Observations of Whistler-mode Waves and Large-amplitude Electrostatic Waves Associated with a Dipolarization Front in the Bursty Bulk Flow

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Abstract

Plasma jets and jet fronts are common phenomena in planetary magnetospheres. They are usually associated with many plasma waves and can play a key role in the energy conversion, the excitation of wave emissions, particle acceleration, and the evolution of many astrophysical phenomena, which are major issues in the study of helio-terrestrial space physics. In this paper, we carefully investigated the properties of the whistler-mode wave and large-amplitude electrostatic wave in a plasma jet (bursty bulk flow (BBF)) using the Magnetospheric Multiscale mission data on the Earth’s magnetosphere. At the leading part of the BBF, intense whistler-mode waves were observed inside the ion mirror-mode structures, which should be excited by the perpendicular temperature anisotropy of trapping electrons. A small-scale dipolarization front (DF) was then observed at the center of this BBF as a boundary between the leading and trailing parts of the BBF. Behind the DF, both an ion mirror-mode structure and whistler-mode waves disappear, while a large-amplitude electrostatic wave was detected and was associated with the cold ions at the trailing part of the BBF. The electrostatic wave is supposed to be generated by ion beam instability. These results will significantly improve the understanding of the kinetic process associated with the important boundary layer DF within plasma jets. The corresponding wave–particle interaction in space and the plasma environment can be further understood.

1. Introduction

Plasma jets are ubiquitous phenomena and play an important role in the energy transport of space and astrophysical plasmas (Bridle & Perley 1984; Opher et al. 2015; Zhou et al. 2019), such as the astrophysical jets found in active galactic nuclei (Urry & Padovani 1995; Sironi & Giannios 2014), stellar-mass black holes (Saikia et al. 2019), and young stellar objects (Anglada et al. 2018). The typical earthward high-speed plasma jets called bursty bulk flows (BBFs) occur frequently in the Earth’s magnetotail (Baumjohann et al. 1990; Angelopoulos et al. 1992; Nakamura et al. 2004; Cao et al. 2013). These plasma jets are thought to be responsible for the particle acceleration and the transport of mass, momentum, energy, and magnetic flux (Webb et al. 2018; Matthews et al. 2020). However, due to the limitation of in situ observations in astrophysical environments, the kinetic process of plasma jets is not yet known in detail. Using the high-resolution data of terrestrial satellites, we can deeply investigate the particle properties of similar plasma jets (BBFs) in the Earth’s magnetotail to further understand the kinetic processes of a plasma jet in other planetary magnetospheres. Generally, the occurrence of BBFs is related to the onset of a substorm (Shiokawa et al. 1997; Baumjohann 2002) or wave activities in the plasma sheet (Li et al. 2013; Wang et al. 2016b). It is considered to be a signature of instantaneous local magnetic reconnection (Nakamura et al. 2002; Angelopoulos et al. 2008; Zhang et al. 2010).

Dipolarization fronts (DFs) are often accompanied by the observations of plasma jets, which have been characterized by a sharp increase in the magnetic field B, and a decrease in plasma density (Sergeev et al. 2009; Runov et al. 2012; Xu et al. 2018). Many studies indicate that the DFs play a key role in planetary magnetotails and are closely related to the interactions with ambient plasmas, e.g., Saturn (Smith et al. 2018), Jupiter (Artemyev et al. 2013), Mercury (Sun et al. 2016; Dewey et al. 2017), and Earth (Divin et al. 2015; Khod intimsev et al. 2017). DFs are believed to efficiently lead to particle heating and acceleration (Fu et al. 2011; Liu et al. 2017; Zhong et al. 2019a; Ma et al. 2020). In Saturn’s magnetotail, Xu et al. (2022) demonstrated that electrons are stepwise accelerated by successive DFs during substorms. The DF has also been suggested to be associated with electron and ion heating in the Jovian magnetotail (Kasahara et al. 2011). The test particle simulation of DFs has revealed that they can effectively transfer the energy of the plasma flow to heavy ion energy in planetary magnetotails (Greco et al. 2015). However, due to the limited accuracy of the observations of the astrophysical system, the kinetic processes, and corresponding wave–particle interactions around DFs within a plasma jet still need further investigation.

Previous works show that the DF is a boundary layer usually suggested to separate the intruding hot tenuous plasma and the ambient cold dense plasma (Runov et al. 2011, 2015), and is often associated with different instabilities in the Earth’s magnetotail, such as mirror instability (Shustov et al. 2019),
streaming instability (Yang et al. 2017), and ion beam instability (Liu et al. 2019), etc., which are conducive to the excitation of wave activities (Zhou et al. 2009; Huang et al. 2012; Li et al. 2015). The analysis of plasma waves is an important way to study the complicated ion and electron kinetics of DFs. The observation and study of DFs in the Earth’s magnetosphere will help us to have a better understanding of DFs and compare them with other planets with similar structures.

In addition, it has also been reported that cold ions are commonly detected in the magnetosphere, which can significantly affect the reconnection kinetics (Alm et al. 2018) and the generation of plasma waves (Liu et al. 2019). Recently, Xu et al. (2019) reported that ionospheric cold ions have been detected by the Magnetospheric Multiscale (MMS) mission behind the DF, which can drive the instabilities around the DFs and affect the growth and decay of the DF. Liu et al. (2019) reported an electrostatic solitary wave (ESW) event excited by two cold ion beams behind the DF, and found that those ESWs can affect the heating and acceleration of particles in the BBFs. However, the locations of the generation of the plasma waves and how the plasma impacts the kinetic process of DFs/BBFs remain to be not well understood; therefore, the interactions among cold ions, reconnected outflow particles, and the driving process of plasma waves are worthy of further discussion.

In this study, we used MMS high-resolution data to demonstrate two types of plasma wave generation mechanisms and proved that they are locally excited in different background environments around a DF at the center of a BBF. We analyzed the influence of mirror instability and ion beam instability around the DF and also discussed the relationship between the DF, the plasma waves, and the wave–particle interaction, which can provide a further understanding of the plasma properties, energy conversion, and kinetic processes of the BBF/DF.

The remainder of this paper is organized as follows. In Section 2, we present an overview of the observation of the BBF on 2017 June 25, the whistler-mode waves before the DF, and the electrostatic wave behind the DF are analyzed in detail. Finally, Section 3 gives the discussion and summary of this study.

2. Observations

2.1. Overview

In the present study, we use magnetic field data from the Flux Gate Magnetometer instrument (Russell et al. 2016), with a sampling frequency of 128 Hz in burst mode and 16 Hz in survey mode, and the Search Coil Magnetometer (Le Contel et al. 2016) instruments, which have a sampling frequency of 8192 Hz. The electric field data was obtained from the Electric Double Probe (Ergun et al. 2016; Lindqvist et al. 2016) instrument, which has a sampling rate of 8192 Hz. The plasma measurements are from the Fast Plasma Investigation (FPI; Pollock et al. 2016) instrument, whose resolution of electrons and ions in burst mode is 30 and 150 ms, respectively.

Figure 1 presents an overview of the plot of the BBF event observed by MMS1 from 04:04:00–04:09:00 UT on 2017 June 25 when the MMS spacecraft was located at $[-22.3, -1.9, 3.5]$ $\text{Re}$ (Earth’s radius) in the Geocentric Solar Magnetospheric (GSM) coordinate system. During the interval of 04:05:10–04:07:00 UT, the $B_x$ component shows a reversal from negative to positive (Figure 1(a)), which implies that MMS crossed the neutral plane and was located in the northern hemisphere. Meanwhile, the ion flow velocity is significantly enhanced. It can be seen that the peak speed of the high-speed ion bulk flow reaches $V_{hi} \sim 600 \text{ km s}^{-1}$ (Figure 1(b), (c)), which indicates that MMS1 observed a typical earthward-moving BBF. With the appearance of the BBF, the electron density suddenly decreases (Figure 1(b)), and the high-energy ion/electron fluxes close to 1 keV are also reduced (Figure 1(e), (f)). At 04:06:45 UT, a DF was observed within this BBF, which was characterized by a sharp increase in $B_z$ from 13 to 18.5 nT, and the electron density suddenly decreases from 0.4 to 0.2 cm$^{-3}$ in about 1 s. Before and after the DF, $V_{bi}$ changes from strengthening to weakening, and the DF corresponds to the peak of $V_{bi}$, indicating that the DF is located in the center of the BBF. We perform a timing analysis (Russell et al. 1983) on the magnetic field during the time intervals around the $B_z$ reversals to determine the normal speed ($V_n$) of the DF, and the $V_n$ was about 191 km s$^{-1}$ along the normal direction of $[0.78, 0.09, -0.62]$ in the GSM coordinate system. Then, the thickness of the DF can be estimated as $V_n \times \delta t = 191 \text{ km s}^{-1} \times 0.47$, where $\delta t$ is the duration of the DF and $d_i$ is the local ion inertial length. Behind the DF, cold ion injection has been obviously observed (Figure 1(e)). The black solid line in Figure 1(e) represents the energy corresponding to the $E \times B$ drift, which is coincident with the $H^+$ energy range corresponding to the cold ions. It indicates that the cold ions drift from the inner magnetosphere. After 04:07:50 UT, since the magnetic field tends to be stable and the electron density decreases, MMS transitioned to the lobe region.

2.2. Whistler-mode Waves

Figure 2 illustrates detailed observations in the vicinity of the DF. Figures 2(a) and 2(b) show a close-up view of the magnetic field $B_z$ and electron density $n_e$ from 04:06:42–04:06:48 UT. The red dashed vertical lines mark the time where the increase in $B_z$ and decrease in $n_e$ are detected around 04:06:44.8 UT, exhibiting a typical DF feature. As the DF is in the center of the BBF, Figures 2(c)–(m) show the different plasma environments before and after the DF over a long period. From 04:06:10–04:06:45 UT before the DF, the background magnetic field decreases (Figure 2(d)) when the electron density increases (Figure 2(e)), indicating that there may be a mirror-mode structure, which is shown as the gray shadowing. We then calculated the threshold of the ion mirror instability (Figure 2(f)) by using the formula derived by Hasegawa (1969), $K = T_{i\parallel}/T_{i\perp} - 1/\beta_{i\perp} - 1$, where $T_{i\parallel}$ and $T_{i\perp}$ are the parallel and perpendicular components of the ion temperature and $\beta_{i\perp}$ is the perpendicular ion beta. Since the mirror instability is unstable when $K > 0$, it can be determined that there are ion mirror modes (Figure 2(f)). Using the timing analysis method, the normal velocities of these mirror-mode structures can be calculated at about 397–468 km s$^{-1}$, which is close to the local ion bulk flow velocity (Figure 1(c)). This means that these mirror-mode structures are approximately stationary in the BBF. Then, the scale of these mirror-mode structures can be estimated at about 1985–5616 km s$^{-1}$ correspond to $\sim 4.7–13 d_i$, suggesting that they are the ion-scale mirror mode. It should be noted that, behind the DF, the ion mirror mode remains stable ($K < 0$). At the same time,
both the electron temperature (Figure 2(g)) and the ion temperature (Figure 2(h)) have reversals from $T_{\perp} > T_{\parallel}$ to $T_{\perp} < T_{\parallel}$, which indicates that the local conditions for background parameters before and behind the DF have undergone a dramatic change. Figures 2(i) and (l) show the wave properties resolved from the singular value decomposition method (Santolík et al. 2003). We observed that the magnetic field power spectral density has an obvious enhancement in the frequency range of $0.1 - 1 f_{ce}$, which only appears inside the mirror-mode structures before the DF ($f_{ce}$ is the electron gyrofrequency). These waves correspond to a positive ellipticity (which approaches 1 as shown in Figure 2(j)), and wave normal angles tend to be quasi-parallel ($\theta < 15^\circ$, Figure 2(k)). Thus, we conclude that the wave emissions at the DF correspond to the right-hand polarized and parallel propagation whistler-mode waves (Tang et al. 2014; Tang & Summers 2019; Zhang et al. 2021; Zhong et al. 2021). Figure 2(l) shows that the Poynting flux of whistler-mode waves has two propagation directions (parallel and antiparallel to the background magnetic field), which should be indicators of wave source regions.

Figure 2(m) displays the effect of the ion mirror structure on the high-energy electrons ($3000 - 30,000$ eV), in which the white solid lines represent the mirror-mode trapping angles $\theta$. 

Figure 1. Overview of the BBF event observed by MMS1 from 04:04:00–04:09:00 UT on 2017 June 25. (a) Three components and total magnetic field, (b) electron density, (c) ion and (d) electron bulk velocity, (e) ion and (f) electron differential energy flux; the black solid line represents the energy corresponding to the $E \times B$ drift coinciding with the energy of cold ions. (g) A sketch showing the process of the event observed by MMS.
Figure 2. Characteristics of whistler-mode waves. (a) $B_z$ component and (b) electron density over a short time interval. (c) Three components and (d) total magnetic field, (e) electron density, (f) ion mirror instability threshold, (g) electron, and (h) ion temperature. The magnetic field (i) and electric field (j) power spectral density, (k) ellipticity, (l) angle of Poynting flux, and (m) 3000–30,000 eV electrons pitch angle distribution. The dashed black lines, solid black lines, dotted–dashed lines, and the solid blue lines in Figures 2(i)–(l) represent the $1f_{ce}$, $0.5f_{ce}$, $0.1f_{ce}$, and $f_{pi}$, respectively. The gray shadowed region represents the mirror-mode structures. (n) The fitting (solid lines) and observed (circles) electron PSD, (o) dispersion relations (black), and growth rates (magenta) of the whistler-mode wave (the red circle marked in Figure 2(i)). The green dotted line in Figure 2(o) represents the maximum growth rate.
and $180^\circ - \theta$. The trapping angle of the magnetic mirror mode is calculated by $\theta = \sin^{-1} \left( \frac{|B|}{B_{\text{max}}} \right)$, where $B$ is the local magnetic field strength (Breuillard et al. 2018). In the whole region where the whistler-mode waves exist, high-energy electrons with pitch angles between $\theta$ and $180^\circ - \theta$ are deeply trapped in the mirror structure. Moreover, whistler-mode waves also correspond to electron temperature anisotropy $T_{e,1}/T_{e,\|} > 1$ (Figure 2(g)). Therefore, we infer that the observed whistler-mode waves should be generated by cyclotron resonance with electron temperature anisotropy (Tang et al. 2014; Zhang et al. 2020; Summers & Tang 2021), which is caused by the ion mirror structure. Based on the fitting process to the electron distribution, we calculate the growth rates of whistler-mode waves (red circle in Figure 2(i)) from the Waves in Homogeneous Anisotropic Multicomponent Magnetized Plasma (WHAMP; Rönmark 1982), and then compare the result with the observation. The parameters obtained from the electron distribution fitting (Figure 2(n)) are $B = 12$ nT, $n_e = 0.24$ cm$^{-3}$, $T_{e,1} = 1700$ eV, $n_{i,cold} = 0.18$ cm$^{-3}$, $T_{i,cold} = 1700$ eV, $T_{i,hot} = 2210$ eV, $n_{i,hot} = 0.04$ cm$^{-3}$, $T_{i,hot} = 1300$ eV, $\theta_{\perp} = 2210$ eV, and $V_{d1} = V_{d2} = 0$ km s$^{-1}$, where $V_{d1}$ and $V_{d2}$ are the drift velocities along the magnetic field. As shown in Figure 2(o), there is a significant positive growth rate with the maximum growth of $\gamma/\omega_{ce} = 0.0078$ for whistler-mode waves occurring at a frequency of $\omega/\omega_{ce} = 0.2$, which further indicates that whistler-mode waves can be locally excited within the ion mirror modes before the DF. The wave frequency obtained by the WHAMP result is also approximately consistent with the frequency of the observed waves ($> 0.1 f_{ce}$). However, behind the DF, the whistler-mode waves disappear due to the unsatisfactory conditions of electron temperature anisotropy. The DF should be a boundary layer to separate local plasma conditions. More interestingly, as can be seen in Figure 2(j), a strong enhanced power in the parallel electric field at the frequency close to the ion plasma frequency ($f_{pi}$, the blue solid line) has been observed behind the DF, which indicates that MMS observed significant broadband electrostatic wave activity.

### 2.3. Electrostatic Wave

We now focus on the electric field fluctuations behind the DF and the details are shown in Figure 3. Figure 3(b) displays the electric field fluctuations after bandpass filtering of 10–400 Hz. It can be seen that $E_{\parallel}$ is the dominant component of the electric field behind the DF and it has a maximum amplitude of $\sim 150$ mV m$^{-1}$. The 1D reduced electron and ion distributions in Figures 3(c) and (d) have a distinct difference. The parallel phase space density of electrons (Figure 3(c)) barely changes before and after the DF, indicating the generation of the electrostatic wave is independent of the instability associated with electrons. However, the ion distribution behind the DF shows an obvious separation of cold and hot ion beams, in which the speed of the cold ion beam is $\sim 50$ km s$^{-1}$ from the inner magnetosphere and the speed of the hot ion beam is $\sim 1200$ km s$^{-1}$ from the outflow region of reconnection. In such a case, we infer that the hot and cold ion beams may play a key role in the excitation of the electrostatic wave, and a sketch of this process can be seen in Figure 1(g).

Figure 3(e) displays the phase velocity and length scale of the electrostatic wave from 04:06:50–04:06:55 UT. We use the method in Graham et al. (2015, 2016) to calculate the frequency-wavenumber power spectrum $P(f, k) / P_{\text{max}}$ of the electrostatic wave obtained from $E_{sc \sim p1}$ and $E_{sc \sim p2}$ of MMS1. The dispersion relation shows that the wavenumber $k_\| E$ of the electrostatic wave is around 0.001–0.002 m$^{-1}$ corresponding to the wavelength $\lambda \sim 3.1–6.3$ km or $\sim 4.5–9.5$ $\lambda_0$ ($\lambda_0$ is the Debye length $\sim 0.66$ km), and the phase velocity ($V_{ph}$) of the electrostatic wave is calculated as $\sim 212.3$ km s$^{-1}$ by fits the linear dispersion relation $\omega = \nu_{\parallel E}$ to the data. The zoom-in in Figures 3(f)–(h) shows more detailed fluctuation characteristics of the electrostatic wave from 04:06:50.7–04:06:55 UT. The waveform of $E_{\perp}$ is without an obvious isolated bipolar structure (Figure 3(f)), indicating that it is not an ESW. We further use the minimum variance analysis (Sonnerup & Scheible 1998) on the electric field to estimate the properties of the electrostatic wave, which the propagation direction is [0.26, −0.12, 0.96] in the field-aligned coordinates (FAC system). Then, the electrostatic wave is determined to have linear polarization and quasi-parallel propagation. Its wave normal angle is close to $17^\circ$. The ion trapping range obtained from the formula $V_{it,j} = V_0 \pm \sqrt{2}e\theta/m_i \sim [117, 307]$ km s$^{-1}$ further determines the velocity range of ions that can be trapped by electrostatic wave potentials, which there may be an interaction between the electrostatic wave and these ions.

We now further investigate whether the ions that can be trapped by the electrostatic wave are related to the observed hot and cold ion beams. Figure 4(a) shows the observed and fitted (by the Maxwellian distribution) ion/electron 1D reduced velocity distributions. The fitting results are well consistent with the observations, i.e., the ion velocity distribution has peaks in the positive and negative directions. While the electron distribution has not changed significantly during this time, meaning that the electron kinematics process does not play a dominant role in the excitation of an electrostatic wave. However, the ion trapping range is within the velocity range of the interaction between the cold ion and the hot ion beam. In addition, the phase velocity (the brown solid line in Figure 4(a)) is between the velocities of the cold and hot ion beams. These results indicate that the electrostatic wave may be excited by the interaction of these hot and cold ion components. In order to further investigate the excitation of the electrostatic wave, we substitute the electron component, cold ion component, and hot ion component obtained by Maxwellian fitting into the 1D electrostatic wave dispersion relation: $0 = 1 - \sum_j \frac{\omega_j^2}{kV_j} Z^2 \left( \frac{\omega - \nu_{\parallel E}}{kV_j} \right)$, where $j$ represents the electron, cold, or hot ion component, $\omega_j$ is the angular plasma frequency ($\omega_j = \sqrt{n_j q_j^2/m_j} = 0$), $k$ is the wavenumber, $V_j$ is the drift velocity, $V_j$ is the plasma thermal speed ($V_j = \sqrt{2q_j T_j/m_j}$), and $Z^2$ is the derivative of the plasma dispersion function (Fried & Conte 1961). Based on these fittings, the beam parameters can be obtained as $n_{i,\text{cold}} = 0.03$ cm$^{-3}$, $n_{i,\text{hot}} = 0.035$ cm$^{-3}$, $T_{i,\text{cold}} = 32$ eV, $T_{i,\text{hot}} = 2343$ eV, $V_{i,\text{cold}} = -52$ km s$^{-1}$, and $V_{i,\text{hot}} = 1240$ km s$^{-1}$. Figure 4(b) shows the unstable mode with the real frequency $\omega$ (black solid line), growth rate $\gamma$ (red solid line), and the position corresponding to the maximum growth rate (green solid line). In Figure 4(b), the electrostatic wave has a positive growth rate when $\gamma > 0$, indicating that the ions transferred energy to the electrostatic wave. Meanwhile, the wave frequency corresponding to the maximum growth rate is close to 0.6$f_{pi}$ and the $V_{ph}$ related to the maximum growth rate is about $\sim 420$ km s$^{-1}$ (brown dotted line in Figure 4(a)), which is close to the observed frequency (Figure 3(g)) and the $V_{ph}$ calculations from the frequency-wavenumber power spectrum (Figure 3(e), brown solid line in Figure 4(a)). The $V_{ph}$ calculated by these methods are both in the region where the hot and cold
Figure 3. Observation of electrostatic waves. (a) Three components and total magnetic field, (b) filtered electric field waveform, (c) the parallel phase space density of electrons and (d) ions. (e) Frequency-wavenumber power spectra from 04:06:50–04:06:55 UT. (f) Filtered electric field waveform, (g) electric field power spectral density, and (h) electrostatic potential in green shadowing from 04:06:50.7–4:06:55 UT.
ion beams interact. This further confirms that the electrostatic wave after the DF is excited by the cold and hot ion beam instabilities, and clearly shows the interactions between the cold ions and hot ions in the outflow region.

3. Discussion and Summary

The mirror-mode structure can effectively affect the electron kinetics and energy exchange between the plasma and the background field (Huang et al. 2017; Zhong et al. 2019b), and it is usually observed that whistler-mode waves are generated around it (Kitamura et al. 2020; Zhang et al. 2021). For the mirror-mode structure before the DF, it is usually considered to be due to the ion particles reflected and accelerated by the DF (Wang et al. 2016a), and the magnetic pileup ahead of the DF (Zieger et al. 2011). However, previous studies based on Cluster/THEMIS low-resolution data are not enough to provide more detailed observations of the generation of whistler-mode waves within magnetic mirror-mode structures before the DF. In recent years, by using MMS high-resolution data, the generation of the magnetic hole by electron mirror instability and the excited whistler-mode waves in it behind a DF have been reported in detail (Liu et al. 2021). Our results observed several ion-scale mirror-mode structures caused by the ion mirror instability before the DF, and provide the first evidence of the whistler-mode waves in it generated by the cyclotron resonance of the trapped electrons in these ion-scale mirror-mode structures. Behind the DF, since the ion mirror-mode condition is not satisfied, (which is in agreement with the observations of Wang et al. 2016a), and the electron temperature anisotropy reverses, whistler-mode waves are not observed.

Another important observation is the electrostatic wave behind the DF. In previous studies, the electrostatic wave emissions behind the DF are suggested to be excited by electron beams (Yang et al. 2017), or two cold ion beams inside the jet (Liu et al. 2019). For our case, the electrostatic wave is driven by the instability of the cold ion beam from the inner magnetosphere and the hot ion beam from the reconnection outflow region, which provides some new observational aspects for the interaction between cold ions and hot ions at the trailing part of the BBF. Besides, previous studies have proposed that the compression of the magnetic field behind the DF will preferentially heat the ions in the perpendicular direction, resulting in an increase in the ion perpendicular temperature anisotropy (Wu et al. 2006; Ge et al. 2011). While in our case, we have observed the opposite phenomenon, that is, the ion temperature shows that the parallel temperature is greater than the perpendicular temperature. This may be because the satellite is far away from the center of the current sheet in our event, the ion flow is mainly the field aligned, and the acceleration of the ions may be caused by the acceleration of the Fermi mechanism during the dipolarization process of the magnetic field.

In summary, we have presented a detailed analysis of different background parameters before and behind the DF within the BBF and observed two different wave modes: whistler-mode waves and electrostatic waves, respectively. A sketch of the whole process of the interaction is shown in Figure 1(b). As a boundary, the DF separates the background plasma and provides good conditions for wave mode generation in different background environments. Our case provides a detailed analysis of particle instability, cross-scale coupling, and the two types of waves associated with an important boundary layer (like DFs) within a typical plasma jet (like BBFs). They are the whistler-mode waves excited by electron temperature anisotropy (which are trapped by the mirror-mode structure) and the electrostatic wave excited by the hot and cold ion beam instabilities. Based on the two different instabilities observed successively in the two background environments separated by a DF in the same region here, this study would help us better understand the electron and ion kinetics in...
plasma jets, and thus bring further insights into the relevant wave–particle interactions in similar structures in astrophysical plasmas.

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