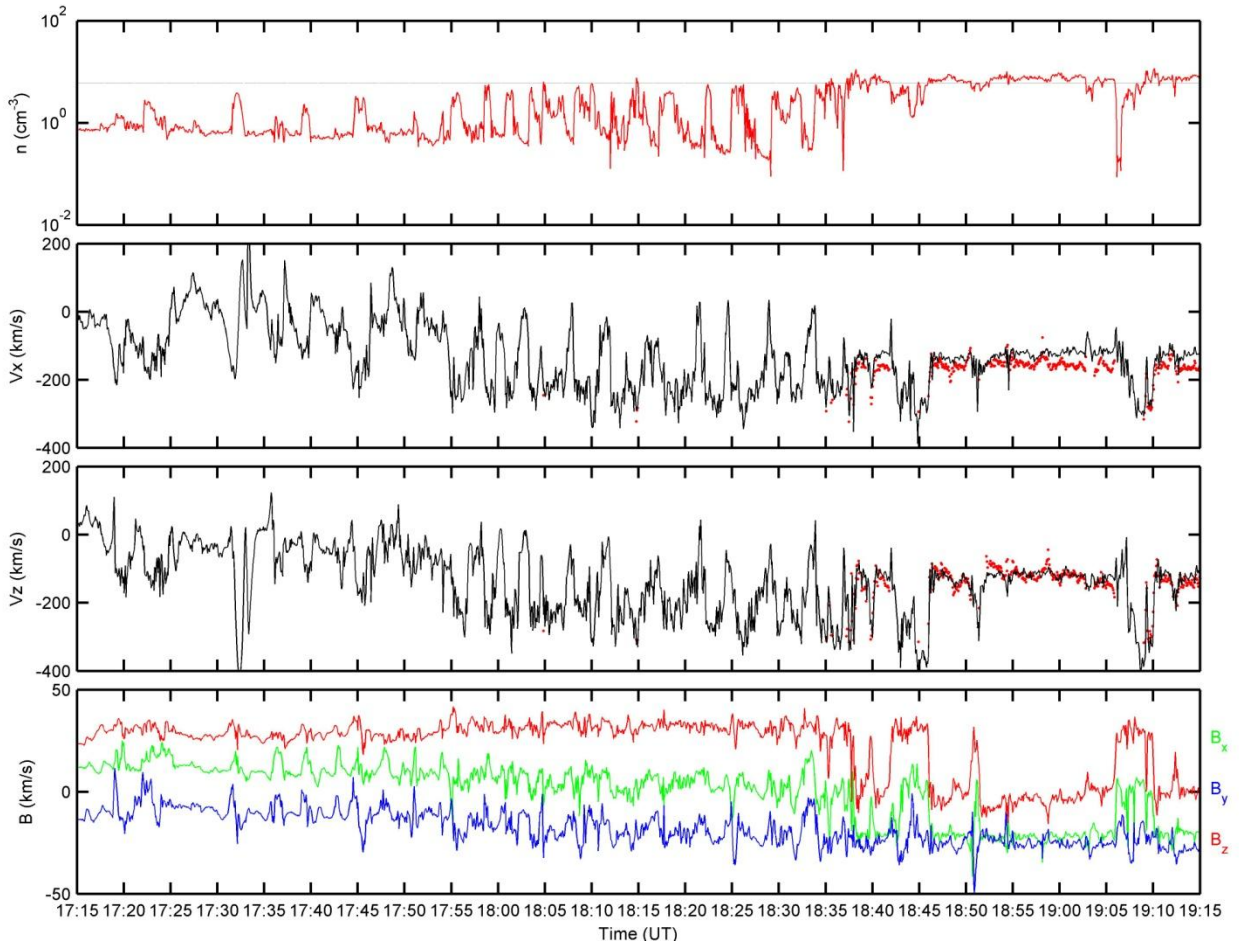

Figure 4. Comparison of the predicted V_x and V_z to the observed velocity. Panel 1 gives the ion density observed by HIA, the straight line in black is the level of 6 cm^{-3}; Panel 2 presents the observed V_x as a black line and the predicted V_x as red dots; Panel 3 indicated the observed V_z as a black line and the predicted V_z as red dots; Panel 4 shows the observed magnetic field measured by TC-1 FGM.

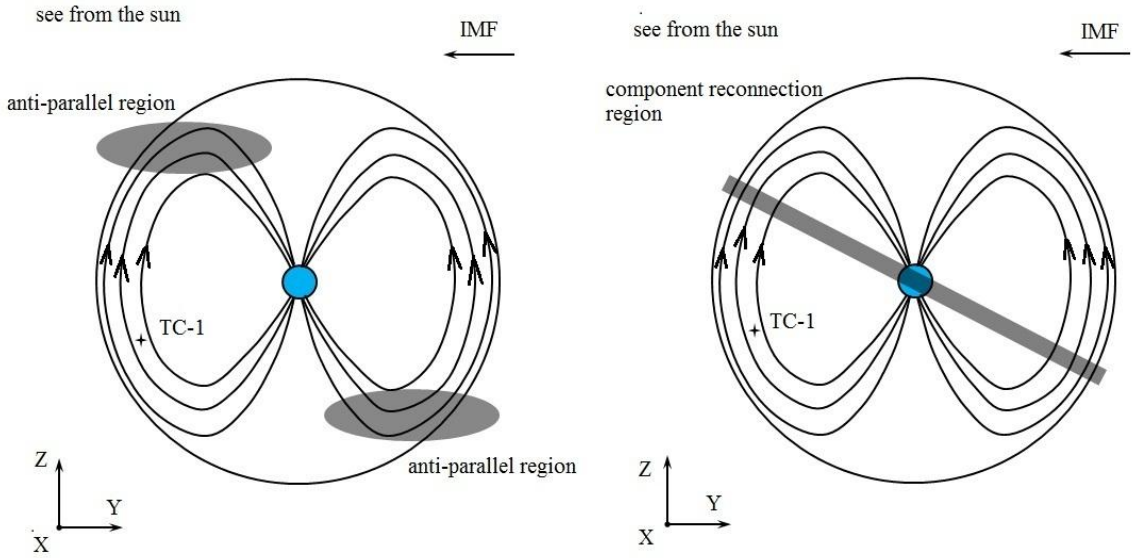

Figure 5. (a) Illustration of the location of the anti-parallel reconnection region under the IMF of $B_z \approx 0$ nT; (b) Illustration of the location of the component reconnection region under the same IMF condition.

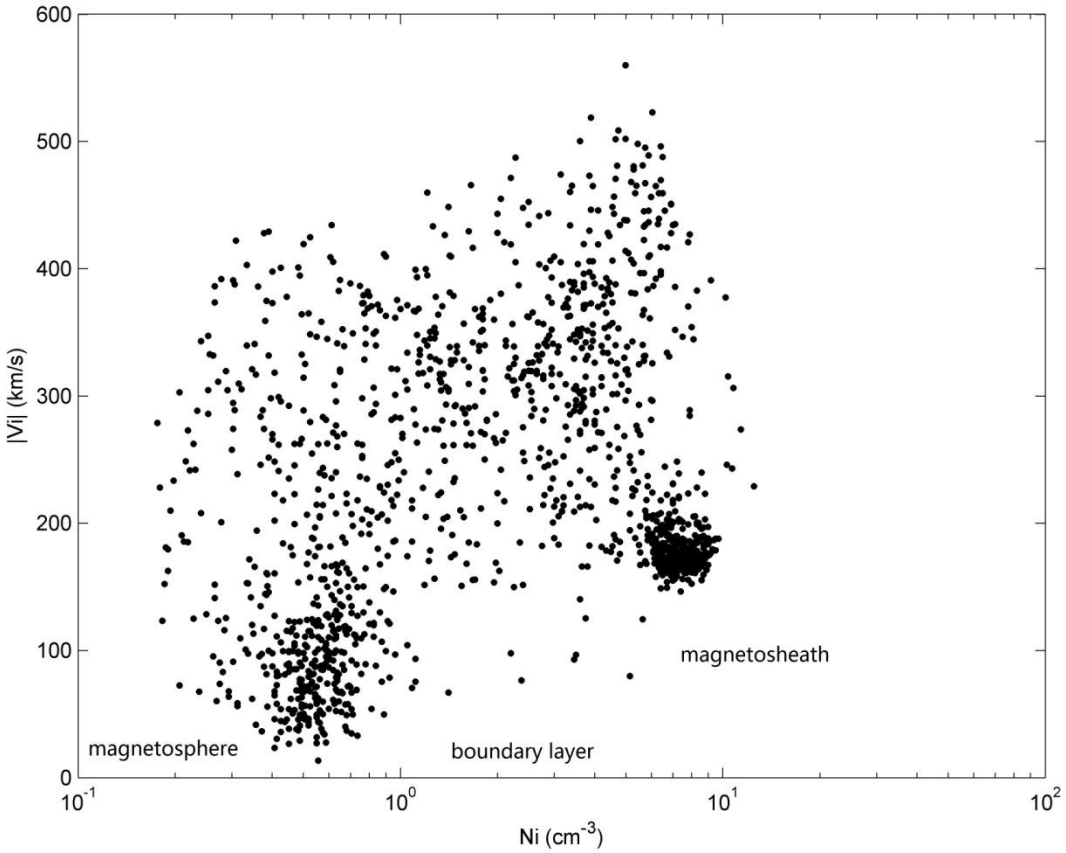

Figure 6 Scatter plot of the ion velocity as a function of ion number density for the interval. The flows in the boundary layer are enhanced relative to the magnetosheath flows at most of the measured points.

Table 1.Walén test results at the magnetopause current sheet crossings. The numbers of the crossings are in the first column. The time intervals of the magnetopause crossings are in the second column. The correlation coefficients between V-V_{HT} and V_A at every crossing are presented in the third column. The slopes of the Walén relationships are in the fourth column, and the fifth column gives the V_{HT}.

NUM	time interval (UT)	cc	slope	V_{HT}
1	18:37:57~18:38:32	-0.85	-0.98	[-268.77, -153.85, -140.30]
2	18:39:30~18:41:50	-0.94	-0.77	[-231.33, -117.93, -120.60]
3	18:45:30~18:46:21	-0.92	-0.96	[-259.05, -76.72, -141.18]
4	18:51:20~18:51:58	-0.89	-0.75	[-261.10, -94.78, -206.55]
5	19:06:21~19:07:43	-0.29	-0.09	test failed
6	19:09:47~19:10:10	-0.96	-0.88	[-258.01, -71.60, -170.98]