BBF Deceleration Down-Tail of $X < -15 \text{R}_E$ From MMS Observation

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Abstract We report the direct observation on bursty bulk flow (BBF) deceleration down-tail of $X < -15 \text{R}_E$ by MMS satellite. Two typical events are presented in the paper. In the first event on 05 June 2018, MMS1 is located at $X \sim -16.1 \text{R}_E$ and records four individual bursty flows (BFs). Each burst flow has distinctly lower velocity than the preceding one. Accompanying with the decelerated BFs, the $B_z/B_x$ continuously increases/decreases. Simultaneous $V_x$-decrease and $B_z$-increase are in coincidence with the scenario of the local BBF deceleration and formation of the magnetic pileup region. In the second event on 03 July 2017, MMS stays in the neutral sheet of $X \sim -24.5 \text{R}_E$, and encounters similar BBF deceleration process. For both events, the decelerated BF series exhibit prominent medium-energy ion component (2–10 keV). Analyses show enhanced parallel current ($J_{//}$) and Kinetic Alfvénic wave (KAW) emitting during the BF intervals. The strength of the emitted KAW has a clear tendency to decay with the BBF decreasing. Power spectra density analysis confirms the substantial Joule dissipation during the BBF deceleration, both $J_{//}$ and $J_{\perp}$. Combined analyses support BBF dissipation via Joule heating as well as KAW emitting. Finally, we propose a possible mechanism on the BBF deceleration, i.e., "collision" with the tailward flow.

1. Introduction

Bursty bulk flows (BBFs) are the most common and significant phenomenon in the Earth's magnetotail (Baumjohann et al., 1990; Baumjohann, 2002; Angelopoulos et al., 1992, 1994; Zhang et al., 2009, 2015, 2016, 2016). 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 et al., 2010). Phenomenologically, BBFs are the groups of the short lifetime of the bursty flows (BFs) in the central plasma sheet with durations of up to 10 min (Baumjohann et al., 1990; Baumjohann, 2002; Angelopoulos et al., 1992). BBF has a perpendicular–predominantly component in the central plasma sheet but a significant parallel component near the boundary layer of the plasma sheet (PSBL) (Zhang, Baumjohann, Wang, Réme, Dunlop, & Chen, 2015).

BBF undertakes the main task of momentum, energy, and flux transport in the plasma sheet (Angelopoulos et al., 1994). As the main energy carrier, the BBF deceleration redistributes the energy in the magnetotail and the ionosphere (e.g., Angelopoulos et al., 2002; Birn et al., 2004; Chaston et al., 2012; Volwerk et al., 2004). Traditionally, the BBF is believed to have a stop/brake while closer to the Earth than 15 $\text{R}_E$ mainly due to the enhanced magnetic and plasma pressure gradient at the earthward side of the BBF (e.g., Baker et al., 1996; Shiokawa et al., 1997, 1998; Birn et al., 1999). BBF braking causes the localized magnetic flux pileup. Say, the kinetic energy of the BBF is conversed into the magnetic energy. BBF deceleration could excite significant wave/turbulence activities in the brake region, such as the K-H vortex and Kinetic Alfvénic wave (KAW) wave/turbulence (e.g., Ergun et al., 2015; Panov et al., 2010, 2013; Stawarz et al., 2015).

Contradict to the scenario of the BBF braking, the low-speed BBF is a very popular phenomenon outside the braking region (beyond 15 $\text{R}_E$). It is prone to postulate that the BBFs could experience the deceleration on their way traveling toward the Earth. The dipolarization front (e.g., Schmid et al., 2015, 2016; Sergeev

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et al., 2009), signed by the sharp enhanced Bz, has been proposed to be the possibly mechanism to decelerate the BBF (Hamrin et al., 2014). Another mechanism is the dissipation of the BBF kinetic energy by emitting KAW (e.g., Angelopoulos et al., 2002; Chaston et al., 2012; Higashimori & Hoshino, 2015; Turkakin et al., 2014).

Till now, the direct evidence on the BBF deceleration outside the braking region is still lacking. In this study, we report the first direct observation of BBF deceleration down-tail of X < −15 Re by MMS spacecraft. Typical event studies show clearly that the BBF experiences the substantial deceleration from super-VA to far below sub-VA (VA is the Alfvénic velocity) and formats the localized magnetic pileup region before they access to the braking region. Associated studies show enhanced field-aligned current and KAW emitting during the BBF deceleration. The possible mechanism on the BBF deceleration is discussed also.

2. Data Description

While operating in the Earth’s magnetotail, the measurement data have the resolution of 0.1 s for fluxgate magnetometers (FGM) (Russell et al., 2016; Torbert et al., 2016), 0.04-s resolution for 3-D Electric Field Instrument (EDP) (Lindqvist et al., 2014), and 4.5 s for Fast Plasma Investigation (FPI) (Pollock et al., 2016) on board the MMS.

All data are collected in GSM coordinates. A 10-min low-pass filter is applied to separate the background and perturbed E/B field. The obtained unperturbed and perturbed E and B are used to calculate the Poynting vector \( \mathbf{P} = \mathbf{E} \times \mathbf{B} / B^2 \) and its parallel and perpendicular components. Considering their different measurement time, the measured E data, with a higher time resolution, are rearranged to match the B time sequence by the linear interpolation (best fit). Though sacrificing the high resolution of E data, the calculated value of \( \mathbf{E} \times \mathbf{B} \) is more reasonable and reliable.

3. Case Studies

3.1. The 05 June 2018

Temporal evolutions of the field and ions from 18:20 to 19:00 UT are shown in Figure 1. MMS1 is located at \((-16.1 \text{ Re}, -9.9 \text{ Re}, 3.9 \text{ Re})\) (GSM coordinate). From (a) to (h), panels are the ion velocity from FPI measurement, parallel (\(V_{//}\)) and perpendicular (\(V_{\perp}\)) and total velocity (\(V_T\)), electric drift velocity \(V_{EB}\) (calculated by \(E \times B / B^2\)) and electron perpendicular drift velocity \(V_{e\perp}\), the measured magnetic field B, the perturbed and unperturbed Bz, the measured electric field, and measured ion density and temperature.

The BBF lasts from 18:34 to 18:55 UT (within the two black vertical lines), comprised of four individual BFs. From first to the last, the Vx of the BBF continuously decreases from ~425 to ~80 km/s. The deceleration process ends at 18:54. Another BF shows up at 18:56 UT after the end of the BBF deceleration. This flow does not participate in the deceleration process.

Accompanying with the Vx decreasing, the Bx continuously decreases from 15 to about 4 nT, while the strength of the unperturbed B_{z0} (in panel e) continuously increases from 2 to 10 nT. Therefore, the configuration of the magnetic field becomes very dipolar-like. During this interval, the By component keeps almost unchanged. Simultaneous Vx decreasing and Bz enhancement agrees with the formation of the localized magnetic pileup region. From panel (d), Bz increases and Bx decreases but the total magnetic field remains almost constant. Based on the magnetic energy transport equation, it would mean that locally the divergence...
of the Poynting flux is almost balanced by the Joule dissipation during the BBF sequence leaving the magnetic energy almost unchanged.

Prior to the end of the BF1 (18:36 UT marked by the red vertical line), the perpendicular component of the electron drift velocity ($V_{e\perp}$) and the electric drift velocity ($V_{EB}$, calculated by $E \times B / B^2$) are in well agreement (panel c). After 18:36 UT, the $B_z$ continuously increases and the $V_{e\perp}$ suddenly becomes much greater than the $V_{EB}$. The large discrepancy found after 18:36 UT corresponds to a drift velocity between ions and electrons of about 600 km/s. Assuming a density of 0.1 cm$^{-3}$, it would correspond to a perpendicular current density $j_{\perp} = e(n_{i}V_{i\perp} - n_{e}V_{e\perp}) = 10$ nA/m$^2$. This is consistent with the Curl_B result (Figure 3e).

With the appearance of the BBF, the ion density/temperature has a sudden decrease/increase. During the whole deceleration process, the ion density keeps almost constant while the ion temperature slightly decreases from 5 to 3 keV. HPMA result confirms that the ion temperature during the BF series is higher than that of the background. The decrease trend is mainly contributed to the flux decrease/increase of He++/O+ which temperature is higher/lower than H+ (not shown).

### 3.2. The 03 July 2017

On 03 July 2017, MMS1 stays in the neutral sheet and encounters the similar BBF deceleration process. From 21:00 to 24:00 UT, MMS1 moves gradually toward the apogee from ($-24.1$ RE, $-1.0$ RE, $4.6$ RE) to ($-24.4$ RE, $-1.8$ RE, $4.8$ RE). The associated evolutions of the magnetic field and ions are shown in Figure 2. Continuous tailward flow with $+B_z$ lasts from 21:10 to 21:55 UT. A near-Earth X-line (the red solid vertical line) retreats, denoted by the intense tailward flow with $-B_z$ followed by the fast earthward flow with $+B_z$, and passes by the MMS satellite at 22:00 UT. The reconnection generated earthward/tailward BBFs are perpendicular predominantly.

From 22:00 to 23:45 UT, MMS records six individual BF's. All BF's have similar ion density and temperature, ~0.3 cm$^{-3}$ and ~4 keV. All three components of the magnetic field oscillate strongly within the BF's. The $B_z$ becomes the dominant component of the magnetic field. This implies the localized magnetic pileup and formation of the dipolar-like plasma sheet. The amplitude of the $\Delta B_z$ is comparable to the strength of the $B_0$. The measured electric field $E$ (panel f) have substantial enhancement during the BF intervals. The perturbed $E/B$ dominates the BBF. The $V_{e\perp}$ and $V_{EB}$ are in well agreement (panel c). Hence, the ion/electron motion is dominated by the $E \times B$ drift.

As shown in panel (b), the six BF's belong to two different deceleration processes. The first BF is strong and the second BF is small. This is the first BBF deceleration process. From third to sixth, the $V_x$ of the BF has a continuous deceleration from ~750 to ~250 km/s. This is the second deceleration process.

### 4. Evolution of the Current and E/B Perturbations With BBF Deceleration

#### 4.1. Event on 05 June 2018

In the event on 05 June 2018 the magnetic field data from the FGM instrument on board all four spacecraft are available. The curlometer method ($J = V \times B / \mu_0$) is applied to calculate the electrical current density $J$ (Dunlop et al., 2002; Paschmann & Daly, 1998; Robert et al., 1998). MMS1 is settled to be the reference point in our curlometer analysis (refer to Zhang et al., 2019). Thus, $J$ is an average quantity at the position of MMS1. This enables us to compare the temporal evolution tendencies of the $J$ and directly measured $E/B$ perturbations.
The distances between the MMS1 to the other three satellites in X‐Y and X‐Z planes (GSM ordinates) are shown in panels (h) and (i). MMS4 is very close to MMS1, only 0.07 km in x axis, 14.8 km in y axis, and 18.3 km in z axis. MMS3 is the farthest one to MMS1, 68.3 km in x axis, 79.7 km in y axis, and 78.2 km in z axis. MMS2 is away from MMS1 mainly in y axis, ~68.3 km.

From panel (a), from BF1 to BF4, the flow velocity directly decreases to far below local Alfvénic velocity ($V_A = B/\sqrt{\mu_0 \rho}$, $B$ and $\rho$ are the averaged values during the BBF). The $\Delta E_y$ from four satellites have basically consistent evolutions. All tend to enhance within the BF series. The $\Delta B_z$ at MMS1 and 2 and MMS3 and 4 are very close to each other. The strength of $\Delta B_z$ has prominent enhancement within the BF. Current has substantial enhancement during the period of the BFs (panel e). The BF‐interval current is characterized by the significant field‐aligned component. In this event, the parallel current ($J_{||}$) has a clear tendency to decrease with the BBF decelerating.

Parallel Poynting vector ($P_{||}$) and perpendicular Poynting vector ($P_\perp$) are shown in panel (f). In this events, the $P_{||}$overwhelms the $P_\perp$. The parallel‐predominantly Poynting flux is in coincidence with the KAW emitting. Panel (g) shows the ion energy spectra. Before the BBF shows up, the plasma sheet is overwhelmed by the low‐energy (200 eV to 2 KeV) and medium‐energy (2–10 KeV) ions. As a
contrast, the deceleration region (between the two vertical lines) is overwhelmed by the medium-energy and high-energy ions (above 10 KeV). The former causes clear “finger-like” structure during the BF series in the ion energy spectrum.

4.2. Event on 03 July 2017

Due to lack of FGM/MMS4, curlometer technique is inapplicable for this event. FPI moment measurement is used instead to calculate the current, by $J = ne (v_i - v_e)$, where i/e represents ion/electron, n is the plasma density, and e is the electron charge.

Detail evolutions of associated current and perturbed E/B during the second BBF deceleration process are shown in Figure 4. The BBF gradually decelerates from super-$V_A$ to sub-$V_A$ ($V_A$ is ~520 km/s). Comparing $n_e$ from FPI (partial moment from 20 eV to exclude the photoelectrons effect), $n_i$ from FPI, and $n_{H+}$ from HPCA, we can see the distinct discrepancy between $n_i$ and $n_e$. The $n_e$ and $n_{H+}$ are well consistent, except that $n_e$ is very faintly higher than $n_e$. It is reasonable to choose $n_e$ as the realistic plasma density. The FPI-momentum current result is shown in panels (e) and (f). Similarly, the intensification of the $J_{||}$ can be clearly seen during the BF intervals. From BF3 to BF6 the amplitude of the $\Delta E_y/\Delta B_z$ distinctly decreases. Consequently, the strength of $P_{||}$ decreases with the $V_x$ decreasing. In this event, the $P_{||}$ is the dominant component. The $P_{||}$-dominating Poynting flux could be linked to the flow eddies in which the compressible MHD wave is outstanding (Zhang et al., 2019).

From panel (h), the background plasma sheet is filled by the low- and medium-energy populations. The BF3 is dominated by the high-energy ions. As a contrast, the subsequent BFs (BF4 to BF6) are characterized by the prominent medium-energy ions. It appears that the medium-energy ions of the BFs are closely associated with the deceleration process.

5. PSD Result on 05 June event

To evaluate the Joule dissipation in the pileup region, we detailedly analyze the power spectra density (PSD) of the current during the BBF deceleration interval on the 5th of June event. The PSD analysis from 18:35 to 18:55 UT is shown in Figure 5a. The breakpoint of the spectra locates at 0.2 Hz (ion gyro-frequency), where the slope of the spectra translates from Kolmogorov-like ($-5/3$) to dissipation-like ($-2.5$). Below 0.2 Hz, the $J_{||}$ has relatively steeper scaling than $J_{\perp}$. For comparison, the spectrum of $B_z$ is also presented. The evolution of the $B_z$ spectrum is basically consistent with $J_{\perp}$ spectrum, at both MHD and kinetic scales.

The evolutions of the $J_{||}$ and $J_{\perp}$ spectra during four BF intervals are shown in Figure 5b. For each BF, the $J_{||}^2$ and $J_{\perp}^2$ are quite close. From BF1 to BF2, the $\overline{J}$ (average value of $J_{||}^2$ and $J_{\perp}^2$) decreases from ~0.02 to ~0.008 (nA/m²²/Hz at 1 Hz (ion dissipation regime), further to ~0.005 (nA/m²²/Hz) for BF3. $\overline{J}$ of the BF4 is unexpectedly high, ~0.03 (nA/m²²/Hz), higher than BF1. The abnormal of BF4 could be due to the followed stronger BF. Despite the abnormal of BF4, the temporal evolution of $\overline{J}$ seems true. The spectrum slope has a slight tendency to decrease with the BBF $V_x$, also. The tendency needs to be verified in the statistical sense.

Figure 4. Evolution of the J and perturbed E/B field with the BBF deceleration on 03 July, 2017. (a) Ion drift velocity and Alfvénic velocity ($V_A$). (b) Perturbed $E_y$. (c) Perturbed $B_z$. (d) Ion density FPI, electron density from FPI (partial moment from 20 eV), and proton density from HPCA. (e) Calculated current $J$ from FPI-moment measurement ($J = ne (v_i - v_e)$). (f) Parallel and perpendicular components of the $J$ ($J_{||}$ and $J_{\perp}$). (g) Parallel and perpendicular Poynting vector ($P_{||}$ and $P_{\perp}$) at MMS 1. (h) Ion energy flux spectrogram.
6. Discussion

6.1. BBF Dissipation in the Magnetic Pileup Region: Joule Heating and KAW Emitting

Case studies show that the decelerated BFs are characteristic of the medium-energy ion constituent (2–10 KeV). Finger-like structure (Figure 3g) strongly suggests the local energization/thermalization of the ions. Joule dissipation and KAW emitting supply the possible mechanisms of the local thermalization (e.g., Drake et al., 2009; Eastwood et al., 2018).

Our analysis shows the enhanced E/B perturbation in the course of the BBF. KAW emitting always occurs during BBF intervals (e.g., Angelopoulos et al., 2002; Chaston et al., 2012; Dai et al., 2011; Huang et al., 2012; Zhang et al., 2019). According to Chaston et al. (2012), the frequency range of the KAW during the BBF intervals is 0.2–20 Hz (Doppler shift). As shown in Figure 5a, the spectrum of \( J_{\parallel}/J_{\perp} \) have a frequency range of 0.2–4 Hz. This is consistent with the KAW frequency range during BBF intervals (Chaston et al., 2012). Emitting of the KAW and/or compressional wave could increase the dissipation of the electromagnetic energy of the BBF. This could explain the steeper slope of \( J_{\parallel} \) than that of the \( J_{\perp} \).

On the other hand, the thin current sheet is embedded within the BBF (e.g., Vörös et al., 2004, 2006; Nakamura et al., 2008; Dai 2009; Dai et al., 2011). Due to the permanently turbulent current sheet, Joule dissipation is inevitable. Our analysis reveals the substantial \( J_{\parallel} \) during BBF intervals. The \( J_{\parallel} \) has significant Joule dissipation in the course of the BBF, and \( J_{\perp} \) as well.

6.2. New Possible Mechanism of the BBF Deceleration

The newly generated BBF has “upstream/inflow” Alfvénic velocity in the reconnection exhaust region (e.g., Drake et al., 2009; Drake & Swisdak, 2014; Shay et al., 1998). This inflow Alfvénic velocity (depending on the inflow plasma density and the inflow magnetic field) could change during the series of BBF events. Here we would like to point out that the deceleration process does not rule out the effect of the efficiency/intensity of the acceleration mechanism (source) on the velocity variation of the BF series. But, the low-speed BF (~200 km/s) appears to be produced only by the deceleration process.

A possible mechanism for BBF deceleration in these events is the “collision” of earthward BBF with the tailward flow. Tailward plasma flows (with positive Bz) is ubiquitous in the plasma sheet (e.g., Ohtani et al., 2009; Schödel et al., 2001; Zhang et al., 2015, 2015). A simple cartoon is illustrated in Figure 6 to show the “collision” and BBF deceleration process. The new-born BBF travels toward the Earth in the super-VA after it leaves the reconnection region. After meeting the tailward flow, the BBF is decelerated to sub-VA. The “colliding” between the tailward flow and BBF leads to form the flow interaction region where the magnetic flux is piled up. After colliding, the decelerated BBF (if still alive) keeps traveling toward the braking region and eventually stops there.

For both events presented in the paper, the continuous tailward plasma flow (with positive Bz) emerges before the appearance of the BBF. When the tailward flow and the BBF meet together, the “colliding” naturally decelerates the BBF. Assuming that thermal exchange/evolution and kinetic effect can be neglected, then, the total momentum of the earthward BBF and the tailward flow before and after the collision is conserved (idea MHD condition). Assuming that after collision the tailward and earthward flows have the same speed, there has \( m_{E}V_{E} + m_{T}V_{T} = (m_{E} + m_{T})V_{D} \). The terms in the left hand are before-collision, where \( V_{D} \) in the right-hand represents the decelerated flow velocity after the collision. The subscript \( E \) and \( T \) represent
the earthward and tailward flow, respectively. Assuming that $m_p = m_T$, given $V_E$ of 700 km/s (typical value of $V_A$) and $V_T$ of $-100$ km/s, after colliding, the velocity of the BBF is dropped to 300 km/s. We can see that even small tailward flow could dramatically decelerate the BBF. It is worthy to point out that the “colliding” could play the role in the braking region too.

7. Conclusions

As a conclusion, the BBF can experience substantial deceleration down-tail of $-15$ RE. The decelerated BBF is characteristic of the prominent medium-energy ion constituent (2–10 keV). Associated analyses show the intensification of the $J_{\parallel}$ and KAW emitting during the BF intervals. The strength of the $P_{\parallel}/P_L$ tends to decrease with the BBF decelerating. PSD result confirms the Joule dissipation in the BBF deceleration region, both $J_{\parallel}$ and $J_L$. Finally, the “collision” with the tailward flow in the plasma sheet is proposed to be the possible mechanism of the BBF deceleration down-tail of $-15$ RE.

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Figure 6. A schematic diagram of the BBF deceleration and formation of the localized magnetic pileup region. The solid black lines mark the magnetic field lines. The new-born BBF experiences the deceleration by “colliding” with the tailward flow. The “colliding” between the tailward flow and BBF leads to the formation of the localized magnetic pileup region. After then, the decelerated BBF travels earthward toward the braking region and eventually stops there.
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