Conjunction of anti-parallel and component reconnection at the dayside MP: Cluster and Double Star coordinated observation on 6 April 2004

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[1] Previous theoretical and simulation studies have suggested that the anti-parallel and component reconnection can occur simultaneously on the dayside magnetopause. Certain observations have also been reported to support global conjunct pattern of magnetic reconnection. Here, we show direct evidence for the conjunction of anti-parallel and component MR using coordinated observations of Double Star TC-1 and Cluster under the same IMF condition on 6 April, 2004. The global MR X-line configuration constructed is in good agreement with the "S-shape" model.
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1. Introduction

[2] Introduced first by *Dungey* [1961], magnetic reconnection (MR), which opens the magnetopause (MP) and provides a channel of mass and energy exchange between the magnetosphere (MSP) and the magnetosheath (MSH), has become one of the most fundamental basis of space physical studies [see, e.g., *Paschmann*, 2008].

[3] Taking into account the MSP asymmetry and nonzero IMF B_Y and B_X components that modifies purely southward/northward IMF conditions, two different scenarios were raised to explain the observed patterns of dayside MP reconnections. Based on the reconnection model with no guide field, the "anti-parallel reconnection" model [*Crooker*, 1979] suggested that the dayside MR occurred at the locations where the MSP and MSH magnetic fields were anti-parallel, forming two separate reconnection X-lines in different hemispheres. However, the "component reconnection" model [*Cowley*, 1973] predicted that MR occurred near the subsolar point where the solar wind first encountered the MSP, extending continuously along the guild field direction to form a tilted reconnection X-line on the MP. Both scenarios were proved by observations [see, e.g., *Gosling et al.*, 1990; *Chandler et al.*, 1999; *Fuselier et al.*, 2000; *Onsager et al.*, 2001; *Pu et al.*, 2005].

[4] Component and antiparallel MR scenarios were later found to be related and tend to co-exist in the theoretical studies of *Moore et al.* [2002] and *Dorelli et al.* [2007]. In observation studies, using 3D plasma data from Polar observations, *Trattner et al.* [2007] concluded that the two models could both work at the MP, depending on the specific IMF conditions, and *Pu et al.* [2007] carried out a statistical study of 290 accelerated flows in both low and high latitudes under predominantly dawnward IMF conditions. Examples of both anti-parallel and component MR were revealed in this study under similar IMF clock angles. By characterizing magnetic null points, *Dunlop et al.* [2009] reported a high-latitude anti-parallel MR event accompanied with a low-latitude FTE. Nevertheless, direct case by case evidences are requisite for this issue.

[5] In this paper, we show a direct evidence for co-existence of anti-parallel and component MR with a detailed investigation on 6 April 2004 event when the IMF remained stable for over 2 hours [*Dunlop et al.*, 2005; *Wang et al.*, 2008]. During the event, FTEs observed by TC-1 were very likely generated via component MR and less than an hour later, Cluster passed by a MR region where observations favored the anti-parallel configuration. Features of a global MR X-line on the MP were also obtained.

2. Observations

[6] As shown in Figure 1, both TC-1 and Cluster were located near the dayside MP. Figure 2 gives the IMF condition and magnetic field, plasma observations. As presented by 1-min spacecraft-interspersed data set at the bow shock nose (the High Resolution OMNI data set, See ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/high_res_omni and related documents), the IMF remained southward with strong duskward B_Y from ~03:30 UT for more than 2 hours and the solar wind bulk velocity remained above 500 km/s. As indicated by vertical black lines, TC-1 crossed the MP at 04:13 UT, outbound from MSP to MSH, while Cluster tetrahedron was also traveling outward and encountered the MP at 04:34 UT, and all spacecrafts (SCs) stayed in the MSH until the end of this period.

[7] It is clear that B_N bipolar signatures were observed in the adjacent MSH. Together with the enhanced $|B|$, the reduced ion density and increased temperature, it is easy to characterize that both TC-1 and Cluster encountered several FTEs in the interval, as indicated by dashed lines. The HIA

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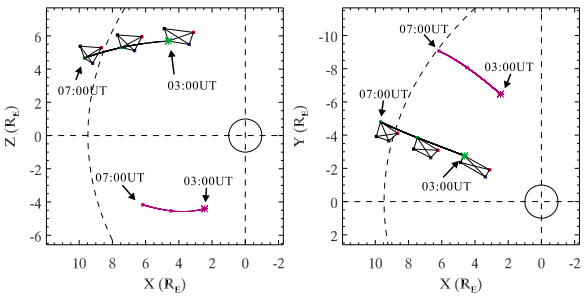

Figure 1. The locations and orbits of Double Star TC-1 and Cluster. The Cluster orbit also shows the SC configurations (scaled up by a factor of 30). The black dashed line indicates the MP, based on Shue model.

energy spectrograms from TC-1 and Cluster C3 also showed possible mixing of MSP and MSH plasmas, in agreements with the FTE crossings. As stated in previous work [*Dunlop et al.*, 2005], these FTEs were very likely generated around the subsolar region via component reconnection.

[8] It is noteworthy to see that the last B_N bipolar observed by Cluster at 05:20 UT, indicated by blue solid line in Figure 2, was quite different from the others. After removing an averaged flow speed, a flow reversal over ±150 km/s in the L direction is revealed, in corresponding to B_N bipolar signature, as indicated by vertical black lines in Figure 3a. Right at the moment of the jet peaks, ion heating was observed. It is very likely that the SC encountered an MR site.

[9] Although the encounter of MP was nearly an hour ago, as indicated in Figure 2, the plasma velocity perpendicular to the MP remained around zero for the whole period, thus we can reasonably conclude that the SC was departing from the MP very slowly and the distance between the SC and the MP was quite limited. Which is more important, the OMNI data show a continuous IMF with no evidence of magnetic shear which may induce reconnection within the MSH magnetic fields. This implies that the only possible site of the magnetic shear, i.e., the source of the MR, is the MP.

3. Detailed Analysis

3.1. FTEs and Low Latitude Component MR

[10] The maximum and minimum variance analysis [*Sonnerup and Scheible*, 1998] and the deHoffmann-Teller analysis [*Khrabrov and Sonnerup*, 1998] were applied to obtain orientations and motions of the two TC-1 FTEs. The results are listed in Table 1, consistent with *Dunlop et al.* [2005]. The axis "clock angle" is defined clockwise from GSM + Z direction to the FTE axis [*Wang et al.*, 2008]. The "core field" is given as the maximum of magnetic field along the FTE axis.

[11] In the previous work of *Dunlop et al.* [2005], the TC-1 FTEs were very likely to be generated around the subsolar region by a tilted X-line. Taking that the SC was located ~9 R_E away from the subsolar point and the velocities of FTEs(122 ~ 171 km/s in the X-Y plane), we could then roughly obtain that the FTEs were produced 5 ~ 8 min before being observed, i.e., at 04:20 ~ 04:30 UT, when the IMF clock angle was ~−140°. The MR location and the IMF condition, together with the observation of strong FTE "core field" (50 ~ 70 nT), lead to the conclusion that the MR was a component one.

3.2. Fast Flows and High Latitude Anti-parallel MR

[12] As presented in Figure 3b, the Walén test was also applied to the period of 05:20 ~ 05:21 UT and yielded reasonably good Walén relations, indicating a pair of oppositely propagating Alfvén waves observed by C1 and C3 simultaneously, and implying an MR occurring nearby.

[13] All the above results confirmed that an MR event occurred near the location of Cluster C3. Although a very clear mixture of MSP and MSH plasma was observed, it is worthy to mention that neither clear Hall effect nor "D-shape" distribution was found, possibly due to the fact that C3 was passing over the reconnection area in the MSH at a distance away from the magnetopause current sheet, rather than a traversal through the major MR region.

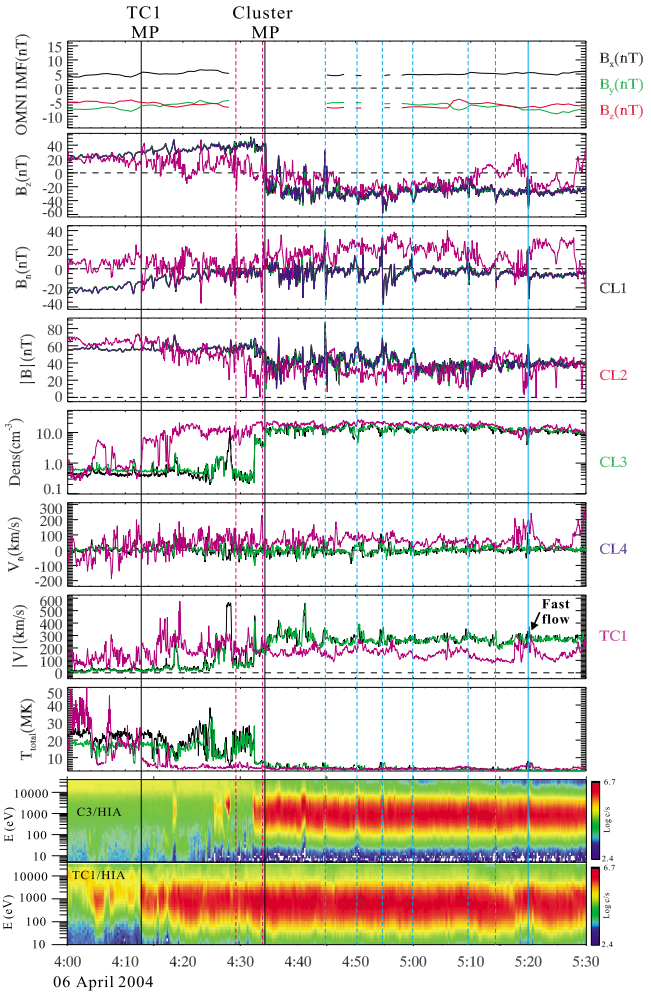

Figure 2. The observations of cluster and TC-1 from 04:00 UT to 05:30 UT, 6 April 2004. From top to bottom, OMNI IMF data, B_Z in GSM, B_N in boundary normal coordinates (BNC), total magnetic field, hot ion density, V_N in BNC, total velocity, temperature, and energy spectra of C3/HIA and TC-1/HIA. The vertical black line indicates the MP crossing of TC-1 and Cluster and the magenta blue dashed line shows the B_N bipolar observed, respectively, by TC-1 and Cluster. The fast flow observed by Cluster at 05:20 UT is also pointed out.

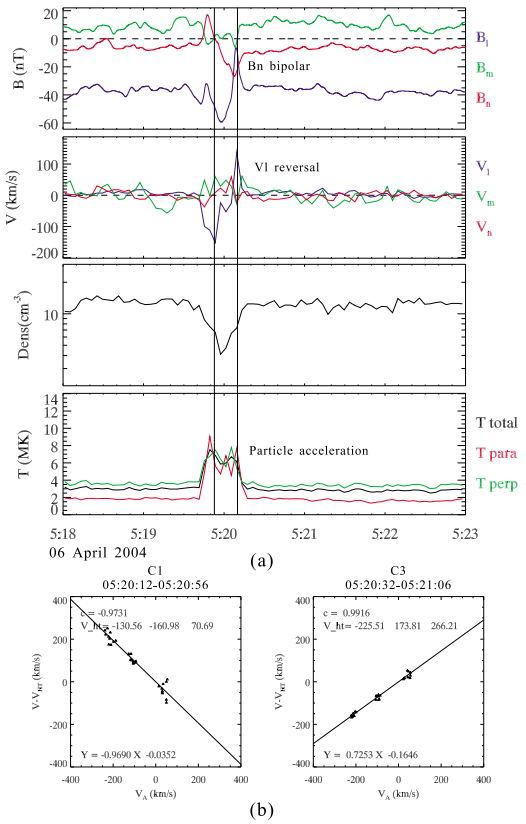

Figure 3. The observations of Cluster/C3 on the MR region on 6 April 2004. (a) From top to bottom, magnetic field, velocity, density and temperature. (b) Walén results during 05:20 ~ 05:21 UT from C1 and C3.

[14] Besides, the peak velocity of outflow jet can be estimated as (47.0, −74.1, −67.5) and (−83.0, 76.6, 93.6) km/s (GSM) and at 05:20 UT and the local MSH field was (10.3, −24.3, −28.8) nT (GSM). Geometry studies show that the angles between the MSH field and the two jets are 12.1° and 160.8°, indicating that these two fast jets were, respectively, almost parallel and anti-parallel to the IMF.

[15] In the component MR scenario, a notable guide field is present in the MR X-line direction, so the magnetic field is not perpendicular to the X-line and thus obviously not parallel to the outflow jets. Based on the observations and calculations above, it is reasonable to infer that the MR event, which Cluster passed by and observed distantly, was essentially anti-parallel.

3.3. Global Pattern of Reconnection

[16] Although the observations on FTEs and the flow reversal were about an hour apart, the IMF varied little during this period of time, with only less than 10° of the IMF clock angle variation. These two MR events can be considered happening under the same IMF condition. This result agrees very well with the simulation of *Berchem et al.* [2008].

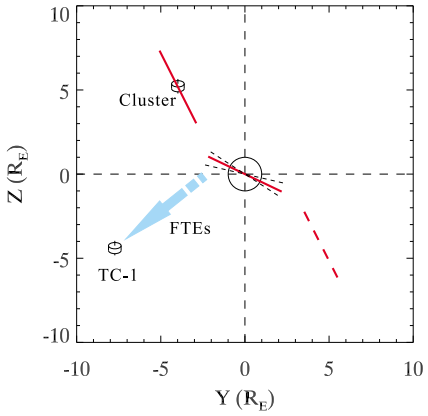

Figure 4. The obtained configuration of dayside MR X-line, in good agreement with predicted "S-shape" model. The red solid lines gives the X-lines in low latitude and northern high latitude, and the red dashed line the mirror in southern high latitude. The two dashed black lines present the FTE axes.

[17] We have also constructed the global configuration of the dayside MR X-line under this IMF orientation, as shown in Figure 4. Based on the FTE generation theories [*Lee and Fu*, 1985; *Scholer*, 1988; *Wang et al.*, 2008], the FTE axis should be along the X-line at the location of generation. Following *Dunlop et al.* [2005], the FTEs observed by TC-1 are not far away from the generation site, thus we average the "clock angle" of the two FTE axes and regarded it as the X-line orientation at low latitudes (with standard deviation of ~17°). At the northern high latitudes, the X-line should elongate along the MP and perpendicular to the reconnection plane. Therefore, by solving the over-determined equation set $\mathbf{n} \cdot \mathbf{A} = 0$ ($\mathbf{A}$ presenting the local MSH magnetic field, the two jets and the MP normal direction, respectively), we obtain the most perpendicular direction $\mathbf{n}$ as the high latitude X-line orientation. With the absence of related measurements on the southern high latitude MR, we mirror the northern hemisphere X-line to the south, indicated as the dashed line. The final result of the X-line configuration is quite similar to the prediction of *Moore et al.* [2002] given by maximizing the reconnecting component.

[18] It is worth mentioning that the equivalence between the FTE and the X-line orientation is based on 2D FTE generation theories/models. 3D flux ropes can easily have local orientations which differ greatly from the X-line orientation prior to FTE formation. This gives a potential source of error of the low-latitude X-line orientation. A similar problem exists in determining the high-latitude northern X-line. In 3D situations, the X-line may bend while elongating and therefore would be no longer perpendicular to the observed fast jets. It should also be noticed

Table 1. The Velocity, Axes and Maximum Core Field of the FTEs Observed by TC-1, All in GSM

Time (UT)	Velocity (km/s)	Axis	Axis "Clock Angle"	Core Field (nT)
04:29	−189, −81, −91	0.421, 0.883, −0.206	103	67
04:34	−216, −141, −97	0.631, 0.605, −0.485	128	48

that the IMF had a notable B_X component which would violate the south/north symmetry. Our result in the southern hemisphere should only be treated as a reference instead of representing the actual situation.

4. Conclusion

[19] In this study, a conjunction of Double Star TC-1 and Cluster on the dayside MP is analyzed. The five SCs traversed the MP within 20 min and encountered a series of FTEs and fast flows. Detailed studies show results as follows:

[20] 1. FTEs were observed by TC-1 at the southern hemisphere, not far away from the equator plane. The presence of a strong core field indicated that these FTEs were very likely related to component MR happening near the subsolar region.

[21] 2. A fast flow reversal and corresponding B_N bipolar signature were detected by Cluster. Detailed analysis showed that Cluster passed nearby an anti-parallel MR region.

[22] 3. Due to the long duration of stable IMF condition, these two MR events can be considered as simultaneously happening but at different locations, and therefore a direct evidence of simultaneous occurrence of component and anti-parallel reconnections, agreeing well with previous theoretical and simulation works.

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