

Article

Constraints on Electron Temperature Anisotropy of Plasma Jets in Terrestrial Magnetotail

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Abstract

Plasma jets are important carriers of mass and magnetic flux and are favorable regions for development of various waves and instabilities in Earth's magnetotail. Here we conduct a comprehensive investigation of electron temperature anisotropy constraints from electron microinstabilities inside magnetotail jets. We find that data distributions (temperature anisotropy vs. electron parallel beta) are well constrained by electron microinstability thresholds, with stronger magnetic fluctuations near the instability thresholds, providing direct evidence for the operation of microinstability instabilities. We reveal that the jets' leading and inner regions typically host stronger magnetic fluctuations than their trailing regions, indicating that the microinstabilities are typically developed in association with jets' interaction with ambient plasma. We find that instability-related magnetic fluctuations generally become weaker during the jets' Earthward propagation, indicating gradual relaxation of the jets' free energy. These results suggest that electron microinstabilities play an important role in controlling electron thermodynamics in plasma jets.

Keywords: plasma jets; electron temperature anisotropy; microinstability

1. Introduction

Plasma jets, i.e., transient fast plasma flows, are ubiquitous in space plasma. In the terrestrial magnetotail, these jets are generally thought to be generated by midtail magnetic reconnection, a process that converts magnetic field energy into particle thermal and kinetic energy [1,2], and are commonly referred to as bursty bulk flows (BBFs) [3–5]. Plasma jets are often preceded by flow leading boundaries called jet fronts (JFs; traditionally referred to as dipolarization fronts, DFs), across which northward magnetic field component B_z in Geocentric Solar Magnetospheric (GSM) coordinates rises sharply [6–8]. Jets can play a crucial role both in large-scale transport of mass and flux and local-scale transfer of various forms of energies [9,10], leading to geomagnetic disturbances during magnetospheric activities [11].

As plasma jets propagate through the magnetotail plasma sheet, they interact strongly with the ambient plasma, giving rise to magnetic disturbances [7,12], particle acceleration [13], wave–particle interactions [14–18], and so forth. These processes can substantially modify electron distributions and often lead to strong electron temperature anisotropy, quantified by $T_{e\perp}/T_{e\parallel} \neq 1$ (where $T_{e\perp}$ and $T_{e\parallel}$ denote the electron temperatures perpendicular and parallel to the ambient magnetic field, respectively). In a colli-

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sionless plasma, this anisotropy stores free energy for kinetic instabilities, such as electron firehose instability, the mirror instability, and the whistler mode instability. Their marginal stability boundaries are commonly described in the $(\beta_{e\parallel}, T_{e\perp}/T_{e\parallel})$ space, where $\beta_{e\parallel}$ is the electron parallel plasma beta. This framework provides a useful basis for evaluating how electron temperature anisotropy is constrained. For example, observations have showed that electron anisotropy is often close to marginal stability limits of whistler and oblique electron firehose instabilities near dipolarizing flux bundles [19]. Quasilinear effects of whistlers can regulate electron anisotropy during its evolution [20]. Statistical studies have quantified proton temperature anisotropy in plasma jets [21,22]. In contrast, the statistical constraints on electron anisotropy in plasma jets and the controlling mechanisms remain not well understood.

To determine how electron temperature anisotropy is generated, regulated, and relaxed in magnetotail jets, observations must resolve electron distributions and associated field fluctuations on sufficiently short timescales. This capability is provided by NASA's Magnetospheric Multiscale (MMS) mission, a four-spacecraft constellation designed for kinetic plasma physics in key regions such as the magnetotail current sheet [23]. Its Fast Plasma Investigation (FPI) provides full 3D electron distributions at 30 ms cadence [24], enabling direct examination of rapid electron anisotropy evolution and associated wave activity in jet/JF environments.

In this paper, we use MMS observations to build a large sample of magnetotail jet events from 2017 to 2019. We quantify electron temperature anisotropy in $(\beta_{e\parallel}, T_{e\perp}/T_{e\parallel})$ space and compare the observed distributions with the instability thresholds of the electron firehose, mirror, and whistler. We perform separate statistics for the jets' leading, inner, and trailing regions to examine how electron anisotropy and associated magnetic fluctuations vary within the jet structure. We further investigate how these instability constraints and fluctuation signatures evolve during jets' global propagation.

2. Materials and Methods

This study uses high-time-resolution particle and magnetic field measurements from the Magnetospheric Multiscale (MMS) mission, primarily from the Fast Plasma Investigation (FPI), the Fluxgate Magnetometer (FGM), and the Search Coil Magnetometer (SCM). In particular, we use high-cadence electron moments measured by the FPI instrument to calculate electron temperature anisotropy and electron parallel beta. Magnetic field data from the FGM and SCM instruments is used to determine the background magnetic field and characterize magnetic field fluctuations [25–28]. All data are presented in the GSM coordinates unless noted otherwise.

In order to characterize low-frequency magnetic field fluctuations, we first obtain the background magnetic field B_0 from the FGM data by low-pass filtering below 0.2 Hz, and the low-frequency fluctuating magnetic field δB was obtained by band-pass filtering between 0.3 and 10 Hz. For the high-frequency magnetic field fluctuations, δB was obtained from the SCM data band-pass filtering between 10 and 100 Hz. The frequency ranges are selected based on the typical particle cyclotron frequency and lower hybrid frequency in the magnetotail plasma sheet. The magnetic field fluctuation amplitudes were then calculated, and a 3 s sliding root mean square (RMS) was applied to obtain the effective fluctuation level. The resulting RMS amplitude was further normalized through the background magnetic field magnitude, yielding a dimensionless quantity $\delta B/B_0$ used in the subsequent statistical analysis.

We select the magnetotail jet events by using MMS1 burst-mode data collected between May 2017 and September 2019. Similar to previous studies [4,5], we set the following criteria: $|Y_{\text{GSM}}| < 18R_E$ (Y_{GSM} is the dawn–dusk position and R_E is the Earth's radius), $\beta_i > 0.5$, $N_i < 10 \text{ cm}^{-3}$, $T_i > 1000 \text{ eV}$ (β_i is ion plasma beta, N_i is ion number density, and

T_i is ion temperature), and $V_x \geq 150 \text{ km s}^{-1}$ (V_x is the x-component of the ion bulk velocity in the GSM coordinate system). Based on these criteria, we have selected 2706 earthward-propagating jet events in the tail.

For each jet event, the peak speed is defined as $V_{\max} = \max(V_x)$. Using $V_{\max}$, we classify the jet's local region into three different subregions: (1) the jet leading edge where V_x increases from 150 km/s to $0.8V_{\max}$; (2) the jet inner region where V_x increases from $0.8V_{\max}$ to $V_{\max}$ and then decreases down to $0.8V_{\max}$; (3) the jet trailing edge where V_x decreases from $0.8V_{\max}$ to 150 km/s. If $0.8V_{\max} < 150 \text{ km/s}$, the event is considered to have no sufficiently distinct peak relative to the event threshold, and the whole event is classified as the inner region. This classification is used to compare local electron thermodynamic and related wave activity at different subregions of the jets.

3. Results

Figure 1 shows an overview of a typical jet event observed by MMS1 from 21:22:25 to 21:22:45 Universal Time (UT) on 16 September 2018. Two vertical dashed lines divide the event into the leading edge, inner region, and trailing edge, as defined above. Ion and electron energy spectrograms show characteristic plasma sheet particle energy fluxes during the whole interval (Figure 1a,b). Prior to the jet's leading edge, electromagnetic field and particles are basically steady, without clear electromagnetic fluctuations. When MMS entered the leading edge where ion speed begins to increase (the pink-shaded region), electromagnetic field and particle profiles exhibit distinct variations: magnetic field dramatically increases (from ~4 to ~12 nT, Figure 1c), electron speed clearly raises, with intermittent peaks reaching the order of 10^3 km/s (Figure 1e), electron density gradually drops (from ~0.6 to ~0.2 cm^{-3} , Figure 1f), ion and electron temperature are both enhanced, with the ion temperature rising from ~1.5 to ~4 keV and the electron temperature increasing from several hundred eV to ~2 keV (Figure 1h), and electromagnetic fields also show intense fluctuations (from ~10 to several tens Hz, Figure 1k), indicating that the jet leading edge was in a dynamical state. The jets' inner region (the blue-shaded region) is more dynamical than its leading edge, with faster electron jets, higher ion and electron temperatures, and more intense electromagnetic emissions. When MMS entered the jet trailing edge, local electromagnetic field and particles basically become steadier. These differences suggest that the jet's dynamics clearly varies in different subregions, with stronger wave and particle activity inside the leading edge and inner region. Within these two subregions, stronger electron temperature anisotropy is also observed (Figure 1g,h), possibly providing free energy for the observed waves. Such region-dependent feature provides a basis for the statistical analysis below.

To statistically investigate electron temperature anisotropy and associated magnetic fluctuations developed within the jets, we plot plasma parameters in the two-dimensional $\beta_{\parallel e}$, $T_{\perp e}/T_{\parallel e}$ plane, in which plasma properties with linear microinstability thresholds can be directly compared. In this plane, data points measured in each jet events are mapped into the histogram bins. We overplot three marginal stability thresholds in the $\beta_{\parallel e}$, $T_{\perp e}/T_{\parallel e}$ space. For $T_{\perp e}/T_{\parallel e} > 1$, the whistler and electron mirror thresholds are taken as $T_{\perp e}/T_{\parallel e} - 1 = 0.21/\beta_{\parallel e}^{0.58}$ and $T_{\perp e}/T_{\parallel e} - 1 = 0.74/\beta_{\parallel e}^{0.50}$, respectively. For $T_{\perp e}/T_{\parallel e} < 1$, the oblique electron firehose threshold is set as $T_{\perp e}/T_{\parallel e} - 1 = -1.29/\beta_{\parallel e}^{0.97}$. These thresholds are empirical marginal stability fits obtained from the linear theory [29–31]. In general, whistler is the more easily excited mode when $T_{\perp e}/T_{\parallel e} > 1$, whereas oblique electron firehose provides the relevant constraint when $T_{\perp e}/T_{\parallel e} < 1$. Note that in the nonlinear regime, electron mirror mode may dominate over whistler mode [32]. Nevertheless, transition to the nonlinear regime typically requires sufficiently strong electron temperature anisotropy, which is not frequently observed inside the jets.

Figure 2 shows the data distributions in the $\beta_{\parallel e}$, $T_{\perp e}/T_{\parallel e}$ space for all the jet events, including the jet's leading edge, inner region, and trailing edge. To allow a direct comparison among different regions, the two-dimensional counts are normalized by a common 95th percentile obtained from all the samples. We find that in all subregions, the majority of the data samples are basically well constrained by the microinstability thresholds, indicating that electron microinstabilities indeed play a central role in relaxing the free energies within the jets. For different subregions, we find that the data distributions in the leading edge and inner region are broader than those in the trailing edge, suggesting that the electron microinstabilities are more active in these two subregions, consistent with the result derived from the prior case study.

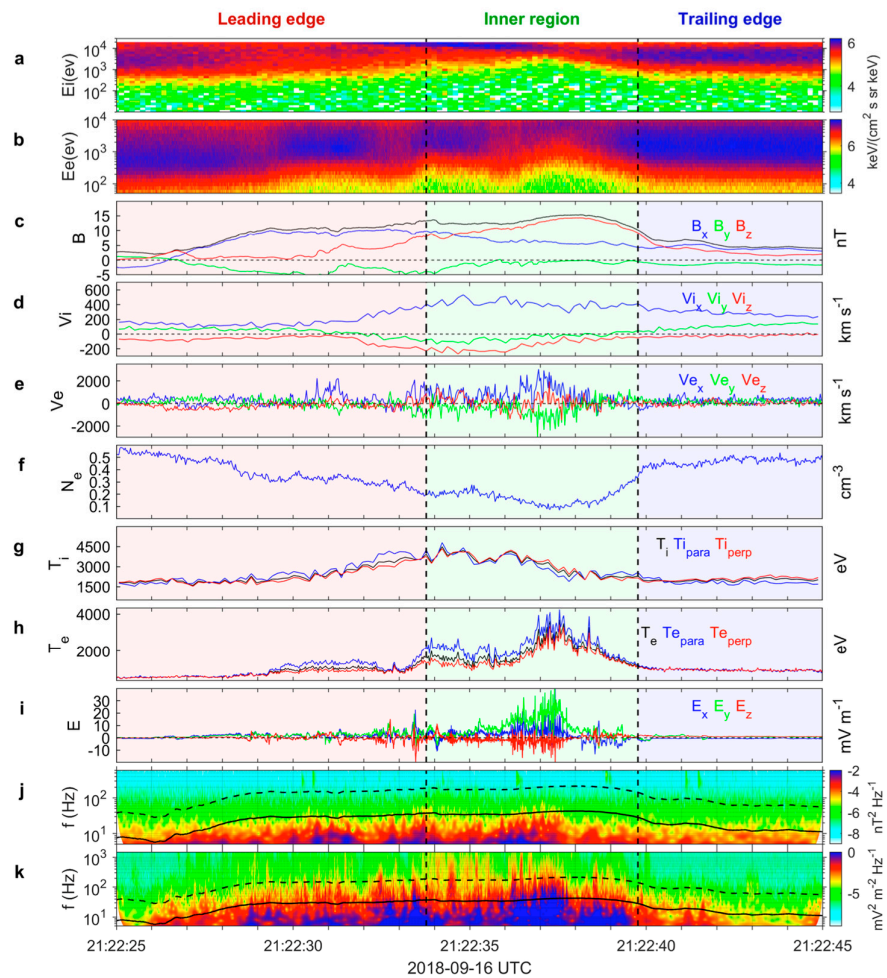


Figure 1. Overview of a typical jet event observed by MMS1 from 21:22:25 to 21:22:45 UT on 16 September 2018. (a) Ion energy spectrogram; (b) electron energy spectrogram; (c) magnetic field; (d) ion bulk velocity; (e) electron bulk velocity; (f) electron number density; (g) ion temperatures; (h) electron temperatures; (i) electric field; (j) magnetic field wave power spectrum; (k) electric field wave power spectrum. The two vertical dashed lines mark the boundaries of the leading edge, inner region, and trailing edge. In panels (j,k), the black solid and dashed curves indicate $0.1 f_{ce}$ and $0.5 f_{ce}$ (f_{ce} is electron cyclotron frequency), respectively.

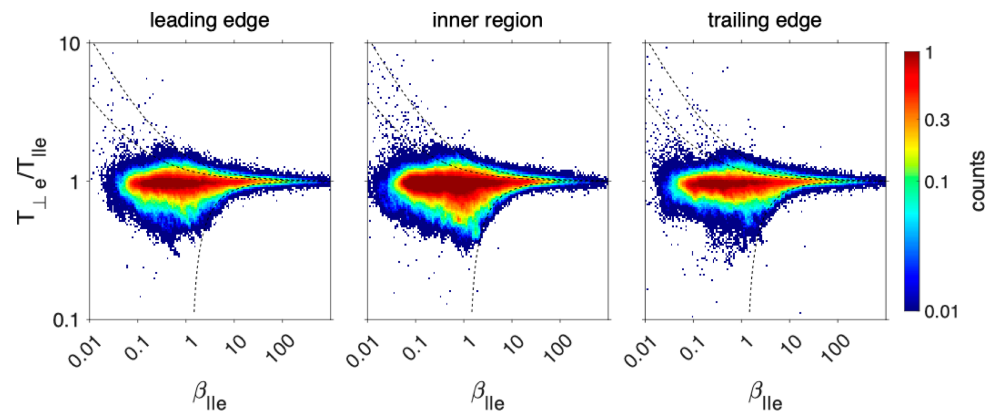


Figure 2. Data distribution of 1239 jet events in the leading edge, inner region, and trailing edge in the $\beta_{\parallel e} - T_{\perp e}/T_{\parallel e}$ space. The two-dimensional counts for all three subregions are normalized by a common 95th percentile based on the combined samples. The dashed curves indicate the marginal stability thresholds of the whistler, electron mirror, and oblique electron firehose instabilities.

We find that for all subregions, data samples with $T_{\perp e}/T_{\parallel e} > 1$ partly exceed the electron whistler threshold, indicating that the jets typically remain unstable to the electron whistler instability. This is in agreement with the ubiquity of whistler mode waves inside the jets [31,33]. The mirror instability thresholds set clear boundaries for data samples with larger $T_{\perp e}/T_{\parallel e}$, indicating that the jets typically remain stable to the electron mirror mode instability. This is also in line with that fact that electron mirror mode waves have so far rarely observed, with very few direct observations [33,34]. For data samples with $T_{\perp e}/T_{\parallel e} < 1$, their lower boundary is well limited by the oblique electron firehose threshold, indicative of the operation of electron firehose instability in mediating the electron distribution. This is in line with recent event observations showing that electron distributions with dominant parallel temperature can excite electron firehose fluctuations and relax through wave–particle interactions [28,33].

We further project magnetic field fluctuations at different frequency bands into in the $\beta_{\parallel e}, T_{\perp e}/T_{\parallel e}$ space to examine their relation with electron temperature anisotropy. We construct two quantities from the band-pass filtered magnetic fluctuation δB : one is the normalized total fluctuation level $\delta B/B_0$; the other is the ratio $\delta B_{\perp}/\delta B$, which describes perpendicular fluctuations with respect to B_0 . Data are also normalized by the same 95th percentile from all the samples of the jet regions, such that the relative changes in magnetic field fluctuations in the jets’ leading, inner, and trailing regions can be compared directly.

The low-frequency magnetic fluctuations in the anisotropy-parallel beta space are shown in Figure 3. We find clear enhancements of magnetic field fluctuations near mirror and firehose instability thresholds (Figure 3a–c), providing further evidence for the operation of these two low-frequency-mode microinstabilities. For different subregions, we find that magnetic fluctuations in the leading edge and inner regions are stronger and more broadly distributed than those in the trailing edge. This is in agreement with the region-dependent feature of the data distribution revealed in Figure 2. This is also in line with the fact that mirror and firehose instabilities are typically driven by pressure anisotropy, which can more easily develop when jets interact with ambient plasma (in the leading edge) and experience flow-driven expansion or contraction (in the inner region) [35]. For the low-frequency fluctuations near the mirror instability thresholds, they are dominated by parallel components, consistent with the compressive nature of mirror mode waves (Figure 3d–f). In contrast, magnetic field fluctuations near the firehose instability thresholds are mainly contributed by the perpendicular components (Figure 3d–f), in agreement with the incompressive nature of firehose-mode waves.

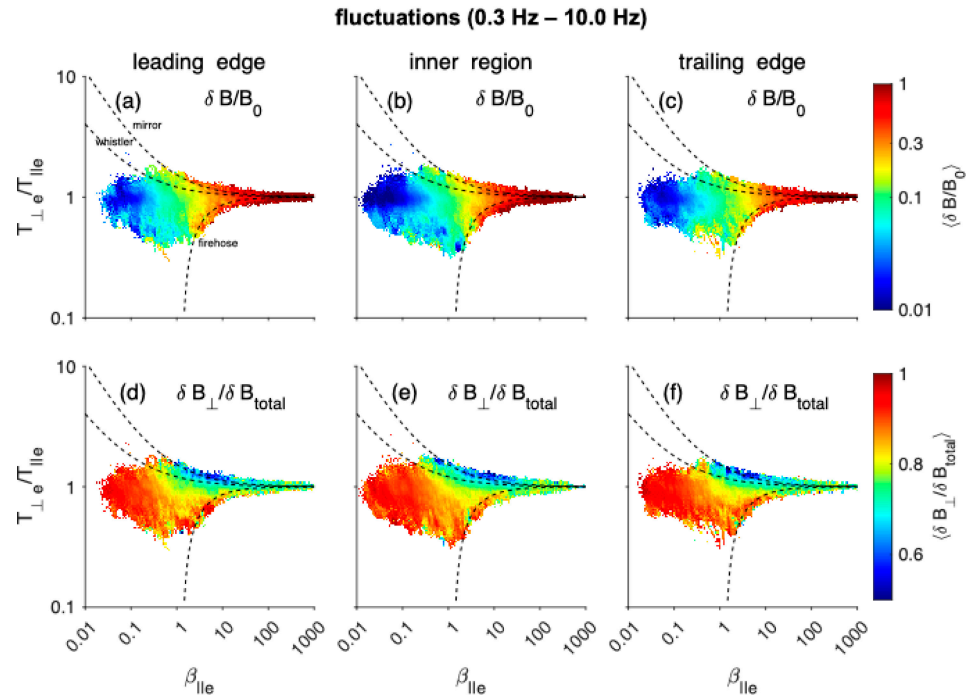


Figure 3. Statistical distributions of low-frequency magnetic fluctuations in the $\beta_{\parallel e}, T_{\perp e}/T_{\parallel e}$ space. Panels (a–c) show the normalized total magnetic fluctuation level $\delta B/B_0$ in the leading edge, inner region, and trailing edge, respectively. Panels (d–f) show the corresponding directional quantity $\delta B_{\perp}/\delta B_{\text{total}}$ in the same three subregions. The top-row maps are normalized by a common 95th percentile from the combined samples of the three subregions. The dashed curves indicate the thresholds of the whistler instability, electron mirror instability, and oblique electron firehose instability.

Compared with the low-frequency fluctuations, the high-frequency magnetic fluctuations displayed in Figure 4 show a clearer organization by all the instability thresholds, with $\delta B/B_0$ mainly enhanced near the thresholds of the electron whistler instability, mirror instability, and oblique electron firehose instability. Again, we find that the magnetic fluctuation enhancements are generally stronger in the leading edge and inner region than in the trailing edge, similar to the region-dependent feature of the low-frequency waves. Magnetic field fluctuations near the whistler and mirror instability thresholds are mainly contributed by the perpendicular components (Figure 4d–f), indicating that waves are mainly incompressive whistler mode and/or the mirror cascade high-frequency waves are transfer into incompressive modes. Magnetic field fluctuations near the firehose instability thresholds are dominated by the perpendicular components (Figure 4d–f), akin to the low-frequency waves.

Aside from studying the local evolution of temperature anisotropy-related magnetic field fluctuations within the jets' subregions, we further investigate global evolution of magnetic field fluctuations during the jets' earthward propagation. Figure 5 shows the 90th percentile of the high-frequency magnetic fluctuations, $P_{90}(\delta B/B_0)$, used to represent the magnetic fluctuation strength developed inside each jet. We uncover two features: (1) jets with intense magnetic field fluctuations usually occur in the distant magnetotail, whereas jets closer to the near-Earth tail typically hosts weaker wave activity; (2) jets with intense magnetic field fluctuations preferentially occur in the dusk side. These two features suggest that, as jets are generated in the distant tail and then propagate closer toward Earth, the free energies deposited in electron temperature anisotropy within the jets may be gradually released, due to their interaction with the ambient plasma. Such a global

trend was also observed for the ion temperature anisotropy of the jets [21]. The dusk–dawn asymmetry of the temperature anisotropy-related magnetic field fluctuations within the jets may be related to the well-studied duskside preference of jet activity reported in previous studies [36].

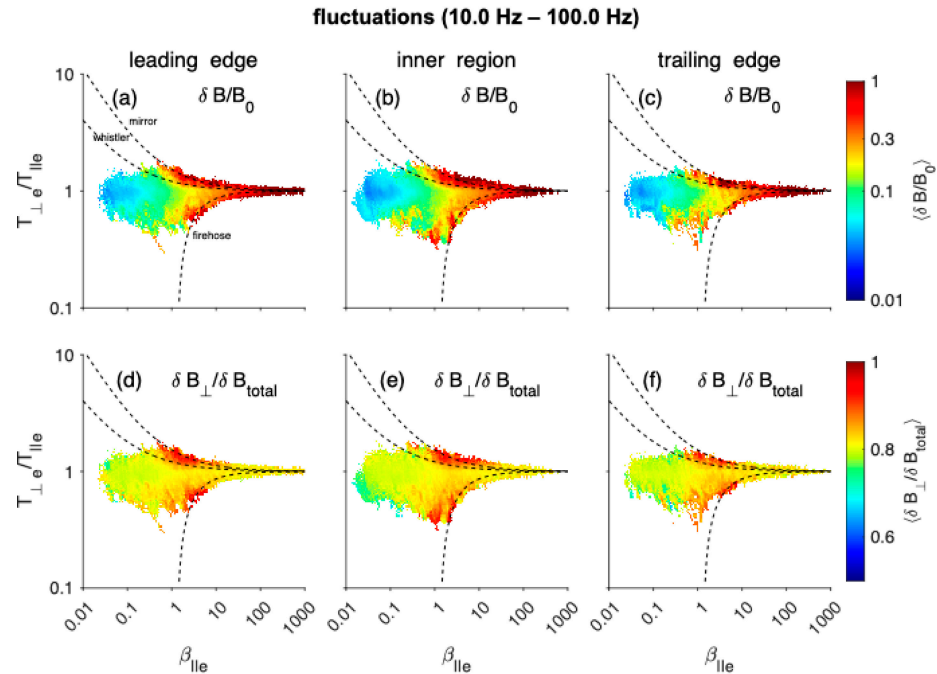


Figure 4. Statistical distributions of high-frequency magnetic fluctuations in the $\beta_{\parallel e}, T_{\perp e}/T_{\parallel e}$ space. Panels (a–c) show the normalized total magnetic fluctuation level $\delta B/B_0$ in the leading edge, inner region, and trailing edge, respectively. Panels (d–f) show the corresponding directional quantity $\delta B_{\perp}/\delta B_{total}$ in the same three subregions. The top-row maps are normalized by a common 95th percentile from the combined samples of the three subregions. The dashed curves indicate the thresholds of the whistler instability, electron mirror instability, and oblique electron firehose instability.

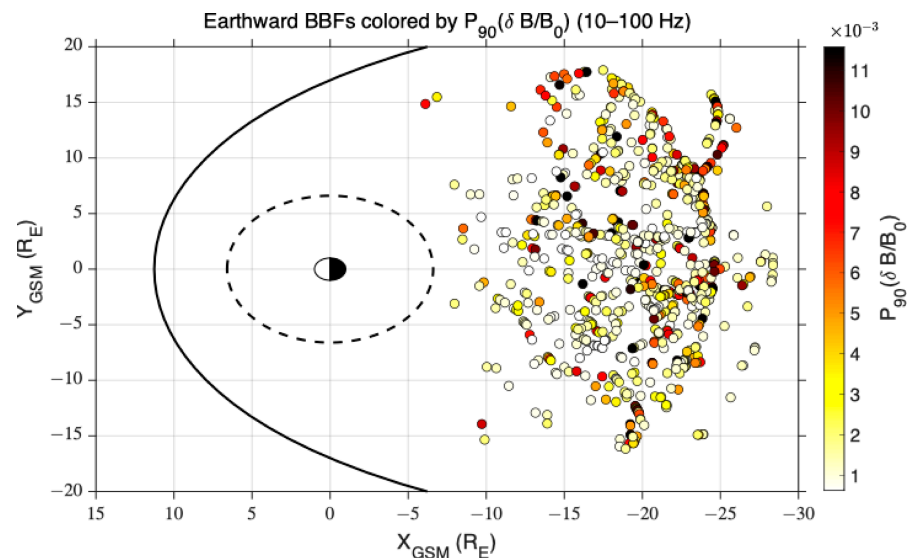


Figure 5. Spatial distribution of Earthward jet events in the $X_{GSM} - Y_{GSM}$ plane. The color indicates the 90th percentile of the normalized magnetic fluctuation, $P_{90}(\delta B/B_0)$, for each event. The fluc-

tuation is calculated in the 10–100 Hz band using the total mode. Each circle represents one Earthward jet event.

4. Discussion

Based on MMS observations of a large number of magnetotail plasma jet events during 2017–2019, we find clear evidence for the constraints on electron distributions from electron microinstabilities, with clear boundaries near the marginal stability thresholds of the whistler, electron mirror, and oblique electron firehose instabilities. Enhanced magnetic fluctuations near these thresholds provide further evidence that these instabilities are active inside the jets and regulate the electron distributions through wave–particle interactions. These results suggest that electron thermodynamics in plasma jets cannot be explained by adiabatic response alone, but is controlled jointly by electron kinetic microinstabilities.

We also reveal that the operation of these kinetic microinstabilities exhibits clear local and global features. At the jets' local scale, their leading and inner regions usually have stronger electron anisotropy and magnetic fluctuations, compared with the trailing regions. This suggests that electron free energy is mainly built up and released in regions where the jets interact more strongly with the ambient plasma. The jet–ambient plasma interaction may generate strong flow shear which can also serve as free energy sources [37,38]. At the global scale, we find that jets with intense magnetic field fluctuations usually occur in the distant magnetotail, with duskside preference. This suggests that the free energy available for instability release gradually decreases as the jets propagate Earthward. These local and global features of the operation of kinetic microinstabilities within the jets are consistent with the feature of jet-driven energy transfer and transport. Previous studies have shown that jet fronts in the jets' leading edge and flux pileup regions in the jets' inner region can typically host strong electron magnetic field energy conversion [35], which can be related to the development of kinetic microinstabilities. Previous study had indeed shown that electron distribution functions at dipolarization fronts inside the jets can form anisotropic features that are closely related with whistler waves [39]. As jets propagate Earthward and undergo braking, the internal free energy is gradually released, and the instability-driven magnetic fluctuation hence becomes weaker.

Overall, our results suggest that electron microinstabilities not only limit local electron temperature anisotropy, but also participate in the release of jet free energy. Electron microinstabilities should therefore be regarded as a key physical process for understanding electron thermodynamic evolution, local wave enhancement, and energy dissipation inside magnetotail plasma jets. Because plasma jets are important carriers of magnetotail energy transport and local dissipation, these results also help connect electron-scale physics to the multiscale energy release process in plasma jets. Note that other types of instabilities, such as current filamentation and beam mode, may also develop within the jets when small-scale electric currents can be generated [39–42]. A more detailed assessment of the relative roles of different instabilities will likely require direct wave mode identification, magnetic compressibility analysis, and high-time-resolution case studies in the future.

Author Contributions: Conceptualization, C.L.; methodology, S.Y.; formal analysis, S.Y.; writing—original draft preparation, S.Y.; writing—review and editing, C.L., Y.L. and X.X.; supervision, C.L. and J.C.; funding acquisition, C.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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