Electron Thermalization and Electrostatic Turbulence Caused by Flow Reversal in Dipolarizing Flux Tubes

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Abstract

During magnetic reconnection in Earth’s magnetotail, a dipolarizing flux tube (DFT) is formed and carries large amounts of energy toward the Earth to produce the aurora. Electrons inside the entire DFT are generally hot and tenuous, because they originate from the low-density lobe region and subsequently are heated by reconnection. Here, we report a special DFT hosting both hot-tenuous and cold-dense electrons, and we observe unique electron thermalization and associated electrostatic turbulence inside such a DFT. Analyses of the ion dynamics indicate that formation of the special phenomenon might be due to the flow reversal on the DFT flank, which is found to be an isobaric process in the direction perpendicular to the magnetic field. Correlation analysis shows that electrostatic waves at frequencies of 2–70 Hz are well correlated with the temperature anisotropy of electrons in the range of 300–27,000 eV, and waves at a frequency above one electron gyrofrequency ($f_{ce}$) have a strong negative correlation with the electron temperature anisotropy as well. This study can improve our understanding of electron dynamics in the magnetotail.

Unified Astronomy Thesaurus concepts: Magnetic fields (994); Space plasmas (1544); Planetary magnetospheres (997)

1. Introduction

A dipolarizing flux tube (DFT) is a transient magnetic field structure in the Earth’s magnetotail, where the magnetic field lines change from an elongated shape to a more dipolarized configuration. The DFTs contribute to the majority of mass and flux transport in the Earth’s magnetotail (Nakamura et al. 2009; Ge et al. 2011; Hamrin et al. 2013; Liu et al. 2014), disrupt the dawn-dusk cross-tail currents and divert them toward the ionosphere (Fu et al. 2011; Zheng et al. 2012; Wang et al. 2017; Grigorenko et al. 2018; Xu et al. 2019), produce large-scale ion flow vortices and field-aligned currents (Keiling et al. 2009; Sun et al. 2013, 2014; Yao et al. 2013, 2016; Liu et al. 2018), and accelerate electrons up to suprathermal energies and inject them into the radiation belts (Fu et al. 2011, 2013a, 2019; Wu et al. 2013; Duan et al. 2014; Liu et al. 2017b; Xu et al. 2018a; Chen et al. 2019). Therefore, they play key roles in the magnetotail dynamics (Lu 2000; Kepko et al. 2015).

A DFT is generated typically by magnetic reconnection (Sitnov et al. 2009; Fu et al. 2013b; Xu et al. 2018b) in the midtail region (Birn et al. 2004, 2013), then propagates toward the Earth with a speed close to local Alfvén speed, and finally braces in the near-Earth region due to its interaction with the dipolar geomagnetic field (Shikawa et al. 1997; Birn et al. 2011; Khotyaintsev et al. 2011; Nakamura et al. 2011; Fu et al. 2014; Ergun et al. 2015; Panov et al. 2015; Liu et al. 2017b; Sun et al. 2019). In the dawn-dusk direction, the DFT scale is about a few $R_E$ (Earth radii) (Nakamura et al. 2004), and such a scale may evolve temporally during the DFT propagation. To maintain pressure balance with the ambient plasmas (Li et al. 2011; Zhou et al. 2011; Fu et al. 2012c), a DFT usually carries a strong magnetic field and usually hosts two sharp boundaries, which are traditionally referred to as dipolarization fronts (Nakamura et al. 2002; Runov et al. 2009; Fu et al. 2012a, 2020; Liu et al. 2018). Plasma waves/turbulence have been widely observed inside the DFT. For example, near the electron gyrofrequency ($f_{ce}$), whistler mode waves driven by the electron temperature anisotropy that is formed via betatron acceleration are often detected (e.g., Deng et al. 2010; Hwang et al. 2011, 2014; Khotyaintsev et al. 2011; Fu et al. 2014; Viberg et al. 2014; Li et al. 2015; Grigorenko et al. 2020). At frequencies above $f_{ce}$, the electrostatic solitary wave and the electron cyclotron harmonic wave were observed, and the electron cyclotron harmonic waves were probably related to the positive slope in the perpendicular velocity distribution of electrons (e.g., Zhou et al. 2009; Zhang et al. 2011).

Since the source of a DFT is the low-density lobe region (the connection inflow region) and subsequently would be thermalized by the reconnection process (Vaiyads et al. 2011; Fu et al. 2019; Liu & Fu 2019; Norgren et al. 2020), previous studies have concluded that the DFT is generally hot and tenuous. Such hot, tenuous DFTs have been widely observed inside the DFT. For example, near the electron gyrofrequency ($f_{ce}$), whistler mode waves driven by the electron temperature anisotropy that is formed via betatron acceleration are often detected (e.g., Deng et al. 2010; Hwang et al. 2011, 2014; Khotyaintsev et al. 2011; Fu et al. 2014; Viberg et al. 2014; Li et al. 2015; Grigorenko et al. 2020). At frequencies above $f_{ce}$, the electrostatic solitary wave and the electron cyclotron harmonic wave were observed, and the electron cyclotron harmonic waves were probably related to the positive slope in the perpendicular velocity distribution of electrons (e.g., Zhou et al. 2009; Zhang et al. 2011).
2. Observation

2.1. Event Overview

All of the data are presented in Geocentric Solar Magnetospheric (GSM) coordinates unless noted otherwise. The event of interest was detected by the MMS on 2017 July 24 at 12:56–12:57 UT, when the spacecraft was located at [−18.5, −0.1, −5.4] R_E in the Earth’s magnetotail, forming a regular tetrahedron with an inter-spacecraft distance of ~10 km. Since the Y_GSM coordinates were quite small, the MMS was located in the midnight sector. Since the spacecraft separation was small (10 km), the four MMS spacecraft measured very similar fields and plasmas. Below we show measurements from MMS1.

An overview of this event is shown in Figures 1(a)–(i). During 12:55:40–12:57:05 UT, the magnetic field B_z component was very small (|B_z| < 2 nT; see Figure 1(a)) and the plasma beta was larger than 0.5 (not shown), indicating that the MMS was in the central plasma sheet. At ~12:55:57 UT (see the left vertical line in Figures 1(a)–(j)), the MMS detected a sharp increase of B_z from 2 to 17 nT (Figure 1(a)), in association with a sudden drop of the plasma density (from 0.25 to 0.1 cm^{-3}; Figure 1(b)) and an increase in the electron temperature (from 2.5 to 4 keV; Figure 1(e)). While at ~12:56:52 UT (see the right vertical line in Figures 1(a)–(j)), the MMS detected a dramatic decrease of B_z from 18 to 4 nT (Figure 1(a)) in association with a slight increase of the plasma density (from 0.08 to 0.2 cm^{-3}; Figure 1(b)) and a decrease in the electron temperature (from 6.4 to 4.2 keV). These two sharp boundaries, characterized by the dramatic change of B_z at 12:55:57 and 12:56:52 UT, are identified as dipolarization fronts (DFs), according to the previous definition (see Fu et al. 2020 and references therein). The durations of these two boundaries are ~5 s, consistent with the statistical duration of DFs (Fu et al. 2020), and based on timing analysis we can estimate their spatial scales as 1520 km and 945 km, respectively (see Table 1), equivalent to 2 and 1.28 ion thermal gyroradii. At both DFs, the electric fields increase significantly up to 40 mV m^{-1} (Figure 1(c)). Such impulsive electric fields are quite common at the DF boundary and are primarily balanced by the Hall term (Fu et al. 2012a); they are important for the ion acceleration around the DF structure (Zhou et al. 2010). Since the Hall electric field (j × B/ne) is theoretically normal to the DF boundary (Fu et al. 2012a), the dominance of Ex observed in this event (Ex ≈ +40 mV m^{-1} at 12:55:57 UT and Ex ≈ −40 mV m^{-1} at 12:56:52 UT) may indicate that the normal directions of two sharp boundaries are mainly along the X_GSM direction. Actually, the results of the timing method also confirmed this (see Table 1).

Enclosed by the two DF boundaries (from 12:55:57 to 12:56:52 UT) is the structure we are particularly interested in. Since this structure has a strong magnetic field (Figure 1(a)), a low plasma density (compared to that in the plasma sheet before 12:55:57 UT; see Figure 1(b)), and a relatively high electron temperature (Figure 1(e)), it can be identified as a DFT (Chen & Wolf 1993; Fu et al. 2011, 2012b, 2012c; Khotyaintsev et al. 2011; Liu et al. 2013, 2014). However, in contrast to the general DFTs reported in previous studies, the DFT observed in this event exhibits different properties. Specifically, (1) the plasma density in the former part (12:55:57–12:56:25 UT) is lower than in the latter part (12:56:25–12:56:52 UT; see Figure 1(b)); (2) the electron temperature in the former part is higher than in the latter part (Figure 1(e)); (3) the omnidirectional differential energy fluxes of low-energy (0.2–2 keV) electrons in the former part is lower than in the latter part (Figure 1(j)); (4) the pitch angle distribution of high-energy (2–27 keV) electrons is a pancake type (Fu et al. 2012c; Liu et al. 2017a; Zhao et al. 2019) in the former part but is a cigar type (Liu et al. 2017a) in the latter part (Figure 1(i)); (5) the ion flow velocity components V_\parallel and V_\perp are primarily negative in the former part but are primarily positive in the latter part (Figure 1(d)), indicating a flow reversal; and (6) the electric field in the former part is more turbulent and has a larger amplitude than in the latter part (see Figure 1(c)). Obviously, the former part of the DFT is hot, tenuous, and turbulent, whereas the latter part of the DFT is relatively cold, dense, and quiet.

Interestingly, such a DFT is not unique. We survey the MMS measurements in the Earth’s magnetotail and find another event on 2018 August 19 at [−16.6, 1.7, 4.5] R_E. Figures 1(k)–(t) present the overview of this event, in the same format as in Figures 1(a)–(j). As can be seen, all of the field and particle characteristics in this event are very similar to those in the 2017 July 24 event: the former part of the DFT is hot, tenuous, and turbulent, whereas the latter part of the DFT is relatively cold, dense, and quiet. The two sharp boundaries (DFs) of the DFT were detected at 18:22:58 UT and 18:23:36 UT, respectively. The normals of the two boundaries are primarily along the Y_GSM (18:22:58 UT) and X_GSM (18:23:36 UT) directions (see Table 1). The ion flow reversal signature in this event is much clearer (see Figure 1(n)). The detection of this additional event indicates that this DFT may not be unique in the Earth’s magnetotail.

2.2. Formation Mechanism

The DFTs reported in this study are very interesting, but how are they formed? We show a longer-term overview of this event, and combine it with the measurement of the geomagnetic index to further investigate its formation (Figure 2). For the case of 2017 July 24, we observed the signal of the substorm onset at 12:50:00 UT: the AE index increased from 250 to 600 nT, and the AL index drastically decreased from ~100 to ~450 nT (Figures 2(a) and (b)); For the case of 2018 August 19, the DFT was observed during the substorm recovery phase: the AE index decreased from 500 to 100 nT, and the AL index dramatically increased from ~400 to ~50 nT (Figures 2(g) and (h)). Previous studies have shown that the tail reconnection may be triggered during the substorm (e.g., Nagai et al. 1998; Angelopoulos et al. 2008); therefore, these special DFTs may be associated with the reconnection. We indeed observed reconnection jets (earthward BBF) at 12:50:00 UT 2017 July 24 (Figure 2(f), vertical line) and 18:22:30 UT 2018 August 19 (Figure 2(i), vertical line) just before these DFTs. These indicate that the formation of these DFTs is related to magnetic reconnection.

The reconnection jet is mainly earthward; however, the DFT in our study has an obvious ion flow reversal from dawnward to duskward (see Figures 1(d) and (n)). Figures 4(a) and (e) show the direction of the flow velocity vector, in which we indeed find the flow reversal. The possible explanation is that when the DFT moves earthward at a high speed, ion vortices are generated due to the speed shear on its flank. The vortex on the flank of the DFT has been referred to in previous observations and simulations (e.g., Birn et al. 2004; Runov et al. 2013; Drake et al. 2014; Lu et al. 2015). The MHD
simulation results show that the flow vortex is generated typically outside of the DFT, which is the low \( B_z \) region (e.g., Birn et al. 2004). However, the MHD simulation overlooked kinetic effects that could significantly affect local flow evolution. Recently, both Hall-MHD and particle-in-cell simulations show that during an interaction with ambient plasma, a DFT can evolve into a mushroom-shaped structure and generate a rolled-up flow vortex that can further affect the magnetic field \( B_z \) (e.g., Drake et al. 2014; Lu et al. 2015), which can explain why the flow vortex can be inside the strong-\( B_z \) region. Specifically, the MMS crossed the vortex

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Two dipolarizing flux tubes (DFTs) detected by the MMS on 2017 July 24 (left) and 2018 August 19 (right). (a), (k) The magnetic field \( B_x, B_y, \) and \( B_z \) components; (b), (l) the plasma number density; (c), (m) the electric field \( E_x, E_y, \) and \( E_z \) components; (d), (n) the ion flow velocity \( V_x \) and \( V_y \) components; (e), (o) the electron parallel, perpendicular, and total temperatures; (f), (p) the perpendicular electron pressure; (g), (q) the current densities \( J_x \) and \( J_y \) components; (h), (r) the pitch angle distribution of the 0.2–2 keV electrons; (i), (s) the pitch angle distribution of the 2–27 keV electrons; (j), (t) the omnidirectional differential energy fluxes of electrons. What is listed at the bottom are the spacecraft positions. All of the data are presented in GSM coordinates. Since the ion flow velocity \( V_z \) is very small, it is not shown. The left and right vertical lines denote the two boundaries of the DFT; before the middle vertical line is the thermalized region and after the middle vertical line is the nonthermalized region.}
\end{figure}

\begin{table}[h]
\centering
\begin{tabular}{ll}
\hline
Normal direction in GSM coordinates & \\
Case 2017–07–24 & Case 2018–08–19 \\
\hline
Leading DF & \\
304 \times [0.91, -0.39, -0.14] km s\(^{-1}\) & 189 \times [0.34, -0.85, -0.14] km s\(^{-1}\) \\
Trailing DF & \\
297 \times [0.96, -0.16, -0.23] km s\(^{-1}\) & 186 \times [0.81, -0.58, -0.02] km s\(^{-1}\) \\
\hline
\end{tabular}
\caption{The Normal Directions of the DFT Boundaries, Derived from the Timing Method}
\end{table}
through the dawnside flank of the DFT, and thus dawnward was observed first and was followed by slightly tailward flow while the satellites enter the high-$B_z$ region (increasing $B_z$), and then return flows along the duskward and earthward directions were observed at its trailing boundary (decreasing $B_z$). The sharp magnetic field variation at the vortex boundary is indicative of the presence of a local current flow, and indeed, a duskward current was observed at the leading boundary and a dawnward current was observed at the trailing boundary (Figure 1(g)). Figure 3 is a schematic diagram of the above description. The return flow may lead to an entrainment of the surrounding medium; thus the plasma temperature and number density in the cold part of the DFT associated with the return flow (Figures 1(b) and (e), 12:56:25–12:56:52 UT) is similar to that of the surrounding medium (Figures 1(b) and (e), 12:55:40–12:55:50 UT), and the $B_z$ is lower in the latter part (12:56:25–12:56:52 UT) than in the former part (12:55:57–12:56:25 UT), caused by the entrainment of the surrounding medium.

We also examine the thermal pressure across the vortex structure. Interestingly, we find that the thermal pressure inside the whole DFT is generally a constant in the perpendicular direction ($N_e \cdot k \cdot T_{e\perp} = 0.072$ nPa for the case of 2017 July 24 and $N_e \cdot k \cdot T_{e\perp} = 0.081$ nPa for the case of 2018 August 19), although the electron temperature decreases significantly and the plasma density increases considerably after the flow reversal (see Figures 1(f) and (p) and Figures 4(b) and (f)). This means that the perpendicular pressure stays constant across the vortex. However, in the parallel direction, we cannot find any clear physical rules (a random correlation between $N_e$ and $T_e$; see Figures 4(c) and (g)), suggesting that the thermal pressure in this direction may be stochastic.

2.3. Observation and Correlation Analysis of Turbulence and Thermalization

We further compare the turbulence intensity at the thermalized region (from 12:56:05 to 12:56:25 UT, marked with a black bar in Figure 5) with that at the nonthermalized region (from 12:56:30 to 12:56:47 UT, marked with a gray bar in Figure 5). The power spectrum of $B$ (Figure 5(h)) shows no clear turbulence activity; therefore, the detected wave turbulence is...
mainly electrostatic. Figures 5(a) and (b) show the power spectrum density (PSD) of $E_\perp$ and $E_\parallel$ obtained by the Fast Fourier transform (FFT) of the electric field. Below the electron gyrofrequency ($f_{ce}$), the electrostatic turbulence at the thermalized region (black line) is more intense than that at the nonthermalized region (gray line); and above the $f_{ce}$, the...
electrostatic turbulence in the thermalized region is weaker than that at the nonthermalized region, and approaches the noise level (yellow lines). The wave spectrum of $E_\perp$ and $E_\parallel$ also shows similar characteristics in regions between these two regions (Figures 5(f) and (g)).

We further analyze the correlation between electrostatic turbulence and thermalization. We notice that the electron perpendicular temperature anisotropy ($T_{e\perp} > T_{e\parallel}$; see the red dots in Figures 4(d) and (h)) and the parallel temperature anisotropy ($T_{e\perp} < T_{e\parallel}$; see the black dots in Figures 4(d) and (h)) are, respectively, observed at the thermalized and nonthermalized regions, and thus the temperature anisotropy may be related to the electrostatic turbulence, which exhibits distinct characteristics in the two regions. First, in order to determine the electron anisotropy at different energy ranges, we define the electron anisotropy at each energy range as $Q = F_\perp / F_\parallel - 1$, and $F_\perp$ and $F_\parallel$ are the differential particle fluxes (dPFs) of each energy range in the perpendicular and parallel direction, and the black line represents the total temperature. Second, we perform a correlation analysis between $Q$ and the electric field PSD at each frequency. Figures 6(c) and (d) show the correlation between $Q$ and wave PSD in the perpendicular and parallel directions, respectively. For electrostatic turbulence in the perpendicular direction, the electron anisotropy $Q$ at 400–27,000 eV is well correlated with the wave

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**Figure 5.** The turbulence properties and the temperature anisotropy of dipolarizing flux tubes (DFTs); the time interval in which the thermalized region and nonthermalized region were observed is marked by a black bar and gray bar, respectively. (a), (i) The turbulence power spectrum density (PSD) of $E_\parallel$ obtained by the Fast Fourier transform (FFT); the black line and gray line represent the thermalized region and the nonthermalized region, respectively, and the yellow line represents the noise level measured in the closest calm electric field (2017 July 24, 12:19:05.00–12:19:15.00 UT; 2018 August 19, 17:30:30.00–17:30:30.00 UT); (b), (j) the turbulence power spectrum density (PSD) of $E_\perp$; (c), (k) the parallel and perpendicular electron temperatures; (d), (l) the electron temperature anisotropy ($Q = F_\perp / F_\parallel - 1$) in each energy range; $F_\perp$ and $F_\parallel$ are the differential particle fluxes (dPFs) of each energy range in the perpendicular and parallel direction, and the black line represents the total temperature; (e), (m) the electric field $E_x$, $E_y$, and $E_z$ components; (f), (n) the power spectrum of $E_\perp$; (g), (o) the power spectrum of $E_\parallel$; (h), (p) the magnetic field power spectrum.
PSD at 9–70 Hz (correlation coefficient, CC > 0.8), with CC peaking around [9300 eV, 13 Hz] (CC_{max} = 0.82; see Figure 6(a)). For electrostatic turbulence in the parallel direction, the electron anisotropy $Q$ at 300–27,000 eV is strongly correlated with the wave PSD at 4–30 Hz (CC > 0.7), with CC approximately peaking around [9300 eV, 9 Hz] (CC_{max} = 0.73; see Figure 6(b)). Above the electron gyrofrequency ($f_{ce}$), the electron anisotropy $Q$ is negatively correlated with the wave PSD of both the $E_\parallel$ and $E_\perp$ fields (CC ≈ −0.6).

The characteristics of electrostatic turbulence and its correlation with the electron temperature anisotropy in the second event are similar to those in the 2017 July 24 event, particularly in the direction perpendicular to $B$: (1) the turbulence in the thermalized region is more intense than that in the nonthermalized region at frequencies below $f_{ce}$, but it is weaker than that in the nonthermalized region at frequencies above $f_{ce}$ (see Figure 5(i)); (2) the temperature anisotropy at 400–27,000 eV is strongly correlated with the electric field PSD at 9–70 Hz (CC > 0.6; see Figure 6(g)); (3) at frequencies above 1 $f_{ce}$, the temperature anisotropy and the PSD are negatively correlated (CC ≈ −0.6; see Figure 6(g)). However, in the direction parallel to $B$: (1) the turbulence enhancement in the thermalized region is greater than that in the nonthermalized region, but at frequencies below and above $f_{ce}$, there is no clear difference in the turbulence activity in these two regions (Figure 5(i)); (2) the $Q$ and $E_\parallel$ are not clearly correlated (−0.6 < CC < 0.58; Figure 6(h)). In the field-aligned direction, we cannot find the same physical constraints as those in the 2017 July 24 event. Considering that the flow reversal is isobaric in the direction perpendicular to $B$, but stochastic in the direction parallel to $B$, the development of electrostatic turbulence may be related to the development of the isobaric process within the DFT.

3. Conclusions

In summary, using the MMS measurements, we report a special DFT in the magnetotail. Different from the traditional DFTs, this special DFT is hot, tenuous, and turbulent on one side but cold, dense, and quiet on the other side. We show that this special phenomenon might be caused by the flow reversal on the dawnside flank of the DFTs. After the reversal, the ambient cold and dense plasma mixes with the return flow, and thus the DFT properties, e.g., temperature and density, become inhomogeneous. In addition, the flow reversal is an isobaric process in the perpendicular direction but is stochastic in the parallel direction.

We also studied the enhancement of electrostatic turbulence and analyzed the correlation between the electrostatic turbulence and electron temperature anisotropy within the DFT. Based on the analysis of these two events, we discover the following. (1) In the direction perpendicular to $B$, the electrostatic turbulence is more intense in the thermalized region than in the nonthermalized region at frequencies below $f_{ce}$, but it is weaker than that in the nonthermalized region at frequencies above $f_{ce}$ (see Figure 5(i)); (2) the temperature anisotropy at 400–27,000 eV is strongly correlated with the electric field PSD at 9–70 Hz (CC > 0.6; see Figure 6(g)); (3) at frequencies above 1 $f_{ce}$, the temperature anisotropy and the PSD are negatively correlated (CC ≈ −0.6; see Figure 6(g)). However, in the direction parallel to $B$: (1) the turbulence enhancement in the thermalized region is greater than that in the nonthermalized region, but at frequencies below and above $f_{ce}$, there is no clear difference in the turbulence activity in these two regions (Figure 5(i)); (2) the $Q$ and $E_\parallel$ are not clearly correlated (−0.6 < CC < 0.58; Figure 6(h)). In the field-aligned direction, we cannot find the same physical constraints as those in the 2017 July 24 event. Considering that the flow reversal is isobaric in the direction perpendicular to $B$, but stochastic in the direction parallel to $B$, the development of electrostatic turbulence may be related to the development of the isobaric process within the DFT.
physical rules. Therefore, the development of electrostatic turbulence should be related to the isobaric process.

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