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ORIGINAL ARTICLE

Dawn-dusk scale of dipolarization front in the Earth's magnetotail: multi-cases study

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Abstract We analyze three dipolarization front (DF) events to investigate their dawn-dusk scales in the Earth's magnetotail using the Cluster measurements in year 2007, when the spacecraft separation is about 1.8 Re (Re is the Earth's radius) and is appropriate for investigating the DF scale. Based on the Minimum Variance Analysis (MVA) and the general shape of the DF, we found that Cluster detected the center and the flank (or just beyond the flank) of DF in the same event. This means that the scale of DF is about 3.6 Re in the dawn-dusk direction, larger than that reported in previous studies. Using the semicircle function to fit the observations, we got the dawn-dusk scale of ∼3.2–3.6 Re, consistent with the rough estimation. Considering large separation among the spacecraft, the timing analysis cannot be used to obtain the normal of DF and the propagation velocity along the normal. One should be careful when performing timing analysis of DF using the Cluster data, and have to carry on MVA analysis to check the normal of DF before do timing analysis.

Keywords Magnetotail · Dipolarization front · Dawn-dusk scale · Timing analysis

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1 Introduction

The dipolarization front (DF) in the plasma sheet of Earth's magnetotail is a tangential discontinuity (Sergeev et al. 2009; Fu et al. 2012a) separating the dense plasma from the reconnection flow; it is characterized by the sharp increase in the Z-component of magnetic field in the GSM coordinates, always together with the decrease in the plasma density and the increase in the temperature (Runov et al. 2009). Kinetic simulations have shown that the dipolarization fronts (DFs) can be produced by transient reconnection, and likely to be a new regime of collisionless reconnection in contrast to magnetic islands or plasmoids (Sitnov et al. 2009). Based on 3D magnetohydrodynamics (MHD) simulation, DFs are found to be formed in downstream of reconnection region, and to be affected by the kinking flux ropes and can lead to interchange instability (Lapenta and Bettarini 2011). Recently, Fu et al. (2013b) provided observational evidence from multi-point observations that the near-Earth dipolarization front is induced by transient reconnection. In addition, MHD and Hall MHD simulations have shown that interchange instability is also a source of DF (Guzdar et al. 2010; Lu et al. 2013).

DFs are frequently detected by Cluster (e.g., Nakamura et al. 2002; Fu et al. 2012b) and THEMIS (e.g. Runov et al. 2009; Liu et al. 2013a) in the near-Earth magnetotail ranging from $X_{\mathrm{GSM}} \sim -20$ Re to $X_{\mathrm{GSM}} \sim -10$ Re (GSM: Geocentric Solar Magnetospheric). The occurrence rate of earthward-propagating DFs has been investigated by using 9 years of Cluster data from 2001 to 2009 (Fu et al. 2012b). The maximum occurrence rate is found to be at $Z_{\mathrm{GSM}} \approx 0$ and $r \approx 15$ Re with one event occurring per 3.9 hours, where r is the distance to the center of the Earth in the XY_{GSM} plane. The thickness of the DF is suggested to be comparable to the ion inertial length or the ion Larmor radius (e.g., Runov et al. 2009; Sergeev et al. 2009; Zhou et al. 2009, 2011; Schmid et al. 2011; Huang et al. 2012a, and reference therein). Various wave activities around the DF region including the lower hybrid drift waves, electron cyclotron harmonic waves (Zhou et al. 2009), whistler waves (e.g., Deng et al. 2010; Khotyaintsev et al. 2011; Huang et al. 2012a), and other high frequency waves such as electrostatic solitary wave and double layer (Deng et al. 2010), are observed; the intense electric field (e.g. Fu et al. 2012a, 2014; Huang et al. 2012a) is also reported. In addition, acceleration of electrons (e.g., Deng et al. 2010; Fu et al. 2011, 2013a; Ashour-Abdalla et al. 2011; Huang et al. 2012a, 2012b; Zheng et al. 2012; Zhou et al. 2013) and ions (e.g., Zhou et al. 2010; Wu and Shay 2012) are also reported around the DF.

There is a close relation between DFs and bursty bulk flows (BBF) (e.g., Runov et al. 2009; Schmid et al. 2011; Fu et al. 2012b, 2012c; Liu et al. 2013a). Usually they propagate with the same speed, and the DF is roughly a tangential discontinuity (Fu et al. 2012a). The scale of BBF was reported to be 2–3 Re in the dawn-dusk direction and 1.5–2 Re in the north-south direction (Nakamura et al. 2004), while the scale of DFs has not been full well determined. Understanding of dawn-dusk scale of the DF can be applied to estimate transport of plasmas, magnetic fluxes and energies by DF in the magnetotail. Using observations from the four Cluster spacecraft with separation of 4000 km (0.6 Re), Nakamura et al. (2005) have inferred the scale of DF from the change of orientation to be 1.5–2.2 Re in dawn-dusk direction. However, this Cluster separation (4000 km) was too small compared to the scale of DF. To better understand the DF scale, an appropriate separation of spacecraft should be considered.

In this paper, we consider the observations should satisfy the criteria that the spacecraft separation should be comparable to the reported scale of BBFs (Nakamura et al. 2004), and the four spacecraft have to be almost in the same X-Y plane (in other words, the separation in the Z direction should be very small), at least three spacecraft should detect the DFs. Thus, we use the Cluster measurements in 2007, when the spacecraft separation is about 10000 km (1.8 Re) almost within the same X-Y plane in the Earth's magnetotail (maximum of ΔZ_{GSM} is 0.25 Re), and choose three different DF events to investigate the dawn-dusk scale of DF. Magnetic field and spacecraft position data from the fluxgate magnetometer (FGM) experiment (Balogh et al. 2001), and plasma data from the Cluster ion spectrometry (CIS) experiment (Rème et al. 2001) presented in the GSM coordinates, are used in this study. We introduce the general shape of DF in the magnetotail and analyze three DF events according to this shape in Sect. 2. In Sects. 3 and 4 the discussions and conclusions are presented.

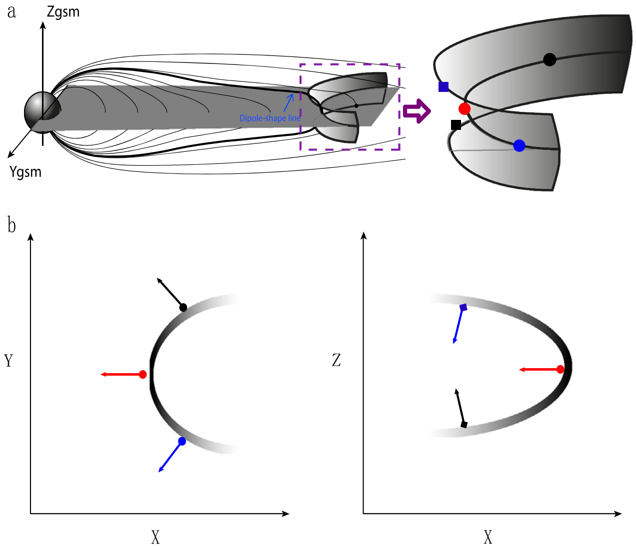

Fig. 1 Schematic of DF in the magnetotail (**a**) and the normal vectors of DF at different locations (**b**). The five points in (**b**) correspond to that in (**a**), but shown in the X-Y and X-Z plane respectively

2 Shape of DF and observations

2.1 Shape of DF

According to the analysis of Runov et al. (2009), Fu et al. (2012a) and Liu et al. (2013a), DF is structured like a saddle in the magnetotail (Fig. 1a). In the X-Z plane, the magnetic field lines of DF are connected with the Earth, i.e. dipolar field. In the X-Y plane, the structure of DF is like a crescent or semicircle due to plasma flow from the reconnection site in the mid-tail. We fetch five points to describe the normal direction of DF in different regions (Fig. 1b). One can see that the normal direction expands in X-Y plane, like a semicircle (it will be used to fit the observations later), but converges in the X-Z plane. At the center of the DF (red dot), the normal is almost along the X-direction.

2.2 Overview of DF event

Figure 2 is an overview of the DF event on 06 October 2007. A sharp increase of B_z preceded by a small dip with variation amplitude ~10 nT in less than 10 s around 02:12:50 UT and without large fluctuation of B_z preceding this increase in B_z (Fig. 2a) in the central plasma sheet where plasma $\beta > 1$ (Fig. 2f). Such B_z increases are accompanied with density decrease (Fig. 2d), temperature increase (Fig. 2e), plasma β decrease and earthward plasma flow (Fig. 2g). All these features suggest that Cluster observed one typical earthward propagating DF event. In addition, during the DF event, B_x and B_y fluctuate with small amplitude (Fig. 2b and 2c). As for the two other DF events analyzed in this paper, their ambient plasma parameters have been shown by Fu et al. (2011).

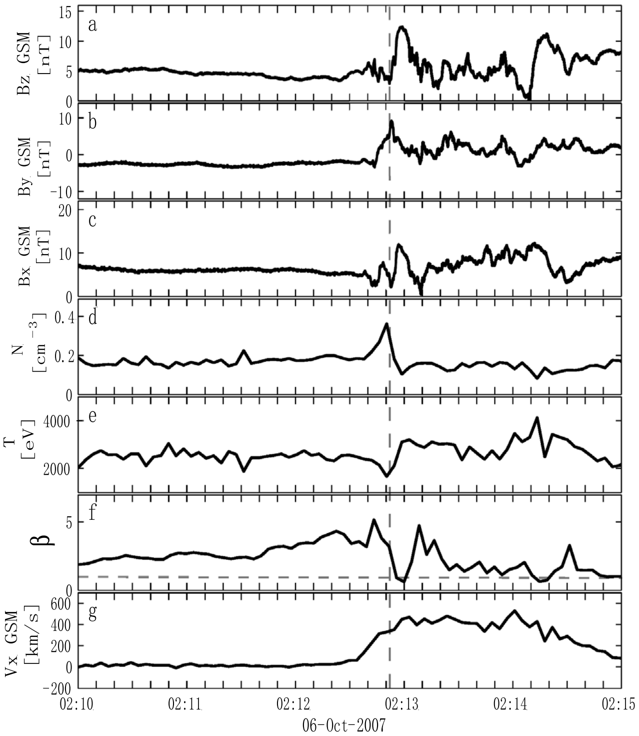

Fig. 2 A DF event measured by the Cluster 1 on 06 October 2007. (**a**)–(**c**) three components of magnetic field, (**d**) density, (**e**) ion temperature, (**f**) plasma β (the ratio between plasma pressure and magnetic pressure) and (**g**) the X component of plasma flow. The *vertical dashed line* mark the DF occurrence

2.3 Case 1:07:16UT on 01/10/2007

DF in the magnetotail is characterized by the sharp increase in B_z (less than 10 s) preceded by a magnetic field dip (e.g. Runov et al. 2009; Fu et al. 2012b). Figure 3a1–d1 present the DF observations by the four Cluster spacecraft from 07:14 to 07:19 UT on 01 October 2007, which has also been discussed by Fu et al. (2011). The sharp increases in B_z, preceded by magnetic dips, are observed sequentially by C2, C1 and then C3, C4 (marked by vertical black dashed lines in Fig. 3a1–d1). Because the measurements are within 20 s (from 07:16:20 UT to 07:16:40 UT), the DFs detected by four spacecraft may be a same structure. The separation between C3 and C4 is very small (∼30 km), so that they captured the DF almost at the same time. In this study, we assume all four spacecraft detected the same DF.

To determine the normal direction of DF, the Minimum Variance Analysis (MVA) (Sonnerup and Scheible 1998) is applied to the magnetic field time series data for four Cluster spacecraft. The MVA results are summarized in Table 1. The three MVA eigenvectors, $\mathbf{n}_1$, $\mathbf{n}_2$, and $\mathbf{n}_3$, corresponding to the three eigenvalues, λ_1, λ_2, and λ_3, define the direction of the maximum, intermediate, and minimum variance of the magnetic field in the GSM coordinates, respectively. When the ratio λ_2/λ_3 is greater than 10, $\mathbf{n}_3$ can be interpreted as the normal vector of DF. Figure 3e1 shows the normal direction of DF detected by each spacecraft. We focus on the dawn-dusk scale of the DF, thus we only present the normals of DF in the X-Y plane. As can be seen, the normal determined by C2 is almost along the X-direction in the X-Y plane. According to the general shape of DF (Fig. 1b, left), C2 should be located near the center of DF in the X-Y plane. In contrast, the normal determined by C1 is almost along the Y-direction in the X-Y plane, indicating that C1 is at the dawn flank of DF. The angle of normal direction between C1 and C2 is 105°, nearly vertical in the X-Y plane. C3 and C4 are located between C1 and C2 in the Y direction, also have the medial normal directions between C1 and C2. Considering that all spacecraft are located almost in the same Z axis; C1 measured the flank of DF; C2 measured the center of DF; and the separation between these two spacecraft, ∼1.8 Re, are almost along the Y direction, we can cursorily infer that the dawn-dusk scale of this DF is ∼3.6 Re.

In order to more quantitatively investigate the dawn-dusk scale, we used the semicircle function to fit the observation data (position and the normal of DF) under the assumption that the DF is consistent with semicircular shape, and moves with a constant velocity in the X-Y plane. Two equations are used to fit the observation data.

$$(\mathbf{R_m} - \mathbf{R_0} - \mathbf{V_0} t_{m1})^2 = r_0^2 \tag{1}$$

$$\mathbf{R_m} - \mathbf{R_0} - \mathbf{V_0} t_{m1} = \mathbf{n_m} r_0 \tag{2}$$

where $\mathbf{R_m}$ is the position of the m_{th} ($m = 1, 2, 3, 4$) spacecraft, $\mathbf{R_0}$ is the position of the center of the circular DF when the first spacecraft encounter the DF, $\mathbf{V_0}$ is the propagation velocity of the DF in the X-Y plane, $\mathbf{n_m}$ is the normal of the DF detected by the m_{th} spacecraft, t_{m1} is the time lag when the m_{th} spacecraft detects the DF compared to the first one ($t_{11} = 0$ for the first spacecraft), r_0 is the radius of the semicircle. Equation (1) is the function of circle, and Eq. (2) is determined by the normal. We used a least square method to fit the observations, and obtained the radius r_0. Then, the dawn-dusk scale of the DF is $2r_0$. The fitting results are plotted in Fig. 3e1. The radius of the fitted semicircular is 1.61 Re, meaning that the dawn-dusk scale of this DF is 3.22 Re. In addition, we also notice that the DF duration measured by C2 is shorter than that measured by C1, C3, and C4. The increase in B_z at the DF is largest at the center as well.

2.4 Case 2: 08:42UT on 01/10/2007

Figure 3a2–d2 display the DF observations by the four Cluster spacecraft from 08:40 UT to 08:45 UT on 01 October 2007. The sharp increases of B_z, preceded by the magnetic

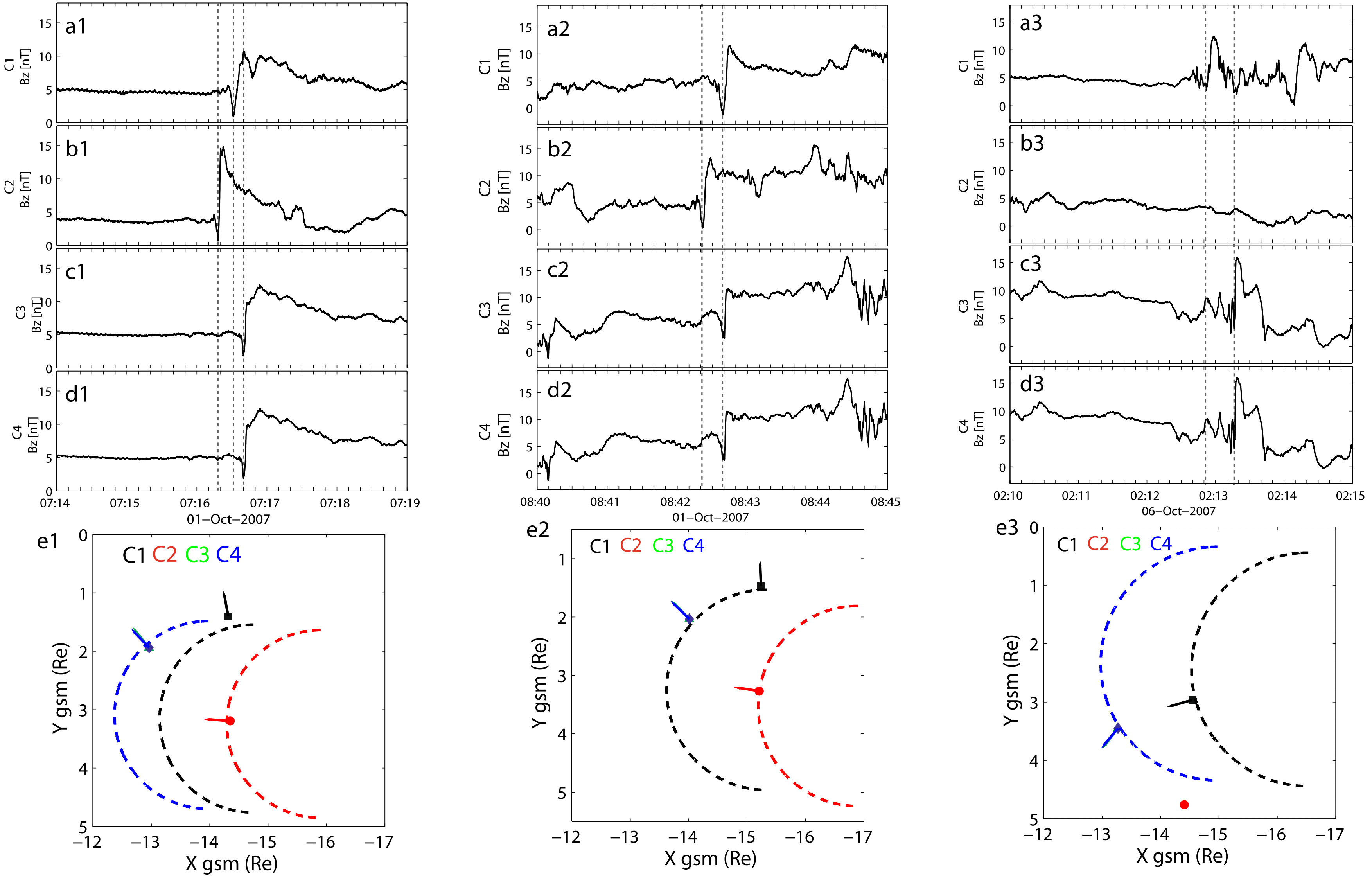

Fig. 3 Observations of B_z by four Cluster spacecraft (**a1**)–(**d1**), (**a2**)–(**d2**), and (**a3**)–(**d3**) for three DF events; the normal directions of DF detected by each spacecraft (**e1**), (**e2**), and (**e3**). *Black square*, *red dot*, *green triangle*, and blue square represent the position of C1, C2, C3, and C4, respectively. The fitting results are presented in X-Y plane in (**e1**), (**e2**), and (**e3**)

Table 1 MVA Results of three DF events. The numbers in brackets are the values of λ_2/λ_3

SC	2007-10-03 07:16 UT	2007-10-03 08:42 UT	2007-10-06 02:13 UT
C1	$[0.18, -0.95, -0.26]$ (34)	$[0.04, -0.99, 0.11]$ (16)	$[0.62, 0.18, -0.76]$ (10)
C2	$[0.80, -0.06, -0.59]$ (110)	$[0.65, -0.10, 0.75]$ (26)	–
C3	$[0.43, -0.53, -0.73]$ (28)	$[0.53, -0.56, 0.64]$ (15)	$[0.64, 0.76, -0.08]$ (35)
C4	$[0.45, -0.47, -0.76]$ (65)	$[0.56, -0.54, 0.63]$ (11)	$[0.62, 0.18, -0.76]$ (23)

dip, is detected sequentially by the four spacecraft, implying that Cluster encounter the same DF. C2 captured the DF first, and then C1, C3 and C4 almost simultaneously captured the DF.

Figure 3e2 presents the normal vectors of DF (also shown in Table 1) measured by each spacecraft. All spacecraft are in a constant Z_{GSM} plane. The normal derived from C2 measurement is almost along the X-direction, indicating that C2 is at the center of DF according to the general shape of the DF (Fig. 1b, left). The normal derived from C1 measurement, however, is along the negative Y direction, implying that C1 is located at the dawn flank of DF. The angle between the normal directions detected by C1 and C2 is about 80°. C1, C3 and C4 simultaneously observed the DF, meaning that three spacecraft touched DF structure at the same time. C1, at the flank of DF, and C2, at the center of DF, are close in the X-axis (less than 160 km, i.e. $\sim$0.026 Re), implying that the scale of DF is likely $\sim$3.6 Re in the dawn-dusk direction. Besides, we used the semicircle function to fit the observations, and got the radius of $\sim$1.71 Re, meaning that the dawn-dusk scale of this DF is 3.42 Re (close to the rough estimation). The fitting results can been found in Fig. 3e2. In the X-Y plane, the increase in B_z is largest at the center of DF (C2 measurement, see Fig. 3b2) similar as that shown in Case 1.

2.5 Case 3: 02:13UT on 06/10/2007

The third DF event is shown in Fig. 3a3–d3. It was measured by C1, C3 and C4 on October 06 2007 from 02:10 UT to 02:15 UT, however, missed by C2.

The MVA results of the DF are also summarized in Table 1. Figure 3e3 displays the normal vectors of DF measured by three spacecraft in X-Y plane. C2 did not observe the same DF, so it may be beyond the DF region in Y axis. The normal of C1 is close to the X-direction with small duskward direction, indicating that C1 is located duskward region of DF, but near the center in the X-Y plane. C1 and C2 have very small separation ($\sim$800 km) along the X-direction. Therefore, the half width of DF should be smaller than or about the separation between C1 and C2, implying that the scale of DF is $\lesssim$3.6 Re in the dawn-dusk direction.

3 Discussion

DFs and BBFs are two important energy carriers. BBFs are companied with prominent decrease of entropy, so they are sometimes called plasma bubbles (Chen and Wolf 1993; Pang et al. 2012). The scales of BBFs/plasma bubbles have been well studies by now; while the scales of DFs are still poorly understood. Concerning the scale of plasma bubble, Sergeev et al. (1996) have found it is about 1–3 Re in the dawn-dusk (cross-tail) direction. Nakamura et al. (2004) have confirmed this conclusion by using the multi-point Cluster measurements. In their study, the spatial scale of BBFs is found to be 2–3 Re in the dawn-dusk direction. Actually, the scales of DF and plasma bubble/BBF are not necessarily consistent. The plasma bubble/BBF is quite possibly associated with dipolarization event (Sigsbee et al. 2005), but not DF. DF is just a special type of dipolarization event as the former (DF) has a typical duration of several seconds while the latter (dipolarization event) can last from near zero to more than 10 min (Fu et al. 2012a). The identification of DF requires the existence of BBF ($\max(V_i) > 150$, see Schmid et al. 2011 and Fu et al. 2012b), but not all the BBFs include DF structures. We would not like to say that the DF scale estimated here represent a common situation. In fact, the DF scale may vary from middle tail to near-Earth region, as the DFs in these two regions may be formed via different mechanisms (Fu et al. 2013b).

The scale of DF was estimated to be 1.5–2.2 Re in dawn-dusk direction by Nakamura et al. (2005). This result somehow may not be reliable as the Cluster separation used to estimate the DF scale is $\sim$0.6 Re (Nakamura et al. 2005), much smaller than the expected separation. Recently, Liu et al. (2013b) have also estimated the dawn-dusk scale with the same method of Sergeev et al. (1996) and the observations of two probes of THEMIS mission. They found that the DF radius is typically about 1 Re (i.e., $\sim$2 Re of dawn-dusk scale). However, the separations between two probes in the z direction ($\Delta Z < 3$ Re, typically $\Delta Z > 1$ Re for THEMIS mission) are much large than the ones of our events. This would lead to underestimate the DF scale in the dawn-dusk direction. In this paper, we used the observations from four Cluster spacecraft with much larger separation in the dawn-dusk direction ($\sim$1.8 Re) and much smaller separation in the Z direction (< 0.25 Re), to investigate the scale of DF in the dawn-dusk direction. Three DF events measured in the near Earth magnetotail are analyzed. Summarizing the analysis of three cases, the scale of DF in the dawn-dusk direction is ∼3.2–3.6 Re, which is much larger than that estimated by Nakamura et al. (2005) and Liu et al. (2013b). The main reasons for the differentiation may be the different separation of Cluster and the assumption of linear gradient of the normal orientation of DF used in Nakamura et al. (2005) and Liu et al. (2013b).

We notice that the dawn-dusk scale of DF (3.2–3.6 Re) is slightly larger than the dawn-dusk scale of plasma bubble (1–3 Re, see Sergeev et al. 1996) and BBF (2–3 Re, see Nakamura et al. 2004), probably because the event presented in this study was observed close to the jet braking region, where DF may expand significantly in the azimuthal direction (e.g., Birn et al. 2011), or the large separation among these Cluster spacecraft which would lead to select the large dawn-dusk scale DF.

Recently, 3D simulations were performed to investigate the formation and evolution of DF (e.g., Ashour-Abdalla et al. 2011; Lapenta and Bettarini 2011). Lapenta and Bettarini (2011) have found that the DF with chaotic structures formed downstream of reconnection region are strongly affected by the kinking flux ropes whose scale is about 1.0 Re, much smaller than our observations. The structureless DF can also be found in the 3D global MHD simulation (Ashour-Abdalla et al. 2011), but with much larger scale in the dawn-dusk direction (∼3 Re, close to our observations) in the near Earth's magnetotail. The earth magnetotail current sheet actually shows evident dawn-dusk asymmetry (e.g. Rong et al. 2011). The dawn-dusk scale of DF versus the Y coordinates may also show some similar asymmetry. We will investigate this topic in future.

Usually when the discontinuity is a plane structure, its normal direction and the propagation velocity along the normal can be resolved from the timing analysis of multi-spacecraft measurements (Cao et al. 2012). The DFs observed in this study look like saddle (Fig. 1a), not plane structures. Therefore the timing analysis for the DF may be not always reliable. For example, in Case 2, C1, C3 and C4 observe the DF almost at the same time. However, they are separated by ∼1.5 Re. If performing the timing analysis for this event, we will get a meaningless result. On the other hand, if the Cluster spacecraft have very small separation (for example, 200 km in 2003), the observed DF can be assumed in a same plane, therefore the normal of DF and the propagation velocity along the normal can be obtained by timing analysis (e.g. Fu et al. 2012a). In this way, whether Cluster can be used for the timing analysis of DF depends on the spacecraft separation. Only when the separation is enough small, can the timing results be reliable. We suggest that one should check the normal of DF by MVA analysis before perform timing analysis on the DF. If all the normals from MVA analysis basically have the same orientation, or more or less, then the DF is supposed to be seen as a planar structure on the scale of Cluster tetrahedron, and timing analysis can be applied, vice versa.

4 Conclusion

Based on previous studies, a shape of DF, whose normal direction expands in the X-Y plane and converges in the X-Z plane, is shown in Fig. 1. According to this shape of DF, we analyzed three DF events to investigate the spatial scale in the dawn-dusk direction. The estimated scale is ∼3.2–3.6 Re for these three cases, larger than the statistical spatial scale of plasma flow (Nakamura et al. 2004) and the estimated DF scale by Nakamura et al. (2005). For non-plane structure of DF and large separation among the spacecraft, the condition of timing analysis is violated, and timing analysis is not available ever.

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