COMPARATIVE CLUSTER/DOUBLE STAR OBSERVATIONS OF THE HIGH AND LOW LATITUDE DAYSIDE MAGNETOPAUSE.

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ABSTRACT

The launch of the Double Star mission has provided the opportunity to monitor events at distinct locations on the dayside magnetopause, in coordination with the quartet of Cluster spacecraft. We present results of two such coordinated studies. In the first, 6 April 2004, both Cluster and the Double Star TC-1 spacecraft were on outbound transits through the dawn-side magnetosphere. Cluster observed northward moving FTEs with +/- polarity, whereas TC-1 saw -/+ polarity FTEs. The strength, motion and occurrence of the FTE signatures changes somewhat according to changes in IMF clock angle. These observations are consistent with ongoing reconnection on the dayside magnetopause, resulting in a series of flux transfer events (FTEs) seen both at Cluster and TC-1. The observed polarity and motion of each FTE signature advocates the existence of an active reconnection region consistently located between the positions of Cluster and TC-1, lying north and south of the reconnection line, respectively. This scenario is supported by the application of a model, designed to track flux tube motion, to conditions appropriate for the prevailing interplanetary conditions. The results from the model confirm the observational evidence that the low-latitude FTE dynamics is sensitive to changes in convected upstream conditions. In particular, changing the interplanetary magnetic field (IMF) clock angle in the model predicts that TC-1 should miss the resulting FTEs more often than Cluster, as is observed. For the second conjunction, on the 4 Jan 2005, the Cluster and TC-1 spacecraft all exited the dusk-side magnetosphere almost simultaneously, with TC-1 lying almost equatorial and Cluster at northern latitudes at about 4 R_E from TC-1. The spacecraft traverse the magnetopause during a strong reversal in the IMF from northward to southward and a number of magnetosheath FTE signatures are subsequently observed. One coordinated FTE, studied in detail by *Pu et al*, [*this issue*], carries and inflowing energetic electron population and shows a motion and orientation which is similar at all spacecraft and consistent with the predictions of the model for the flux tube dynamics, given a near sub-solar reconnection line. This event can be interpreted either as the passage of two parallel flux tubes arising from adjacent x-line positions, or as a crossing of a single flux tube at different positions.

1. INTRODUCTION

The Earth's magnetopause, and its associated boundary layers which contain modified plasma distributions and a system of electromagnetic fields and currents, are known to depend upon conditions in the local, upstream, adjacent magnetosheath, and on magnetospheric location. These upstream conditions also have a global context, linked by the local magnetic field to the interplanetary magnetic field (IMF) orientation, and therefore affect the process of magnetic reconnection of the Earth's dayside magnetic field with the adjacent magnetosheath magnetic field; a process which readily facilitates the transfer of momentum and energy from the solar wind into the Earth's magnetosphere. This process of plasma penetration through the magnetopause, via reconnection, was first discussed by [1], assuming a purely southward-directed IMF field which presents the optimal conditions for reconnection in the subsolar region. Different IMF orientation and solar wind conditions give rise to varying rates of reconnection [2] as well as variations in the location of the reconnection site (e.g. [3],[4],[5]). The morphology and dynamics of this momentum and energy transfer is still a very active area of space plasma research, in particular the nature of flux transfer events (FTEs) [6]. FTEs are considered to be the signatures of transient or bursty (sporadic) reconnection, with newly reconnected flux at the subsolar region convecting tailward in the form of a tube-like structure threading the magnetopause [6],[7],[8],[9],[10]. FTEs were originally characterised according to their bipolar oscillation in the magnetic field component normal to the magnetopause and have also been attributed to the effect of solar wind pressure pulses, inducing large-amplitude magnetopause waves (e.g. [11]).

It is therefore expected that the study of occurrence, orientation and motion of FTE signatures, and the evolution of

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their field and plasma signatures can shed light on the debate on dayside magnetic merging. An aspect of this debate centres on the issue of whether anti-parallel or component merging dominates the reconnection process. Rather than attempt to address this question directly we limit this study to the demonstration of plausible reconnection scenarios for some key events by comparison to known, characteristic reconnection signatures. For example, the polarity of the magnetic field signature of an FTE can be used as an indication of which hemisphere the flux tube is connected to (e.g. [8],[11]), at least sufficiently near the subsolar region, where the magnetosheath flow is sub-Alfvenic. It is also expected that FTEs will have corresponding signatures in the high-altitude cusp region, as an extension of the low latitude boundary layer (LLBL), and on the flanks, although the characteristic signatures could differ from dayside exterior boundary layer observations ([12]). In fact, recent high-latitude, *in situ* measurements [13],[12],[14] by the four spacecraft of the European Space Agency's Cluster mission [15] have provided extremely detailed and revealing multi-point measurements of the high-latitude magnetopause. Nevertheless, because of the often sporadic nature of the interaction of the solar wind with the magnetosphere, simultaneous coverage over a wide range of different magnetopause sites, previously only available through fortuitous spacecraft conjunctions (e.g. [16]), provides key information not available with single point measurements. The recent launch of the Double Star TC-1 spacecraft into an equatorial orbit provides a unique opportunity to investigate the dayside magnetopause region at northern (Cluster) and southern (TC-1) latitudes simultaneously across the whole dayside region.

The combined data set has therefore achieved conjunctions at widely spaced magnetopause locations and can contribute to a number of the open questions relating to the debate on the process of magnetic reconnection, such as: the location and number of merging sites; the extent of the X-line, and the link to ionospheric and ground-based observations. In this paper we present results of the analysis of two Double Star/Cluster conjunctions on 6 April 2004 and 4 January 2005 (see also Pu et al., *this issue*), to investigate the evolution of FTEs across the dayside magnetopause. We put our results in context by comparing them to a model of flux tube motion across the magnetopause [17] to ascertain limits on the size and location of the expected reconnection site.

2. INSTRUMENTAL ARRANGEMENT

The Cluster spacecraft were launched in pairs in July and August 2000 into a polar orbit, with an orbital period of 57 hours and with a perigee and apogee of 4 and 19.6 Earth radii (R_E), respectively. Since the orbital plane of Cluster is fixed in the inertial frame of the Earth, apogee precesses through 24 hours of Local Time (LT) with a 12-month periodicity. In April 2004, apogee was in the pre-noon sector, near 10 LT. In this paper we compare observations from Cluster with those from the first of the pair of Double Star spacecraft, TC-1[18]. The TC-1 spacecraft was launched in December 2003 into an equatorial orbit at 28.2° inclination, with an orbital period of 27.4 hours, a perigee altitude of 570 km and an apogee of 13.4 R_E.

We concentrate, in this preliminary study, mainly on data from the magnetic field and thermal plasma instruments on Cluster and TC-1. This is facilitated by common instrumentation on the two missions. The four Cluster spacecraft and in fact both Double Star satellites carry FluxGate Magnetometers (FGM). Each FGM instrument comprises a pair of fluxgate magnetic field sensors mounted on an axial boom, although Double Star uses a sensor design different to that used on Cluster (for descriptions of each, see [19] and [20]. The PEACE - Plasma Electron And Current Experiment - instrument on Cluster, as discussed by [21], comprises two separate electron sensors, LEEA (Low-Energy Electron Analyzer) and HEEA (High-Energy Electron Analyzer). The payload of Double Star TC-1 includes the Cluster flight spare of the PEACE/LEEA sensor whilst the spare PEACE/HEEA sensor is carried on the polar Double Star TC-2 spacecraft [22]. Similarly, whilst the CIS - Cluster Ion Spectrometry [23] - experiment onboard Cluster comprises both CODIF (COmposition DIstribution Function) and HIA (Hot Ion Analyser) components, TC-1 carries only the HIA instrument [24], which provides three-dimensional distributions of the ions which are assumed to be protons. Energetic electron measurements, taken from the RAPID instrument [25], on Cluster, is also used in the second event.

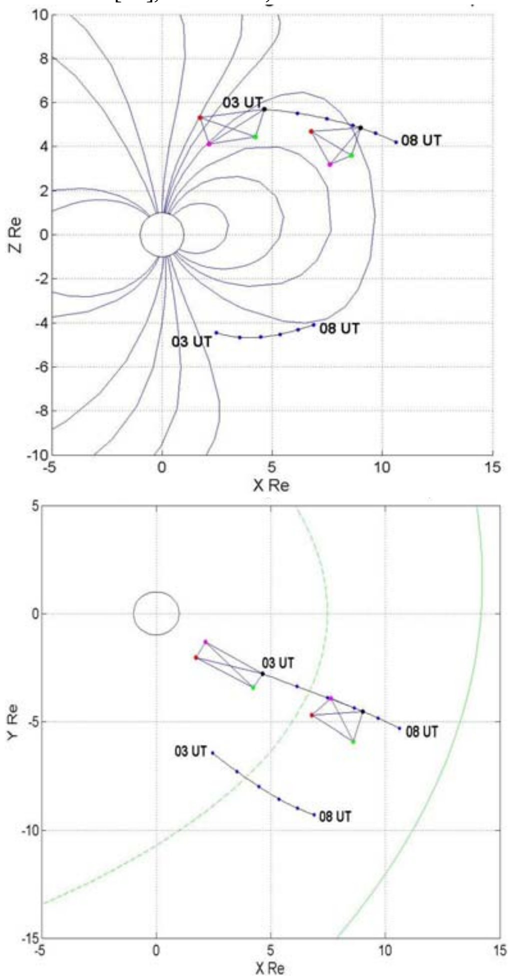


Fig 1. Cluster s/c1 and Double Star TC-1 tracks in GSM coordinates for the interval 03 to 08 UT on 6 April 2004. The Cluster orbit also shows two spacecraft configurations (scaled up by a factor x50). Each orbit has hour markers. Model field lines are shown for the projection into the X,Z plane and cuts through the bow shock and magnetopause are shown for the X,Y plane. For the X,Z plane field lines are drawn from the Tsyganenko '89 model for guidance.

3. RESULTS

3.1 The event of 6 April 2004

Figure 1 presents the tracks of both the Cluster and TC-1 spacecraft for the interval that extends from 03 to 08 UT on 6 April 2004, in the X-Z (left hand panel) and X-Y (right hand panel) planes, in the Geocentric Solar Magnetic (GSM) coordinate system. Also shown is the configuration of the Cluster spacecraft array, at two points along the orbit; the inter-spacecraft separations were a few hundred kilometres during this pass. The interval corresponds to an outbound magnetopause traversal by Cluster at about 10 LT, which crosses through the dayside magnetosphere to exit into the magnetosheath at high northern latitudes as shown (note that the actual magnetopause crossing occurred at ~04:30 UT at Cluster). The plot also shows that TC-1 was also outbound and passed through the magnetopause in the pre-noon sector, dawnwards of Cluster at ~8 LT. The TC-1 spacecraft, however, was located in the southern hemisphere. It happened that both the four Cluster spacecraft and TC-1 exited the magnetopause within half an hour of each other.

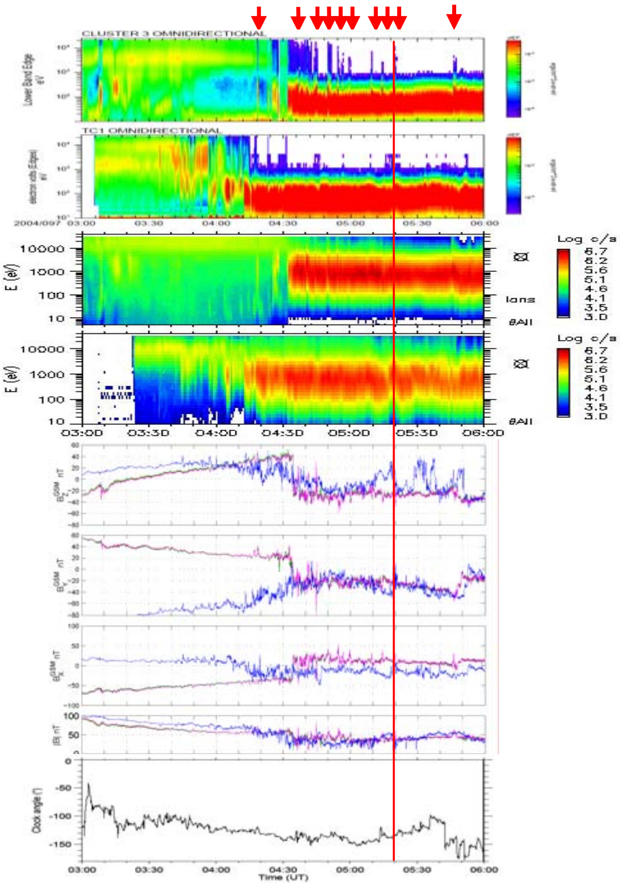


Fig 2.Summary of the PEACE, HIA, and FGM measurements for the interval shown. The plots for PEACE and HIA are in the same format for Cluster 3 and TC-1 respectively in both cases and show spin and pitch angle averaged, differential energy flux. The FGM plots show data from all four cluster spacecraft (1-black, 2-red, 3-green, 4-magenta) and TC-1 (in blue). A number of the FTE signatures are indicated by arrows at the top of the plot. The FTE discussed in the text is indicated also by the vertical red line (timed at Cluster). The lagged, IMF clock angle, obtained from ACE data, is shown in the bottom panel.

The solar wind conditions for the interval 03-06 UT, corresponded to a predominantly southward (B_Z negative, when lagged to the Earth) and exclusively dawnward (B_Y negative) IMF, as diagnosed by the MAG experiment [26] on the ACE spacecraft [27]. For most of this interval, B_Z, was around -5 nT (in GSM coordinates) and the B_Y component varied between -8 and -4 nT, so that the IMF clock angle (see bottom panel of Figure 2) varied. We highlight here that during the interval 04:00-05:40 UT (lagged time), the clock angle (see Figure 2, bottom panel) first decreased from around -100 to -150 deg at 05 UT and subsequently increased back to ~-100 deg. The solar wind density, from the ACE/SWEPAM instrument [28] reduced from 6 to 3 cm^{-3}, through the interval, whilst the solar wind velocity varied between 500 and 560 km/s, resulting in a prevailing solar wind dynamic pressure of ~3-2 nPa. The existing IMF conditions were conducive to dayside low-latitude (subsolar) reconnection (see, for example, [29]).

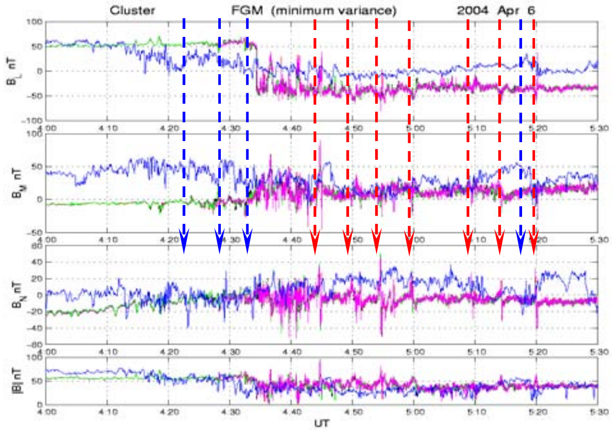


Fig 3. A multi spacecraft plot of the magnetic field in LMN (MVA) coordinates. The analysis of Cluster gives: [n=0.720 0.163 0.675, m=-0.379 -0.722 0.579, l=-0.582 0.672 0.458], λ=5 and TC-1 gives [n=0.233 -0.682 -0.694, m= -0.679 -0.625 0.385, l=0.696 -0.381 0.609], λ=3 (components in GSM). Clear FTEs are observed at Cluster (all spacecraft) with +/- polarity. The FTEs at TC-1 are less clear, but most have -/+ (reverse) polarity.

Data from all four Cluster spacecraft and for the Double Star TC-1 spacecraft, are summarised in Figure 2. The first and second panels of Figure 2 present spectrograms of spin-averaged, differential electron energy flux from the HEEA sensor of PEACE on the Cluster spacecraft 3 and TC-1 respectively. The third and fourth panels present differential ion energy flux from the HIA sensor for the same two spacecraft. The lower panels show magnetic field data from FGM on all Cluster spacecraft and on TC-1, with the lagged, IMF clock angle at the bottom. A number of distinct features within the interval are immediately apparent. Exits into the magnetosheath are clear both in the plasma and magnetic field data, and indicate magnetopause crossings at 04:15 UT for TC-1 and 04:33 UT for Cluster (the latter indicated by the large magnetic shear at 04:33 UT). Due to the southerly and dawnward location of the TC-1 spacecraft the X and Y components of the magnetospheric field are reversed compared to Cluster. In addition, some significant draping of the magnetosheath field between the spacecraft locations is apparent, with a negative X_{GSM} component at TC-1 and a positive component at Cluster. Both of these factors result in a much lower local magnetic shear across the magnetopause at TC-1 so that the magnetic field signature of the magnetopause crossing at TC-1 is less clear than at Cluster. The plasma data from TC-1 shows a number of partial crossings of the boundary layer before final entry into the magnetosheath.

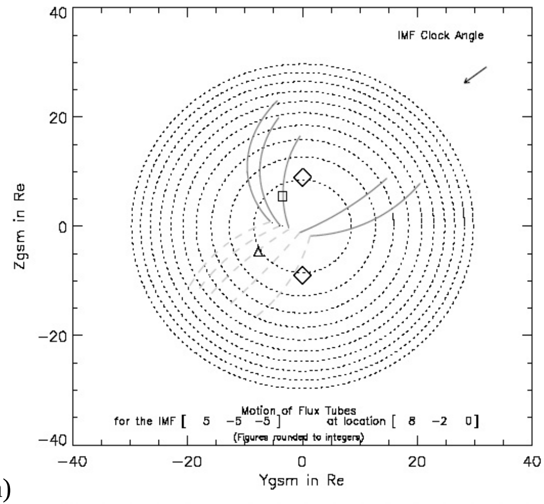
Superimposed on the underlying time series signatures of both Cluster and TC-1, in both the magnetosphere and magnetosheath, are a number of transient, mixed plasma signatures characteristic of FTEs. For the interval near the magnetopause crossings (~4:10-4:35 UT), both magnetosheath and magnetospheric FTE signatures are seen at each spacecraft location. Since there is a low magnetic shear across the magnetopause at TC-1, the observation of FTEs at this spacecraft suggests that these signatures are not locally generated, but arise from a (possibly common) distant reconnection site. Furthermore, it is apparent that, in the interval between 04:30 UT and 05:30 UT when both spacecraft are in the magnetosheath, there are significantly more and better defined FTEs observed at the Cluster spacecraft than at TC-1. We investigate further below the degree to which the FTE occurrence and behaviour are as a result of the respective spacecraft locations and observed changes in IMF clock angle. Indeed, for a number of these signatures, FTEs are found to occur within 1-2 minutes of each other at Cluster and TC-1, both on the magnetosheath and magnetospheric sides of the magnetopause and therefore possibly arise from a common merging point (see the model comparison below). One such common FTE, discussed below, is indicated by the vertical red line in Figure 2.

Table: Catalogue of Cluster FTE motions for the FTEs marked on Figure 3. The normal, n, is obtained directly from timing analysis and represents the direction of the velocity, V. Polarities are marked for each spacecraft. These were not clearly resolved for four of the TC-1 FTEs.

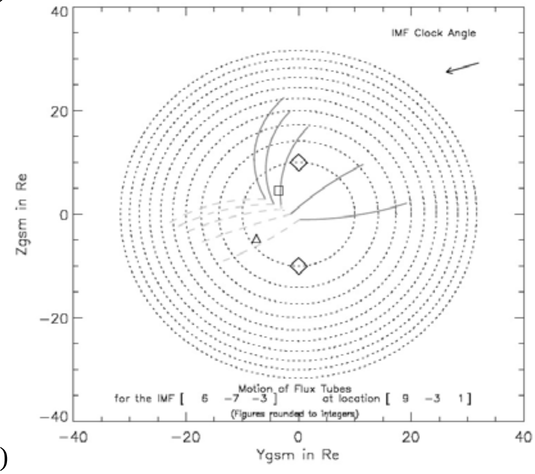
UT_Cluster	Polarity	n_{GSE} (motion)	n_{GSE} (FTE)	|V|	UT_TC-1	Polarity
04:18:00					04:19:00	
04:23:00					04:23:00	-/+
04:32:00					04:31:00	-/+
04:37:00					04:37:00	-/+
04:45:00	+/-	-0.9, 0.1, 0.2	0.61, -0.25, -0.75	190	04:46:00	
04:50:00					04:48:00	
04:54:00	+/-	-0.8, 0.4, 0.4	0.34, 0.44, -0.83	250	04:53:00	
04:56:00	+/-	-0.8, 0.5, 0.4	0.34, 0.44, -0.83	110		
05:00:00	+/-	0.2, -0.2, 0.9	-0.19, 0.68, -0.71	170		
05:09:00	+/-	-0.4, -0.5, 0.7	-0.69, 0.49, -0.54	210		
05:14:00	+/-	0.2, -0.7, 0.7	-0.55, -0.61, -0.58	160		
05:20:00	+/-	-0.5, -0.5, 0.7	0.52, 0.50, -0.69	230	05:18:50	-/+

In order to show these FTE signatures more clearly, Fig 3 presents magnetic field components in minimum variance (MVA) coordinates [30] for Cluster and TC-1 from 04:00 to 05:30 UT on 6 April 2004. The analysis is performed independently on the magnetic field data from the Cluster and TC-1 spacecraft for a short (~4 minute) interval around the main magnetopause crossing. The ordering during the interval shown is clearly much better in the case of Cluster than TC-1, which is as a result of the less well defined magnetic field signature at the magnetopause crossing in the case of TC-1. We refer to these MVA coordinates as LMN, since for both Cluster and TC-1, the intermediate and maximum eigenvectors lie closely parallel (<5^o) to the LMN coordinates in the system of [5], defined such that N is in the outward, magnetopause boundary normal direction, L lies in the boundary and points north (such that the L-N plane contains the GSM Z-axis), and M also lies in the boundary, pointing west. The clearest FTEs in the data from both spacecraft are identified by the dashed, vertical arrows (red for Cluster and blue for TC-1). The last pair of these corresponds to the FTE already mentioned and indicated (for Cluster) by the vertical line in Figure 2. All FTEs marked on Figure 3 are listed in the Table.

In the case of Cluster, all of the FTEs indicated in Figure 3 have been analysed to determine their orientation and motion and the results of this analysis is briefly summarised in the Table. The four Cluster spacecraft provide timing information that easily verifies (see, for example, the techniques in [31] that all FTEs at Cluster are moving consistently northwards, each with different X and Y motions, depending on the time of the FTE. The FTE speeds range from ~170 *km/s* to ~250 *km/s*. The observed motion of the FTEs changes from eastward (+Y_{GSM}) to westward (-Y_{GSM}) as we move through the magnetosheath interval, and this is related to the change in IMF clock angle. All FTEs observed at Cluster show standard +/- polarity (as can be observed in Figure 3), consistent with a draped flux tube signature moving predominantly northward. Conversely, the signatures at TC-1 are much less clear and are fewer in number during the same magnetosheath interval. Moreover, where it can be ascertained, the FTEs at TC-1 show -/+ (reverse) polarity, consistent with a location southward of a reconnection line.



(a)



(b)

Fig 4. The Cooling model result is projected in the YZ plane, looking earthward from the Sun. Concentric dotted circles are magnetopause radii at 5 R_E intervals along the X direction, with the innermost representing X=5 R_E. The diamonds represent the cusps for a MP standoff distance of 9 R_E. The triangle is the position of Double Star and the square, Cluster. Pairs of open reconnected flux tubes are initiated along the merging line (dot-dashed), with the motion of each calculated for 500 seconds (the extent of the line: solid lines represent connection to the northern cusp; dashed lines to the southern cusp). The IMF is indicated by the arrow in the upper right hand corner. The location information is for the mid point of the merging line. Other parameters are discussed in the text. Figure 4a shows the results for parameters representing the FTE signature seen at Cluster ~5:20 UT and at TC-1 at ~5:18:50 UT. Figure 4b shows the effect of modifying the IMF clock angle which moves the region of FTE evolution such that one can envisage Double star to move out of this region under certain clock angle values.

These observations suggest that quasi-steady, or sporadic reconnection is ongoing somewhere between the Cluster and Double Star spacecraft locations, such that Cluster is better located to observe any resultant FTEs. The motion of the flux tubes, although consistently northward at Cluster, appears to be sensitive to prevailing conditions (the changing IMF clock angle) and precise spacecraft locations. Furthermore, it is possible that some nearly coincident signatures arise from a common reconnection onset, which would send north and south branches of reconnected flux to each of the Cluster and TC-1 locations, respectively. These features, and whether they arise from the establishment of multiple or a common X-line, can be tested to some degree using the model of flux tube motion discussed below.

3.2 Model comparison for the 6 April 2004 event

We have employed the model implemented by [17] to study the motion of newly reconnected field lines across the dayside magnetopause. This model tracks the dynamics of implied flux tubes from a given X-line, using a draped magnetosheath magnetic field, a Spreiter-like sheath density and flow model and a simple treatment of Earth's field. It is a development from that of [32], in which a planar approximation to the magnetopause was adopted. The model initially determines, for given IMF conditions and known magnetopause position, the draping and strength of the magnetosheath field and the flow velocity and density over the entire surface of a paraboloid magnetopause, so setting up a test for a reconnection geometry.

If, for a given location on the magnetopause, the applied condition for steady state reconnection between the magnetosheath and modelled magnetopause is satisfied, the subsequent motion of the newly reconnected field lines across the magnetopause into the magnetotail is traced. The corresponding reconnection X-line of predefined length (taken here to be 5 R_E), centred at a chosen location, is constructed in the direction of the merging current calculated at the reconnection site. The output of the model is summarised by Figure 4 and discussed below. In general, the selection of the reconnection point implicitly accepts component reconnection as a viable possibility but the model can use the magnetic shear and corresponding magnetopause current to suggest the most likely X-line location, which would generally be the position corresponding to the anti-parallel reconnection condition.

We have run the Cooling model with those conditions in the solar wind occurring just before 05:00 UT on 6 April 2004, in order to be optimum for an FTE signature seen at Cluster at ~05:20 UT and at TC-1 at ~05:18:50 UT. To this end the model was input with values of the IMF-B=$(5,-5,-5)_{GSE}$, a solar wind density of ~6 cm^{-3}, a solar wind velocity of ~520km/s, and a fitted magnetopause position (to match the magnetopause crossing locations at TC-1 and Cluster) of ~9 R_E at the subsolar point.
The set of flux tube tracks shown in Figure 4a deeply engulf both spacecraft and their geometry suggests that oppositely directed FTEs, from northward moving and southward moving branches, may well be seen at each spacecraft location. Moreover, the tracks at Cluster, emanating from the whole length of the X-line, show a wide spread of Y directions, suggesting that FTEs may be observed with speeds having different Y components, as is the case. Thus, for this run, the merging line position and flux tube evolution fits well with the direction and timing of the FTE motion observed by Double star and Cluster. For the particular linked pair of tracks passing through the spacecraft positions, the southward branch of the model flux tube arrives at TC-1 about 70 seconds before the one at Cluster: as was the case for the particular pair of FTEs observed at ~05:20 UT (Cluster) and ~05:18:50 UT (TC-1). Note that in the model, the velocity is known along the track of each flux tube and each track has a particular, known length, so that the predicted time to arrive at all positions along the length of the track is known and the times of the FTE pair, in particular, can be calculated.

Comparative runs were also made to explore the sensitivity of the results to different clock angles and X-line location. An example of this is shown in Figure 4b, using the minimum clock angle that occurred during the interval 03:30 to 05:40 UT. In this case, one can see that such modification of the driving conditions could result in the convection flow of reconnected flux tubes turning more dawnward, moving TC-1 to the edge of the FTE convection region, and so reducing the number of clear FTEs observed by TC-1 as compared to those observed by Cluster during this crossing. This fits very well with the observation that TC-1 sees few clear FTEs between 04:30 and 05:30 UT. In addition it is evident that the northern pattern of tracks, which shows a spread of Y directions are possible for any FTE motion, is fairly stable to changing conditions, again consistent with Cluster observing FTEs all through the interval, with consistent polarity, but each with different motion in the Y_{GSE} direction.

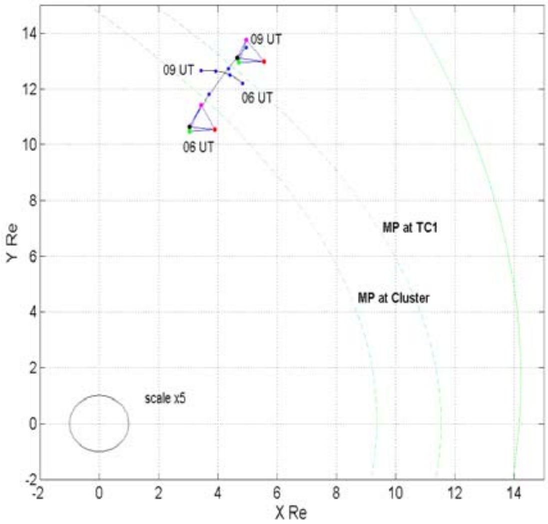
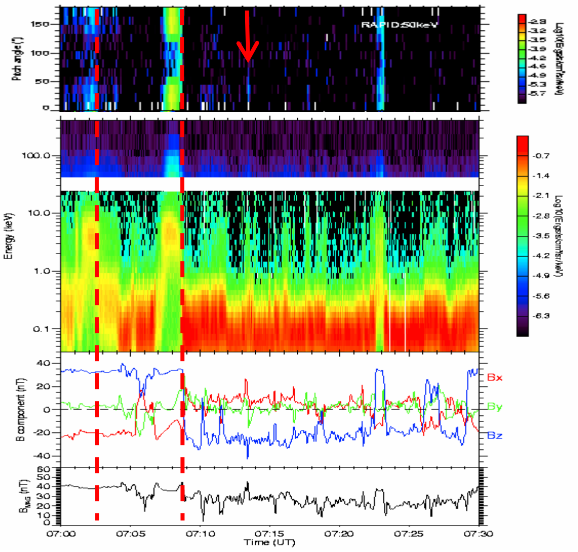


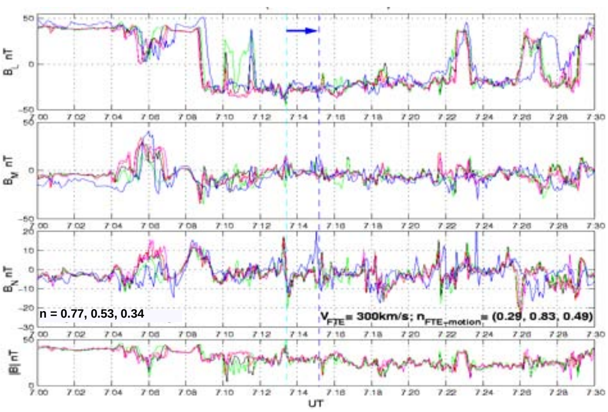
Fig 5. As for Figure 1 in the X,Y plane, but for the event of thew 4 January 2005. The orbital configuration is shown near the conjunction at 07 UT, where Cluster lies about 4 R_E northward and TC-1 remains nearly equatorial.

We also note here that [16] also present a comparative study of FTE signatures observed by Cluster and Geotail. The authors were able to demonstrate that their observations were consistent with the motion of northward (southward) and tailward moving flux tubes anchored in the northern (southern) hemisphere passing in close proximity to the Cluster (Geotail) spacecraft, and infer an approximate position of the reconnection site, which in that case was near-equatorial. In the present study, TC-1 lies further south and therefore further from the X-line studied by [16], Cluster and TC-1 being nearly equidistant from the X-line. Nevertheless, both studies suggest that a single reconnection site, near the subsolar point, is the very likely explanation of the events.

In summary, the polarity of the B_N signatures suggests Cluster lies north and TC-1 south of a X-line placed near the sub solar point. Four spacecraft timing at Cluster gives FTE velocities ~200 km/s northward, some with dawn-ward and others, duskward components. One selected pair of signatures show a possible, correlated FTE, delayed by ~70s to Cluster. The Cooling model is used to estimate the expected FTE velocities and X-line position and tracks have both dawn-ward and dusk-ward components, consistent with motion at Cluster. The time delay (between TC-1 and Cluster) for the common pair of tracks arising from the same point on the X-line is ~70 seconds aslo consistent with observations. For the modified clock angle, it is predicted that TC-1 (at the edge of the set of tracks) will see fewer flux tubes.



(a)



(b)

Fig 6. (a) Combined RAPID and PEACE Cluster data for the half hour interval containing the FTE studied, showing two re-entries to the magnetosphere and the FTE studied. The lower panels show FGM data and the top panel shows energetic electron pitch angles. (b) The magnetic field plotted in LMN (MVA) coordinates for the same half hour, showing the FTE at Cluster and TC-1. The MP normal is indicated with the FTE velocity.

3.3. The event of 4 January 2005

The solar wind conditions for the second conjunction we consider, 06 to 09 UT, on the 4 Jan 2005, also corresponded to a southward IMF orientation, but this followed a sudden turning from an initially northward orientation, near 07:00 UT. This reversal occurred as all Cluster and TC-1 spacecraft moved from the magnetosphere into the magnetosheath. The details of this event are shown in [Pu et al, *this issue*]. Figure 5 shows the spacecraft configuration during the event. All five spacecraft exit the dusk-side magnetosphere almost simultaneously since all spacecraft lie at the same LT and same radial position, but with Cluster lying at higher latitudes. An initial traversal into the magnetosheath occurs at around 06 UT during northward IMF conditions and a number of magnetopause crossings subsequently result.

Figure 6a shows combined RAPID, FGM and PEACE Cluster data and summarises the short interval containing the significant features, including the last two re-entries into the magnetosphere, which occurred during the arrival of a Heliospheric current sheet (HCS), associated with the sharp turning of the IMF from northward to southward, just after 07 UT. The last magnetopause crossing at 07:08 UT occurs under large magnetic shear, consistent with a southward IMF orientation, mapped into the magnetosheath. This southward turning suggests a possible onset of reconnection just before the spacecraft exit into the magnetosheath, since a number of FTE signatures are subsequently observed. No FTE signatures are observed prior to 07 UT.

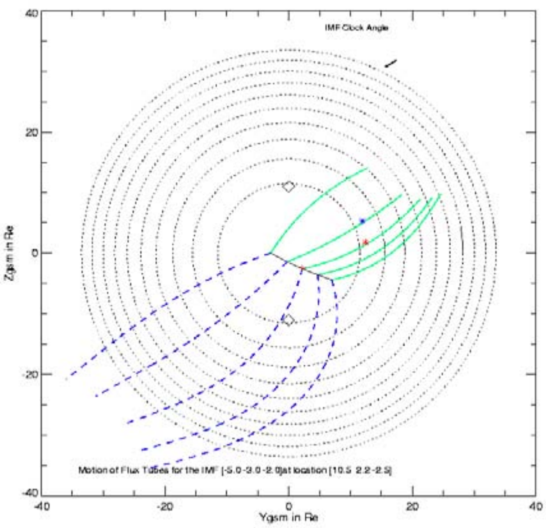


Fig 7. Cooling plot for conditions at the time of the FTE.

Figure 6a also shows that there are significant enhancements in the flux of energetic electrons observed at the magnetopause crossings, with the last crossing containing a bi-directional pitch angle distribution in the magnetopause layer. One correlated FTE signature occurs at 7:13:30 UT at Cluster and 07:15 UT at TC-1, with the Cluster signature carrying a field aligned beam of energetic electrons (perhaps suggesting recently reconnected field lines on this flux tube). Figure 6b shows the MVA analysis for the magnetic field traces (in LMN related coordinates). The magnetopause normal (indicated) is consistent with this LT and latitude for Cluster. Four spacecraft timing at Cluster gives a predominantly eastward and northward velocity of ~300 km/s for the FTE motion. The FTE is observed about 100s later at TC-1, with similar characteristics and similar implied orientation of the associated flux tube [details in Pu et al, *these proceedings*]. The coordinated signatures on all five spacecraft, and the calculated flux tube orientation, suggest that it is possible for the same flux tube to be crossed at different positions by all spacecraft. For example, Pu et al find the correct time delay (~90 s) for a tilted flux tube to move rigidly from Cluster to TC-1 with this velocity (confirmed by detailed modelling of the flux tube and de Hofmann-Teller analysis). Figure 7 shows a run of the Cooling model for the conditions prevailing at the time of this FTE and exhibits flux tube tracks that are consistent with the motion of structure seen at Cluster, using a sub-solar x-line location, as indicated. Identical tracks result at both Cluster and TC-1 locations, suggesting that either two parallel flux tubes are observed arising from different X-line locations, or confirming that a single flux tube is observed at different positions along it.

4. CONCLUSIONS

In this paper we have presented data during two magnetopause conjunctions between Cluster and the Double Star, TC-1 spacecraft. During the first event both spacecraft are outbound, with Cluster situated north and just dawnward of the sub-solar region and TC-1 situated south and further dawnward of the sub-solar region. The data suggest a period of ongoing reconnection with a common X-line extending over limited LT (modelled at ~$5R_E$ length) located between Cluster and TC-1. In particular, a series of FTE signatures are observed at both spacecraft locations with those at Cluster having +/- polarity (and a northward motion, confirmed by four spacecraft timing analysis) and those at TC-1 have -/+ polarity (implying a southward motion), consistent with moving flux tubes arising from a single reconnection line. The position of TC-1, which crosses into the magnetosheath earlier than Cluster, is consistent with the FTEs observed at TC-1 having significant southward and dawnward directions of motion. The Cluster-FTEs (with speeds ranging over ~170-250 km/s) move either duskward or dawnward until around 05 UT and then move predominantly dawnward. Moreover, the FTE observations by TC-1 are more concentrated around a short time after its exit into the magnetosheath (before Cluster crosses the magnetopause) and subsequently, TC-1 does not see as many or such clear signatures as Cluster until after 05 UT. Both this change in the FTE motion at Cluster and the FTE occurrence at TC-1 can be understood since, during the same period, the IMF clock angle is variable, ranging between -120 to -100 deg, until just after 05 UT, subsequently becoming more negative, at around -140 deg. For the second event the spacecraft lie at almost the same LT, with TC-1 at a near equatorial location and Cluster at high latitudes. This results in an almost simultaneous exit into the magnetosheath of all five spacecraft, occurring just after a sudden southward turning of the IMF. The key feature observed is a correlated FTE signature seen by all five spacecraft with a computed motion and time delay which is consistent with a tilted flux tube model which is crossed at different positions at Cluster and TC-1.

In both cases the interpretation is quantitatively borne out by the application of the Cooling model, which places the X-line near the sub-solar point and extending dawnward (a result of the strong negative IMF-B_Y) in the first case and duskward in the second. The precise location of the X-line is selectable in the model and was chosen here to result in a good timing fit for the expected flux tube motion. We note that this selection of the reconnection point implicitly accepts component reconnection as a viable possibility, although the model may be run so as to identify an anti-parallel location. Nevertheless, in the first event, there are periods between Cluster and TC-1 where common FTE signatures are possible (i.e. the opposite branches of the Cooling model). One possible, common signature occurs at 05:20 UT, where TC-1 sees the signature ~70 *s* before Cluster. The model has been run for the particular conditions most relevant to that FTE and results in coincident tracks for the north and south branches of flux tubes, which arrive at each spacecraft location very close to the respective times observed. Overall, the x-line fit agrees well with all the features mentioned above as observed by both Cluster and TC-1. Subsequent runs of the Cooling model were carried out to examine the effect of modified X-line location and clock angle, and suggest that TC-1 can often miss the convection region of the FTEs and that the dawn-dusk motion, in particular with the case of Cluster, is modified by slight change in the solar wind conditions (as occurs between 04:30-05:30 UT). We note that the sampling by both spacecraft of other common flux tube signatures may depend upon proximity of the spacecraft to the magnetopause and this analysis does not preclude other north/south pairs of reconnected flux tubes being missed more often by TC-1, which exits into the magnetosheath earlier than Cluster. In the case of the second event, the flux tube tracks passing through each spacecraft location (and arising from different points on the x-line) are closely similar. This is consistent with multiple flux tubes passing by each spacecraft with the motions computed from the data, but the timing between Cluster and TC-1 and the computed flux tube orientation [Pu et al, *this issue*], is suggestive of a single flux tube being crossed at different positions by each spacecraft.

In summary, we have shown here:

- Two close magnetopause conjunctions between Cluster and TC-1, dawnward and duskward of noon, during a period of ongoing reconnection, with the occurrence of an X-line between the spacecraft.
- A series of FTE signatures observed on all spacecraft which are consistent in polarity and motion with a subsolar geometry.
- That fewer TC-1 FTEs observed than Cluster FTEs, are consistent with the model prediction.
- A possible common signature (flux tube branches arising from the same reconnection point) occurring at ~5:20 UT, an interpretation quantitatively born out by the application of the Cooling model.
- Comparative runs of the model which confirm changes arising from: modified X-line location and modified clock-angle and that the dawn-dusk motion of FTEs at Cluster can be modified by slight changes in clock angle.
- A possible simultaneous flux tube crossing, moving duskward and arising from the subsolar region, by all five spacecraft.

This preliminary study is part of a wider activity to focus on the opportunities arising from the simultaneous flight of the Cluster and Double Star missions. The current work represents an example of the capability of such mission synergy and further work will address a wider database of such events.

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