Chapter 5

Structural Characteristics of Dipolarization Fronts Associated with Bursty Bulk Flows (BBFs)

5.1 Introduction

The Earth’s magnetosphere is in an out of equilibrium state because it is continuously powered by the turbulent solar wind. Some of the strong evidences for this non-equilibrium state of the magnetosphere are – the dependence of the magnetospheric dynamics on the direction of the IMF $B_z$ field especially the occurrence of the storms and substorms during the southward turning of the IMF $B_z$ [Sharma et al., 2005], the variable asymmetric shape of the magnetosphere with the long ($\sim 100\, R_E$) nightside magnetotail region compared to the relatively short ($\sim 10\, R_E$) day-side magnetosphere, and plasma convection and intermittent energy transport phenomena known as Bursty Bulk Flows [Angelopoulos et al., 1994].
Plasma convection in the Earth’s magnetosphere is considered to be the consequence of the plasma processes such as magnetic reconnection occurring both at the magnetopause and magnetotail. Solar wind energy flows inside the magnetosphere during the periods of magnetopause reconnection. When the IMF is oriented southward, magnetic reconnection occurs as the IMF can connect to the Earth’s northward magnetic field. The solar wind then drags the reconnected field lines from the dayside to the nightside, allowing the plasma to pour into the tail of the magnetosphere. This drag stretches the field lines, and stores the energy in the form of magnetic tension. As the field lines pile up on the nightside the system becomes unstable. Reconnection happens again, this time in the middle of the tail (a phenomenon associated with substorm): the newly open magnetic field lines reconnect to form closed field lines, which return back to the Earth. When this occurs, stored particles and energy are released both Earthward and tailward. These phenomena energize ions and electrons and leads to plasma convection both Earthward and tailward.

Various magnetic structures are observed in the plasma sheet region during the plasma convection towards Earth. The most common structures are – dipolarization fronts, flux ropes and travelling compression regions. In our study, we have focused mainly on the dipolarization fronts. These magnetic structures are characterized by a sharp increase in the z-component of the magnetic field on time scales of the order of few seconds. They are often found to be associated with the Earthward high velocity flow events which are termed as BBFs. So before going through the DFs, we first define the BBFs and their characteristic features.
5.2 Bursty Bulk Flows (BBFs)

The average flow velocity in the central plasma sheet is small ($\sim 50 \text{ kms}^{-1}$) due to the predominant of low velocity flows. However, although the central plasma sheet ion flow is most often nearly stagnant and with no preferred direction, it is interrupted by high speed earthward flow events known as bursty bulk flows (BBFs). BBFs are enhanced bulk velocity ($> 100 \text{ kms}^{-1}$) events with time scales of the order of about 10 minutes, containing many short-lived ($< 60 \text{ s}$) high velocity ($400 \text{ kms}^{-1}$) flow bursts [Ma et al., 2009]. They are the most dynamics events occurring in the central part of the plasma sheet between $X=-7 \text{ R}_E$ to $X=-30 \text{ R}_E$ of the magnetotail. Though they are short-lived events, they are reported to be the main process responsible for the transport of mass, energy and flux from the midtail plasma sheet to the near-earth tail region [Angelopoulos et al., 1994, 1997; Baumjohann, 1993]. BBFs have been defined in different ways by different researchers. There is no precise definition of high-speed flows. However, if the bulk speed of protons is higher than 300–400 kms$^{-1}$, it is generally considered as a fast flow event. The typical time scale may change depending on the selection criteria. Angelopoulos et al. [1994] have defined BBFs as segments of continuous total ion flow velocity ($> 100 \text{ kms}^{-1}$) with a peak in the velocity ($> 400 \text{ kms}^{-1}$) whilst the observing spacecraft was in the inner plasma sheet ($\beta > 0.5$). The BBFs are positively correlated to the AE index, however, there is no one-to-one correspondence between a substorm and BBF. This means that although most of the substorms are accompanied by one or more BBFs, BBFs also occur during the low activity conditions. However, their occurrence is most frequent during high auroral electrojet activity [Baumjohann, 1993].
There are several models proposed for the origin of the BBFs. Magnetic reconnection in the near-earth neutral line (NENL) model is one among the many models that have been used to explain the transport of mass and momentum at high speed toward Earth [Baumjohann et al., 1990; Runov et al., 2012]. On the other hand, NENL model is considered as the main mechanism for substorm onset triggering. Since there is no one-to-one correspondence between the occurrence of substorms and BBFs, NENL model has limitations in explaining the origin of BBFs. Several other models have also been proposed for the BBFs. Russell et al. [1994] suggested that BBFs can be triggered by the sudden changes in solar wind dynamic pressure. Another possible mechanism for the BBFs was proposed by Lakhina [1996] in terms of bursty type driven reconnection which is induced by perturbations due to the solar wind forcing.

BBFs are spatially and temporally limited structures in both latitude and longitude. It is important to quantify the spatial and temporal scales of BBFs in order to understand their contribution to the energy transport process. There have been a number of studies in finding the spatial scale size of BBFs. Comparing the single spacecraft measurements with the ground based data the spatial extent of the BBFs were found to be limited to 3–5 $R_E$ [Angelopoulos et al., 1997; Nakamura et al., 2001]. However, there were many difficulties in the calculation of the spatial scale of BBFs by using data obtained by single satellite. The temporal and spatial variations of BBF can not be separated by the data of single satellite. Sergeev et al. [1996] used two spacecraft measurements of ISEE 1 and 2 and found the spatial extent to be 1–3 $R_E$. With the launch of multiplescacrft satellites, both the spatial and temporal scales of BBFs could be measured more accurately. Nakamura et al. [2004] using measurements from
the four spacecraft Cluster mission provided more direct evidence on the spatial scale which was about 2–3 \( R_E \) in the dawn-dusk direction (Y-direction) and 1.5–2 \( R_E \) in the north-south direction (Z-direction). The spatial extent is composed of three dimensions: the dawn–dusk, the north-south and the Sun-Earth direction scale size. The scale size along the Sun-Earth direction can be easily estimated knowing the typical duration and the velocity of BBFs. The spatial scale along the X-axis is approximately about 10 \( R_E \). One way of looking at the structural features of the fast BBFs is achieved by determining the orientation of the dipolarization fronts.

### 5.3 Dipolarization Fronts (DFs)

Dipolarization fronts are magnetic structures of time scales of the order of few seconds and are often found to be associated with earthward fast flows. They are characterized by a sharp increase in the z-component (north-south component) of the magnetic field. Local enhancement in \( B_z \) field is attributed to the interaction of the BBFs with the ambient plasma ahead of them, forming a thin boundary layer in between them. DFs preceded by a small decrease in \( B_z \) or even negative \( B_z \) field accompanied by electric and magnetic field fluctuations were reported in a number of studies [Ohtani et al., 1992, 2004; Shiokawa et al., 2005]. Evidences for the DFs propagating towards the earth have been reported in a number of earlier studies [Nakamura et al., 2002; Runov et al., 2011; Sergeev et al., 1996; Sitnov et al., 2009]. DFs are believed to be essential ingredients of the substorm process, and are generally considered as the region where the charged particles get energized and contribute to the further auroral
Chapter 5: Structural Characteristics of Dipolarization Fronts

104

intensifications in the ionosphere. One possible mechanism of the generation of DFs is that the near-Earth neutral line (NENL) formed in the midtail, causes large amounts of magnetic flux to be transformed Earthward accompanied by fast earthward flows. As the flow approaches the earth, it is decelerated because the background magnetic field strength or the plasma pressure increases and as a result, large amounts of magnetic flux starts to pile up in the near magnetotail region earthward of the reconnection site [Baumjohann, 2002; Nakamura et al., 2009; Runov et al., 2012; Sitnov et al., 2009].

5.4 Aim of the study

Dipolarization fronts of both small $B_z$ variation amplitudes ($\sim 6$ nT) [Schmid et al., 2011] and large $B_z$ variation amplitudes ($> 10$ nT) [Huang et al., 2012; Runov et al., 2012] have been studied extensively and they are mostly associated with bursty bulk flows. Bursty bulk flows are usually considered to begin when the Earthward ion flow velocity component is above 100 kms$^{-1}$ and exceeds 400 kms$^{-1}$ for at least one sample period during the flow event [Angelopoulos et al., 1994]. In this chapter, we discuss the results of a multicase study of four consecutively observed dipolarization fronts associated with moderately high velocity BBFs, each of which is simultaneously detected by all the four Cluster spacecrafts. We analyze the variations in magnetic and electric fields, plasma moments, and particle and energy fluxes detected during front crossings. We also study the motion and structural properties of these dipolarization fronts. These informations are essential for understanding the physics of DF formation and evolution and the role of fronts in energy transport in the magnetotail.
This chapter is organized in the following manner. In the following section we discuss the instrumentations on the Cluster spacecrafts relevant to the present study. This is followed by overview of the dipolarization front events. Determination of the motion and the scale of the DFs are given in the next section. Summary is given in the last section.

5.5 Data and selection criteria of Dipolarization Fronts

In our study, we used 4 sec time averaged plasma data obtained from the CODIF of Cluster Ion Spectrometry (CIS) instrument, 0.20 sec time averaged magnetic field data provided by the Fluxgate Magnetometer (FGM) instrument. The electric field data is provided by Electric Field and Wave (EFW) instrument. The electron moment is from the Plasma Electron And Current Experiment (PEACE) instrument. High energy proton and electron differential particle flux data are obtained from the Research with Adaptive Particle Imaging Detectors (RAPID) instrument. All variables are in Geocentric Solar Magnetospheric (GSM) coordinate system.

The Cluster mission has a half-year tail season and a half-year dayside season every year. The tail season usually falls during July to October of each year. To study the spatial characteristics of the DFs, it is important to select an event in which the front is detected simultaneously by all the four cluster spacecrafts. A DF event detection simultaneously by all the four spacecrafts could be possible when the interspacraft separations are very small. For the selection of the DF events, we used dataset from Cluster obtained during the first three/four
years (i.e., 2001 to 2004) of its launch, during which the spacecraft separations were smallest lying in the range 250 km to 4000 km, and also since the apogee of the Cluster is 19.6 \( R_E \), we have limited the data when the spacecraft were located between \(-20 \text{ } R_E \leq X \leq -10 \text{ } R_E \) and \(|Y| \leq 15 \text{ } R_E \) to avoid magnetopause crossings and \(-4 \leq Z \leq 6 \text{ } R_E \) to avoid mantle crossings. Here, we refer to \( X, Y, Z \) as the three orthogonal directions in the Geocentric Solar Magnetospheric (GSM) coordinate system.

We have selected BBF associated DF events satisfying the selection criteria used by Schmid et al. [2011]. The requirements for the selection of the DF events are given as follows:

1. The spacecraft is located in the plasma sheet region which is identified as the region with \( \beta > 0.5 \).

2. The observed Earthward plasma flow \( V_x \) is at least in one data point greater than 150 \( \text{kms}^{-1} \) i.e, \( V_x \geq 150 \text{ kms}^{-1} \).

3. The duration of the DFs is taken as the duration from the minimum \( B_z \) value to the maximum \( B_z \) value.

### 5.6 Overview of the events

In our study, we have examined four different dipolarization front events associated with BBFs of velocities ranging from about 150 \( \text{kms}^{-1} \) to about 800 \( \text{kms}^{-1} \). We have chosen these events using the selection criteria stated in the previous section.
5.6.1 5 August 2003, 19:10–23:20 UT

On 5 August 2003, the four Cluster spacecrafts were in a regular tetrahedron arrangement with inter-spacecraft separations less than 260 km. Four DFs were detected between 19 UT to 23:30 UT on August 5, 2003 – the first three were detected between 19:10–19:20 UT and the fourth occurred between 23:05–23:10 UT. The average locations of the spacecrafts (C1, C2, C3, C4) during the two time intervals are (-15.05, -9.57, 1.54) RE, (-15.06, -9.53, 1.54) RE, (-15.08, -9.55, 1.54) RE, (-15.06, -9.56, 1.51) RE and (-16.36, -9.22, -0.78) RE, (-16.39, -9.19, -0.79) RE, (-16.39, -9.20, -0.78) RE, (-16.37, -9.21, -0.81) RE, respectively. Fig. 5.1 shows the Bz magnetic field component, Earthward plasma flow velocity Vx, ion density ni, ion temperature T, magnetic pressure Pm, plasma pressure Pp and plasma beta β within the intervals 19:10–19:20 UT and fig. 5.2 shows the same variables for the time interval 23:05–23:10 UT. Here we have shown only the data measurements obtained from C1 since due to very small spatial separations between the spacecrafts, the signatures observed by the four spacecrafts are almost identical to one another with very small time delays between them.

The solar wind dynamic pressure and bulk velocity during the two time intervals were close to \(\sim 2.5 \text{ nPa}\) and \(\sim 420 \text{ km s}^{-1}\), respectively; the IMF Bz component varied around zero not exceeding 6 nT in absolute value. Fig. 5.3 shows the AE and AL indices between 19:00 UT of 5 August 2003 to 02:00 UT of 6 August 2003. During the interval of the depolarization front, the AE index increases from about 50 nT to 900 nT while the AL index decreases from about -50 nT at 19:00 UT to about -800 nT at 2:00 UT. During the first time interval (DF1, DF2, DF3), the AE index is at around 100 nT whereas during the second
Figure 5.1: Overview of the Magnetic field and plasma moments measurements between 19:10:00 UT–19:20:00 UT on 5 August 2003. Bz components of magnetic field from the spacecrafts C1, C2, C3, C4 are plotted in panel (a), Earthward component of ion velocity Vx from C1 in panel (b), ion density from C1 in panel (c), ion temperature, ion parallel temperature, ion perpendicular temperature in panel (d), total pressure in panel (e), magnetic pressure in panel (f), plasma beta in panel (g), and Alfven velocity in panel (h); red vertical lines mark the starting times of the DFs.

time interval the AE index is having values at around 600 nT. This shows that DF1, DF2 and DF3 occurred during geomagnetically quite time whereas DF4 occurred during the expansion phase of a substorm.

DFs characterized by sharp enhancements in the z-component of the magnetic field accompanied by small fluctuations in Bx and By fields occurred at around 19:12:40 UT, 19:13:54 UT, 19:15:58 UT for the first three events (DF1, DF2, DF3) and at around 23:05 UT for the fourth event (DF4). These DFs are with variation amplitudes (δBz) approximately 12 nT, 5.3 nT, 8.6 nT and 13 nT respectively. DF1, DF2, and DF3 occurred during a BBF event with peak velocity of the order of 150 kms⁻¹ spanning a period of 6 mins and DF4 during
Chapter 5: Structural Characteristics of Dipolarization Fronts

Figure 5.2: Overview of the Magnetic field and plasma moments measurements between 23:05:00 UT–23:10:00 UT on 5 August 2003. Panel names same as fig. 5.1.

Figure 5.3: AE and AL indices observed from 19:00UT, 5 August to 02:00UT, 6 August.

the follow up BBF event with a peak velocity of $\sim 250 \text{ kms}^{-1}$ spanning a period of $\sim 4$ mins. Panels (c) and (f) in figures 5.1 and 5.2 show the ion density and plasma pressure. Here it is observed that there are slight increases in ion density and plasma pressure ahead of the DF crossings by the spacecraft. This
has been reported in earlier works and has been attributed to the compression of the ambient plasma by the approaching dipolarized flux tube [Li et al., 2011]. Then at the start of the dipolarization of the magnetic field, transient reduction in the ion density is observed, which is most probably due to the latitudinal (and Earthward) expansion of the plasma by field aligned flows both northward and southward [Ohtani et al., 2004]. Panel (d) [fig. 5.1 and 5.2] shows the ion temperature measured during the time intervals. Increase in temperature occurs during both the DF crossings showing particle accelerations at the DFs. The rapid decrease in the ion pressure ($P=n_i kT$) just behind the DF is caused by the rapid density decrease, which is not compensated by the gradual increase in the ion temperature. Increase in the magnetic pressure is observed during the DF crossings (shown in panel (c)). As the plasma pressure increases while the magnetic pressure decreases, decrease in the plasma-$\beta$ (ratio of plasma pressure to the magnetic pressure) is observed, however the value remains above 0.5 during the intervals implying that the spacecraft was located well in the central plasma sheet region. These are some of the typical characteristic features of the DFs and these are similar to the characteristic features of plasma bubble in the near-earth region reported earlier [Chen and Wolf, 1993; Sergeev et al., 1996].

5.6.2 Particle acceleration at the DFs

Acceleration of energetic particles, increase in the energetic electron flux and large variation in electron temperature have been reported to be observed within the DFs in the magnetotail [Ashour-Abdalla et al., 2011; Runov et al., 2012]. Particle acceleration has been attributed to mechanisms such as adiabatic acceleration (Fermi acceleration, betatron acceleration, etc.), and non-adiabatic
acceleration (wave particle injections, inductive electric fields, parallel electric fields, etc.). Lower energy electrons are usually accelerated in the diffusion region of magnetic reconnection by the process of Fermi acceleration whereas acceleration of energetic electrons (30–200 keV) within the DFs occur as a result of betatron acceleration. The concept of betatron acceleration is that by conserving \( \frac{v^2}{B} \) when \( B \) increases (a result of dipolarization), particles get energized along the perpendicular direction. Figure 5.4(a) shows the perpendicular (\( v_\perp \)) and parallel (\( v_\parallel \)) electron velocities during the time interval 19:10–19:20 UT of the first DF. It is observed that the \( v_\perp \) is increased to \( \sim 1000 \) kms\(^{-1} \) during the DF event with small variations in \( v_\parallel \). This clearly indicates that increase in \( v_\perp \) occurs as the \( B_z \) increases showing that betatron acceleration as the mechanism responsible for the acceleration of energetic electrons within the DF. Another way to reveal the enhancement of energetic electron flux within the DFs is by observing the anisotropic structure of electron distribution. The enhancements of the energetic electron

![Figure 5.4: Electron measurements from PEACE instrument, Top panel: Perpendicular (red) and parallel (blue) electron flow velocity, Bottom panel: Perpendicular (red) and parallel (blue) electron temperature.](image-url)
flux at large pitch angles (around 90°) are caused by betatron acceleration due to magnetic field compression as DFs propagate earthward, and at small pitch angles (around 0° or 180°) by Fermi acceleration due to a decrease of the distance between mirror points Pan et al. [2012]. These adiabatic acceleration processes can affect the pitch angle distributions of these energetic electrons. The betatron acceleration leads to pancake distributions (peak in pitch angle around 90°)[Birn et al., 2004] while the Fermi acceleration leads to cigar distributions (peak in pitch angle around 0° and 180°) [e.g. Wu et al. [2006]]. Fu et al. [2011] observed cigar distributions inside a decaying flux pileup region and pancake distributions in a growing flux pileup region, which were considered to be caused by Fermi and betatron accelerations, respectively. In the pitch angle distributions for DF1, DF2 and DF3 in the energy range 500 eV to 1500 eV (figure not shown), it is observed that the distribution peaks at around 90° for all the four spacecraft measurements indicating that betatron acceleration is still a mechanism for the enhancement of low energy electron flux within the DFs. This statement is against the statement of Zhou et al. [2013] which stated that the high energy electron flux increases while the low energy electron flux decreases inside the DF.

5.6.3 Current density enhancement at the DFs

The small interdistance between the four Cluster spacecraft enables us to calculate the electric current density during each DF event by using a method called the Curlometer technique [Dunlop et al., 2002]. This technique is one among the several techniques for calculating the current density $\mathbf{J}$. It is based on the application of the Maxwell-Ampere’s law which according to this law, the curl
Chapter 5: Structural Characteristics of Dipolarization Fronts

of a magnetic field is proportional to current density. Maxwell-Ampere’s law can be written as

$$\mu_0 J = \text{curl} \, B$$

(5.1)

assuming the stationarity of the studied medium. In order to measure the curl of a magnetic field in space the magnetic fields measured with high accuracy from four non-coplanar points is required. The tetrahedron shape of the four Cluster mission enables this measurement of magnetic field.

![Graphs showing electric current density](image)

**Figure 5.5:** Electric current density by the Curlometer technique for the DF events (top panels) 19:10:00–19:20:00 UT and (bottom panels) 23:05:00–23:10:00 UT, 5 August 2003. The three components $J_x$, $J_y$, and $J_z$ are drawn together in upper panel and the ratio of the Divergence $B$ to Curl $B$ is shown in lower panel of each time interval.
We know that the divergence of the magnetic field is zero from the Gauss’s law and thus, any measured divergence highlights the limitations of this analysis technique. Therefore, we can use the measured divergence as a numerical check by comparing this with the measured curl of the magnetic field. The ratio of the divergence of the magnetic field and modulus of the curl of the magnetic field acts as an indication of the quality of the result from the curlometer technique, with lower ratios indicating more reliable results. Figure 5.5(a) shows the components of electric current densities $J_x, J_y, J_z$ and figure 5.5(b) shows the ratio of $\nabla \cdot B$ to $|\nabla \times B|$ measured during the first and second time intervals. Usually if this ratio is less than 0.5, than the result is considered to be reliable. As can be seen from figure, the ratio is much less than this value thus showing the validity of the applied method in finding the current density. We observe that the currents during the DF crossings are enhanced to large values and are flowing mainly in the YZ plane for the first DF event and XY plane for the second DF event as indicated by the larger components of the current. The maximum current obtained during the two DFs crossings are about 40 nAm$^{-2}$ and 20 nAm$^{-2}$ respectively. These enhancements in the current densities across the DFs can be explained by a diamagnetic effect ($BBJ = BBB \times \nabla P / B^2$) occurring due to the compression of the plasmas ahead of the DFs (decrease in magnetic pressure and simultaneous increase in plasma pressure indicates a diamagnetic effect due to plasma compression ahead of the DF) [Huang et al., 2012]. These enhancements in the current densities across the dipolarization fronts are important in the plasma sheet dynamics since the force produced by these currents is responsible for plasma injections towards the Earth contributing to the intensification of the auroral brightening in the ionosphere. Enhancement in current density also indicates current sheet thinning which is a signature of substorm growth.
5.7 Motion and spatial scale of the depolarization fronts

5.7.1 Method description

In order to determine the orientation, normal propagation velocity and spatial scale of the depolarization fronts, we have employed the Minimum Variance Analysis (MVA) and Multi-spacecraft Timing Analysis (MTA) techniques. A brief review of the methods are presented as follows.

5.7.2 Minimum Variance Analysis (MVA)

MVA technique is a discontinuity analysis method based on the single spacecraft time series data and it is the most commonly used technique in finding the geometry, dynamics and structural characteristics of magnetic discontinuities such as magnetopause, shock regions, depolarization fronts, etc. This method assumes the discontinuity to be planar and unchanging in time. This technique was introduced by Sonnerup and Cahill, [1967] and applies strictly in form to magnetic field data. It is based on the condition that $\text{div} \mathbf{B} = 0$, according to which the magnetic field component normal to the discontinuity, $B_n$, should be constant across the discontinuity. Although this ideal situation is never perfectly met in application to actual observations in space, this condition would mean that the variance of the magnetic field along the normal direction should
be minimum, but the normal component of the steady field is not necessarily smallest.

MVA consists of constructing a variance matrix and then finding its eigenvalues and eigenvectors. The time series of the magnetic field data can be represented by the set \( \{ B^{(m)} \} ; m = 1, 2, \ldots, N \); for measurements taken at \( \{ t \} \) over some interval. If \( \mathbf{n} \) is the unit vector along the normal direction to the discontinuity then the method identifies that direction in space along which the field component set \( \{ B^{(m)} \cdot \mathbf{n} \} \) has minimum variance. This normal unit vector \( \mathbf{n} \) can be determined by the minimization of the mean quadratic deviation, which is given by

\[
\sigma^2 = \frac{1}{N} \sum_{m=1}^{N} |(B^{(m)} - \langle B \rangle) \cdot \mathbf{n}|^2
\]  

(5.2)

where \( \langle B \rangle = \frac{1}{N} \sum_{m=1}^{N} B^{(m)} \) is the mean value of the sample and the minimization is subject to the normalization constraint \( |\mathbf{n}|^2 = 1 \).

The principal directions of the magnetic field variances can be obtained by solving \( \sigma^2 \). This is done by using the Lagrange’s multipliers method, which are given by the set of three homogeneous linear equations

\[
\frac{\partial}{\partial n_x} \left\{ \sigma^2 - \lambda |\mathbf{n}|^2 - 1 \right\} = 0
\]  

(5.3)

\[
\frac{\partial}{\partial n_y} \left\{ \sigma^2 - \lambda |\mathbf{n}|^2 - 1 \right\} = 0
\]  

(5.4)

\[
\frac{\partial}{\partial n_z} \left\{ \sigma^2 - \lambda |\mathbf{n}|^2 - 1 \right\} = 0
\]  

(5.5)
Here $\mathbf{n}$ is represented in terms of its three components ($n_x, n_y, n_z$) along the Cartesian co-ordinate system $X, Y, Z$ in which the field data $\{B^{(m)}\}$ are given. When the differentiations in the above equations have been performed, the resulting set of three equations can be written in the matrix form as

$$\sum_{j=1}^{3} M_{ij}n_j = \lambda n_i \quad (5.6)$$

where $M_{ij} = \langle B_i B_j \rangle - \langle B_i \rangle \langle B_j \rangle$ and $\langle B_i B_j \rangle = \frac{1}{N} \sum_{m=1}^{N} B_i^m B_j^m$. The subscripts $i, j = 1, 2, 3$ denote Cartesian components along the $X, Y, Z$ system. The variance matrix $M_{ij}$ is a symmetric variance matrix, and hence the eigenvalues $\lambda_1, \lambda_2$ and $\lambda_3$ (in order of decreasing magnitude) are all real and the corresponding eigenvectors $x_1, x_2$ and $x_3$ are orthogonal. The three eigenvectors represent directions of maximum, intermediate and minimum variance in the field components along each vector. The corresponding $\lambda$ values represent the actual variances in those field components and are therefore non-negative. The eigenvector $x_3$ corresponding to the smallest eigenvalue $\lambda_3$ is used as the estimator for the direction normal to the discontinuity and $\lambda_3$ itself represents the variance of the magnetic field component along the estimated normal. The eigenvectors $x_1$ and $x_2$ corresponding to the maximum and intermediate variances, are then tangential to the discontinuity layer.

The quality of the MVA results is determined by the ratio of intermediate to minimum eigenvalues. In this method, it is considered that the discontinuity has a well defined normal direction if the ratio of the intermediate to the minimum eigenvalue is greater than 2. Higher values of this ratio indicates better result from the method.
Chapter 5: Structural Characteristics of Dipolarization Fronts

5.7.3 Multi-Spacecraft Timing Analysis (MTA)

MTA is another method to determine the normal direction to a DF. We have used this method in order to validate the results of MVA by comparing the results from the two methods. This method also enables us to calculate the magnitude of the normal propagation velocity $v$ and hence the thickness of the DF knowing the duration of the DF. This method uses both the time differences and spatial separations between the spacecrafts encountering the same magnetic structure. Here it is assumed that the time delay between the spacecraft measurements is due to a planar structure passing the spacecraft with a constant velocity [Harvey, 1998]. We assume that the discontinuity lies in a plane defined by the direction of its normal $\mathbf{n}$, and that this plane is moving in the direction $\mathbf{n}$ with velocity $v$. If the DF passes several spacecraft, the relative positions and timings can be used to construct the DF normal and the normal flow velocity $v$, from the relation

$$ \mathbf{r}_{\alpha\beta} \cdot \mathbf{n} = v(t_{\alpha\beta}) $$

where $\mathbf{r}_{\alpha\beta}$ is the separation vector between any spacecraft pair and $t_{\alpha\beta}$ is the time difference between this pair for a particular DF. Thus, for a 4 spacecraft distribution, the normal vector $\mathbf{n}$ and the normal propagation velocity $v$ are obtained from the solution of the following system of equations:

$$ \begin{pmatrix} \mathbf{r}_{12} \\ \mathbf{r}_{13} \\ \mathbf{r}_{14} \end{pmatrix} \cdot \begin{pmatrix} \frac{1}{v} \\ \mathbf{n} \end{pmatrix} = \begin{pmatrix} t_{12} \\ t_{13} \\ t_{14} \end{pmatrix} $$

$$ (5.8) $$
\[ \Rightarrow \mathbf{p} = \frac{1}{v} \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix} = \begin{pmatrix} r_{12} \\ r_{13} \\ r_{14} \end{pmatrix}^{-1} \begin{pmatrix} t_{12} \\ t_{13} \\ t_{14} \end{pmatrix} \]  

(5.9)

From this we obtain

\[ v = \frac{1}{|\mathbf{p}|} \]  

(5.10)

\[ \mathbf{n} = v(\mathbf{p}) \]  

(5.11)

5.8 Analysis results

5.8.1 Orientation and Normal Propagation velocities of the DFs

Minimum variance analysis method is applied to the magnetic field data measured by the four Cluster spacecrafts during the DF time intervals. We have defined the DF time interval from the time of minimum \( B_z \) value to the first peak \( B_z \) value. A summary of the MVA results for all the DFs are given in table 5.1. Here, the start time corresponds to the min \( B_z \) value and the end time to the peak \( B_z \) value. The average durations of the DFs are 3 sec, 3.7 sec, 9.5 sec and 3.05 sec, respectively. The normal directions of each DF at the four spacecraft locations all lie close to each other with small angular separations (\(< 15^\circ\)). Almost in all the cases, the ratio of the intermediate eigenvalue
to the minimum eigenvalue is greater than 5. This indicates reliable and well-defined normal directions determined by the MVA method. Figure 5.6 shows the possible projections of the DFs at each spacecraft locations in the XY and XZ planes clearly showing nearly identical projections of each of the DF at the four spacecraft locations. These nearly identical projections of a DF at the 4 spacecraft locations suggest a planar structure of the front layer. The directed lines correspond to the normal directions to the fronts at the location of the spacecraft. From these observations it can be inferred that the DFs are propagating Earthward (as indicated by the positive and dominant X-components of the normal vectors) and towards duskward for DF1 (indicated by the positive Y-component) and toward dawnward for the other three DFs (indicated by the negative Y-component). These duskward and dawnward propagation of the BBF associated DFs indicates to be the consequence of magnetic reconnection in the midtail region. This is in accordance to the observations of Birn and Hesse [1996] and Birn et al. [1999] which showed that the earthward reconnection flows are diverted dawnward and duskward in association with the depolarization of the magnetic field.

In table 5.2 we have shown the details of the Multi-spacecraft timing analysis (MTA) results for all the DFs. The normal directions of the DFs determined by the MTA technique are very close to the average normal directions determined by the MVA method. This agreement of the results from the two methods indicate reliable normal directions of the DFs. The magnitude of the normal propagation velocity of each of the DFs determined by the MTA are included in the table. These are approximately equal to their corresponding earthward ion flow velocities.
5.8.2 Discontinuity associated with the DFs

We have also determined the type of discontinuities associated with each of the depolarization fronts. Discontinuities are defined as the regions or boundary layers where the field and plasma properties usually change significantly.
Understanding the type of discontinuities associated with the DF layers has important implications for the topology and origin of the DFs. There are two commonly observed discontinuities in space plasmas. They are tangential and rotational discontinuities. Tangential discontinuity is defined as a surface where there is neither magnetic flux nor mass flux across it (that is, the normal flow speed must be zero) i.e, \( v_n = B_n = 0 \) [Fu et al., 2012; Sergeev et al., 1996], or in other words, it can be described as a surface separating plasmas of different densities and temperatures. Here, \( B_n \) is the normal magnetic field component to the discontinuity. A rotational discontinuity is defined as a surface where the plasmas on the two sides of the discontinuity layer are magnetically connected, and densities and temperatures are the same i.e. \( v_n \neq B_n \neq 0 \). The normal magnetic field component \( B_n \) is the primary quantity used to distinguish tangential discontinuities from rotational discontinuities. In practical applications, the normal magnetic field component \( B_n \) is very small nearly equal to zero for tangential discontinuities whereas non–zero for rotational discontinuities. There is also another quantity that can be used to identify the type of discontinuities. The total pressure must be conserved across the boundary, however this condition is not necessarily conserved across the boundary because the front layer may not be in a stationary state because of the force imbalance.

We have computed the average magnetic field along the normal directions of the DFs (\( B_n \)) [or \( \langle B \rangle \cdot n \)] for each spacecraft measurement (shown in table 5.1). Determination of \( B_n \) requires knowledge of the orientation of the DFs, which can be obtained by MVA of the magnetic field [Sonnerup and Scheible, 1998]. It is observed that in most of the cases these values are very small close to zero. These observations clearly suggest that these magnetic structures are tangential.
Table 5.1: Summary of the MVA results for all the DFs

<table>
<thead>
<tr>
<th>S/C</th>
<th>Time interval (UT)</th>
<th>( \mathbf{n} ) by MVA</th>
<th>( \lambda_2/\lambda_3 )</th>
<th>(&lt; B_n &gt; )nT</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF1</td>
<td>C1 19:12:41.1-19:12:43.7</td>
<td>0.7935, 0.5040, 0.3411</td>
<td>163</td>
<td>-0.13</td>
</tr>
<tr>
<td></td>
<td>C2 19:12:41.7-19:12:44.7</td>
<td>0.8108, 0.5206, 0.2675</td>
<td>23</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>C3 19:12:40.5-19:12:43.7</td>
<td>0.7803, 0.5259, 0.3384</td>
<td>46</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>C4 19:12:40.9-19:12:44.1</td>
<td>0.7217, 0.5854, 0.3694</td>
<td>53</td>
<td>-0.90</td>
</tr>
<tr>
<td>DF2</td>
<td>C1 19:13:57.9-19:14:01.7</td>
<td>0.8086,-0.4566,-0.3711</td>
<td>19</td>
<td>-0.39</td>
</tr>
<tr>
<td></td>
<td>C2 19:13:54.3-19:13:58.1</td>
<td>0.9405,-0.3065,-0.1465</td>
<td>6</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>C3 19:13:54.1-19:13:57.7</td>
<td>0.8588,-0.4467,-0.2510</td>
<td>10</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>C4 19:13:58.1-19:14:01.9</td>
<td>0.7392,-0.5574,-0.3781</td>
<td>5</td>
<td>-0.39</td>
</tr>
<tr>
<td>DF3</td>
<td>C1 19:16:00.3-19:16:09.3</td>
<td>0.7172,-0.1165, 0.6871</td>
<td>13</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>C2 19:15:59.7-19:16:09.3</td>
<td>0.7501,-0.3729, 0.5461</td>
<td>7</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>C3 19:15:58.3-19:16:08.1</td>
<td>0.6987,-0.1604, 0.6972</td>
<td>25</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>C4 19:15:58.5-19:16:08.1</td>
<td>0.7548,-0.1218, 0.6446</td>
<td>22</td>
<td>0.25</td>
</tr>
<tr>
<td>DF4</td>
<td>C1 23:05:38.1-23:05:41.1</td>
<td>0.9089,-0.3998, 0.1182</td>
<td>11</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>C2 23:05:36.9-23:05:39.7</td>
<td>0.8785,-0.4458, 0.1717</td>
<td>65</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>C3 23:05:36.7-23:05:39.9</td>
<td>0.8775,-0.4566, 0.1469</td>
<td>38</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>C4 23:05:37.3-23:05:40.5</td>
<td>0.9629,-0.2212, 0.1544</td>
<td>20</td>
<td>3.20</td>
</tr>
</tbody>
</table>

Table 5.2: Summary of the MTA results for DF1 and DF2

<table>
<thead>
<tr>
<th></th>
<th>DF1</th>
<th>DF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{n} ) (MVA)</td>
<td>0.7284,0.5339,0.3291</td>
<td>0.8368,-0.4418,-0.2867</td>
</tr>
<tr>
<td>( \mathbf{n} ) (MTA)</td>
<td>0.8318,0.5545,0.0616</td>
<td>0.8945,-0.4322,-0.1045</td>
</tr>
<tr>
<td>( \theta )</td>
<td>16(^\circ)</td>
<td>11(^\circ)</td>
</tr>
<tr>
<td>( v )</td>
<td>148</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 5.3: Summary of the MTA results for DF3 and DF4

<table>
<thead>
<tr>
<th></th>
<th>DF3</th>
<th>DF4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{n} ) (MVA)</td>
<td>0.7302,-0.1929,0.6438</td>
<td>0.9069,-0.3808,0.1478</td>
</tr>
<tr>
<td>( \mathbf{n} ) (MTA)</td>
<td>0.8680,-0.0255,0.4851</td>
<td>0.6900,-0.6900,0.1971</td>
</tr>
<tr>
<td>( \theta )</td>
<td>15(^\circ)</td>
<td>22(^\circ)</td>
</tr>
<tr>
<td>( v )</td>
<td>82</td>
<td>157</td>
</tr>
</tbody>
</table>
Table 5.4: Comparison of the thickness of the DFs with the ion inertial length \(d_i\) and ion gyroradius \(r_g\)

<table>
<thead>
<tr>
<th>Front duration (\Delta t) (sec)</th>
<th>(\delta_D = v \times \Delta t) (km)</th>
<th>(d_i) km</th>
<th>(r_g) km</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF1</td>
<td>3</td>
<td>442</td>
<td>265</td>
</tr>
<tr>
<td>DF2</td>
<td>3.7</td>
<td>106</td>
<td>188</td>
</tr>
<tr>
<td>DF3</td>
<td>9.5</td>
<td>774</td>
<td>261</td>
</tr>
<tr>
<td>DF4</td>
<td>3.07</td>
<td>479</td>
<td>576</td>
</tr>
</tbody>
</table>

discontinuities and are in agreement with the studies reported earlier [Sergeev et al., 1996].

5.8.3 Thickness of the DFs

The thickness of DF layers have been calculated in earlier studies and were found to be of the order of ion inertial length and ion gyroradius [Huang et al., 2011; Runov et al., 2011]. We have also estimated the average thickness of the dipolarization fronts. It is determined by the product of the estimated normal propagation velocity \(v\) of the DF obtained from the timing analysis and the average duration of the dipolarization front crossing time \(\Delta t\). The thickness of the DFs are given in table 5.4 and they compare well with either of the ion inertial length and the ion gyroradius. The ion inertial length is calculated from the ion density measurement using the relation \(d_i = 228 \times \sqrt{n_i}\) km, where \(n_i\) is the ion density in cm\(^{-3}\). The ion gyroradius is calculated from ion temperature and magnetic field measurements using the relation \(r_g = 1.02 \times 10^2 \sqrt{T_i/B}\) cm, where \(T_i\) is in eV and B is in Gauss.
5.9 Summary

In this chapter, we have investigated the structural characteristics of four consecutively observed dipolarization fronts detected by the multi-spacecraft Cluster during the growth phase of a substorm on August 5, 2003. The first three DF layers occurred within a BBF event whereas the fourth DF layer was accompanied by another BBF event. For our analysis, we have used plasma data from the CIS instrument, electron moments from the PEACE and RAPID instruments, and magnetic field data from the FGM instrument. All of these DF events exhibited several common features: sharp enhancement in the z-component of the magnetic field, increase in ion temperature, magnetic pressure and decrease in ion density and ion pressure. These characteristic features are consistent with those that have been defined in the earlier studies.

Increased in electron temperature is observed during each of the DF events indicating electron acceleration across the DF layers. These electron accelerations have been caused by the betatron acceleration as indicated by the increase in the perpendicular electron velocity across each front layer. This result has also been supported by the pancake electron flux distributions.

Enhancement in the current density across each of the fronts has also been observed. These current enhancements in the plasma sheet could be one of the factors contributing to the intensification of the auroral brightening in the ionosphere.

Projections of each of the DF layers have also been determined by using both single and multi-spacecraft based methods. All the front layers have been found propagating Earthward and dusk-side for the first layer whereas dawn-side for
the other three layers. The MVA method also enabled to determine the type of discontinuity associated with front layer. All the four DF layers are found to be tangential discontinuities. The thickness of the DFs have also been computed knowing the duration of the DFs and the normal propagation velocities. These thicknesses are found approximately to be in the range of ion inertial lengths or ion ion gyroradius. This observation is also in agreement with the earlier studies.
Bibliography


Nakamura, R., W. Baumjohann, B. Klecker, Y. Bogdanova, A. Balogh, H. Reme, J.M. Bosqued, I. Dandouras, J.A. Sauvaud, K.H. Glassmeier, L.


