OBSERVATIONS OF FLUX ROPES AND X-LINES IN THE NEAR EARTH MAGNETOTAIL

J. P. Eastwood [(1)], D. G. Sibeck[(2)], J. A. Slavin[(2)], B. Lavraud[(3)], E. A. Lucek [(4)], A. Balogh[(4)], I. Dandouras[(5)]

[(1)]NRC RRA, Code 612.3, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA,
Email:Jonathan.P.Eastwood@gsfc.nasa.gov
[(2)]Code 612.3, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[(3)]Space Science and Applications, Los Alamos National Laboratory, NM 87545, USA
[(4)]Space and Atmospheric Physics Group, The Blackett Laboratory, Imperial College London, London SW7 2BW, UK
[(5)]CESR, 9 avenue du colonel Roche, 31028 Toulouse, France

ABSTRACT

Magnetic reconnection in the Earth's magnetotail plays a key role in controlling the dynamics of the Earth's magnetosphere. Recent results based on Cluster multi-spacecraft analysis have raised important questions about the traditional interpretation of reconnection-associated phenomena observed by single spacecraft.

Cluster has shown that observations conventionally interpreted as a single X-line can correspond to multiple X-line structure [1]. Single point observations cannot distinguish between these two possibilities, and previous interpretations have invoked the simpler picture. This case study is put into a wider context by examining the plasma dynamics following this particular event. Within this picture, one can make the hypothesis that further loop-like structures – small flux ropes – ought to be observed in conjunction with this event. We present such evidence here, and in particular use the curlometer technique to analyse the observations.

1. INTRODUCTION

Magnetic reconnection plays a key role governing the transport of plasma within the magnetosphere [2]. In the simplest terms, reconnection at the dayside magnetopause and in the geomagnetic tail during periods of southward interplanetary magnetic field (IMF) allows solar wind plasma to enter and circulate through the Earth's magnetosphere [3]. A number of models have been put forward to explain the specifics of observed magnetospheric dynamics (see e.g. [4]).

Theories based on magnetic reconnection predict that high-speed earthward and tailward flows in the magnetotail should be correlated with northward and southward magnetic field, as has been observed [5;6;7]. Furthermore, a number of studies have been published studying the reconnection site itself. These studies have largely concentrated on ion scale phenomena such as the quadrupole magnetic field structure caused by Hall currents [8;9;10;11].

The manner in which reconnection occurs in the magnetotail, and the way in which it is initiated are topics of considerable debate. Reconnection in the near Earth tail leading to the ejection of a plasmoid downtail has been termed the Near Earth Neutral Line (NENL) model [12]. However, the basic NENL model does not account for certain magnetospheric phenomena, for example earthward moving flux ropes in the near-Earth magnetotail [8;13;14;15;16]. Earthward moving flux ropes are typically only a few Earth radii (Re) in size (i.e., tens of ion inertial lengths, c/w_{pi}) and are therefore smaller than the main NENL tailward moving plasmoid. They have been used to explain the existence of Traveling Compression Regions (TCRs) exhibiting a southward/northward (S/N) perturbation of the magnetic field [17]. More recent work from Cluster has shown that earthward moving TCRs are not only a common occurrence in the near tail, but can also occur several times in a single 'event' [18].

Earthward moving flux ropes and associated S/N TCRs are most easily explained by the existence of multiple reconnection X – lines, forming magnetic islands on the mesoscale (tens of c/ω_{pi}) level [15]. As argued by [19], the rate of reconnection at each X – line will not necessarily be the same; consequently, once the point of fastest reconnection begins to process the outer plasma sheet and lobe flux tubes, everything Earthward of this point will be swept up Earthward. However, the (in)stability of the magnetotail current sheet with respect to the tearing mode is still to be fully elucidated by theory (see e.g. [4]). The breakup of the current sheet has also been investigated numerically, for example by [20], who observed breakup of the magnetotail current sheet on scales of tens of c/w_{pi}.

Cluster provides a new way to explore these theories by providing unparalleled multipoint experimental observations. In this paper we review some recent Cluster observations of the magnetotail that have such a bearing on the published theories of magnetotail dynamics, and conduct a more detailed analysis of the

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data. These observations are also of note because the single spacecraft interpretation of the observations is inconsistent with the multi-spacecraft analysis. This in itself has important implications for the interpretation and perhaps reinterpretation of single spacecraft data.

In Section 2, the Cluster observations are introduced and the previous analysis is reviewed. In Section 3, the context of these observations is investigated, revealing the existence of multiple earthward moving flux rope structures. In Section 4, the curlometer technique is used to study the current density and forces within the flux ropes. In Section 5 the subsequent development of the magnetotail is described. Conclusions are presented in Section 6.

2. 2 OCTOBER, 2003

This case study is based on observations made by Cluster during the third tail season on 2nd October 2003. Fig. 1 shows the trajectory of Cluster 1 during 12:00UT 1 October 1 – 12:00UT 2 October 2003.

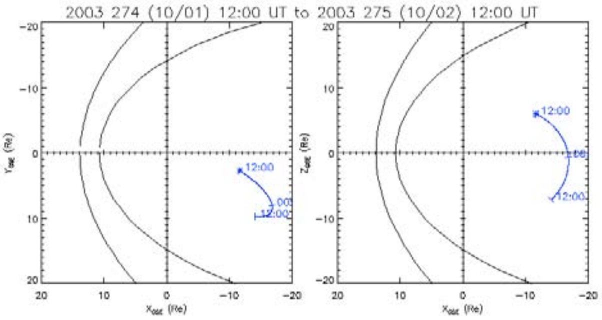

Fig. 1. Cluster 1 trajectory 12:00UT 1 October – 12:00UT 2 October 2003 projected into the x-y and x-z GSE planes. The separation of the Cluster spacecraft at this time was ~ 300km. This figure was produced by the on-line trajectory plotting facility maintained by the Satellite Situation Center at NASA Goddard Space Flight Center (http://sscweb.gsfc.nasa.gov/)

During this interval, the four Cluster satellites crossed the magnetotail plasma sheet, moving from the northern to the southern lobe at ~22 Magnetic Local Time (MLT). The satellites crossed the ecliptic plane at ~00:00UT. At this time, the magnetosphere was in the recovery phase of a moderate (Dst ~ 56nT) geomagnetic storm. The Interplanetary Magnetic Field (IMF) was southward for practically all of 1 October, with a significant -B_y component from ~23:00UT on 1 October. We shall concentrate on the interval 00:30UT – 01:30UT on 2 October.

This interval has been studied in part by [1]. The data reported there are shown in Fig. 2. Data from the Flux Gate Magnetometer (FGM) [21] and Cluster Ion Spectrometry (CIS) [22] experiments are shown. In particular, data from the Hot Ion Analyser (HIA) section of the CIS experiment, which does not discriminate between ion species, are shown.

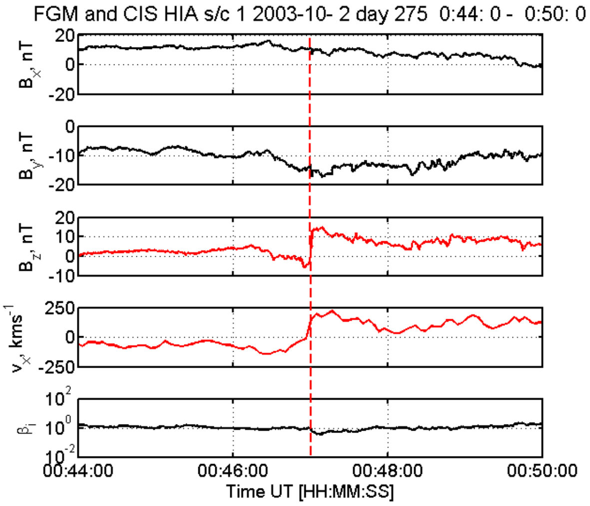

Fig. 2. B_z field and v_x flow reversal observed by Cluster on 2 October 2003. The top three panels show the magnetic field in GSM coordinates measured by the FGM experiment (at 22 vectors/s). The fourth panel shows v_x as measured by CIS-HIA (at 0.25 vectors/s), and the bottom panel shows the ion plasma beta derived from the FGM and CIS measurements

Fig. 2 shows a correlated reversal in both the x component of the plasma flow and the z component of the magnetic field, marked by the dashed line. In single spacecraft analysis, this signature is conventionally interpreted as an X-line retreating down the tail. This hypothesis is illustrated in Fig. 3, which shows a sketch of the reconnection geometry in the context of the Earth's magnetotail. A satellite, moving from right to left through this plasma configuration, will observe a characteristic simultaneous reversal in both the z component of the magnetic field and in the x component of the bulk flow velocity.

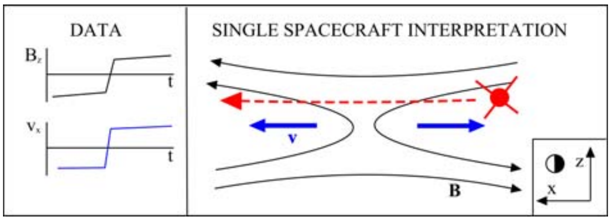

Fig. 3. Sketch of magnetic reconnection geometry in the Earth's magnetotail. The satellite moves relative to the X-line from right to left (equivalent to an X-line moving tailward), and observes the B_z and v_x time series shown on the left.

The single spacecraft hypothesis shown in Fig. 3 may be tested by multi-spacecraft analysis. In particular, timing analysis can be used to determine the proper motion of the magnetic field structure [e.g., 23]. However, for this event timing analysis shows that the structure was in fact moving Earthward, with a speed of 140±13 kms^{-1}, along **n** = [0.778 0.595 0.158] GSM [1]. The error is based on the small uncertainty in the timing of the event. Consequently, the picture shown in Fig. 3 is incorrect in this case. The interpretation consistent with the multi-spacecraft analysis is shown in Fig. 4 (Figure 4 of [1]).

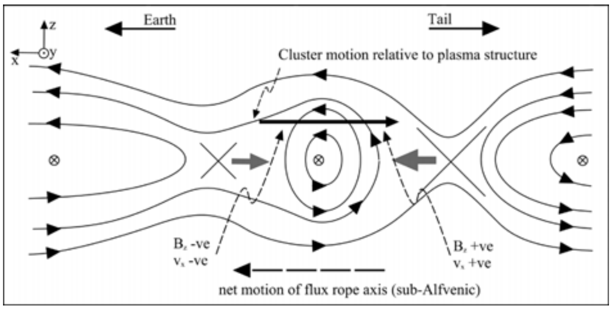

Fig. 4. Interpretation of the data shown in Fig. 2 based on multi-spacecraft analysis

(From [1], reproduced by permission of American Geophysical Union)

This leads to two important conclusions. The first is that the simplest interpretation of the data is incorrect here. The second is that the two observed flows come from topologically different sites. If one accepts that these flows arise as a result of magnetic reconnection, it is concluded that reconnection is taking place simultaneously at multiple points in the magnetotail current sheet.

3. MULTIPLE FLUX ROPE OBSERVATIONS

In the previous section, observations were reviewed that indicated the existence of multiple reconnection sites in the magnetotail. As a result, one can propose the hypothesis that reconnection was occurring not just at the two points inferred thus far, but at other locations as well. In particular, on the basis of this hypothesis we may predict that other flux-rope type signatures or X-line signatures should be present. A survey of the data reveals such structure, which is presented here.

A few minutes after the observations shown in Fig. 2 were made, a second flux rope structure was observed; the data are shown in Fig. 5. The duration of this event was similar to the first. Timing analysis was used to establish that this structure was moving Earthward, at a speed comparable to the observed plasma flow; the structure was therefore being convected in the flow. In addition to the -/+ perturbation in B_z (a characteristic property of earthward moving flux ropes), an increase in the magnitude of B_y was observed. However a similar perturbation in B_x was observed, suggesting that this flux-rope had an anomalous structure. Henderson et al. [*this issue*] also identified this event in their independent survey of the Cluster dataset for magnetotail flux ropes. The results of their analysis are reported elsewhere in this volume. Our analysis is consistent with their results, and as such, we refer the reader to their study.

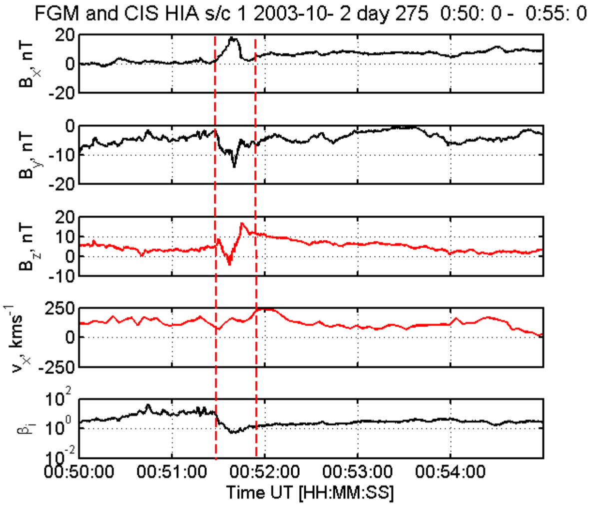

Fig. 5. Second earthward moving flux-rope structure observed by Cluster on 2 October 2003. The data are shown in the same format as Fig. 2, but here the centre of the event is contained by the dashed lines

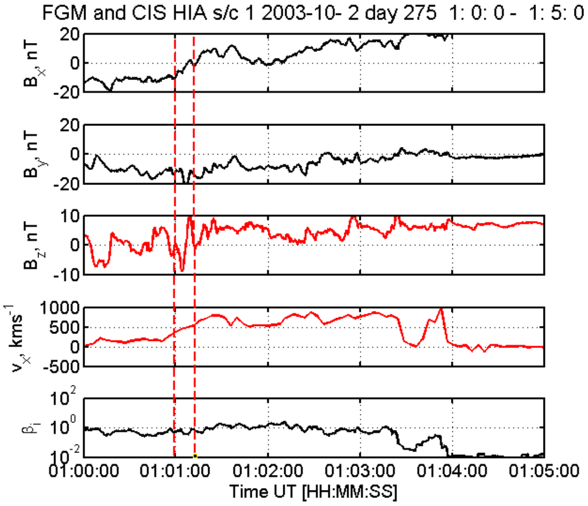

Fig. 6. Third earthward moving flux-rope structure observed by Cluster on October 2 2003, shown in the same format as Fig. 2

A few minutes after the structure shown in Fig. 5 was observed, a third flux rope, shown in Fig. 6, was identified.

A bipolar -/+ perturbation in B_z was again observed (with an amplitude of ~10 nT), together with an increase in the strength of B_y. This structure was embedded in faster earthward flow; calculations based on timing analysis again show that the structure was being convected in the flow. Therefore this also corresponds to an Earthward moving flux rope feature. It should be noted that the duration of the signature in the time series is only a few seconds. In fact, the size of the structure is similar to the first two; its brief signature is simply due to the relatively fast plasma flow. This illustrates a particular problem of magnetic field time series analysis – the degree of structure that is observed is a function of the plasma flow speed. Also, the use of lower resolution data would not have revealed this structure; consequently, surveys of low-resolution data should be carried out with this in mind.

4. FLUX ROPE CURLOMETER ANALYSIS

In this section we present the curlometer analysis of the third flux rope observed in this interval. The curlometer technique, originally conceived by [24], has been used in a number of different Cluster data analyses. In particular, it has previously been used to analyse another flux rope observed by Cluster in the tail [25]. It is worth describing here some of the limitations associated with the technique. The basic methodology is illustrated in Fig. 7.

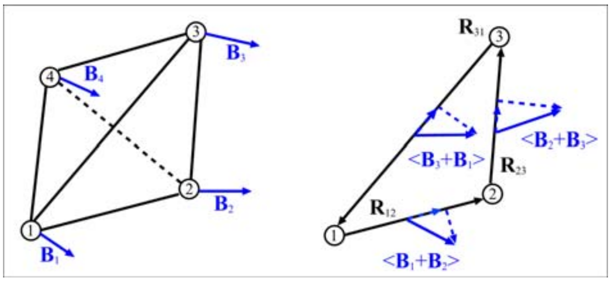

Fig. 7. Illustration of the curlometer technique

The left hand side of Fig. 7 shows the Cluster tetrahedron and the magnetic field (in blue) measured by each spacecraft. The right hand side of Fig. 7 shows one face of this tetrahedron. The three measurements are used to make a linear estimate of loop integral of the magnetic field by projecting the average field onto each separation vector. Stokes' theorem is then used to estimate curl **B** perpendicular to the surface. This calculation is repeated for the other surfaces, giving the projection of curl **B** onto each of the four surface normals. This information is easily inverted to provide an estimate of curl **B**. The estimated curl **B** is uniform throughout the tetrahedron. Div **B** is calculated in a similar manner by estimating the magnetic flux through each face and applying Gauss' theorem.

Although this description is perhaps the easiest to illustrate, several other formalisms have been developed [26;27;28]. It can be shown mathematically that all published formalisms, in their basic form, give the same result [28].

By using the curlometer technique, it is effectively assumed that the magnetic field varies linearly between the spacecraft. Consequently, the technique is best used to study magnetic field structures whose scale size is larger than the tetrahedron, such that the magnetic field does indeed vary in an approximately linear manner. To illustrate this point, consider a thin current sheet that bisects the tetrahedron. Application of the technique effectively smears the current density out over the whole tetrahedron, significantly reducing the estimated current density.

It is widely assumed by the community that the estimated divergence of the magnetic field, which in general is non-zero, provides a good characterisation of the error associated with the estimate of curl **B**. It is important to remember that the Ampere-Maxwell law and div **B** = 0 are not coupled in Maxwell's equations, and there is no mathematical reason, a priori, why the estimate of div **B** can be used to characterise curl **B**. Physically, they are related to the variation of different field components in different directions. However, if statistically the fluctuations in different field components are the same, then one may conclude that if the estimate of div **B** is significantly different from 0, the estimates of curl **B** are likely to be unreliable. Tests with synthetic data appear to show that div **B** can be used in this way [26].

An interesting question one can ask about magnetotail flux ropes is whether they are force free. Cluster provides a novel way to study this by calculating the current density, and then comparing its orientation with the magnetic field. This was first investigated by [25] who concluded that the flux rope they observed was not force free. We may speculate that the degree to which a flux rope is force free indicates its age – if it is assumed that magnetic field configurations evolve to a lowest energy state, then a flux rope ought to become force free. Of course, this statement is only correct in the absence of external forcing, which is not necessarily the case here.

In a force free configuration, the current density inside the flux rope is expected to be everywhere parallel to the magnetic field [29]. We may therefore use the curlometer technique to compute the current density, and compare the orientation of the current density with the magnetic field. The curlometer analysis, applied to the third flux rope structure observed here is shown in Fig. 8. The scale size of the structure is a few Re, or 10^4 km. The scale size of the tetrahedron is of the order of 10^2 km. Consequently, our assumption of linear variation in the magnetic field is likely to be well met. This scale size is significantly smaller than that used in [25], although the data used there were chosen carefully to ensure the accuracy of the curlometer analysis.

We observe that the majority of the current is carried in the y_{GSM} direction. The current density peaks at ~ 30 nAm^{-2}, which compares favourably with [25]. In this interval, div **B** was estimated to be ~ 0.005 nT/km, an order of magnitude below the estimated value of curl **B** (~ 0.05 nT/km).

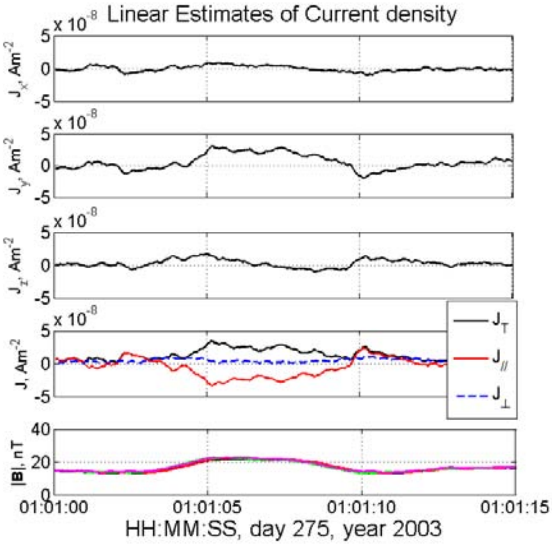

Fig. 8. Curlometer analysis applied to the third flux rope observed by Cluster, shown in Fig. 6. The top three panels show the components of the current density in GSM coordinates. The fourth panel shows the total current (black) and the current parallel (red) and perpendicular (blue) to the magnetic field. The bottom panel shows the field strength observed by the four spacecraft, using the standard colours.

As discussed above, it is of particular interest to assess the force free nature of the flux rope. In a force free flux rope, the current density vector is everywhere parallel to the magnetic field such that **J** = α**B**. Here we use the field averaged over the four spacecraft at each time step. It is evident from Fig. 8 that the current is mainly parallel to the field within this flux rope. Fig. 9 shows how alpha varies through the third flux rope that was observed. In fact, we show $\alpha = |\mathbf{J}|/|\mathbf{B}|$ and $\alpha_{//} = J_{//}/|\mathbf{B}|$. It can be seen that the flux rope is indeed force free (since $\alpha = \alpha_{//}$), and moreover that α ~ 1 through the centre of the flux rope.

These calculations (not shown) were repeated for the other two events, and the parallel currents were found to be significantly larger, indicating that these structures were less force free. For example, in the first event, the peak parallel current was ~50 nAm^{-2}, compared to a peak perpendicular current of ~30 nAm^{-2}.

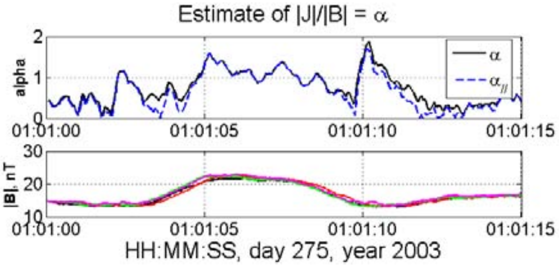

Fig. 9. Investigation into the force free nature of the flux rope. In the top panel, the solid line shows how α computed from the total current varies through the flux rope. The dashed line shows how α computed from the parallel current varies. The bottom panel shows the field strength observed by the four spacecraft

The fact that this particular flux rope appears to be force free implies that it has evolved to its lowest-energy configuration. One interpretation of these observations is that all three formed at a similar time (when the first was observed), and were observed at different times in their evolution. However, these events are subject to complicated forcing by the ambient plasma flows and further work is required to confirm this picture.

5. FLOW DEVELOPMENT

To conclude this paper, we outline the further development of the plasma flow. In particular, thus far, we have shown the existence of three closely separated flux rope signatures in the tail, all moving earthward. The first appeared to be in the process of development, the second was not force free, and the third, embedded in faster earthward flow, was force free.

Since these structures are being driven earthward, then we may make the hypothesis that this is due to events occurring tailward of the spacecraft. In particular, we might expect a point of fast reconnection to exist tailward of the spacecraft. Further inspection of the data suggests that this is the case.

Fig. 10 shows the subsequent development of the magnetotail plasma sheet between 01:00UT and 01:30UT on 2 October 2003. At 01:04UT, the Cluster spacecraft encountered low (~10^{-2}) beta plasma, corresponding to the magnetospheric lobes. The spacecraft were moving at a few kms^{-1} at this time; the transition is most likely due to a thinning of the plasma sheet. Prior to this boundary crossing, the spacecraft were embedded in fast (>500kms^{-1}) plasma sheet flow.

Over the next 30 minutes, the Cluster spacecraft made at least 11 further crossings of the lobe/ plasma sheet boundary layer. We note that these crossings are qualitatively consistent with a slow mode shock [30]. A simple test that can be used to distinguish between a tangential discontinuity and a slow mode shock is to compute the boundary normal, and calculate whether the magnetic field threads the boundary (i.e. $\mathbf{B}\cdot\mathbf{n} \neq 0$). Based on multi-spacecraft calculations of the boundary orientation, the magnetic field does appear to thread the boundary in this case. Consequently, we may make the hypothesis that these observations correspond to a set of Petschek type shocks connected to a site of magnetic reconnection tailward of the Cluster spacecraft, and that this site is responsible for the earthward motion of the previously observed magnetic structure. Further work is planned to test this hypothesis in more detail.

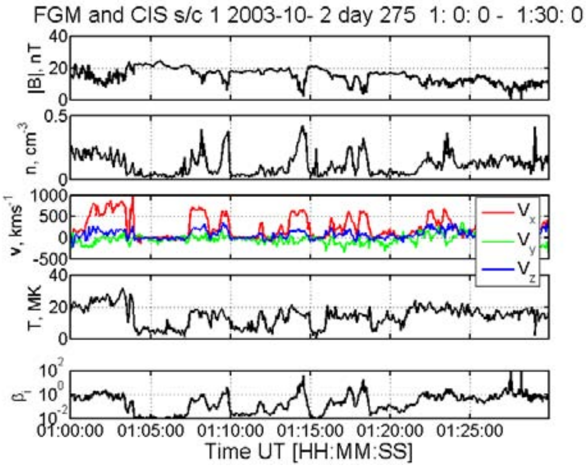

Fig. 10. Subsequent development of the plasma sheet observed between 01:00UT and 01:30UT on October 2 2003. From top to bottom, the magnetic field strength, HIA plasma density, plasma velocity, temperature and plasma beta are shown

6. CONCLUSIONS

In this paper we have discussed the dynamics of the terrestrial magnetotail plasma sheet on 2 October 2003. We have, for the first time, demonstrated the existence of multiple earthward moving flux ropes in the plasma sheet, and used multi-spacecraft analysis to study their size and current structure. This has allowed us to examine their force free nature.

We have also shown that the earthward passage of the observed magnetic field structure is due to a more disruptive event tailward of the Cluster spacecraft, which is subsequently observed. Cluster encounters what may be a series of slow mode shocks; further work is planned to test this hypothesis.

Based on the analysis performed thus far, we note the qualitative similarities of our observations to theories of multiple X line reconnection. Further work is required to establish this connection on a more quantitative basis. In particular, it would be interesting to test predictions of tearing mode island size against these observations.

Finally, we note that this analysis fundamentally relies on multi-spacecraft data. Analysis of the first event using single spacecraft data alone leads to an incorrect conclusion about the structure of the magnetic field. The ramifications of this result in the context of previously published analysis have not yet been elucidated.

7. ACKNOWLEDGEMENTS

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