# CLUSTER OBSERVATIONS OF FLUX ROPE STRUCTURES IN THE NEAR-TAIL

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## ABSTRACT

An investigation of the 2003 Cluster tail season has revealed small flux ropes in the near-tail plasma sheet of Earth.

This paper contains a brief description of two flux ropes, observed on the 2nd October and the 13th August 2003. These flux ropes are explored in greater detail in a paper submitted to Annales Geophysicae, September 2005 [3].

The flux rope observed on the 2nd October (13th August) was travelling Earthward (tailward). Throughout the flux ropes, but more significant in the outer sections, the magnetic force **J** × **B** was large. The components of **J** × **B** suggest that magnetic pressure was acting to radially expand the flux ropes, i.e. directed away from the centre of the flux ropes. Electron pressure was reduced inside the flux ropes, suggesting a compressional force from the exterior plasma.

The observations of a large **J** × **B** signature in the outer sections of the flux ropes may be explained if they are observed at an intermediate stage in their evolution. We suggest that following creation by reconnection at multiple X lines near the Cluster apogee, they evolve towards the force-free like configuration often observed further down the tail. The centre of the flux ropes may contain older reconnected flux at a later evolutionary stage and may therefore be more force-free.

## 1. INTRODUCTION

Flux ropes have been interpreted as evidence for multiple X line reconnection (MXR) in the near-tail associated with substorms (e.g. [6]). In MXR, instead of creating one single X line in the tail, the conditions required for reconnection can be satisfied in numerous places, creating a number of X lines. Given an IMF $B_Y$ component which penetrates into the tail, flux ropes can be created between the X lines. Reconnection acts first on closed plasma sheet field lines, but subsequently proceeds at the dominant X-line onto open field lines in the lobe. At this point the newly-formed flux ropes become embedded in Alfvenic jets from the dominant X line and thus move away from the point at which they were created.

Flux ropes are characterised by a bipolar $B_Z$ signature which may be accompanied by a large increase in the magnitude of **B**. Events with a south-then-north (north-then-south) signature are seen to move Earthward (tailward), and are usually embedded in fast plasma flows [6].

The simplest flux rope model is the 'force-free' flux rope. This model represents the minimum energy state for helical magnetic field lines and could therefore represent the cores of well developed, fully evolved flux ropes observed in the deep tail.

Minimum variance analysis has previously been used to determine the orientation of flux ropes. For the force-free model, a variance analysis on the magnetic field gives an intermediate variance direction which corresponds to the axis of the flux rope [7]. The minimum variance direction lies along the trajectory.

By noting the time at which different spacecraft measure the same level of |**B**|, multi-spacecraft timing can be used to construct moving planar surfaces (and normal vectors) to approximate the curved outer boundaries of the flux ropes (Fig. 1). The produced timing vectors define a plane whose normal is the axis of the structure. This technique can therefore be used to estimate the axial orientation of flux ropes.

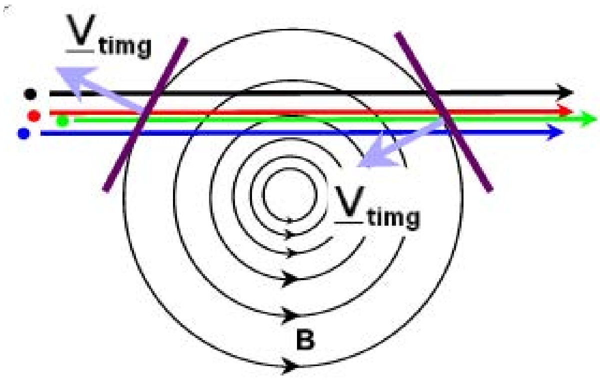


Fig. 1. Multi-spacecraft timing using constant flux surfaces. The normals to the inbound and outbound planes defined by this technique can be used to determine the axis direction of the flux rope.

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Furthermore, the curlometer technique, [2], can be used to determine the internal current systems in flux ropes. With knowledge of the current, the magnetic force, **J** × **B**, can be calculated. This can then be resolved into magnetic tension and pressure forces. For more details and caveats of the above techniques see [3].

## 2. RESULTS

On the 2nd October 2003 at approximately 01:00:00 UT, the Cluster spacecraft were located ~ (-17, 8, -3) $R_E$ (GSM coordinates will be used throughout this paper unless otherwise stated). Fig. 2 shows three components of the magnetic field from all spacecraft (C1 - black, C2 - red, C3 - green, C4 - magenta) and their magnitudes for the period 00:47:00 to 00:57:00 UT from FGM [1], hereafter referred to as case A. Panel 5 shows the ion plasma beta ($\beta_i$) from CIS [5] on Cluster 1, with $\beta_i = 0.3$ marked by a dotted line. Values of $\beta_i$ above this value are indicative of plasma sheet conditions. Panel 6 shows the components of plasma velocity from CIS ($V_x$ black, $V_y$ red, $V_z$ blue) on Cluster 1. The bottom panel contains a spectrogram of the direction-averaged differential energy flux for electrons in the energy range 30 eV - 30 keV recorded by the PEACE instrument [4] on Cluster 4.

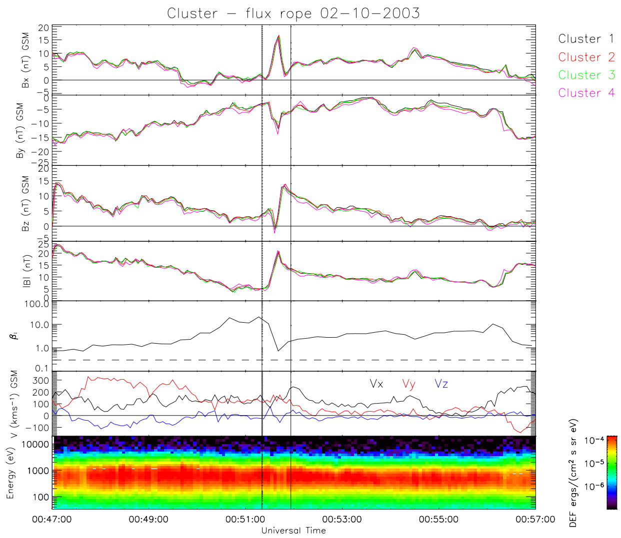


Fig. 2. Cluster observations from 2nd October 2003, case A. Panels 1 to 4 show components of **B** and |**B**| from each spacecraft. Panels 5 and 6 show plasma $\beta_i$ and velocities from CIS respectively. Panel 7 contains an electron spectrogram recorded by the PEACE instrument on Cluster 4. The flux rope event is marked between two vertical black lines.

On the 13th of August at approximately 03:00:00 UT, all four Cluster spacecraft were located at ~ (- 18, - 7, 0) $R_E$. Fig. 3 shows the components of the magnetic field, $\beta_i$ and velocity, and the electron spectrogram in the same format at Fig. 2. This case is hereafter referred to as case B.

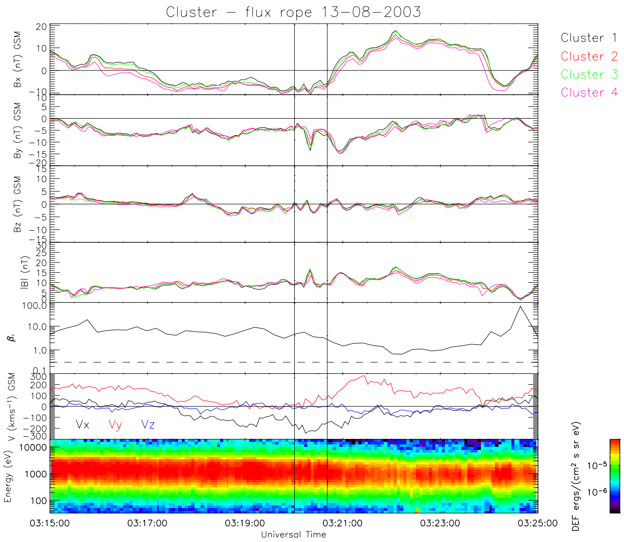


Fig. 3. Cluster observations from 13th August 2003, case B, in the same format as Fig 2.

During these periods the Cluster spacecraft were in the plasma sheet, shown by a large differential energy flux of ~ 1 keV electrons, and a high plasma $\beta_i$. The flux ropes can be seen as an increase in |**B**| and bipolar $B_Z$, south-then-north in case A (indicating an Earthward moving flux rope) and north-then-south in case B (indicating a tailward moving flux rope).

Minimum variance analysis and multi-spacecraft timing were carried out on these periods of data. For case A, these analyses showed that the flux rope was moving Earthward (~ 150 $kms^{-1}$) and duskward (~ 150 $kms^{-1}$). The axis of the structure closely matched the intermediate variance direction, which was orientated out of the GSM X-Y plane. The size of the flux rope, calculated using the duration of the bipolar signature, the CIS moments and multi-spacecraft timing, was ~ 0.3 $R_E$. For case B, the flux rope was moving tailwards (~ 200 $kms^{-1}$), with a bipolar signature duration corresponding to a size of ~ 0.3 $R_E$. The axis in this case closely matched the maximum variance direction of the magnetic field, and was aligned across the tail.

The curlometer technique [2] was also used on these periods. For both cases, the current was not a maximum in the centre of the flux rope, and had significant components in the direction perpendicular to the magnetic field. These flux ropes were thus not force-free. The current was not mainly axial, but had a tangential component, i.e. circulating around the axis. Calculation of **J** × **B** showed that the magnetic forces were larger in the outer section of the flux ropes than in the centre. The direction of the **J** × **B** force was directed as to expand the flux rope radially, i.e. acting away from the centre of the flux rope. There was little magnetic tension, **J** × **B** being dominated by magnetic pressure, in agreement with a strong axial magnetic field. The electron pressure was reduced inside both flux ropes, suggesting a compressional force from the exterior plasma.

The main results from this paper are summarised in Figs 4 and 5. These figures show the spacecraft trajectory (dotted line) passing through a schematic representation of the flux rope (in variance space). The strong core magnetic field and circulating current causes outward directed magnetic pressure, unbalanced by inward magnetic tension. The multi-spacecraft timing vectors, $V_{timg}$, can be seen to define a plane whose normal is the flux rope axis. The total **J** × **B** force was larger in the outer sections of the flux ropes.

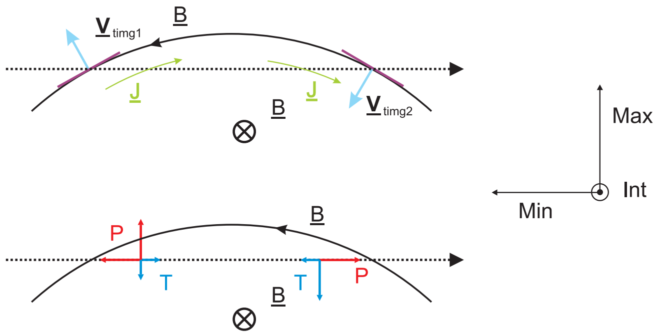


Fig. 4. Schematic summary of results for case A.

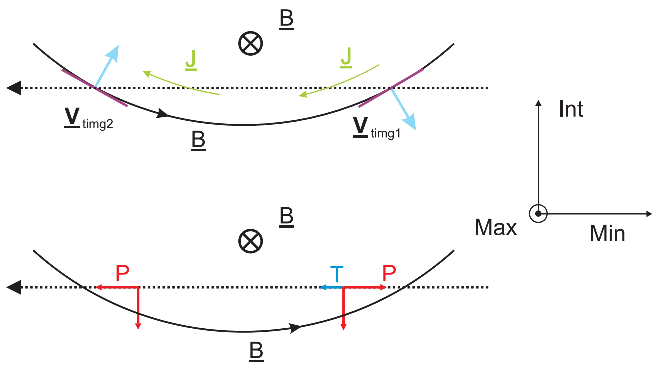


Fig. 5. Schematic summary of results for case B.

## 3. DISCUSSION

The mechanism for the creation of these structures is important for the study of the break-up of current sheets near substorm onset. The flux ropes reported here are not force-free, indeed tending to be less force-free in the outer sections of the flux rope than in the centre. As is the case for those seen in the distant tail, the cores of these flux ropes would perhaps be expected to relax into the force-free state, the lowest energy state of a helical magnetic field, after some time. If the process responsible for the creation of these flux ropes is MXR and if it is occurring close to the point where the flux ropes are observed, the flux ropes might not have had time to fully relax into this force-free state. However, as the flux in the centre of the flux ropes would have reconnected before that in the outer sections, the central flux would have had more time to begin the evolution towards a force-free configuration. The outer sections would therefore be expected to less force-free than the centre, as observed in both flux ropes reported here. For further discussion of these results see [3].

## 4. CONCLUSIONS

- Both flux ropes investigated here were found not to be in a force-free configuration, demonstrated by the computation of the **J** × **B** forces inside the flux ropes.
- **J** × **B** was larger in the outer sections and magnetic pressure dominated in both flux ropes.
- Electron pressure was reduced inside the flux ropes suggesting a compressional force from the plasma.
- Flux rope axes do not always correspond to the intermediate variance direction of the magnetic field (as is the case for a simple force free flux rope); in one case the axis is close to the maximum variance direction.
- Flux rope bipolar signatures were small (~ $0.3R_E$) and slow moving (~ 200 $kms^{-1}$), determined with multi-spacecraft timing and CIS ion moments.
- Observation of a tailward moving flux rope at X (GSM) ~ $-18R_E$ suggests that multiple X line reconnection must have occurred Earthwards of this point.

## 5. REFERENCES

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