Anisotropic Vorticity Within Bursty Bulk Flow Turbulence

L. Q. Zhang1, A. T. Y. Lui2, W. Baumjohann3, Chi Wang1, James L. Burch4, and Yu. V. Khotyaintsev5

1State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing, China, 2Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA, 3Austrian Academy of Sciences, Space Research Institute, Graz, Austria, 4Southwest Research Institute, San Antonio, TX, USA, 5Swedish Institute of Space Physics, Uppsala, Sweden

Abstract: Utilizing Magnetospheric Multiscale (MMS) observation in the tail plasma sheet, we study the vorticity field (\( \omega = V \times \nabla \)) of the plasma bulk (convective) velocity within the bursty bulk flow (BBF) in detailed. Two typical events are presented. In the event on 25 June 2017, \( E_p \) is the main component. In the other event on 6 July 2017, \( E_c \) is the main component. For both cases, the BBF electric field is dominated by the convective electric field (\( E_c = -V \times B \)). Our case studies show clearly the existence of the convective vorticity field within the BBF. The vorticity field has prominent anisotropy (quantified by the anisotropic angle (\( \dot{\alpha} = \arctan(\omega_2/\omega_1) \)). More often, the BBF \( \omega \) field has stronger perpendicular vorticity (\( \omega_1 \)) than the parallel vorticity (\( \omega_2 \)). The dominance of vorticity by \( \omega_1 \)-dominating BBF is confirmed in the statistical sense. In particular, event on 25 June shows the significant evolution of the ion flux energy with the strength of the \( \omega \) field. The strong \( \omega \) field corresponds to the ion flux enhancement at high energy (above 10 keV), while the weak \( \omega \) field corresponds to the ion flux enhancement at medium energy (2–5 keV). Investigation of the subset of channel from fast plasma investigation partial moment measurement reveals that the ion behaviors in the strong and decayed BBFs are distinctly different. The channeled ions form the narrow band distribution in the strong BBF but the multiple-layer distribution in the weak BBF. Finally, spectrum analysis indicates that the BBF \( \omega_1 \) and \( \omega_2 \) have a similar scaling about –2.0 (below 0.2 Hz).

1. Introduction

Bursty bulk flows (BBFs) are the common phenomena in the magnetotail (Angelopoulos et al., 1994; Baumjohann et al., 1989, 1990; Zhang, Dai, et al., 2016; Zhang, Lui, et al., 2016; Zhang et al., 2009, 2020). They are the main driver of the wave/turbulence activities in the plasma sheet (e.g., Angelopoulos et al., 2008; Chaston et al., 2012; Volwerk et al., 2004; Vörös et al., 2004, 2006; Weygand et al., 2005; Zimbardo et al., 2010). BBFs are the groups of the short lifetime of bursty flows with durations of up to 10 min (Angelopoulos et al., 1992, 1994). They undertake the main task of mass, momentum, and magnetic flux transport in the magnetotail (Angelopoulos et al., 1994). BBFs are generally regarded as the signatures of the instantaneous, localized magnetic reconnection in the near-Earth magnetotail (e.g., Angelopoulos et al., 1992; Zhang, Baumjohann, et al., 2015; Zhang et al., 2010; Zhang, Wang, et al., 2015).

BBF in the tail plasma sheet is inherently the turbulent flow (Borovsky et al., 1997; Borovsky & Bonnell, 2001; Borovsky & Funsten, 2003; Dai, 2009; Dai et al., 2011; Zhang et al., 2019). The vorticity (\( \omega = V \times \nabla \)) represents the local rotation rate of fluid particles, carries fundamental information of the turbulence. Recently, utilizing four-point MMS observations, Zhang et al. (2019) first studied the large-scale vorticity (magnetohydrodynamics (MHD)) in the course of the BBF. Their result shows the enhanced \( \omega \) within the BBF. The strength of the \( \omega \) field is positively correlated with the BBF velocity. Particularly, the enhancement of BBF vorticity is in close association with the high-energy ion flux (above 10 keV).

Previous studies show the anisotropy of the MHD turbulence due to the presence of the mean magnetic field (e.g., Chmyrev et al., 1988; Goldreich & Sridhar, 1995; Narita, 2018; Oughton et al., 1994; Shukla et al., 1985, 1986; Sundkvist et al., 2005). Shebalin et al. (1983) first studied the anisotropy of the kinetic Alfvénic wave (KAW) associated drift vorticity numerically. Their simulation result showed dominantly parallel Alfvénic vorticity in the KAW. The parallel anisotropy is consistent with the perpendicular cascade (\( k \perp \gg k \parallel \) in...
the KAW turbulence. Recently, the ω||-dominating vorticity in KAW is confirmed by MMS spacecraft observations (e.g., Phan et al., 2016; Wang et al., 2019).

Till now, study on the anisotropy of BBF vorticity is still lacking. In the present paper, we perform case study on the vorticity field within BBF utilizing MMS observation in the tail plasma sheet. The main purpose of the paper is to show direct observational evidence on the bulk motion (convective velocity) associated vorticity field within the BBF turbulence. The organization of the paper is as follows. In section 2, we introduce the data set used in this study and the selection criterion of BBF. Section 3 is the case study. Defining the perpendicular and parallel components of vorticity relative to the local magnetic field, typical events show clearly that the ω field within the BBF has prominent anisotropy, with stronger perpendicular vorticity (ω⊥) than the parallel vorticity (ω∥). In section 4, we demonstrate the statistical results on the perpendicular-dominating vorticity of the BBF. In section 5, we show the correlation analysis on the evolutions between the BBF Vx and ion energy from fast plasma investigation (FPI) (partial moment) in the typical event on 6 July 2017. Section 6 shows the power spectrum distribution (PSD) analysis. In section 7, we discuss the main observations. The theoretical explanation of the vorticity anisotropy is presented. Main conclusions are given in section 8.

2. Data Description

MMS spacecraft launched on 12 March 2015 consists of four identical spacecraft. The maximum separation distance of MMS is ~200 km. The small distance of MMS spacecraft provides the high spatial resolution. High spatial resolution is due to high temporal resolution together with small separations. This benefits the curlometer measurement. It is necessary to point out that the separation distance between MMS is irrelevant to the scale of the vortex/eddy (Dura et al., 2012; She et al., 1988). The local vorticity is convective or drift dependent on the property of the flow.

MMS operates in the magnetotail from May to October in the year of 2017 and 2018, with the apogee of 24.5 RE. The 0.125-s resolution data of fluxgate magnetometers (Russell et al., 2016; Torbert et al., 2016), 0.03-s resolution of electric field instrument (Lindqvist et al., 2014) and 4.5-s data of FPI (Pollock et al., 2016) on four MMS satellites during the tail seasons of 2017 and 2018 are collected.

The observation time of the fast flow in the plasma sheet is very short. The typical duration of the bursty flow exceeding 400 km/s is usually less than 10 s (Baumjohann et al., 1990). In this study, the burst fast flows are selected by the criterion of the duration of $Vx > 200$ km/s for longer than 15 s. The criterion of three points of $4.5$ s below 200 km/s is used to separate two different bursty flows.

The selection region is confined in the box of $-25 R_E < X < -10 R_E,$ $-10 R_E < Y < 10 R_E,$ and $-3 R_E < Z < 3 R_E$ (Geocentric Solar Magnetospheric [GSM] coordinates). In the present study, only strong bursty flow is considered. With the condition of mean V exceeding 300 km/s, there are totally 759 bursty flows selected out by MMS1.

For each bursty flow, the curlometer method is applied to calculate the vorticity ($\omega = \nabla \times V$) (Zhang et al., 2019). The higher time resolution $B/E$ data are interpolated to match the FPI data steps. The anisotropic angle ($\theta_{\omega a} = \arctan(\omega_i/\omega_i)$) and convective $E$ are calculated by the interpolated $B/E$ data. Here, the $B/E$ refers to the local magnetic/electric field. Then, the parameter of absolute $E_c/E$ is used to evaluate the property of the BBF vorticity, say, convective or drift. Only “convective subset” of the BBF is considered in statistical results. With the threshold of $E_c/E > 0.5$, there are eventually 569 bursty flows selected out.

3. Case Study

3.1. Event on 6 July 2017

From 08:00 to 09:00 universal time (UT), MMS1 stays in the plasma sheet around ($-22.0 R_E,$ $3.0 R_E,$ $2.9 R_E$) and encounters continuous strong fast flow. Associated evolutions of the field and plasma during this interval are shown in Figure 1. The fast flow shows up at 08:17 UT and ends at 08:40 UT. With the emergence of the fast flow, the $B_x$ dramatically decreases from 20 to 10 nT. After the end of the flow, the $B_x$ recovers to the level of pre-BBF. The fast flow comprises of three individual BBFs. The BBF1 is the strongest. The maximum $V_x$ is up to 1,400 km/s. The BBF3 is a bit weaker than BBF1. The maximum of the BBF3 is about 1,000 km/s.
The BBF2 is the weakest. The maximum $V_x$ of the BBF2 is $\sim 750$ km/s. Relative to $V_x$, the $V_y$ and $V_z$ are small and illegible.

Within the flows, the $B_y$ is the dominant component of the magnetic field. All components of $B$ strongly fluctuate. The $E_x$ and $E_y$ components are small. The $E_z$ dominates the electric field variation in the course of the BBFs. All components of $E$ differ from the convective $E_c$ ($V \times B$), by intermittently superposed significant kinetic electric field ($E_k = E - E_c$). The $E_k$ during the BBF intervals are characterized by the rapid large-amplitude fluctuations.

From Figure 1k, the vorticity has substantial enhancement within the BBFs. Considering $E_z$ dominating velocity, the vorticity is convective. The convective vorticity is mainly in the dawn-dusk direction. The strength of the $\omega$ field evolves with the BBF $V_x$. It increases/decreases with the BBF $V_x$ increasing/decreasing. The anisotropy angle averages to 49.6° for BBF1, −47.9° for BBF2, and 55.3° for BBF3. Therefore, the BBF has a stronger perpendicular vorticity than the parallel vorticity.

Figure 1. Evolution of the vorticity field during the BBF intervals on 6 July 2017 by MMS1. The interpolated $E/B$ data is plotted. (a) Ion energy flux spectrogram. (b) Measured $V_x$, $V_y$, and $V_z$. (c) $V_\parallel$ and $V_\perp$. (d) Measured $B_x$ and $B$ total. (e) $B_y$ and $B_z$. (f) Measured $E_\parallel$ and calculated convective $E_\perp$ ($V \times B$). (g) $E_c$. (h) $E_z$. (i) $\omega_x$ and $\omega_y$. (j) $\omega_z$. (k) $\omega_\parallel$ and $\omega_\perp$. (l) Total $\omega$. (m) Anisotropy angle (calculated by $\theta_{aa} = \arctan(\omega_\perp/\omega_\parallel)$).

The BBF2 is the weakest. The maximum $V_x$ of the BBF2 is $\sim 750$ km/s. Relative to $V_x$, the $V_y$ and $V_z$ are small and illegible.
The energy of the ion flux in Figure 1a has significant evolution with the strength of the $\omega$ field. For strong $\omega$ field, the ion flux enhances at high energy (above 10 keV). For weak $\omega$ field, the ion flux enhances at medium energy (2–5 keV).

### 3.2. Event on 25 June 2017

From 05:25 to 05:58 UT, MMS1 is located in the current sheet around ($-22.7 R_E$, $-2.1 R_E$, and $3.9 R_E$) and records two continuous strong BBFs. Associated evolutions of the field and plasma are shown in Figure 2. The maximum $V_x$ of the BBF1 reaches to 1,100 km/s. The BBF2 is a bit lower, ~1,000 km/s. Both are predominantly perpendicular. As shown in Figure 2, the $B_x$ is the main component of the magnetic field. The $B_y$ is small. The $E_z$ overwhelms the $E_x$ during the two BBF intervals. The $E_x$ and $E_z$ component are quite weak. The convective $E_y$ dominates the electric field variations within the BBF.

Similarly, the $\omega$ field has substantial enhancements during the two BBF intervals. The enhanced $\omega$ is mainly in the dawn-dusk direction in BBF1 and north-south direction in BBF2. The anisotropy angle averages to 55.8° for BBF1 and 59.3° for BBF2. Both BBF1 and BBF2 are $\omega_\perp$ dominating.

Figure 2. Evolution of the vorticity field during the BBF intervals on 25 June 2017 by MMS1. (a) Ion energy flux spectrogram. (b) Measured $V_x$, $V_y$, and $V_z$. (c) $V_y$ and $V_\perp$. (d) Measured $B_x$ and $B_y$. (e) and $B$ total. (f) $E_x$. (g) $E_y$. (h) $E_z$. (i) $\omega_x$ and $\omega_z$. (j) $\omega_\perp$. (k) Total $\omega$. (l) Anisotropic angle.
During the two BBF intervals, the high-energy ion flux (above 10 keV) has substantial enhancements. Within BBF2, the strength of the $\omega$ field has an abrupt drop at 05:41 UT (marked by the yellow vertical line). Simultaneously with the decrease of the $\omega$ field, the ion flux energy drops from high energy to medium energy (several keV). No clear velocity variation is seen. The coincident evolution of $\omega$ field and ion flux energy during the stable BBF suggests that the ion flux energy somewhat depends on the strength of the $\omega$ field, or vice versa. Ion flux somehow can affect the vorticity.

4. Statistical Results

Histograms of the probabilities of the BBF $\omega_\perp$ and $\omega_\parallel$ are shown in Figure 3. The distributions of the $\omega_\perp$ and $\omega_\parallel$ are distinctly different. The BBF $\omega_\parallel$ is mostly less than 1/s, and the $\omega_\perp$ is widely distributed below 10/s. In the statistical sense, the BBF has stronger $\omega_\perp$ than $\omega_\parallel$.

The anisotropy angle is defined as that $\theta_{\|\perp} = \arctan(\frac{\omega_\perp}{\omega_\parallel})$. The average $\theta_{\|\perp}$ over each BBF time is calculated to evaluate the vorticity anisotropy. Histogram of probability of the BBF $\theta_{\|\perp}$ is shown in Figure 4. The $\theta_{\|\perp}$ has a symmetric distribution. The BBF is mainly in the regime of 30° < |$\theta_{\|\perp}$| < 90°. Most BBF has the $\theta_{\|\perp}$ greater than 45°. Statistically, the BBF vorticity is dominantly perpendicular.

5. Evolution of the Ion Energy Flux of the BBF Turbulence

To confirm the behavior of ion energy flux and its similar evolution with the vorticity, we investigate the “temperature” (the second moment of PSD) using the subset of channel from FPI partial moment measurement on 6 July 2017. Associated evolutions of the intergradient energy flux and ion flux and parallel/perpendicular temperature from different channels are plotted in Figure 5. Clearly, the evolutions of the BBF $V_x$ (Figure 5a) and ion energy flux (Figure 5b) are well correlated. The ion energy flux is high in the strong BBF and becomes low in the weak BBF.

The ion behaviors in the strong and weak BBFs are distinctly different. For the strong BBF1 and BBF3, the $T_\parallel$ as well as $T_\perp$ of different channels are quite close. Both are concentrated in a narrow band with the center at ~8 keV. The width of the band is ~1 keV. The narrow band distribution indicates that the ions of different channels are following the bulk motion of the BBF. From Figure 5c, the ion flux is higher/lower in the higher/lower energy channel.

Within the decayed BBF2, the channeled ions form the multiple-layer distribution. The multiple-layer distribution covers a wide range from 1 to 20 keV, for both $T_\parallel$ and $T_\perp$. Apparently, the high-energy ions seriously deviate from the bulk motion of the BBF. Comparing with the BBF1 and BBF3, the ion flux at the high-energy channels is distinctly lower. On the contrary, the ion flux of the low-energy channels (below 2 keV) has prominent intensification.

6. PSD Analysis

The evolutions of $\omega_\parallel$ and $\omega_\perp$ on 25 June 2017 are shown in Figure 6a. Generally, the spectra of the $\omega_\parallel$ and $\omega_\perp$ have coincident evolution tendency. Both slopes are about $-2.0$ (below 0.2 Hz). Note that the spectrum has an ambiguous raise at 0.1 Hz. The raise is more prominent in $\omega_\parallel$ spectrum.

The spectra of the $\omega_\parallel$ and $\omega_\perp$ on 29 July 2017 are shown in Figure 6b. Similarly, the $\omega_\parallel$ and $\omega_\perp$ have coincident spectrum evolution tendency with a scaling of about $-2.0$. The rise of the spectrum at 0.1 Hz becomes clearer, for both $\omega_\parallel$ and $\omega_\perp$. 
As a whole, the BBF $\omega$ spectrum has a serious deviation from Kolmogorov scaling (slope = $-5/3$). This implies that the BBF is far from homogeneous isotropic turbulence. The reasons are not clear. The current sheet turbulence and KAW emission could be the main ones (Dai, 2009, 2018; Dai et al., 2017; Nakamura et al., 2006, 2008; Zhang et al., 2019). In addition, the local deceleration of the BBF may also bring the deviation from homogeneous isotropic turbulence (e.g., Zhang et al., 2020).

**Figure 5.** Evolutions of the ion energy flux with the BBF velocity from FPI partial moment measurement on 6 July 2017 (the same interval as Figure 1). (a) Plots BBF $V_x$. (b) The ion energy flux ($n \cdot T$). (c) The integrated ion flux by channels. (d and e) The corresponding $T$ and $T_\perp$ of ion channels in (c). For clarification, only seven energy channels are plotted. Corresponding channel number (CN) is marked by the different line color.
7. Discussion

Case studies show clearly the existence of the large-scale convective-dominating vorticity field within the BBF. The vorticity field within the BBF is predominantly perpendicular. To understand the anisotropy of the BBF vorticity, we perform the theoretical analysis below. In the magnetized plasma environment, the bulk motion of the plasma gives birth to the convective $E_c$, that is, $E_c = -V \times B$. Thus,

$$\mathbf{V} = \mathbf{E_c} \times \mathbf{B} / B^2$$

Here, $V$ represents the velocity of the mass center of the fluid element:

$$V = \frac{m_i V_i + m_e V_e}{m_i + m_e} \approx V_i$$

where $V_i$ and $V_e$ are the velocity of ion and electron and $m_i$ and $m_e$ are the mass of ion and electron, respectively.

Due to the frozen-in effect, the plasma flow and magnetic field are coupled together. Therefore, the magnetic field is expected to affect the flow motion and vorticity generation. With the conditions of that

$$\nabla \cdot \mathbf{B} = 0$$

and

$$\nabla \cdot \mathbf{E_c} = 0$$

The convective vorticity is equivalent to that:

$$\omega = \nabla \times \mathbf{V} = \frac{\mathbf{B} \cdot \nabla \times \mathbf{B}}{B^2} - \frac{(\mathbf{E_c} \cdot \nabla)\mathbf{B}}{B^2}$$

The first term in the right hand of the equation is related to the perpendicular vorticity ($\omega_\perp$), and the second term is the main source of the parallel vorticity ($\omega_\parallel$).

In the case of BBF, we neglect the flow motion in the $Y$ and $Z$ direction. Assuming the magnetic field lies in the $Y-Z$ plane, the convective electric field has two components, $E_y = V_x B_z$ and $E_z = -V_x B_y$. Inserting them into Equation 2) and assuming a constant $B_z/B_y$ in $Y/Z$ direction, we obtain

$$\omega_Y = -\frac{\partial V_x}{\partial z} = \frac{B_y \cdot B_z \cdot \partial V_x / \partial y}{B^2} + \frac{V_x \cdot B_z \cdot \partial B_y / \partial y}{B^2}$$

$$\omega_Z = -\frac{\partial V_x}{\partial y} = -\frac{B_y \cdot B_z \cdot \partial V_x / \partial z}{B^2} + \frac{V_x \cdot B_z \cdot \partial B_y / \partial z}{B^2}$$

We can see that both velocity shear and magnetic gradient contribute to the local vorticity. The velocity shear caused vorticity is perpendicular dominantly, and the magnetic gradient caused vorticity to be dominantly parallel. The only condition used is. Therefore, at MHD scale Equations 5 and 6 always hold. At subion scale in which the motions of ion and electron are decoupled, the drift vorticity takes over.

In terms of Equation 4, the $\omega_\perp$ dominating vorticity field within the BBF mainly arises from the velocity shear. This is consistent with the classical picture of the flow turbulence in the neutral fluid and gas.

On the other hand, the BBF $\omega$ field has a significant parallel component. Physically, the $\omega_\parallel$ implies the vortex/eddy rotating in the plane normal to the magnetic field. While the magnetic field gradient in flow direction accelerates/decelerates the flow, the magnetic field gradient in shear/normal direction enables diversion of the flow. This generates the local vorticity also. The magnetic inhomogeneity caused vorticity is the unique phenomenon in MHD turbulence.

Figure 6. Power spectrum density of the vorticity field within BBFs. (a) The spectrum from 08:17 to 08:40 UT on 6 July 2017. (b) The spectrum from 05:32 to 05:43 UT on 25 June 2017.
Finally, event on 25 June 2017 shows clearly the evolution of the ion flux energy with the strength of the $\omega$ field in the strong and weak BBFs. The evolution of the ion flux energy is accompanied by the transition of the channelled ions from narrow band to multiple-layer distribution. Combined loss of the high-energy ions and intensification of low-energy ions in the multiple-layer distribution suggests the energy exchange between the BBF and background plasma. This can be explained by the eddy associated “viscous diffusion” process. The evolution of the $\omega$ field in the BBF turbulence and its effects on the BBF transport and dissipation are worthy of further study in the future.

8. Conclusions

Our study show that the convective-dominating vorticity field from the plasma bulk velocity exists within the BBF. In general, the BBF $\omega$ field has stronger perpendicular vorticity than the parallel vorticity. Case study on 25 June 2017 shows that the ion flux energy has a significant evolution with the strength of the $\omega$ field. The strong $\omega$ field in the strong BBF corresponds to the ion flux enhancement at high energy (above 10 keV), while the weak $\omega$ field in the weak BBF corresponds to the ion flux enhancement at medium energy (2–5 keV). Moreover, the ion behaviors in the strong and weak BBFs are distinctly different. The ions of different energy channels form the narrow band distribution in the strong BBF but the multiple-layer distribution in the weak BBF. Finally, PSD analysis show that both $\omega_\parallel$ and $\omega_\perp$ have a scaling of $-2.0$ (below 0.2 Hz).

Data Availability Statement

The data of MMS satellite is available online (https://lasp.colorado.edu/mms/sdc/public/).

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