A statistical study of Cluster observations within the Earth’s magnetotail

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Submitted: 24 March 2006

Abstract. A Cluster tail-crossing catalogue containing data from the 2003/2004 tail seasons has been collated. Statistical analysis has revealed a number of distinct conclusions that relate current sheet motion and structure to solar wind and substorm activity.

In addition, the benefit of Cluster’s multi-craft configuration is presented through a timing analysis method implemented on magnetic field data. This has lead to accurate measurements of current sheet components of motion and ultimately current sheet thickness, an important element of substorm dynamics within the magnetotail.

1. Introduction

The significance of Cluster in the field of magnetosphere research cannot be underestimated. The European Space Agency (ESA) mission consists of four craft in a tetrahedron configuration orbiting the Earth in an elliptical polar orbit (19000 x 119000 km) which rotates about the Earth once a year. Each craft is equipped with 11 instruments including a Flux Gate Magnetometer (FGM) and two particle detectors (RAPID and PEACE), details of their operation can be found in ESA document SP-1159. The four-craft configuration uniquely allows for separate spatial and temporal variations in arbitrary geometry measurements in the near-Earth environment. In a region such as the Earth’s magnetotail this method of observation becomes particularly valuable when seeking to understand dynamical processes involved in substorm mechanics and current sheet motion.

Processes involved within substorm cycles are a current topic of debate. It is generally accepted that substorm dynamics are driven by solar wind interactions which cause build-up of magnetic flux in the tail inducing disruptions in the current sheet. Processes taking place there-after are open to interpretation, two hypotheses are at the forefront of this argument: The Near-Earth Neutral Line (NENL) model: Magnetotail reconnection takes place on the NENL at a point known as the X-Line as energy is released from the tail. Flux tail-ward of the X-Line is lost into the interplanetary environment, flux Earth-ward of the X-line contracts back to Earth causing auroral activity before returning the magnetosphere to its ground state. The second model is the Current Disruption (CD) model in which disturbances in the near-Earth environment cause disruptions in the cross-tail current sheet. Current is forced to flow via Earth producing the substorm wedge. This structure causes auroral activity before launching rarefactions tail-wards that induce reconnection at early stages of the recovery phase.

Current sheet deformation plays a crucial role in both of these models therefore thorough investigation into the magnetotail and the current sheet may yield new insights into substorm dynamics. Valuable investigations into the current sheet using data from the Cluster mission have already been carried out. These findings can be reviewed in Baumjohann et al. (2004), Runov et al. (2004) and Petrukovich et al. (2004). The investigation reviewed in this paper consists of a survey of Cluster magnetotail crossings and a subsequent statistical survey aiming to compare internal and external magnetotail parameters. The work presented here is a segment of work from a larger investigation that carried out a coordinated study using observational data from Cluster and Double Star.

2. Method

![Fig. 1: FGM prime parameter data. Plot contains four traces, one for each Cluster craft (C1=Black, C2=Red, C3=Green, C4=Blue). The top B(x) panel depicts current sheet crossings as the trace crossing the 0-axis.](image-url)
Cluster data obtained during this investigation originated from the 2003/2004 tail-crossing season (July – October). An initial survey using low-resolution 6-minute data identified magnetotail crossings and provided an initial indication of current sheet activity. This survey also highlighted crossings that would prove scientifically valuable in the context of a tail-crossing catalogue.

Cataloguing was undertaken using high-resolution 6-second data predominantly from Clusters FGM instrument (fig. 1). Changes in B(x) polarity illustrate current sheet crossings as Cluster moves from a region of Earth-ward field lines above the current sheet, to a region of tail-ward field lines below the current sheet. FGM data provided a number of parameters that could be extracted for cataloguing:

- Temporal and spatial location of Cluster at the time of crossing.
- Current sheet normal velocity and direction, calculated using a timing analysis method that examines the four crafts temporal and spatial positions with respect to each other at the time of crossing (Paaschmann et al. (1998)). The use of this method extends research described in Runov et al. (2005). Crossing duration was inferred by examining the time interval of a particular gradient across the B(x)=0 axis. When used in conjunction with current sheet velocity, distance/speed/time calculations can be used to find current sheet thickness. Further examination of FGM data using Ampere’s law, \( j = \mu_0 \nabla \times B \), yielded current density at the time of crossing. Field curl was obtained using methods explained in Dunlop et al. (2002).
- Internal magnetosphere activity was gauged using Dst and Kp indices available from NASA’s CDAWeb. External solar wind activity was collected from the ACE satellite located at the L1 point. 4-minute resolution data provided solar wind speed and particle density, from which ram pressure (\( P_{\text{ram}} = \rho v^2 \)) could be calculated. 1-hour resolution data provided Interplanetary Magnetic Field (IMF) data from which clock-angle, \( \theta = \arctan(B(y)/B(z)) \), could be calculated. It should be noted an approximate 40-minute lag exists between ACE and the Earth’s magnetopause that had to be considered.

Initial analysis of tail-crossing data proved insignificant with no clear trends or patterns emerging. This emphasised the need to classify the catalogue into coherent datasets. Two methods of classification were imposed on the data:

The first examined the type of current sheet crossings recorded. Fig. 2 reveals four different types of current sheet crossing:

1) Full amplitude crossing: Provide good estimation of sheet thickness as Cluster moves from one extreme to the other.
2) Sub-amplitude crossing: Represent large fluctuations in current but are not full crossings, therefore not full thickness.
3) Half-thickness crossing: Represent only half a crossing, full thickness can be found by doubling the half thickness.
4) Gradual crossings: Calm crossings and good indicators of thickness, however only a small amount were recorded.

The second classification method ensured the direction of current sheet motion was parallel with the Z-axis (GSE-coordinates). A dynamic current sheet will yield a normal vector heavily inclined from the Z-axis and provide an inaccurate estimate of sheet thickness. A limit of twenty degree inclination used, this took into account the eleven-degree tilt of the Earth’s dipole axis and provided a suitably large margin to define inclined movement.

In order to test the validity of a current sheet crossing, data from Cluster’s RAPID and PEACE instruments was utilised in a comparative capacity. This included high-energy particle flux from RAPID and electron-density from PEACE. Fig. 3 demonstrates a comparison between FGM B(x) data and high-energy particle flux from RAPID.

Crossings 1-4 show that as Cluster moves through the magnetotail the flux density of electrons peaks indicating a rise in energetic particle flux. Crossing 5 indicates a general drop in flux as Cluster moves further from the tail. As expected, these comparisons demonstrate that the current sheet is host to a region of high-energy particles and can be used to confirm Cluster’s position inside the current sheet.
3. Statistical Survey Results

One can expect the solar wind to have one of two primary effects on the behaviour of the magnetotail. The first will demonstrate how the solar wind plays its role in the substorm cycle and how its associated processes influence internal magnetotail structure. The second will demonstrate the possible existence of a dynamic link, independent of substorm activity, between solar wind activity and motion within the tail and current sheet. Identifying the difference between these two influences is what makes this statistical analysis so poignant.

The results from the statistical analysis have been categorised into four areas.

3.1 Crossing Characteristics

Fig. 4 shows the location at which Cluster crosses the current sheet in the YZ-plane, the events are distributed within –12 Re < Y < 12 Re and –4 Re < Z < 5 Re. During July/August periods crossings were located within the evening sector (Y > 0) and took place above the Z=0 plane, during subsequent September/October periods crossings were located below the Z=0 plane in the morning sector (Y < 0). The pattern revealed in the plot illustrates current sheet twisting, a characteristic induced by the Y-component of the IMF, similar findings are reviewed in Petrukovich et al. (2004). Fig. 4 can also be used to infer the scale of the current sheet and the scale of its motion. At approximately Y = 10 Re crossings take place near the Z = 0 plane and others take place almost 5 Re away. This demonstrates the intensely dynamic nature of the current sheet and further verifies that it is not a static planar structure.

3.2 Separation of Current Sheet Components

The timing analysis method used in this investigation allowed an accurate determination of the contributing components of current sheet motion, velocity and direction. Consequently it is possible to analyse how these various components effect each other and effect internal magnetotail dynamics associated with substorms.

Initial analysis of current sheet thickness as a function of current sheet position and direction of motion revealed no trends. This is an indication that substorm dynamics are not influenced by current sheet position or direction.

Comparisons of current sheet thickness and current sheet velocity (fig. 5) did reveal trends. The population of events, all of which are z-axis aligned, have a thickness between 0 and 3 Re and velocities between 0 and 75 km/s. At low velocities there is a large spread of sheet thickness, at high velocities thickness becomes limited. This is an important result and demonstrates that a dynamic, fast moving current sheet is associated with substorm onset. During substorm onset build up of magnetic flux in the magnetotail causes the current sheet to become thinly compact, well defined and energetic.

3.3 Internal Correlations

The link between external solar wind parameters (ram pressure/clock angle) and internal substorm activity was not revealed in this investigation. As such, a focused study of internal substorm characteristics was undertaken.

Current sheet thinning, usually caused by substorm dynamics, may also be a more direct influence of dynamical solar wind conditions when substorm activity is low. Separating out these two influences is extremely complex but is something this statistical survey has tried to achieve.

Fig. 6 shows a plot of Dst against current sheet thickness. The current sheet has limited thickness at large negative values of Dst and a large spread of thickness at low values of Dst. Low values of Dst typically relate to post substorm conditions when energy is released from the tail and it loses its dependence on substorm dynamics, hence a large spread of thickness. High vales of Dst indicate pre-storm activity when substorm dynamics reassert their control over the magnetotail causing a build up of magnetic flux that leads to a thin, more defined current sheet.
Additional analyses made of sheet thickness against Kp confirmed these findings. The statements made also support those made about current sheet velocity and indicate a direct link exists between Dst, Kp, current-sheet velocity and current sheet thickness.

The tail-crossing catalogue also allowed an internal study on the current-sheet. Analysis of current sheet thickness revealed increases in current density and electron density as the sheet thinned. This demonstrates that a thin current sheet is more defined as plasma content becomes compressed resulting in higher energies that cause the high sheet velocity and increased Kp/Dst values already discussed.

External Correlations

Whilst a link between external solar wind parameters and internal substorm dynamics has not been found, a simpler dynamical link between solar wind activity and current sheet motion was observed.

Fig. 7 shows the affect ram pressure has on the velocity of the current sheet, this data is representative of a solar wind with a dominant velocity in the Y-direction. The plot indicates the constant presence of a ram pressure on the magnetosphere tending to be between 1 and 2.5 nPa where there is a large spread of current sheet velocity. As ram pressure increases past this nominal level the velocity of the current sheet becomes limited. This indicates that intense solar winds with a dominant Y-component of velocity hinder movement of the current sheet, the reason for this relation has not been identified. A further study was carried out on current sheet Z-axis alignment as a function of ram pressure, however no patterns were found.

4.0 Discussion

This investigation has studied the use of multi-spacecraft configurations as a tool for observing the Earth’s magnetotail, a significant controlling element in substorm cycles.

The creation of a catalogue recording Cluster magnetotail crossings has been the driving objective. This catalogue has been used to carry out a detailed statistical study of current sheet characteristics, internal magnetosphere parameters and external solar wind parameters. The study has allowed a number of statements to be made:

- Crossing Characteristics: Analysis of the location at which Cluster crossed the current sheet revealed evidence supporting current sheet twisting.
- The position of the current sheet and the direction it’s moving have no affect on substorm dynamics. Trends exist between sheet velocity and thickness.
- Substorm onset and expansion activity within the magnetotail is directly related to current sheet thickness and current sheet velocity. A link between external solar wind parameters and internal substorm parameters has not been revealed.
- A simple dynamic link between solar wind intensity and current sheet activity exists. Increased ram pressure (particularly with dominant Y-components of velocity) has an element of control over current sheet velocity.

Whilst this analysis can be considered a success, further study with minor modifications to the implemented methodology may prove advisable. The magnitude of coherent data sets, particularly in data plots, was acceptable, however further scientific validity could be gained by expanding coherent datasets improving the confidence of overall results. Due to the variable nature of current sheet dynamics, statements regarding uncertainty have been omitted for the benefit of simplicity, further credibility would be gained by addressing any errors that may exist within the catalogue. Finally further study may be warranted in order to seek the link between external solar wind parameters and internal magnetosphere substorm activity described in theory but not revealed in this investigation.

References:

Coordinated Data Analysis Website:
http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/
UK Cluster Data Centre:
http://www.cluster.rl.ac.uk