CLUSTER AND TC1 FIVE POINT OBSERVATIONS OF AN FTE ON JAN. 4, 2005: A PRELIMINARY STUDY

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ABSTRACT

Observations of an FTE signature at the dayside magnetopause are reported, which is consecutively observed on Jan.4, 2005 by each of five spacecraft comprising the Double Star TC1 spacecraft and the Cluster quartet, while the spacecraft were traversing through the northern-dusk magnetopause. The GSE locations of Cluster and TC1 were ~ (3.91, 12.03, 5.01) R_E and (4.33, 12.50, 1.93) R_E (GSE), respectively. The event occurred as a magnetosheath FTE at the first Cluster spacecraft at about 07:13 UT on 04 01 2004 and crossed each of the others within 2 minutes. The spatial separations between the Cluster spacecraft were of the order of 200 km and the relative TC1 location was at $\Delta X \sim 0.42R_E$, $\Delta Y \sim 0.47R_E$, and $\Delta Z \sim 3.08R_E$. The TC1 signature occurred about 110s after Cluster. deHoffmann- Teller (H-T) analysis of the signatures implies that the associated flux ropes observed by Cluster and TC1 were moving with similar velocities eastward and northward, consistent with the polarity for the observed FTEs and the spacecraft locations. The orientation of the flux rope can also be computed and is found to be similar at each spacecraft. Reconstruction of the flux rope signature suggests that they contained approximately equal amounts of magnetic flux. The 3-D distributions of thermal ions in the two FTEs were also similar. The distance of TC1 perpendicular to the plane containing the axis of flux rope observed by Cluster and its H-T velocity is much smaller than the cross-section dimension of the flux ropes observed by both Cluster and TC1. These findings strongly suggest that Cluster and TC1 encountered the magnetosheath branch of the same flux tube at two different positions along its length and this is borne out by computation of the expected time delay between the spacecraft based on the estimated orientation of the tube. Four-spacecraft timing is used to confirm the H-T velocity calculation. Several approaches are used to estimate the axis orientation of the flux rope, so that the large-scale configuration of the flux rope is well postulated based on the five-point measurements.

1. INTRODUCTION

Intermittent magnetic reconnection at the Earth's magnetopause (MP) can result in localized bundles of open flux ropes which are thought to carry distinct magnetic field signatures when passing by adjacent to a spacecraft, known as flux transfer events (FTEs) (Russell and Elphic, 1978; Haerendel et al., 1978). These FTE signatures are characterized by bipolar perturbations in the magnetic field B_N component where N denotes the direction normal to the local MP boundary (a representative coordinate system can be constructed for these coordinates, LMN, [Russell and Elphic 1978]). The events are called the magnetosheath (magnetospheric) FTEs when the bipolar B_N signature occurs on the magnetosheath (magnetospheric) side of the MP. Newly opened flux tubes in FTEs provide channels for the solar wind plasma to access to the magnetosphere and for the magnetospheric particles to escape to the interplanetary space (Owen and Cowley, 1991; Owen et al., 2005; Pu et al., 2005).

There have been many papers on observed features of FTEs (see, for example, the review by Elphic (1995)), but there exist only a limited number of papers on the motion and configuration of FTEs (Cowley and Owen,

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2001, Cooling et al., 2001; Kawano and Russell, 2005). Kawano and Russell (2005) statistically analyzed the dual-satellite simultaneous observations of FTEs by ISEE 1 and ISEE. They found that longitudinally tailward motions of FTEs are significant. This finding is consistent with a longitudinally limited spatial size of the FTE structure, rather than a longitudinally elongated structure.

Detection of motions of FTEs is difficult with one satellite. Two-point observation does not completely resolve the problem. It is just recently that coordinate measurements of Cluster and Double Star make it possible to measure the motion of FTEs and flux rope configuration at large-scales (Liu et al., 2005). Dunlop et al. (2005) investigated a Cluster-TC1 conjunction event on April 6, 2004 in which Cluster and TC1 observed a series of direct FTEs at the dawnside northern magnetopause and reversed FTEs at the duskside southern magnetopause, respectively. They showed that the flux ropes observed by Cluster were moving eastward and northward, and the flux ropes observed by TC1 were moving westward and southward. This result is in agreement with the fact that these flux ropes were formed in the dayside equatorial MP in pair and propagated perpendicular to the X-line oppositely away from the source region. Xiao et al. (2005) compared the TC1 multiple FTEs on March 18, 2004 at the duskside southern MP and the Cluster multiple FTEs on January 26, 2001 at the dawnside northern MP. These two events occurred in almost the same IMF and solar wind conditions; the motions of flux rope posses the same features as in Dunlop et al.'s event (2005).

This paper presents a close conjunction FTE of Cluster and Double Star TC1 observed on 04 January 2005, using spin averaged (4s resolution) magnetic field data from FGM (Balogh et al., 2001; Carr et al., 2005), low energy ion data from the Hot Ion Analyzer (HIA) (Reme et al., 2001; Reme et al., 2005), low energy electron data from the Plasma Electron and Current Experiment (PEACE) (Fazakerley et al., 2005) and energetic particle data from particle spectrometer RAPID (Wilken et al., 2001). We show that Cluster and TC1 encountered the same flux tube consecutively at two different positions along its length. The flux rope was found to move mainly eastward. The axis of its magnetosheath branch was essentially orientated northward and eastward.

2. OBSERVATIONS

We briefly study a FTE observed by five spacecraft comprising the Double Star TC1 and Cluster quartet. At about 06:30 UT on Jan.4, 2005 Cluster and TC1 were traversing through the northern-dawn MP, initially remaining near the boundary and then remaining in the magnetosheath after ~07:08 UT. Fig. 1a plots the trajectories of Cluster and TC1. Fig. 1b schematically shows the relative positions of Cluster and TC1 during

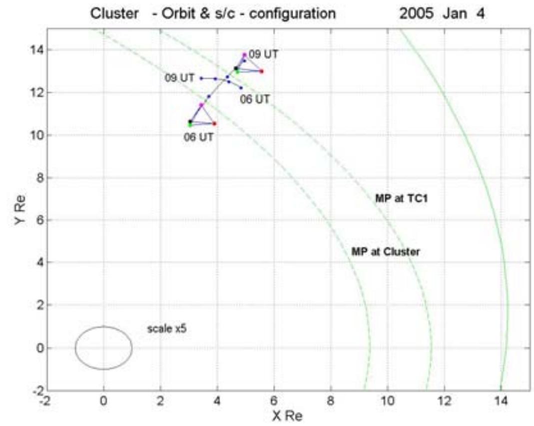

Fig.1a. *The trajectories of Cluster tetrahedron and TC1 from 06:00 to 09:00 UT on 4 Jan. 2005.*

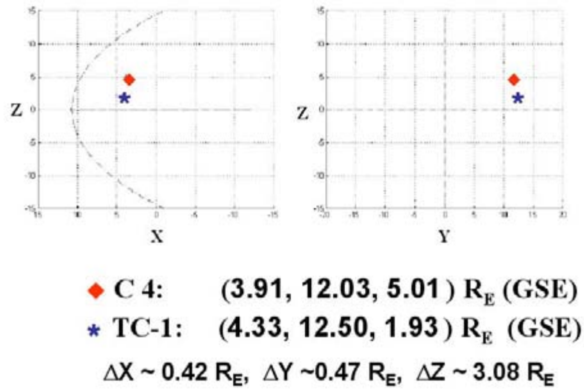

Fig. 1b*. The schematic show of the relative positions of Cluster and TC1 in GSE during the event*

the event. The GSE locations of Cluster 4 (SC4) and TC1 were ~ (3.91, 12.03, 5.01) R_E and(4.33, 12.50, 1.93) R_E, respectively. The separations between the SC4 and TC1 in GSE were $\Delta X \sim 0.42 R_E$, $\Delta Y \sim 0.47 R_E$, and $\Delta Z \sim 3.08 R_E$, somewhat greater than the largest separation between four Cluster spacecraft ($\Delta X23 \sim 0.17 R_E$, $\Delta Y43 \sim 0.17 R_E$, $\Delta Z13 \sim 0.21 R_E$). From ~06:30 to ~07:00 UT, the near-Earth interplanetary magnetic field (IMF) remained northward and both Cluster and TC1 stayed in the magnetosheath boundary layer. At ~ 07:00 the IMF B_z suddenly became negative. Shortly after this, at ~07:08, both Cluster and TC1 made a brief entry into the magnetosphere, and then back into the magnetosheath (see Fig. 2). The Walen test analysis (Khraborv and Sonnerup, 1998) indicates that the MP at this time was an open boundary (not shown in the paper). Fig.3 shows the energetic electron measurements from RAPID on board four Cluster spacecraft. It is seen that just prior to the MP crossing, RAPID saw field-aligned bi-directional energetic electrons in the outer magnetospheric boundary layer. Fig. 4a and 4b display ten min (from 07:10 to 07:20 UT) FGM and CIS measurements of Cluster 3 and TC1,

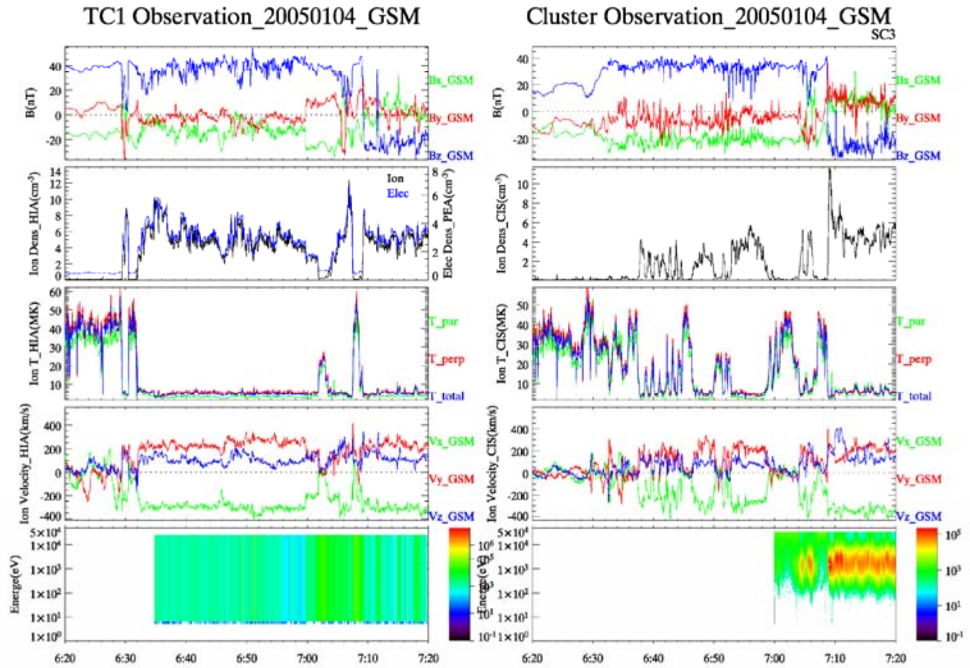

***Fig. 2.** The overview plot of magnetopause crossing for TC1 (left) and Cluster/SC3 (right)*

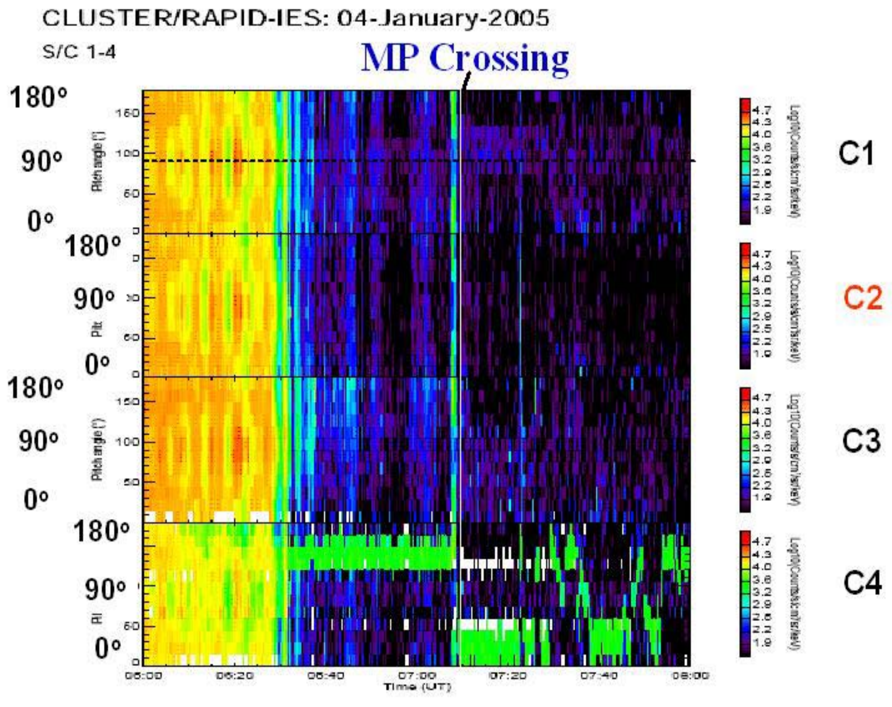

Fig. 3. Cluster/RAPID measurements of field-aligned bi-directional energetic electrons in the outer magnetospheric boundary layer just prior to the magnetopause crossing

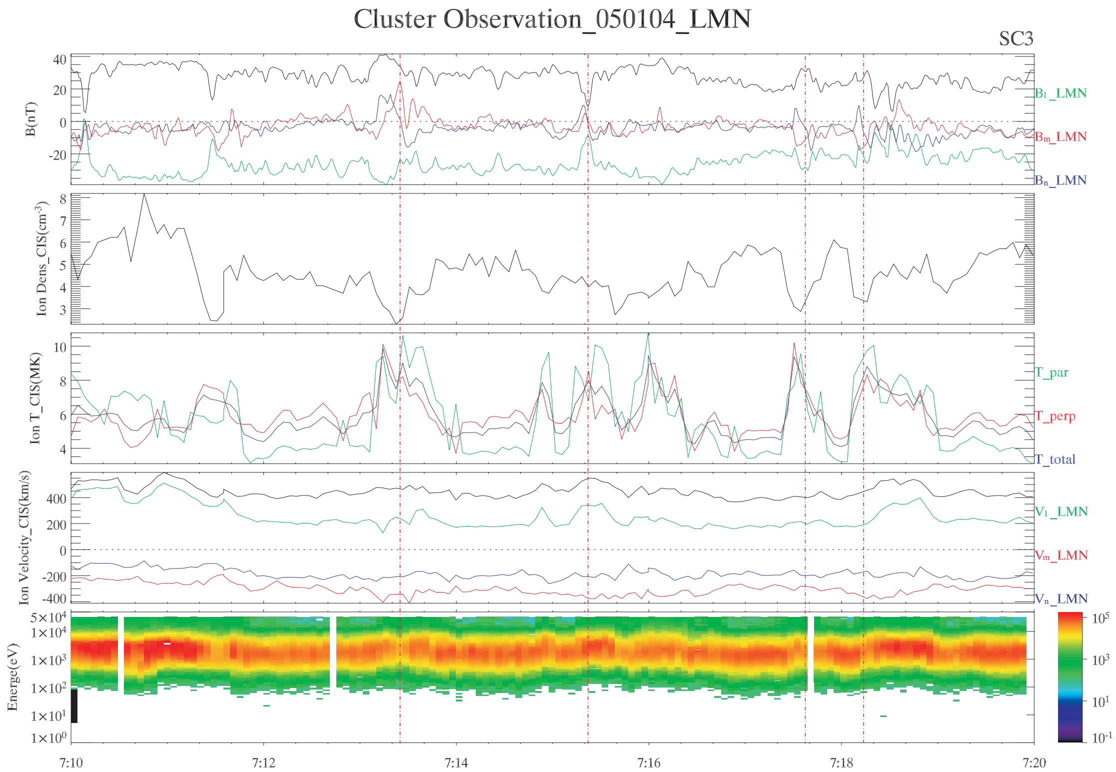

Fig.4a. *Cluster 3 FTEs observation on 04 January 2005.*

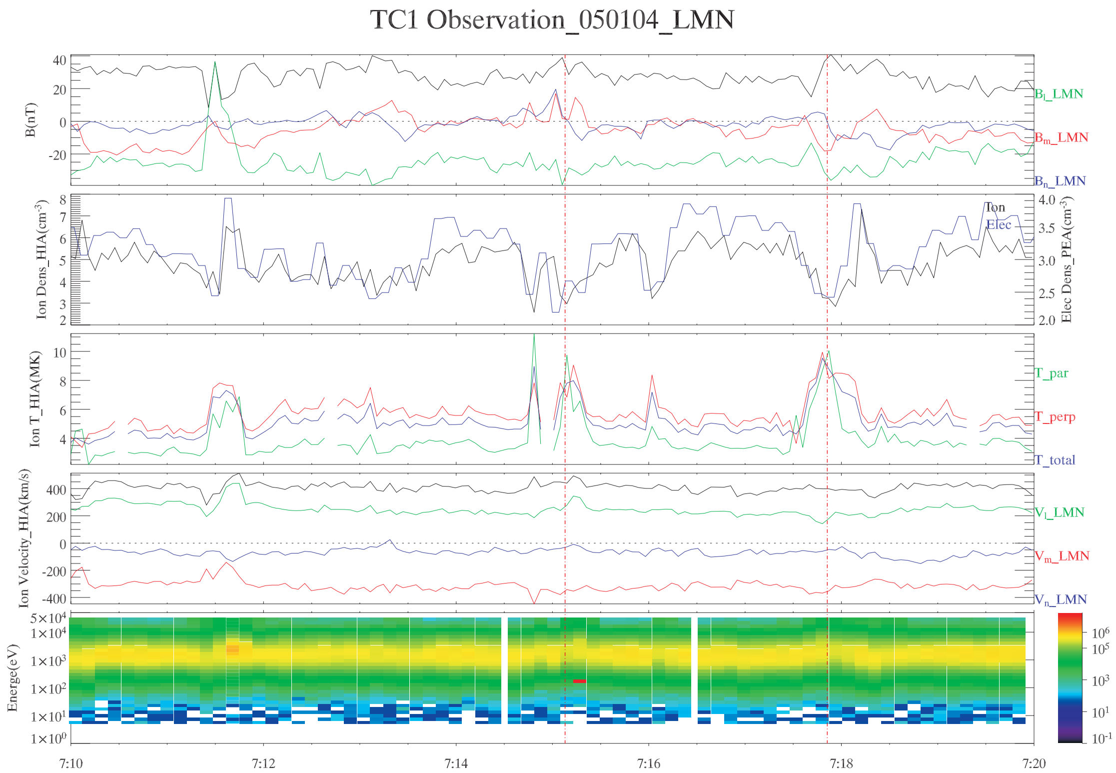

Fig.4b. *TC1 FTEs observation on 04 January 2005.*

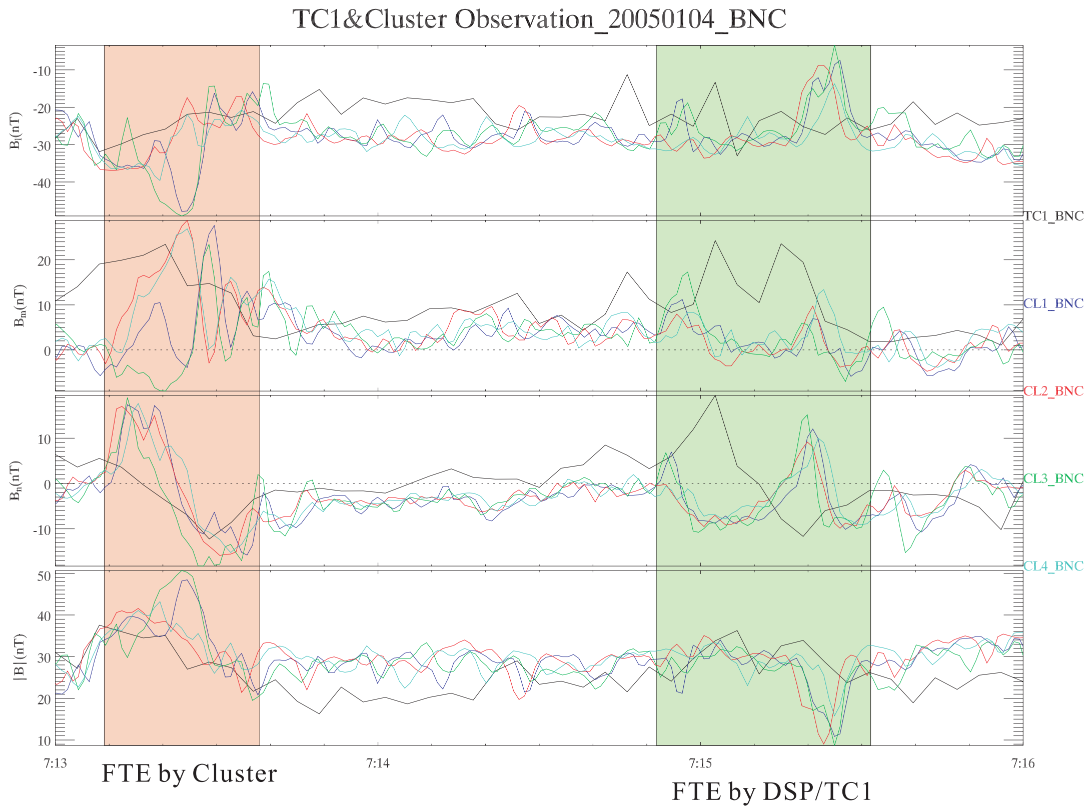

***Fig.5**. consecutive observations of FTEs by Cluster and TC1 within two minutes*

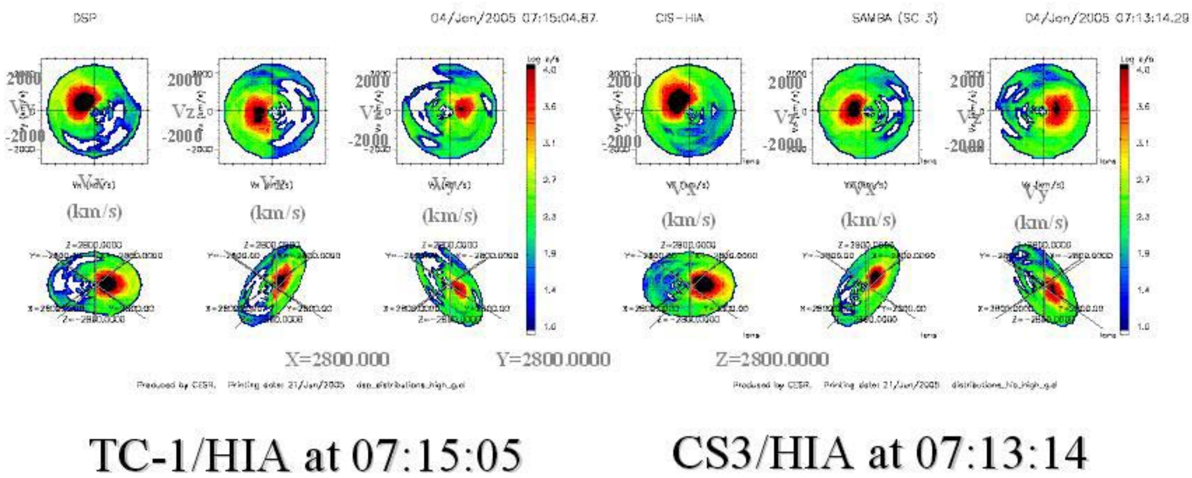

Fig.6. Three-dimensional distributions of thermal ions: left--TC1, right--Cluster/SC3

respectively. The magnetic field data are plotted in the LMN system. The electron density from PEACE on board TC1 is also plotted in the 2nd panel of Fig. 4b for comparison. During this ten minutes Cluster encountered a few FTEs and TC1 met a couple of FTEs as well. Fig. 5 presents detailed observations of an FTE by Cluster at 07:13:10 and an FTE by TC1 about 110s later. In this paper we focus our attention on these two FTEs. We will show that these two FTEs manifest a flux rope successively encountered by Cluster and TC1 at different locations.

It is seen in Fig. 4 that in both the Cluster and TC1 FTEs the hot ion density and temperature were, respectively, lower and higher compared with the surrounding plasmas, indicating that they were both magnetosheath events. In addition, PEACE measurements (not shown here) show that inside the Cluster and TC1 FTE flux ropes, energetic electron fluxes of magnetospheric origin were enhanced for both locations. Fig. 6 plots 3-dimensional distributions of thermal ions detected by SC3 at 07:13:15 and by TC1 at 07:15:05. It can be seen that these two distributions are extremely similar. Table 1 lists the calculated H-T velocities for SC1, SC3, SC4 and TC1 in GSE. All H-T velocities for four satellites are quite similar and are consistent with the calculation of the motion from Cluster timing information (see later). Fig. 6 clearly shows that the flow of the background plasma was tailward and duskward, which is certainly in agreement with Table 1, reflecting the fact that the satellites had traversed outbound across the MP in the dusk sector. By a carefully examining of Fig. 6 one also finds that TC1 saw somewhat fewer ions moving tailward than SC3 did. This is also in accordance with the calculations of the H-T velocities in Table 1, which show that the magnitude of $V_{HT,x}$ for TC1 was less than that of SC3. Fig. 7 shows the results of flux rope reconstruction based on solving the Grad-Shafranov (G-S) equation (Hu and Sonnerup, 2002) and using FGM and CIS data. Table 2 presents the magnetic fluxes contained in the ropes of SC1 and TC1 versus different magnitude of magnetic vector potential A.

***Table 1**. H-T Velocity (km/s)*

Space Craft	V_{HT}
TC-1	-313.86, 269.94, 137.88
Cluster/SC1	-379.22, 270.50, 82.49
Cluster/SC1	-370.44, 274.22, 54.82
Cluster/SC1	-316.47, 237.22, 67.54

***Table 2**. Magnetic flux(E+006) contained in the flux rope*

Spacecraft\A	-0.05	-0.06	-0.07	-0.08
TC-1	15.41	11.56	8.916	6.196
Cluster/SC1	12.76	10.71	8.869	6.244

Apparently, these two flux ropes contain approximately equal amount of flux. All these results strongly suggest that Cluster and TC1 possibly encountered the same flux rope successively at its two different positions.

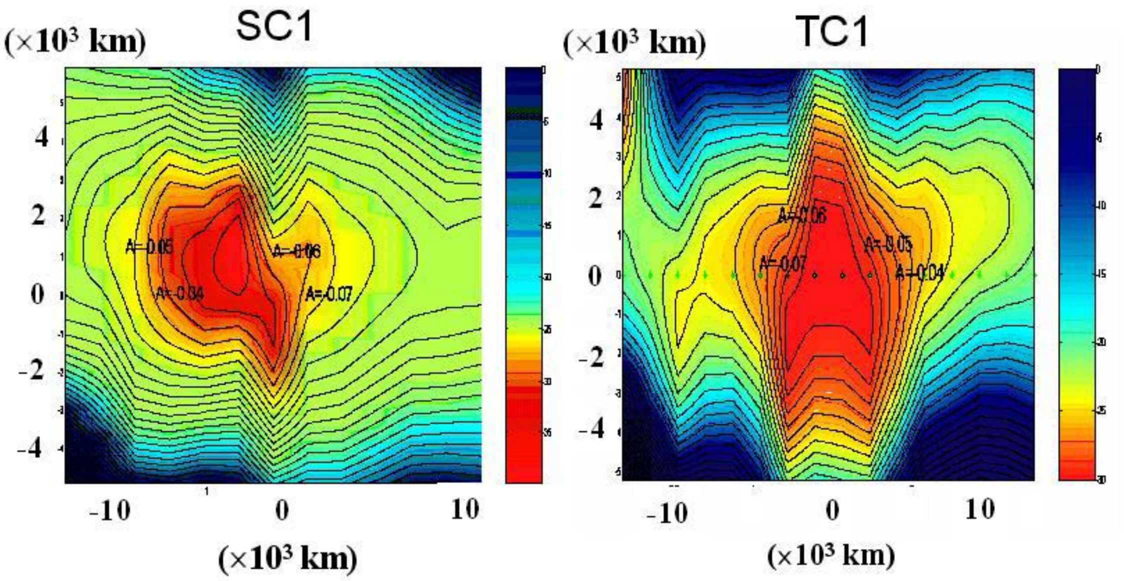

***Fig.7**. Reconstruction of flux rope cross-section: left--Cluster/SC1, right--TC1.*

3. DISCUSSION

First, we have used several approaches to estimate the axis orientation of the flux ropes: The minimum variance analysis based on the magnetic field measurement of single spacecraft (BMVA(a)) (Sonnerup and Scheible, 1998), the minimum variance analysis by using the magnetic field data of four Cluster spacecraft (BMVA(b)) and reconstruction of the cross-section of the flux rope by using G-S reconstruction technique (Hu and Sonnerup, 2002) with FGM and CIS data. The inferred flux rope orientations are listed in Table 3.

***Table 3.** Orientation of Flux Rope*

Methods	TC1	Cluster
BMVA(a)	-0.441, 0.071, 0.895	-0.506, 0.497, 0.705
BMVA(b)	----	-0.241, 0.428, 0.871
GS	-0.404, 0.219, 0.888	-0.545, 0.171, 0.821
Angel From IMF	73	50

Only the result of SC1 for BMAV(a) is presented. Although the details of the derived orientations are somehow different, the main component of the rope axis is clearly in the Z-direction and –X direction. The orientation at the Cluster position is relatively closer to the ambient IMF than at the TC1. This may be explained by the fact that the Cluster position along the flux tube was higher (in the Z-direction) than TC1, hence the Cluster spacecraft was somewhat father away from the MP surface than TC1.

Secondly, by a simple algebraic derivation one obtains $V_{CN} \approx 347.8$ km/s for SC1 and $V_{TN} \approx 308.8$ km/s for TC1. Thus by taking into account the time intervals of FTE encounters, we can get the approximate cross-section scales of flux ropes. The results are presented in Table 4. It is seen that the scale size of the cross-sections for three Cluster spacecraft are equal, while that of TC1 is a little larger than those of the other three.

Table 4. *Scale Sizes of Flux Rope Cross-Section*

TC1	CL/SC1	CL/SC3	CL/SC4
1.94 RE	1.64 RE	1.69 RE	1.40 RE

Thirdly, to verify that Cluster and TC1 encountered with the same flux rope successively at two different positions, we make the following calculations. (1) The G-S reconstruction gives that at 07:13:15 the centre of the flux rope cross-section of SC1 was located at (3.96, 12.03, 4.96) R_E (GSE) and that at 07:15:05 the center of the flux rope cross-section of TC1 was located at (4.29, 12.51, 1.92)R_E (GSE). (2) The flux rope orientation of SC1 (given by GS technique) is ≈ (-0.545, 0.171, 0.821) and $\vec{V}_{HT}$ of SC1 flux rope = (-379.22, 270.50, 82.49) km/s, we obtain that the perpendicular distance from TC1 to the plane containing the axis of SC1 flux rope and $\vec{V}_{HT}$ of SC1 flux rope can be easily derived as d ≈999.8 km = 0.16 R_E. Considering the fact that the scale sizes of both TC1 and Cluster spacecraft are significantly larger than d and that the orientations of the two flux ropes were somewhat close to each other, it is reasonable to expect that Cluster and TC1 in fact successively encountered with the same flux rope at two different positions.

Based on this argument, we have used the Cluster and Double Star five-point measurements to investigate the flux rope motion and configuration. The Cluster four-spacecraft timing can readily determine the direction of FTE motion. The sequence that the Cluster spacecraft encountered the flux rope at the leading edge is: SC2, SC3, SC1 and SC4 (see Figure 5). Figure 8 shows the projection of the Cluster tetrahedron in the GSE (X, Y) plane. As the figure indicates the FTE motion contained significant $-V_x$ and $+V_y$ component, which is apparently consistent with the derivation of H-T velocity in Table 1 and the statistical result of Kawano and Russell (2005).

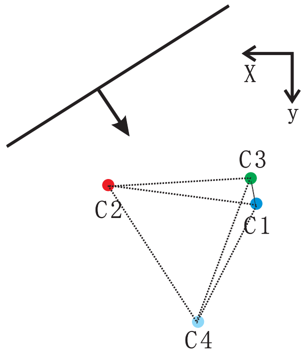

Fig.8. *A schematic diagram showing the direction of FTE motion based on four-spacecraft timing.*

Furthermore, we have made a backward time shift of 110s for the location of TC1 Flux rope with the averaged H-T velocity of TC1 and SC1. The centre of the flux rope was found to be located at (9.88, 7.84, 0.02) R_E (GSE) at the time when SC1 encountered the same flux rope at higher latitude at (3.96, 12.03, 4.96) R_E (GSE). Comparing these two positions along the single flux rope, one can see clearly that its axis was oriented eastward and northward. The five-point measurement thus confirms qualitatively the axis inference results in Table 3. We have further done an extrapolation to draw the large-scale configuration of the flux rope. Fig. 9 shows a dawn side view of the postulated large-scale structure of the open flux tube. In Fig. 9 the T-96 model (Tsyganenko, 1996) was used in drawing the MP surface. The rope axis of the magnetosheath branch is assumed to be asymptotically parallel to the IMF.

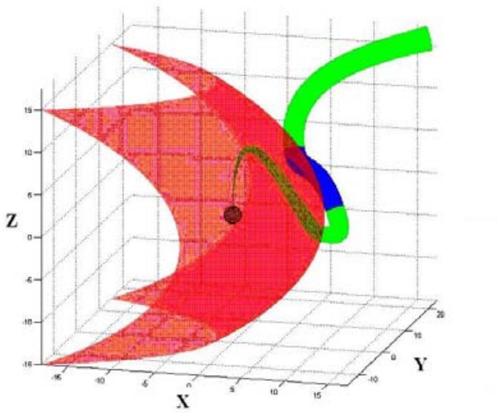

Fig.9. *A downward view of the postulated large-scale structure of the open flux tube. The T-96 magnetic field model and a backward time shift of 110s using TC1 H-T velocity were made in drawing the plot.*

It is worthy to emphasize that all results obtained in the paper are consistent with implications of the relative timing of the observations across the four Cluster spacecraft by using high-time resolution FGM measurements. The motion and polarity of the FTE signatures are in accordance with the predictions found by application of the Cowley-Owen-Cooling model (Cooling et al., 2001). The detailed study regarding the motion and evolution of the flux rope will be presented in a coming paper.

4. SUMMARY

Observations of an FTE signature at the dayside magnetopause are reported, which is consecutively observed on Jan.4, 2005 by each of five spacecraft comprising the Double Star TC1 spacecraft and the Cluster quartet, while the spacecraft were traversing through the northern-dusk magnetopause. Two magnetosheath FTEs seen by Cluster and TC1 within two minutes are shown to manifest a single flux rope moving eastward and northward. Several features of the flux rope (the axis orientation, scale of the cross-section, H-T velocity, 3-D distribution of thermal ions, etc) have been investigated. The FTE motion direction and large-scale configuration of the flux rope are preliminarily studied with the five point measurements.

The Jan.4, 2005 event manifests a close conjunction FTE of Cluster and TC1. The preliminary study undoubtedly shows that the coordinated measurements of Double Star and Cluster have given the possibility to study flux tube evolution along the magnetopause with five-point measurements: first giving a quantitative estimate of the orientation, motion and characteristics of the open flux rope at Cluster and second relating this measurement to an adjacent location along the tube at TC1. We can see the structures of FTEs at small scales within the Cluster tetrahedron, as well as the large-scale evolution with Cluster and Double Star. More work concerning this conjunction event is underway to expand on the context and controlling parameters of the event.

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