Electron Jets in the Terrestrial Magnetotail: A Statistical Overview

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Abstract

Electron jets, common transient phenomena for which the electron velocity is much larger than the ion velocity, play an important role in the energy dissipation and transport in the terrestrial and other planetary magnetospheres. Using the unprecedented high-resolution data provided by the Magnetospheric Multiscale mission from May to August in 2017, we perform one systematically statistical study on the electron jets in the terrestrial magnetotail for the first time. In total, 466 electron jet events are selected, which mainly concentrate in the region $-25 < X < -17 R_E$, $-14 < Y < 12 R_E$, and $0 < Z < 6 R_E$ ($R_E$ is the Earth’s radius). The electron velocity within the electron jets is much larger than the local Alfvén speed, implying that these jets belong to super-Alfvénic flows. The average occurrence rate of electron jets is 0.217 events hr$^{-1}$ in the X–Y plane and 0.189 events/hour in the Z–Y plane. The durations of the electron jets are mostly within 6 seconds with the average value of 2.89 seconds, which are much shorter than the duration of bursty bulk flows (BBFs) having the typical duration of several to tens of minutes. Through further analysis of the magnetic field, we find that electron jets can occur at five different structures, including 224 events detected during the crossing of current sheet, 57 events observed during the crossing of PSBL, 83 events around DFs, 79 events around magnetic holes, and 23 events around flux ropes. In addition, the relative positions of the electron jets in different structures are also identified in the present study. Our statistical results reveal the comprehensive features of electron jets in the terrestrial magnetotail, which can also be applied in other planetary magnetosphere.

Unified Astronomy Thesaurus concepts: Planetary magnetosphere (997); Plasma astrophysics (1261); Plasma jets (1263); Space plasmas (1544); Heliosphere (711)

1. Introduction

Bursty bulk flows (BBFs), with ion velocities larger than 150 km s$^{-1}$, are transient phenomena in the terrestrial and other planetary magnetotails and play an important role in the transport of mass, energy, and magnetic flux (e.g., Angelopoulos et al. 1994, 2013; Huang et al. 2015b). Based on joint observations from four Cluster spacecraft, Cao et al. (2006) have found that the average duration of BBFs is 1105 s ($\sim$18.4 minutes) in the terrestrial magnetotail, much longer than single observations (e.g., Angelopoulos et al. 1992). BBFs can propagate both earthward and tailward (Ohtani et al. 2004), and have been closely related to magnetospheric activities, such as substorms (Angelopoulos et al. 1992; Cao et al. 2006). For example, multisatellite observations show that 95.5% of substorms are accompanied by BBFs (Cao et al. 2006), thus BBFs are believed to be the trigger of substorms (e.g., Angelopoulos et al. 2008; Cao et al. 2010; Jussola et al. 2011). BBFs are usually thought to be generated by magnetic reconnection (e.g., Birn et al. 2011) and have close relationships with particle accelerations (e.g., Fu et al. 2011, 2013, 2019; Huang et al. 2012a; Duan et al. 2014) and wave activities (e.g., Zhou et al. 2009; Huang et al. 2010, 2012b, 2016a, 2017c; Fu et al. 2014; Zhou et al. 2014).

In previous studies, it has been widely believed that the BBFs carry ions and electrons together (in other words, the ion velocity $V_i$ is equal to the electron velocity $V_e$), and thus the magnetic frozen-in condition is satisfied inside the BBFs.

However, recent studies have shown that the ions are not always moving together with the electrons at some subregions inside the BBFs using high-time resolution plasma observations from MMS spacecraft (e.g., Huang et al. 2018; Man et al. 2018; Chen et al. 2019; Zhou et al. 2019b). As a result, the frozen-in conditions for the ions are broken, and the high-speed electron flows occur at these subregions with $V_e$ much larger than $V_i$. Such high-speed electron flows are named electron jets and have been directly observed in the thin current sheets (Huang et al. 2018; Chen et al. 2019), flux ropes (Huang et al. 2019c), and dipolarization fronts (Liu et al. 2018) or dipolarization processes (Huang et al. 2019b) associated with BBFs, recently. In addition, all these observations reveal that strong energy dissipation occurs in the electron jets and suggest that the electron jets may be another channel for the electron accelerations besides the reconnection diffusion region, especially the electron diffusion region (Huang et al. 2018, 2019c; Chen et al. 2019).

However, the previous works are only based on case analysis. Where and when the electron jets occur in the magnetotail, their occurrence rate, and the statistical features of the electron jets are still unknown. In this study, we use the unprecedented high-time resolution data from MMS to perform a statistical study on the electron jets in the terrestrial magnetotail. Our statistical results present the spatial distributions, the occurrence rate, the time durations, the electron velocity of the electron jets, the different structures where electron jets are detected, and the accompanying magnetospheric activities. This provides a comprehensive understanding of the electron jets to the community.
2. Selection of Electron Jets

The magnetic field data with time resolution of 0.078 s from FGM instruments (Russell et al. 2016), the plasma data for ions with time resolutions of 150 ms and electrons with time resolution of 30 ms from FPI instruments (Pollock et al. 2016) are used in the present study. We use the data during the first tail season of MMS, i.e., from May to August in 2017. All parameters are presented in the geomagnetic solar magneto-spheric (GSM) coordinates unless stated otherwise.

2.1. Selection Criteria of Electron Jets

To eliminate the errors and limitations from FPI instrument measurements, we used the following criteria before the selection of electron jets: (1) exclude the events with photoelectron contamination in the electron spectrogram; (2) most of the ion distribution should below 30 keV, which is the limitation of the FPI instrument; (3) most of the electron population cannot be beyond the upper energy limit of 30 keV, to ensure that the measurement range of the FPI instrument cannot be exceeded (Pollock et al. 2016); (4) in principle, the ion density should equal the electron density as a requirement of the charge neutrality (though, in the magnetotail, the plasma density is low, the electron density can usually be affected by the photoelectron; to reduce this impact as much as possible, we require that the difference between electron and ion density should not exceed 0.1 cm$^{-3}$, i.e., almost identical); (5) plasma density should be larger than 0.1 cm$^{-3}$. These criteria ensure that the discrepancy between $V_i$ and $V_e$ is physical, not due to the limitation of FPI instrument.

The selection criteria for electron jets are as follows:

1. One or more components of the highest electron velocity should be greater than twice the ion velocity. Meanwhile, the highest electron velocity must be greater than 500 km s$^{-1}$.
2. The duration of electron velocity higher than ion velocity must last more than 0.5 seconds without a drop.
3. If the duration of $V_e > V_i$ between two samples with $V_2 > V_1$ is less than 1 second, they belong to the same jet. In other words, if the separation between two electron jets is shorter than 1 second, these two jets belong to the same one.

According to these criteria, eventually 466 electron jet events are selected. The current density corresponding to these electron jets is concentrated in $23 \sim 100$ nA m$^{-2}$, much larger than the typical cross-tail current density $4\sim8$ nA m$^{-2}$ (e.g., Rong et al. 2011), implying that the currents are intense enough to contribute to the energy conversion in the magnetotail.

2.2. Case Studies

In this section, we will show five distinguished structures where the electron jets are detected.

Figure 1 shows that the electron jets occur in the current sheet (CS) and plasma sheet boundary layer (PSBL). Figure 1(A) displays the crossing of one CS from 00:57:28 to 00:57:42 UT on 2017 July 6. The typical plasma density (Figure 1(A)(e)), temperature ($\sim$keV, Figure 1(A)(f)), and $\beta_i$ (>1, Figure 1(A)(g)) (e.g., Cao et al. 2006; Huang et al. 2018; Chen et al. 2019; Wei et al. 2019) in the CS are detected. One can see that $B_z$ gradually decreases from positive to negative (Figure 1(A (a))), indicating that MMS crosses the center of the CS (neutral sheet). Although the electron velocity has some fluctuations, the electron velocity clearly increases around 00:57:35 UT and three components $V_{ex}$, $V_{ey}$, and $V_{ex}$ reach up to $-1600$ km s$^{-1}$, $-1700$ km s$^{-1}$, and $1200$ km s$^{-1}$, respectively. While three components of ion velocity $V_{ix}$, $V_{iy}$, and $V_{iz}$ are relatively stable and only $500$ km s$^{-1}$, $300$ km s$^{-1}$, and $50$ km s$^{-1}$, respectively. According to the selection criteria given in Section 2.1, one electron jet is detected in the center of the CS ($|B_z| \sim 0$ nT) with a duration of $\sim3.03$ seconds, as marked by the magenta vertical dashed lines.

The PSBL is dynamic where BBFs often occur (e.g., Baumjohann et al. 1990). Figure 1(B) presents an MMS observation of an electron jet during the crossing of the PSBL on 2017 May 28. Usually, the plasma temperatures in the lobe region are colder than in the plasma sheet, plasma density in the lobe is lower than in the plasma sheet, and the plasma $\beta_i$ is between 0.3 and 0.5 in the PSBL (e.g., Baumjohann et al. 1988; Slavin et al. 2003a). As one can see, plasma $\beta_i$ gradually increases and reaches up to 0.3 at 00:16:07.5 UT with the increase of plasma density. After 00:16:21.2 UT, plasma $\beta_i$ is larger than 0.5, and plasma density is larger than that in the lobe region. This indicates that MMS crossed the PSBL from 00:16:07.5 to 00:16:21.2 UT, as marked by the vertical dashed lines. Around 00:16:18 UT, the electron velocity is much higher than the ion velocity, and can reach up to $1800$ km s$^{-1}$, $1000$ km s$^{-1}$, and $-500$ km s$^{-1}$ for $V_{ex}$, $V_{ey}$, and $V_{ez}$ components, which can be identified as an electron jet with a duration of $\sim2.73$ seconds.

Figure 2 shows the observation of electron jets in the dipolarization front (DF), magnetic hole, and flux rope. DF is a sharp boundary with an increase in the $B_z$ component in a short period (usually $\sim10$ seconds) at the leading edge of BBFs (e.g., Fu et al. 2011, 2012, 2013; Huang et al. 2012b, 2015b, 2015c, 2015a, 2019b). The DF is usually accompanied by a decrease in density and plasma $\beta_i$ and an increase in plasma temperature. Figure 2(A) displays the electron jet observed during the crossing of DF on 2017 May 28. $B_z$ starts to increase at 06:06:23 UT and reaches up to 16 nT within two seconds preceding the magnetic dip (Figure 2(A(a))), which is accompanied with the decrease of plasma density from 0.5 to 0.3 cm$^{-3}$ (Figure 2(A(e))) and the increase of ion temperature (Figure 2(A(f))). Thus, MMS detected one typical DF. Electron velocity increases rapidly ($V_{ex}$ increases up to 1500 km s$^{-1}$ (Figure 2(A(b))), $V_{ey}$ increases up to $-1400$ km s$^{-1}$ (Figure 2(A(c))), and $V_{ez}$ reaches up to 600 km s$^{-1}$ (Figure 2(A(d)))) at the DF. However, three components of ion velocity are always below 300 km s$^{-1}$ in contrast to the electron velocity, which implies that one electron jet is detected at the DF.

Magnetic holes, characterized by magnetic depression with a duration of several seconds to several minutes, are frequently observed in the solar wind, magnetosheath, and planetary magnetosphere (e.g., Zhang et al. 2008; Huang et al. 2017b, 2017a, 2018, 2019a). Figure 2(B) presents one electron jet detected at the interior of the magnetic hole on 2017 May 19. One can clearly see that there is a localized depression in the magnetic field between 15:57:05 and 15:57:16 UT accompanied by an increase of plasma density and temperature. The electron velocity $V_{ey}$ has a peak inside this magnetic hole (Figure 2(B(c))) and is much larger than the ion velocity $V_{iy}$. Therefore, an electron jet was observed at the interior of the magnetic hole.
Flux ropes (FRs) are 3D helical magnetic structures generally with a strong core field in which magnetic field lines twist with each other in the planetary magnetosphere and interplanetary space (e.g., Slavin et al. 2003b; Deng et al. 2004; Huang et al. 2012a, 2014a, 2014b, 2016b, 2019c; Zhou et al. 2012, 2017, 2018). Bipolar signatures in the $B_z$ component and the strong core field $B_y$ component are used to identify the flux rope in the magnetotail plasma sheet. In the earthward (tailward) flow, the spacecraft should observe a bipolar signature from negative (positive) to positive (negative) in the $B_z$ component (e.g., Huang et al. 2012a, 2019c; Zhou et al. 2018). Figure 2(C) presents an electron jet detected in the flux rope on 2017 July 6. The $B_y$ component changes from negative to positive with one peak in $B_x$ and magnitude of magnetic field (Figure 2(C(a))) in the high-speed earthward plasma flow ($V_{ix} > 600 \text{ km s}^{-1}$; Figure 2(C(b))), which is consistent with the typical features of an earthward moving flux rope. At the interior of the flux rope, three components of electron velocity obviously increase compared with the ion velocity. Three components $V_{ex}$, $V_{ey}$, and $V_{ez}$ have peaks at $3000 \text{ km s}^{-1}$, $-2000 \text{ km s}^{-1}$, and $-1000 \text{ km s}^{-1}$, respectively, which are much larger than the $800 \text{ km s}^{-1}$, $200 \text{ km s}^{-1}$, and $-200 \text{ km s}^{-1}$ of the three components $V_{ix}$, $V_{iy}$, and $V_{iz}$ of the ion velocity. This indicates that one electron jet existed inside the observed flux rope.

3. Statistical Results of Electron Jets

3.1. Occurrence Rate of Electron Jets

Following the selection criteria given in Section 2, 466 events of electron jets are identified in total in the terrestrial magnetotail from May to August in 2017.

Figure 3 presents the spatial distribution and occurrence rate of the electron jets in the $X$–$Y$ plane and $Z$–$Y$ plane. One can see that the electron jets are mostly concentrated in the region $-25 < X < -17 R_E$ ($R_E$ is the Earth radius), $-14 < Y < 12$
$R_{E}$, and $0 < Z < 6 R_{E}$ (Figure 3(a)), implying that the spatial distribution of electron jets may have a northern preference. To determine this preference, we should consider the coverage of MMS spacecraft during the tail season. Figure 3(b) gives the total dwell time of MMS in hours from May to August in 2017. The MMS spacecraft spent most of its time in the northern hemisphere, suggesting that one can rule out the northern preference of electron jets. Thus, we conjecture that the preference of electron jets in the northern hemisphere is probably due to the tilting of the plasma sheet to the northern hemisphere during the year of 2017. Moreover, dividing the number of electron jet events in each bin by the dwell time of MMS observations for the corresponding bin, one can obtain the occurrence rate of electron jets. The occurrence rate of electron jets is shown in Figure 3(c). The highest occurrence rate (more than three events/hour) is in the most tailward ($X \approx -23 \sim -25 R_{E}$) and slight duskside ($Y \approx 0 \sim 2 R_{E}$) region in the $X$-$Y$ plane, but not in the longest dwell time region ($X \approx -23 \sim -25 R_{E}$ and $Y \approx 2 \sim 4 R_{E}$), and the second peak of occurrence rate is in the dawnside region ($Y \approx -4 \sim -2 R_{E}$, $X \approx -19 \sim -23 R_{E}$). The peak group of the occurrence rate in the $Y$-$Z$ plane locates in the north ($Z \approx 0 \sim 6 R_{E}$) and in the center of the $Y$-axis ($Y \approx -4 \sim 4 R_{E}$), while the second peak group concentrates in the more dawnside region ($Y \approx -14 \sim -10 R_{E}$, $Z \approx 0 \sim 4 R_{E}$). This dawnside preference is different from the duskside preference of the tail reconnection, which may be due to the fact that not all electron jets are correlated with the reconnection, such as the electron jets around the magnetic holes (the corresponding occurrence rate has a dawnside preference, not shown here).

### 3.2. Relative Position of Electron Jets Associated with Different Structures

To identify where the electron jets can be detected, the electron jets are classified according to different structures. It is
found that there are 224 electron jets detected during 161 current sheet crossings, 57 electron jets detected during 31 PSBL crossings, 83 electron jets occurring around 68 DFs, 79 electron jets observed around 51 magnetic holes, and 23 electron jets occurring around 14 flux ropes. Some electron jets may be located at the reconnection electron diffusion region (e.g., Huang et al. 2018; Zhou et al. 2019a), which are included in the event list during the crossing of the current sheet. To determine the exact location where the electron jets could be observed, the relative positions associated with different structures are statistically investigated in detail in Figure 4. The relative position of electron jets is defined as the location where the electrons have maximum velocity or the peak of the electron velocity occurs. As for current sheet events, we use the values of $B_x$ components when the electron jet reaches its maximum velocity to identify three relative positions: $B_x > 5$ nT corresponding to northern hemisphere of the CS; $B_x < -5$ nT corresponding to southern hemisphere of the CS; and $-5$ nT $\leq B_x \leq 5$ nT corresponding to the center of the CS (as can be seen in the bars on the top of Figure 1(A)). One can see that 13 electron jets are detected in the southern part of the CS, 26 electron jets are detected at the northern part of the CS, and 185 electron jets (82.6% of events) are located at the center of the CS (Figure 4(a)). As for DF events, three relative positions are divided, including dip regions before DFs, DF proper, and flux pileup regions (FPRs) with the large $B_z$ component after DFs (shown in the top of Figure 2(A)). Most (77.1%) of electron jets are detected at the DFs, 16 (19.3%) electron jets are observed in the FPRs, and only 3 electron jets occurred in the dip region (Figure 4(b)). As for the magnetic hole events, the relative positions are divided into two subregions: interior (or center) of the magnetic hole where the magnitude of the magnetic field is weaker than the ambient magnetic field (i.e., dip region), and exterior of the magnetic hole where the magnetic field strength recovers to be similar to the ambient magnetic field but just outside of the hole (shown in the top of Figure 2(B)). One can see 76 electron jets in the interior of the magnetic hole and only 3 electron jets in the exterior of magnetic hole (Figure 4(c)). According to the crossing of PSBL, the relative positions are classified as near the lobe during the crossing of PSBL, near the plasma sheet during the crossing of PSBL, and PSBL (shown in the top of Figure 1(B)). 23 electron jets are detected near the lobe region, 17 electron jets are detected at the PSBL, and 17 electron jets are observed at the region near the plasma sheet (Figure 4(d)). As for flux ropes, two relative positions include the interior of the flux rope, where the $B_z$ component has bipolar variation and the magnetic field amplitude has a peak; and exterior of the flux rope, where the magnetic field strength gradually recovers to be similar to the ambient magnetic field but just outside of the flux rope (shown in the top of Figure 2(C)). There are 13 electron jets observed in the interior of flux ropes and 10 electron jets detected in the exterior of flux ropes (Figure 4(e)). In summary, the occurrence relative position of electron jets is concentrated in the current sheet (especially the center of the current sheet), at the DFs, in the interior of the magnetic hole, and near lobe during the crossing of PSBL.

Considering that the time duration of BBFs can be longer than 10 minutes (e.g., Cao et al. 2006), we check 10 minute data of ion flow magnitude and perpendicular flow speed before and after the electron jets to confirm whether electron jets are associated with BBF. For BBFs, the ion flow magnitude should be above 100 km s$^{-1}$, during which the largest flow speed must be larger than 400 km s$^{-1}$ (Angelopoulos et al. 1994), and perpendicular flow speed should be larger than 250 km s$^{-1}$ (Raj et al. 2002). It is found that 450 electron jets are accompanied with BBFs (in other words, 96.6% of electron jets are detected in the BBFs), implying that the electron jets can also occur in the non-BBFs region.

Figure 3. (a) Statistical spatial distributions of the 466 electron jets, (b) dwell time of orbit coverage of MMS from May to August in 2017, and (c) occurrence rate of electron jets in the $X$–$Y_{GSM}$ plane and $Z$–$Y_{GSM}$ plane.
3.3. Duration of Electron Jets

The criterion to identify the duration of the electron jet is shown as follows: the moment when the electron velocity increases to higher than the ion velocity is set as the begin time of one jet, and the moment when the electron velocity decreases to below the ion velocity as the end time of this jet. Figure 5 displays the histograms of the duration of electron jets. It can be seen that the durations of all electron jets are usually less than 10 seconds, and mostly within 6 seconds. As for different structures, the duration of the electron jets detected during the crossing of CS ranges from 0.61 to 6 seconds; the durations of the most electron jets around DFs and magnetic holes are less than 4 seconds; the durations of the electron jets observed during the crossing of PSBL concentrate 2 ~ 6 seconds; and the durations of the electron jets around flux ropes ranges from 1.1 to 8 seconds. The average duration of all electron jets is 2.89 seconds, which is much shorter than the duration of BBFs (Cao et al. 2006).

3.4. Electron Velocity within the Electron Jets

Considering that the maximum values of electron velocity can occur for different components, we only perform a statistical study on the total velocity of the electrons $V_{et}$. Figure 6 shows the histograms of maximum values of $V_{et}$ for different structures. It can be seen that the maximum values of $V_{et}$ mainly distribute around 2000 km s$^{-1}$, and some electron jets in the flux rope can reach up to 18,000 km s$^{-1}$ (Figure 6(a)). To normalize the electron velocity, we present the average local ion Alfvén speed $V_a$ (referred to as Alfvén speed $V_a$ latter) during each electron jet in Figure 6(b). The local Alfvén speed $V_a$ mainly ranges from 100 to 400 km s$^{-1}$. By dividing by $V_a$, the normalized electron velocity $V_{etmax}/V_a$ is shown in Figure 6(c). It is found that the normalized electron velocity of electron jets concentrates around 1.2 ~ 3.3 during the crossing of in PSBL and 2.16 ~ 2.9 during the crossing of flux ropes due to the large local Alfvén speed $V_a$, 2 ~ 4.85 during the crossing of magnetic holes, 3.2 ~ 14.4 during the crossing of CS, and 2.1 ~ 7 during the crossing of DFs. In other words, the electron velocity within the electron jets can be much larger than the local Alfvén speed, implying that the electron jets are super-Alfvénic flows.

3.5. Substorm and Electron Jet Correlation

To investigate the relationship between magnetospheric activities and electron jets, we choose the AE index, which describes the intensity of substorm when MMS observed the electron jets. The AE index is divided into four ranges: very intense (AE $\geq$ 800 nT), intense (400 $\leq$ AE < 800 nT), high (200 $\leq$ AE < 400 nT), and moderate (AE < 200 nT)(Landry & Wexler 1995). Figure 7 displays the histograms of the durations of electron jets when MMS cross the CS, DFs, magnetic holes, the PSBL, and flux ropes.
Figure 7 presents the histograms of the events for different ranges of AE index. More than half (56.9%) of the electron jets occur in the strong magnetospheric activities with AE $\geq$ 200 nT. There are 201 electron jets occurring at small AE index, but this does not mean that the electron jets are not accompanied by substorms. We check three hour data of AE and AL indices before and after the electron jets to confirm whether or not the substorms happen. For the onset of substorms, AL will suddenly drop by 100 nT (McPherron & Hsu 2002). Correspondingly, AE will increase during the substorms (Davis & Sugiura 1966). As a result, it is found that nearly all (93.6%) electron jets occur during the substorms. A previous study has shown that most BBFs are associated with substorms (Cao et al. 2006). According to Section 3.2, most electron jets are embedded in BBFs; thus, it is reliable that the electron jets are associated with substorms.

4. Conclusions

Electron jets with velocities much larger than the ion velocity are statistically investigated in the terrestrial magneto-tail by MMS from May to August in 2017. 466 electron jet events are identified in total. According to the statistical results, the main conclusions can be summarized as follows:

1. Due to the coverage of MMS spacecraft, the dominating occurrence of electron jets is in the region: $-25 < X < -17$ RE, $-14 < Y < 12$ RE, and $0 < Z < 6$ RE. The average occurrence rate of electron jets is 0.217 events per hour in the $X$–$Y$ plane, and 0.189 events per hour in the $Z$–$Y$ plane.

2. Electron jets are detected in association with five different types of magnetic structures. Our statistical study reveals 224 events detected during the crossing of the current sheet, 57 events observed during the crossing of the plasma sheet boundary layer, 83 events around DFs, 79 events around magnetic holes, and 23 events around flux

Figure 6. Statistical histograms of the electron velocity of electron jets. (a) The max value magnitude of electron velocity ($V_{\text{etmax}}$); (b) the local mean Alfvén speed ($V_a$); and (c) the normalized electron velocity of electron jets $V_{\text{etmax}}/V_a$.

Figure 7. Histogram of the number of electron jet events during different magnetospheric activities.
ropes. The exact relative positions for different structures where electron jets are observed is also identified. The preference of the relative position of electron jets is in the current sheet (especially the center of current sheet), at the DPs, in the interior of magnetic hole, and near the lobe during the crossing of PSBL. The electron jets have almost the same probability at the interior and exterior of flux ropes.

(3) The durations of all electron jets are mostly within 6 seconds with average values of 2.89 seconds, much shorter than those of BBFs derived by Cao et al. (2006).

(4) The maximum values of \( V_{\text{jet}} \) in the electron jets mainly distribute around 2000 km s\(^{-1}\) and are much larger than the local ion Alfvén speed, implying that the jets are super-Alfvénic flows. This indicates that the super-Alfvénic electron flows are not only observed in the reconnection diffusion region, but also in some structures that are far away from the reconnection region.

(5) 93.6% electron jets are accompanied by substorms, indicating that electron jets have a close relationship with the magnetospheric activities. Thus, electron jets may play an important role in the energy transport and dissipation during magnetospheric activities in the terrestrial magnetotail.

Many undiscovered problems, such as the generation mechanism of these electron jets and the precise contributions of these electron jets on the energy dissipation and conversion in the magnetotail, will be studied in the future.

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References

Angelopoulos, V., Kennel, C. F., Coroni, F. V., et al. 1994, JGR, 99, 257
Angelopoulos, V., McFadden, J. P., Larson, D., et al. 2008, Sci, 321, 931
Angelopoulos, V., Runov, A., Zhou, X. Z., et al. 2013, Sci, 341, 1478
Angelopoulos, V., Baumjohann, W., Kennel, C. F., et al. 1992, JGR, 97, 4027
Baumjohann, W., Paschmann, G., & Luithr. H. 1990, JGR, 95, 3801
Baumjohann, W., Paschmann, G., Schopke, N., Cattell, C. A., & Carlson, C. W. 1988, JGR, 93, 11507

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