

Quantitative Analysis of Electron Acceleration in Coalescing Magnetic Flux Ropes at Earth's Magnetopause

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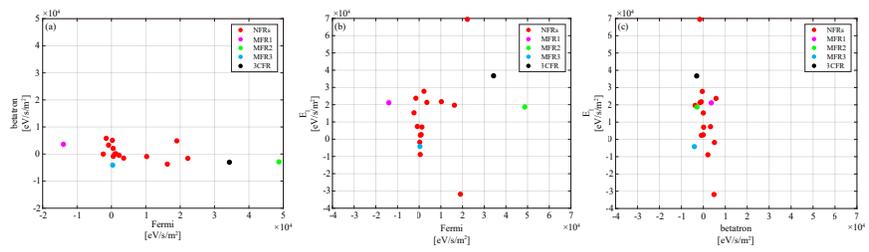
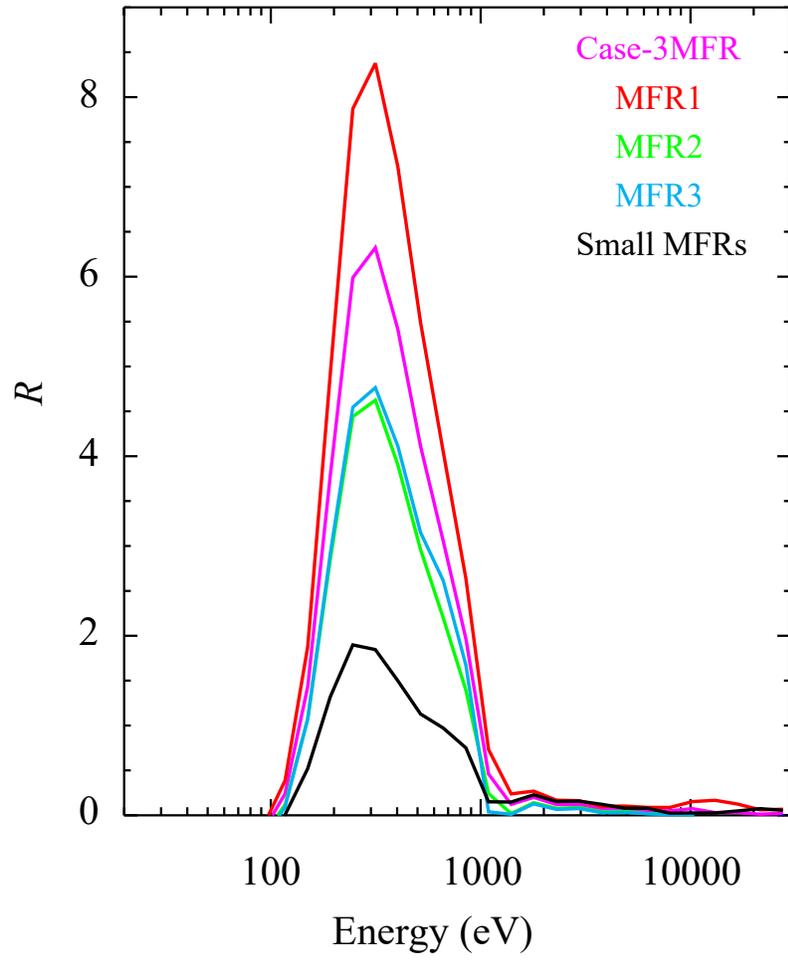
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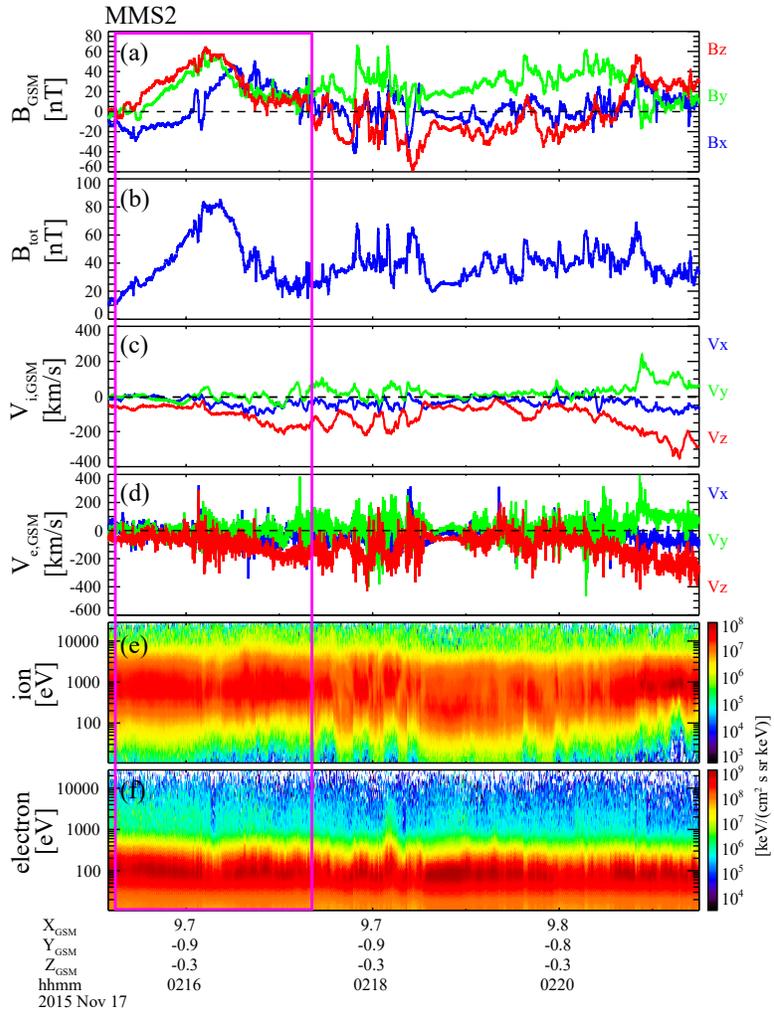
Abstract

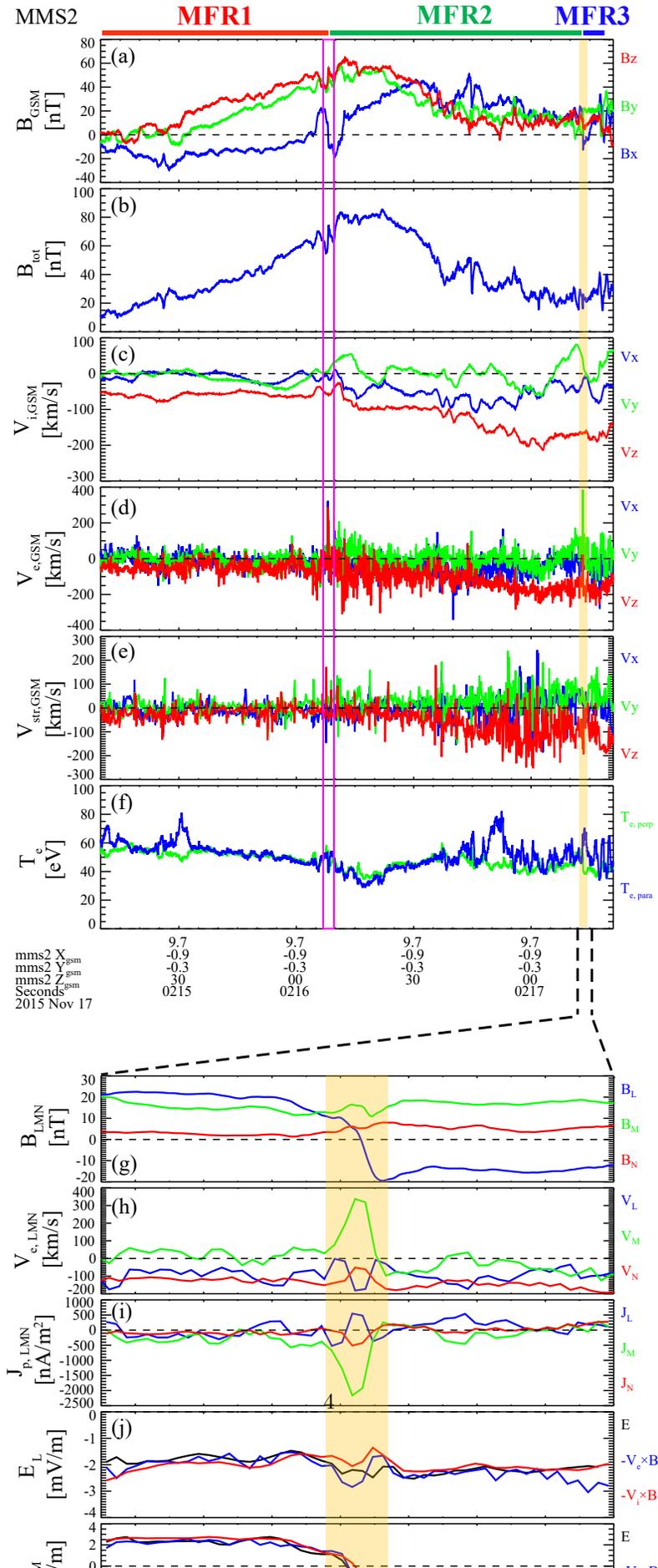
Coalescence of magnetic flux ropes (MFRs) is suggested as a crucial mechanism for electron acceleration in various astrophysical plasma systems. However, how electrons are being accelerated via MFR coalescence is not fully understood. In this paper, we quantitatively analyze electron acceleration during the coalescence of three MFRs at Earth's magnetopause using in-situ Magnetospheric Multiscale (MMS) observations. We find that suprathermal electrons are enhanced in the coalescing MFRs than those in the ambient magnetosheath and non-coalescing MFRs. Both first-order Fermi and E_{\parallel} acceleration were responsible for this electron acceleration, while the overall effect of betatron mechanism decelerated the electrons. The most intense Fermi acceleration was observed in the trailing part of the middle MFR, while E_{\parallel} acceleration occurred primarily at the reconnection sites between the coalescing MFRs. For non-coalescing MFRs, the dominant acceleration mechanism is the E_{\parallel} acceleration. Our results further consolidate the important role of MFR coalescence in electron acceleration in space plasma.

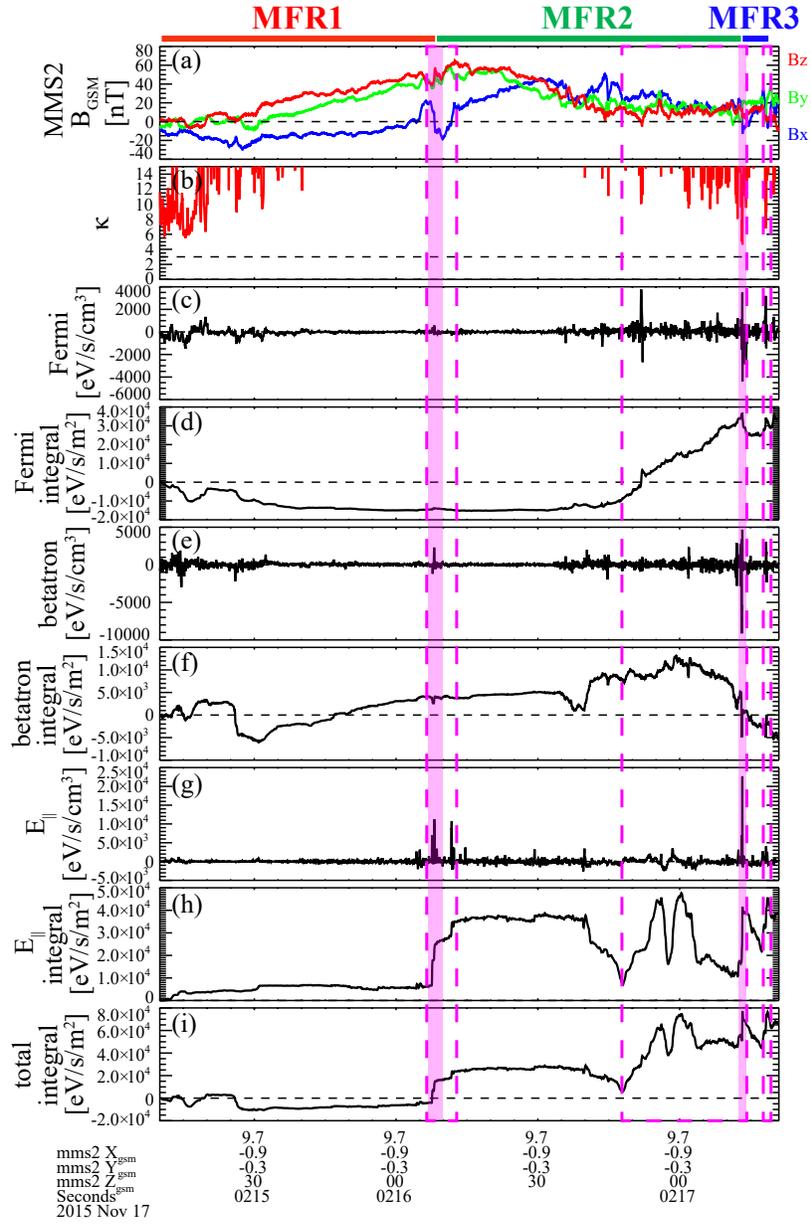
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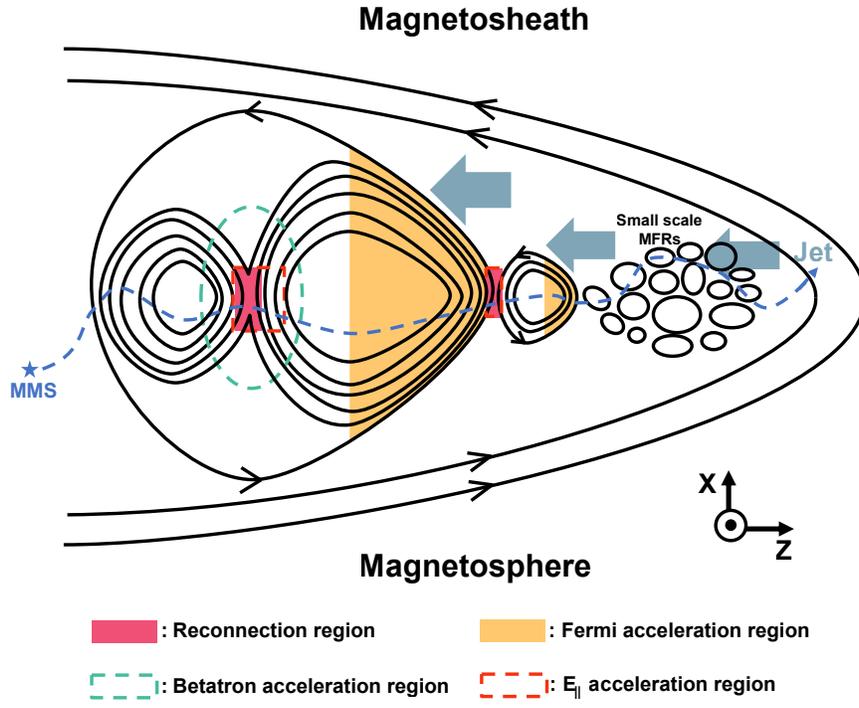
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1 **Quantitative Analysis of Electron Acceleration in Coalescing Magnetic Flux Ropes at**
2 **Earth's Magnetopause**

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12 **Key Points:**

- 13 • First observation of two coalescing reconnections among three magnetic flux ropes
14 (MFRs)
- 15 • Coalescing MFRs result in greater acceleration rates and generate more suprathermal
16 electrons than that in non-coalescing MFRs
- 17 • Fermi and E_{\parallel} accelerations are the dominant mechanisms in coalescing MFRs, while E_{\parallel} is
18 the dominant mechanism in non-coalescing MFRs

19

20 **Abstract**

21 Coalescence of magnetic flux ropes (MFRs) is suggested as a crucial mechanism for electron
22 acceleration in various astrophysical plasma systems. However, how electrons are being
23 accelerated via MFR coalescence is not fully understood. In this paper, we quantitatively analyze
24 electron acceleration during the coalescence of three MFRs at Earth's magnetopause using in-
25 situ Magnetospheric Multiscale (MMS) observations. We find that suprathermal electrons are
26 enhanced in the coalescing MFRs than those in the ambient magnetosheath and non-coalescing
27 MFRs. Both first-order Fermi and E_{\parallel} acceleration were responsible for this electron acceleration,
28 while the overall effect of betatron mechanism decelerated the electrons. The most intense Fermi
29 acceleration was observed in the trailing part of the middle MFR, while E_{\parallel} acceleration occurred
30 primarily at the reconnection sites between the coalescing MFRs. For non-coalescing MFRs, the
31 dominant acceleration mechanism is the E_{\parallel} acceleration. Our results further consolidate the
32 important role of MFR coalescence in electron acceleration in space plasma.

33 **Plain Language Summary**

34 Magnetic flux ropes are common magnetic structures in space environments and are believed to
35 play a significant role in electron acceleration. Adjacent magnetic flux ropes can coalesce
36 through magnetic reconnection, forming larger-scale magnetic flux ropes. The significant
37 efficiency of electron acceleration within coalescing magnetic flux ropes has been reported
38 thoroughly by theoretical and numerical simulation studies, but has not been confirmed by in-situ
39 observation. Our research reports an event of three magnetic flux ropes coalescing in pairs and
40 provides detailed quantitative analyses of associated acceleration mechanisms. Furthermore, we
41 compare the electron accelerations within these coalescing magnetic flux ropes with other non-
42 coalescing flux ropes. Our study contributes to a further understanding of the production
43 mechanisms of high-energy electrons in space plasmas.

44 **1 Introduction**

45 Magnetic reconnection is a pervasive phenomenon in space and astrophysical plasmas,
46 efficiently converting magnetic energy into plasma energy. Part of the magnetic energy is used to
47 energize suprathermal particles, which has frequently been detected in space observations and
48 numerical simulations (Coroniti & Kennel, 1972; Drake et al., 2006; Fu et al., 2006; Fu et al.,
49 2019; Matthaeus et al., 1984; Øieroset et al., 2002; Zhou et al., 2016). High-energy particles

50 generated in the magnetotail may serve as seed particles for relativistic particles in the inner
51 magnetosphere, playing a pivotal role in the dynamics of the radiation belts (Lui et al., 2012;
52 Tang et al., 2017; Turner et al., 2021).

53 Magnetic flux ropes (MFRs), also known as magnetic islands, plasmoids, or flux transfer
54 events, are helical magnetic structures commonly observed in space plasmas (Slavin et al., 2003;
55 Zong et al., 2004). It is widely acknowledged that MFRs are by-products of magnetic
56 reconnection, generated through tearing instability or Kelvin-Helmholtz instability (Zhong et al.,
57 2018; Zhou et al., 2012). MFRs are considered one of the most significant structures for electron
58 acceleration during reconnection (Drake et al., 2006; Chen et al., 2008; Retino et al., 2008;
59 Huang et al., 2012; Zhong et al., 2020; Zhou et al., 2018). Electron acceleration within MFRs
60 primarily involves local betatron acceleration due to the compressed core magnetic field inside
61 the MFR (Zhong et al. 2020), first-order Fermi acceleration resulting from MFR contraction
62 (Drake et al., 2006), parallel electric field acceleration inside and at the perimeter of the MFR
63 (Zhou et al., 2018), island surfing acceleration (Oka et al., 2010a) and non-adiabatic turbulent
64 acceleration mechanism (Fujimoto and Cao, 2021).

65 MFRs may coalesce/merge with each other to form MFRs with larger spatial size through
66 reconnection between them (Pritchett, 2007; Wang et al., 2016a; Zhou et al., 2017).
67 Theoretically, it has been suggested that the coalescence of magnetic islands can efficiently
68 energize electrons, primarily through first-order Fermi acceleration and direct acceleration via
69 the reconnection electric field at the merging site (Oka et al., 2010b; Le Roux et al., 2015;
70 Pritchett, 2008; Wang et al., 2016b; Du et al., 2018; Li et al., 2017). Fermi acceleration results
71 from the shrinking of magnetic field lines during the coalescence. From the perspective of single
72 particle motion, it is due to the curvature drift along the electric field. Drake et al. (2012) propose
73 that the first-order Fermi mechanism is more efficient during the coalescence of multiple
74 magnetic islands than for a single MFR, and the energized particles exhibit a power-law
75 distribution with $f \sim E^{-1.5}$.

76 Although theoretical and simulation studies have widely suggested that MFR coalescence can
77 provide significant electron acceleration, there is currently a lack of in-situ observations to
78 consolidate this scenario. In this paper, we present MMS observations of a series of MFRs in a
79 reconnection exhaust at the magnetopause subsolar region. The first three MFRs in this series

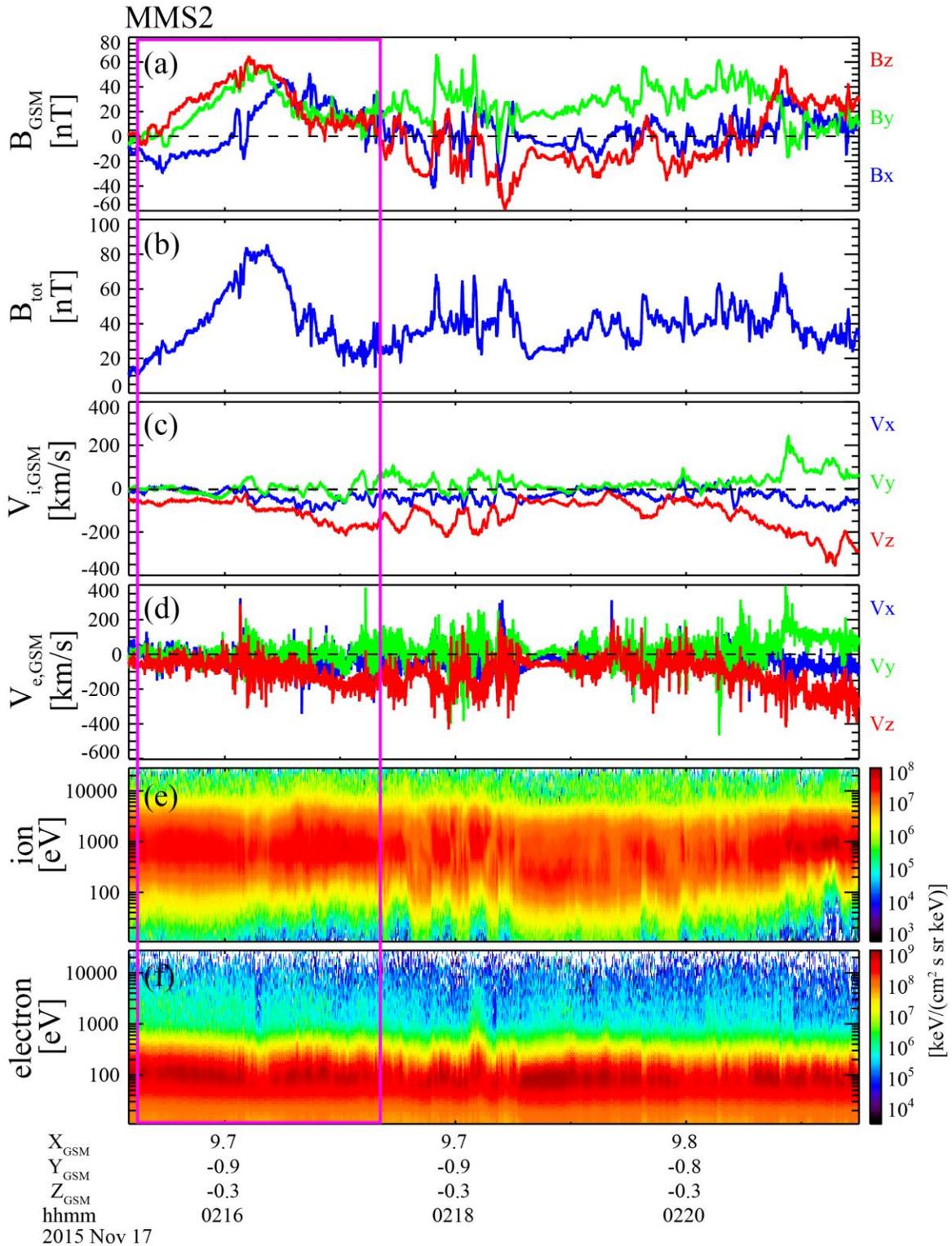
80 were coalescing with each other, while the other MFRs were not. The high-resolution data
81 recorded by the Magnetospheric Multiscale (MMS) mission (Burch et al., 2016) provides us a
82 unique opportunity to study the electron acceleration by the coalescing MFRs and compare the
83 degree of electron acceleration between coalescing and non-coalescing MFRs. The remainder of
84 this paper is organized as follows: Section 2 provides the overview of the MFRs. Section 3 and
85 Section 4 present the evidence of MFRs coalescing and electron acceleration within the MFRs.
86 Section 5 discusses and summarizes our results.

87 **2 Event Overview**

88 On 2015 November 17, from 02:15:00 to 02:21:30 UT, the four MMS spacecraft traversed the
89 subsolar magnetopause at an approximate location of [9.7, -0.9, -0.3] R_E in Geocentric Solar
90 Magnetospheric (GSM) coordinates. The average separation between the four spacecraft was
91 about 20 km, leading to quite similar observations from each of them. The data utilized in this
92 study were obtained from the following instruments onboard MMS: the Fluxgate Magnetometer
93 (FGM) (Russell et al., 2016), which provides three-dimensional magnetic field vectors; the Fast
94 Plasma Investigator (FPI) (Pollock et al., 2016) offering plasma velocity distributions and
95 moments; and the Electric Double Probe (EDP) (Ergun et al., 2016; Lindqvist et al., 2016;
96 Torbert et al., 2016) provides three-dimensional electric field vectors.

97 Figure 1 displays an overview of the observations from MMS2 during this this time interval.
98 Given the spacecraft's proximity to the subsolar point, the GSM coordinate system serves as a
99 reasonable approximation to the boundary normal coordinate system of the magnetopause, as the
100 magnetopause normal closely aligns with the GSM-x direction (e.g., Zhou et al., 2017). Multiple
101 bipolar variations of the magnetic field B_x component are accompanied by peaks of the B_y
102 component and the increases in total magnetic field strength, which are typical signatures of
103 MFRs (Figures 1(a) and 1(b)) (Zong et al., 2004). Magnetic field B_z (Figure 1(a)) exhibits
104 several sign reversals during this period, indicating that MMS repeatedly crossed the
105 magnetopause between the magnetosphere ($B_z > 0$) and magnetosheath ($B_z < 0$). These MFRs
106 were embedded in two large southward bulk flows driven by reconnection (Figures 1(c) and
107 1(d)) within the magnetopause boundary layer (Zhou et al., 2017). These two flows were
108 separated by a quiescent flow period, occurring from approximately 02:18:30 UT to 02:19:30
109 UT. Ions and electrons from both the magnetosphere and the magnetosheath mixed within this

110 reconnection outflow, a clear indication of an opening magnetopause. Our focus will be on the
 111 three consecutive MFRs observed between 02:15:10 and 02:17:20 UT, marked by the magenta
 112 rectangle in Figure 1.



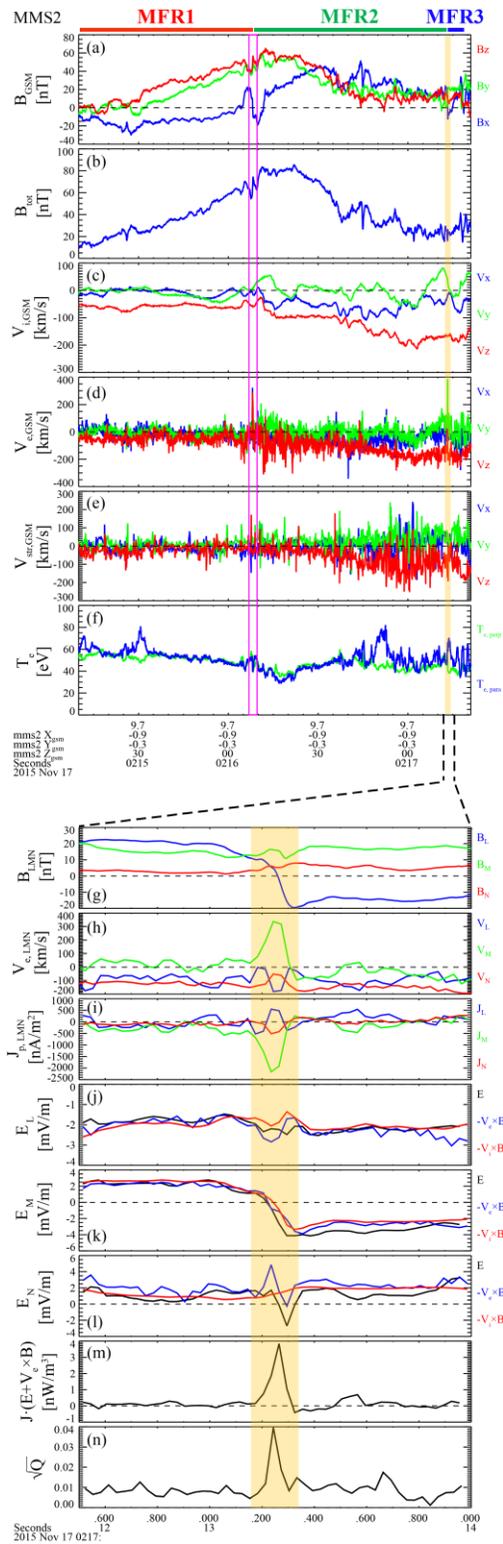
114 **Figure 1.** Overview of MMS2 observations between 02:15:00 and 02:21:30 UT. From the top to
 115 bottom are: (a) magnetic field vectors; (b) magnetic field strength; (c) ion bulk velocity; (d)
 116 electron bulk velocity; (e) ion and (f) electron omni-directional differential energy fluxes. All
 117 vectors are presented in GSM coordinates. The magenta rectangle highlights the observations of
 118 the three coalescing MFRs.

119 **3 Electron Acceleration within Coalescing MFRs**

120 Figures 2(a)-(f) present observations from 02:15:10 UT to 02:17:21 UT, during which the
 121 three consecutive MFRs were observed by MMS. Zhou et al. (2017) reported the merging of the
 122 first two large-scale MFRs, with an electron diffusion region identified between MFR1 and
 123 MFR2. Here we unveil another smaller MFR (denoted as MFR3), which was adjacent to the tail
 124 of MFR2, merging with MFR2. The three MFRs were identified as quasi-2D structures based on
 125 the minimum directional derivative (MDD) analysis (Shi et al., 2005) because $\lambda_1 \sim \lambda_2 \gg \lambda_3$,
 126 where the three eigenvalues λ_1 , λ_2 , and λ_3 represent the maximum, intermediate and minimum
 127 values of the magnetic field directional derivatives. The 2-D structure velocities calculated by the
 128 spatio-temporal difference method (Shi et al., 2006) using the magnetic field data smoothed to
 129 the resolution of 0.03 s are depicted in Figure 2(e). One can see that the structure velocities
 130 closely match both the ion (Figure 2(c)) and electron bulk velocities (Figure 2(d)). Considering
 131 the moving velocities and the observational durations of the MFRs, we estimate the cross-section
 132 sizes of MFR1, MFR2, and MFR3 as approximately $\sim 59 d_i$, $\sim 145 d_i$, and $\sim 15 d_i$, respectively,
 133 with d_i being the ion inertial length, around 42 km, given an average number density of $\sim 30 \text{ cm}^{-3}$.

134 Interestingly, we note that a high-speed electron jet in the Y direction was observed between
 135 MFR2 and MFR3 (the orange shading in Figures 2(a)-(f)). To further understand the nature of
 136 this electron jet, we investigate the details of this electron jet in the local boundary normal
 137 (LMN) coordinates (shown in Figures 2(g)-(n)). The transformation from GSM to LMN
 138 coordinates constructed by the minimum variance analysis (Sonnerup & Scheible, 1998) is given
 139 by: $\mathbf{L} = (0.778, -0.564, 0.276)$, $\mathbf{M} = (0.431, 0.799, 0.419)$, $\mathbf{N} = (-0.457, -0.207, 0.865)$, where \mathbf{N}
 140 is the normal of the current sheet corresponding to the jet, \mathbf{L} is the eigenvector of the maximum
 141 eigenvalue, and \mathbf{M} completes the right-handed orthogonal coordinate system, i.e., $\mathbf{M} = \mathbf{N} \times \mathbf{L}$.
 142 Figure 2(g) illustrates that a reversal of B_L corresponds to a large out-of-plane current in the $-\mathbf{M}$
 143 direction with a peak value of approximately $2,200 \text{ nA/m}^2$ (Figure 2(i)). This current is highly

144 anticorrelated to electron flow, indicating that it is predominantly carried by electrons (the V_{eM}
145 peak ~ -340 km/s in Figure 2(h)). V_{eL} exhibits a tripolar variation relative to the background
146 velocity V_L , approximately -100 km/s, during the current sheet crossing. After removing the
147 background velocity, the peak value of V_{eL} is around 100 km/s, surpassing the asymptotic Alfvén
148 speed of this current sheet. Figures 3(j)-(l) show the three components of the measured electric
149 field \mathbf{E} , convective electric fields for ions and electrons, i.e., $-\mathbf{V}_i \times \mathbf{B}$, and $-\mathbf{V}_e \times \mathbf{B}$. We see that both
150 $-\mathbf{V}_i \times \mathbf{B}$ and $-\mathbf{V}_e \times \mathbf{B}$ deviate from \mathbf{E} in the current sheet, suggesting the decoupling of ions and
151 electrons from the magnetic field in this region. This results in a peak energy dissipation $\mathbf{J} \cdot \mathbf{E}' \sim 4$
152 nW/m^3 at the center of the current sheet (Figure 2(m)). In Figure 2(n), a prominent peak in the
153 electron non-gyrotropy measurement \sqrt{Q} inside the current sheet (Swisdak, 2016) is evident. The
154 peak value of $\sqrt{Q} \sim 0.04$ is about 4 times larger than the background value ~ 0.01 . The above
155 evidences strongly support that MMS encountered a reconnecting current sheet between MFR2
156 and MFR3. The direction of current J_M is consistent with the coalescence of two MFRs rather
157 than the splitting of a larger MFR into two smaller MFRs (Zhong et al., 2023). Consequently, we
158 deduce that MMS observed three contiguous MFRs coalescing in pairs at the dayside
159 magnetopause. The average structure velocities for MFR3 and MFR2 were 125 km/s and 92
160 km/s, respectively, suggesting that the coalescence happened because MFR3 caught up with
161 MFR2.



162

163 **Figure 2.** The top column shows the observation of the first three MFRs in GSM coordinates: (a)
 164 magnetic field vectors, (b) magnetic field strength, (c) ion bulk velocity, (d) electron bulk
 165 velocity, (e) magnetic structure velocity estimated by STD method, (f) electron parallel (blue)

166 and perpendicular temperatures (green). The bottom column displays the observations of the
 167 reconnecting current sheet between MFR2 and MFR3 in LMN coordinates: (g) magnetic field
 168 vectors, (h) electron bulk velocity, (i) current density, (j) – (l) three components of the measured
 169 electric field (black), $-\mathbf{V}_e \times \mathbf{B}$ (blue), and $-\mathbf{V}_i \times \mathbf{B}$ (red), (m) energy dissipation $\mathbf{J} \cdot \mathbf{E}' = \mathbf{J} \cdot (\mathbf{E} +$
 170 $\mathbf{V}_e \times \mathbf{B})$, (n) electron non-gyrotropy measurement \sqrt{Q} . The orange shading marks the
 171 reconnecting current sheet between MFR2 and MFR3.

172 Below we quantitatively evaluate the electron acceleration associated with the three coalescing
 173 MFRs. In principle, the first-order acceleration of a well-magnetized particle includes Fermi,
 174 betatron mechanism, and direct acceleration by parallel electric field (e.g., Northrop, 1963). The
 175 bulk acceleration rates of the first-order Fermi, betatron, and E_{\parallel} mechanism can be estimated
 176 using the following formulas (Dahlin et al. 2014; Akhavan-Tafti et al., 2019; Ma et al. 2020,
 177 2022; Xu et al., 2023; Zhong et al. 2020):

$$178 \quad W_{Fermi} = (P_{e\parallel} + n_e m_e v_{\parallel}^2) \vec{v}_{E \times B} \cdot (\vec{b} \cdot \nabla \vec{b}) \quad (1)$$

$$179 \quad W_{betatron} = P_{e\perp} \vec{v}_{E \times B} \cdot \frac{\nabla B}{B} + \frac{P_{e\perp}}{B} \frac{\partial B}{\partial t} \quad (2)$$

$$180 \quad W_{E_{\parallel}} = J_{e\parallel} E_{\parallel} + \frac{\beta_{\perp}}{2} J_{\parallel} E_{\parallel} \quad (3)$$

181 where P_e is the electron pressure, n_e is the electron density, β_{\perp} is defined as the perpendicular
 182 plasma pressure divided by the magnetic pressure: $\beta_{\perp} = \frac{P_{\perp}}{B^2/2\mu_0}$, $J_{e\parallel}$ is the electron parallel
 183 current, and J_{\parallel} is the total parallel current. Equations (1)-(3) demonstrate the amount of electron
 184 energy gained per unit volume per unit time through the three mechanisms. The bulk
 185 acceleration rates of the three acceleration mechanisms within the merging MFRs are presented
 186 in Figures 3(a)-(i). Note that the applicability of these formulas requires the motion of electrons
 187 to satisfy the guiding center approximation (Northrop 1963). We employ the κ value to evaluate
 188 electron adiabatic motion and determine if the guiding center approximation has been satisfied.
 189 The κ value is defined as follows (Büchner & Zelenyi 1989):

$$190 \quad \kappa = \sqrt{R_C/R_L} \quad (4)$$

191 where R_C and R_L represent the magnetic field curvature radius and the electron Larmor radius,
 192 respectively. A large κ typically corresponds to a magnetized orbit of particles.

193 Figure 3(b) exhibits the κ value of electrons with energy four times the electron temperature,
 194 encompassing the energy range of most electrons (Ma et al., 2020; Xu et al., 2023). Throughout
 195 the entire interval, the κ value consistently exceeds 3, indicating that electrons satisfy the guiding
 196 center approximation within the three MFRs, allowing for the quantification of their bulk
 197 acceleration using Eqs. (1)-(3). We see that the bulk Fermi acceleration rate exhibits large
 198 fluctuations within MFR3, the trailing part of MFR2 and the leading edge of MFR1 (Figure 3c).
 199 The positive peak value reaches about 4,000 eV/s/cm³. Figure 3(e) reveals that the betatron
 200 acceleration rate exhibits several significant peaks in the leading part of MFR1, the trailing part
 201 of MFR2, and throughout MFR3. Specifically, a considerable positive peak of $\sim 2,200$ eV/s/cm³
 202 occurs in the reconnection region between MFR1 and MFR2; along with a significant positive
 203 peak of $\sim 5,000$ eV/s/cm³, accompanied by a conspicuous negative peak of approximately -9,000
 204 eV/s/cm³, appearing in the reconnection region of MFR2 and MFR3. The E_{\parallel} acceleration rate,
 205 illustrated in Figure 3(g), displays several extremely large positive peaks exceeding 10,000
 206 eV/s/cm³, surpassing the peak values of both the Fermi and betatron acceleration rates. These
 207 prominent peaks and disturbances of the E_{\parallel} acceleration rate primarily manifest within and
 208 around the two reconnection regions.

209 To assess the net effects of the three mechanisms, we calculate the spatial integral of the
 210 acceleration rates by the following formula:

$$211 \quad W_S = \int W v_{str} dt \quad (5)$$

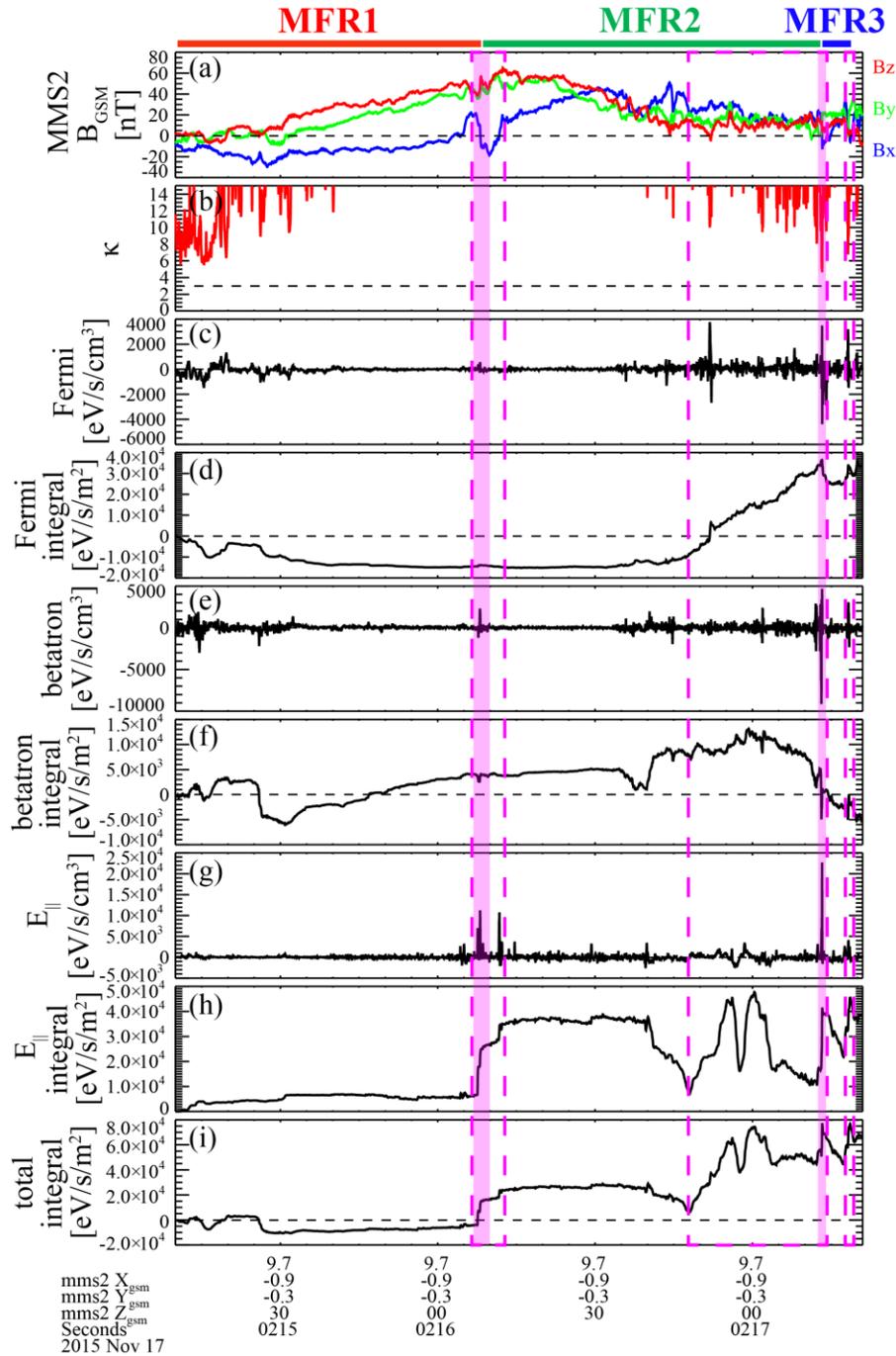
212 where W is the local acceleration rate, and v_{str} is the structure velocity as shown in Figure 2(e).
 213 The rising trend of W_S marks the acceleration region, while the downtrend denotes the
 214 deceleration region. In Figures 3(d), 3(f), 3(h), and 3(i), the spatial integrals of the Fermi,
 215 betatron, and E_{\parallel} mechanisms, along with the total acceleration rate (the sum of the rates from the
 216 three different mechanisms), are presented. It is evident that the Fermi mechanism primarily
 217 functions as a decelerator in MFR1 and the leading edge of MFR3 (Figure 3(d)), while it is
 218 negligible in the leading part of MFR2 and the center of MFR3. Whereas, it shows a significant
 219 net increase in the trailing part of MFR2 and a weak enhancement in the trailing edge of MFR3.
 220 These features are different from the Fermi acceleration within a single FR in which Fermi
 221 acceleration is typically negative on one side of the MFR and positive on the other side (Zhong
 222 et al., 2020; Jiang et al., 2021). The intense Fermi acceleration in the trailing part of MFR2 is

223 probably due to the contraction of the helical magnetic field lines carried by the large bulk flow
224 at the trailing edge of MFR2.

225 Figure 3(f) reveals that betatron acceleration primarily takes place in and around the
226 coalescing region between MFR1 and MFR2, the central area of the newly formed large MFR.
227 Conversely, betatron cooling predominantly occurs within the coalescing region between MFR2
228 and MFR3. This implies that the coalescence of two large MFRs results in significant betatron
229 acceleration, while the merging between the large MFR and the small MFR results in betatron
230 cooling. One of the most notable distinctions between the two coalescences is the strength of the
231 core field. The core field (contributed by B_Y and B_Z) in the coalesced MFR between MFR1 and
232 MFR2 significantly surpasses the reconnecting field B_X . The contraction of the newly formed
233 MFR from MFR1 and MFR2 could lead to an increase in the core field, which exceeds the
234 decrease of B_x due to reconnection, hence resulting in betatron acceleration. In contrast, the
235 coalescence of MFR2 and MFR3 fails to produce a core field with sufficient strength to
236 counterbalance the diminished magnetic field due to reconnection, which results in the magnetic
237 field decrease and betatron cooling.

238 Figure 3(h) illustrates that E_{\parallel} acceleration typically experiences abrupt changes within several
239 narrow regions, indicating that E_{\parallel} acceleration and deceleration are more localized compared to
240 Fermi and betatron acceleration. Particularly, we note that the acceleration from E_{\parallel} is the most
241 intense in the vicinity of the reconnection sites (the magenta regions in Figure 3). These indicate
242 that the acceleration from E_{\parallel} plays a more critical role in the central region of the coalesced
243 MFRs, which is different from the previous results suggesting that E_{\parallel} acceleration mainly occurs
244 at the MFR edges in the single MFR scenario (Zhou et al., 2018; Akhavan-Tafti et al., 2019).

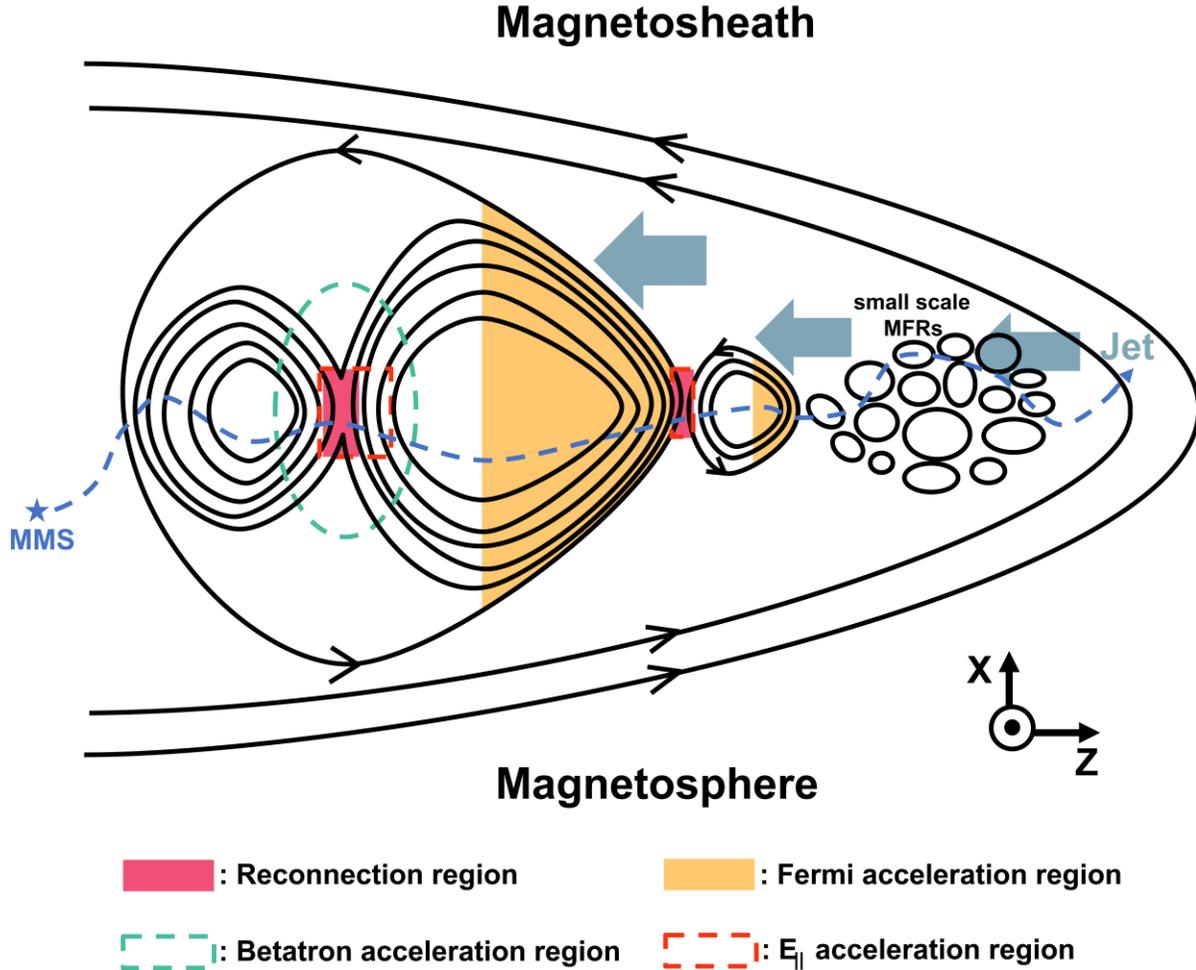
245 Figure 3(i) displays the spatial integral of the total acceleration rate, demonstrating the
246 collective impact of the three mechanisms within these coalescing MFRs. The total integrated
247 rate increases significantly around the reconnection region, as well as at the trailing edges of
248 MFR2 and MFR3, which are highlighted by the magenta dashed box in Figure 3. These areas
249 represent the major acceleration regions in the coalescing MFRs. The primary acceleration
250 mechanisms in these acceleration regions are the Fermi mechanism and the E_{\parallel} mechanism. The
251 maximum integrated values of the two mechanisms are almost identical. The relative positions of
252 the three MFRs and the associated acceleration regions are depicted in Figure 4.



253

254 **Figure 3.** Electron acceleration condition in the MFRs, (a) magnetic field vectors, (b) the κ value
 255 for electrons calculated by 2 times of thermal speed, (c) local Fermi acceleration rate, (d) the
 256 spatial integral of Fermi acceleration rate, (e) local and (f) the spatial integral of betatron
 257 acceleration rate, (g) local and (h) the spatial integral of the E_{\parallel} acceleration rate, (i) the spatial
 258 integral of the total acceleration rate. The magenta shaded areas represent the reconnection
 259 regions, while the magenta dashed boxes encircle the primary acceleration regions.

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261

262 **Figure 4.** A schematic view of the three MFRs with the associated acceleration region. The
 263 dashed curve represents the surmised MMS trajectory across these MFRs.

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4 Comparison between Coalescing and Non-coalescing MFRs

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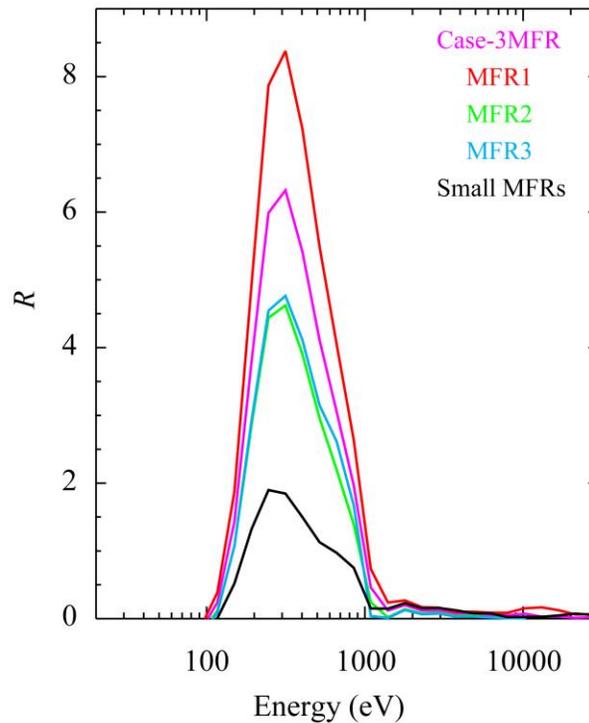
Figure 1 illustrates the presence of a series of short-period MFRs observed from 02:17:25 to 02:21:26 UT, occurring after the observation of the three coalescing MFRs. We do not find clear signatures of coalescence between these MFRs, i.e., no obvious current sheets and energy dissipation observed at their edges, thereby we call them non-coalescing MFRs in the following. We have identified 14 non-coalescing MFRs during this interval in total. The cross-section sizes of these small-scale MFRs are from $6 d_i$ to $48 d_i$, which are derived through the same analysis to infer the cross-section sizes of the three coalescing MFRs as we mentioned in the former section.

272 Subsequently, we compare the electron acceleration associated with these small-scale MFRs to
 273 that associated with the coalescing MFRs.

274 Figure 5 presents the ratio R between the phase space density (PSD) in the MFRs and the PSD
 275 in the magnetosheath for a given energy W . R is defined as

$$276 \quad R(W) = \frac{PSD_{MFR}(W) - PSD_{sheath}(W)}{PSD_{sheath}(W)} \quad (6).$$

277 The magnetosheath reference interval is selected from 03:40:00 to 03:50:00 UT (not shown).
 278 Since the reference interval of magnetosheath lacks burst mode FPI data, R in Figure 5 is
 279 calculated using the fast mode data with a time resolution of 4.5 s. The average PSD within
 280 small-scale non-coalescing MFRs is calculated from FPI fast mode data between 02:17:25 and
 281 02:21:26 UT, during which 14 MFRs were observed sequentially. For energetic electrons ($>$
 282 1,000 eV), the values of R are close to 0 (Figure 5), indicating that there were almost no
 283 magnetospheric energetic electrons in the MFRs. Therefore, the electrons within these MFRs
 284 primarily originated from the magnetosheath. It's noteworthy that R is below 0 for all MFRs
 285 when the energy is below 100 eV, whereas R becomes positive in the 100-1,000 eV range. This
 286 implies that low-energy ($<$ 100 eV) electrons may experience localized acceleration to higher
 287 energy in both coalescing and non-coalescing MFRs. The peaks in R are consistently near 300
 288 eV, which is nearly six times the electron temperature of approximately 50 eV. This suggests
 289 that the acceleration within these MFRs results in the production of suprathermal electrons. R of
 290 MFR1 exhibits the highest peak of ~ 7.5 while R corresponding to small-scale non-coalescing
 291 MFRs has the lowest peak of ~ 1.5 . Therefore, the production of suprathermal electrons is more
 292 significant in coalescing MFRs compared to non-coalescing ones.



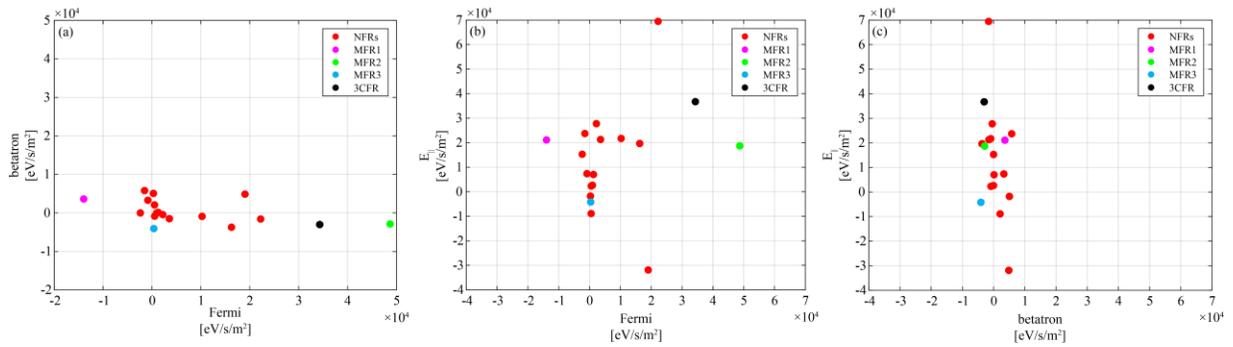
293

294 **Figure 5.** The ratio R within the three coalescing MFRs (magenta), MFR1 (red), MFR2 (green),
 295 MFR3 (blue), and small-scale MFRs (black).

296 We performed a Liouville mapping by setting the magnetosheath electrons as the source
 297 electrons and compared the PSDs in the MFRs to the analytically derived PSD accelerated from
 298 the source. We found that $R=7.5$ in the suprathermal energy range is roughly equivalent to an
 299 adiabatic acceleration factor of 1.3. In other words, there is a 1.3 times enhancement of $|B|$ or
 300 shrinking of field lines in which the electrons are trapped by a factor of 1.3 (Fu et al., 2013). If
 301 the electrons are predominantly accelerated by E_{\parallel} , then an R value of 7.5 corresponds to a
 302 parallel potential of approximately 100 V, which is equivalent to a 100 eV increase in electron
 303 energy. This degree of acceleration is comparable to the electron acceleration associated with
 304 magnetopause reconnection (Graham et al., 2016) and dipolarization fronts in the magnetotail
 305 (Fu et al., 2013).

306 Figure 6 provides a comparison of spatially integrated acceleration rates within the coalescing
 307 MFRs and non-coalescing MFRs. The magenta, green, and blue dots in Figure 6 represent the
 308 rates within each coalescing MFR, the black dot symbolizes the average rate across the three
 309 coalescing MFRs, and the red dots represent the rates within each non-coalescing MFR. An

310 observation is evident that the integrated betatron acceleration rate is consistently close to zero in
 311 all MFRs. The integrated Fermi acceleration rate is near zero in most of the non-coalescing
 312 MFRs. However, it is noteworthy that four non-coalescing MFRs exhibit substantial values
 313 ranging between $(1.0 - 2.5) \times 10^4$ eV/s/m². Particularly, in MFR2, the integrated Fermi
 314 acceleration rate reaches approximately 5×10^4 eV/s/m² (indicated by the green dot in Figure
 315 6(a)), which is larger than the values observed in all non-coalescing MFRs. This contributes to a
 316 higher average Fermi acceleration rate within the coalescing MFRs, denoted by the black dot in
 317 Figure 6(a). Figure 6(b) further compares the integrated Fermi acceleration rate with the E_{\parallel}
 318 acceleration rate in each MFR. It is evident that the integrated E_{\parallel} acceleration rate is typically
 319 larger than the Fermi acceleration in the non-coalescing MFRs, whereas it is nearly equivalent to
 320 the integrated Fermi acceleration rate in the coalescing MFRs. Figure 6(c) reveals that the
 321 betatron acceleration rate is generally smaller than the E_{\parallel} acceleration rate in all MFRs. This
 322 implies that the net Fermi and betatron accelerations in these non-coalescing MFRs are generally
 323 weak, whereas E_{\parallel} acceleration is the primary mechanism responsible for electron acceleration in
 324 the non-coalescing MFRs. Moreover, the integrated Fermi acceleration rate in coalescing MFRs
 325 is larger than that in non-coalescing MFRs.



326

327 **Figure 6.** (a) – (c) Scatter plots of the spatial integrated acceleration rates inside MFRs. Red,
 328 magenta, green, blue, and black dots represent the results of the non-coalescing MFRs (NFRs),
 329 MFR1, MFR2, MFR3, and the three coalescing MFRs as a whole (3CFR), respectively.

330 Table 1 provides a breakdown of the percentage of primary acceleration mechanisms within
 331 non-coalescing MFRs. The dominant acceleration mechanism is determined based on the largest
 332 integrated acceleration rate within a single MFR. It should be noted that the negative value is
 333 consistently smaller than the positive value. We find that E_{\parallel} acceleration accounts for the largest
 334 percentage, $\sim 78.6\%$, signifying that E_{\parallel} acceleration is the predominant mechanism in 11 out of

335 14 non-coalescing MFRs. We also find that Fermi process is the dominant mechanism in none of
 336 the non-coalescing MFRs, which is distinct from that in the coalescing MFRs. There are also two
 337 non-coalescing MFRs in which the total acceleration rate is negative.

338 **Table 1**

339 *Major Acceleration Mechanism and its Percentage in Non-coalescing MFRs*

Major acceleration mechanism	Number of NFRs (14 in total)	Percentage
Fermi	0	0%
betatron	1	7.1%
E_{\parallel}	11	78.6%
No acceleration*	2	14.3%

340 *Note.* The major acceleration mechanism means the one with the largest integrated rate.

341 *"No acceleration" means that the integrated total acceleration rate is negative.

342

343 Table 2 presents the percentage of acceleration (positive value) and deceleration (negative
 344 value) effects for the three mechanisms within these non-coalescing MFRs. It is observed that
 345 Fermi acceleration occurs in 11 out of 14 non-coalescing MFRs, while Fermi deceleration is
 346 observed in 3 out of 14 non-coalescing MFRs. A similar percentage applies to E_{\parallel} acceleration
 347 and deceleration, indicating that both the Fermi and E_{\parallel} mechanisms primarily contribute to
 348 electron acceleration rather than deceleration in most non-coalescing MFRs. However, it is worth
 349 noting that, as indicated by the red dots in Figure 6(b), the integrated Fermi acceleration rate in
 350 most non-coalescing MFRs is typically close to zero, significantly smaller than the integrated E_{\parallel}
 351 acceleration rate. Additionally, the percentage of betatron acceleration is smaller than that of
 352 betatron cooling.

353 **Table 2**

354 *A statistic of acceleration and deceleration effects of each mechanism in non-coalescing MFRs*

Acceleration mechanism	Positive/acceleration percentage (number)	Negative/deceleration percentage (number)
Fermi	78.6% (11)	21.4% (3)

betatron	42.9% (6)	57.1% (8)
E_{\parallel}	78.6% (11)	21.4% (3)

355 5 Summary

356 In summary, our study presents a quantitative analysis of electron acceleration within a series
 357 of MFRs located in a reconnection exhaust at the subsolar magnetopause. These MFRs can be
 358 classified into two distinct categories: coalescing MFRs and non-coalescing MFRs. Our
 359 investigation also involves a comparative assessment of electron acceleration between these two
 360 types of MFRs. The major findings can be summarized as follows:

361 1. MMS observed two MFR coalescences among three MFRs, akin to a rear-end collision where
 362 the faster-moving MFR caught up with the slower one. The first coalescence involved two large-
 363 scale MFRs characterized by a strong core field (Zhou et al., 2017), while the second
 364 coalescence occurred between a large-scale MFR and a small-scale MFR with a relatively
 365 weaker core field.

366 2. Coalescing MFRs generated a higher population of suprathermal electrons compared to non-
 367 coalescing MFRs, consistent with the observed greater acceleration rates within coalescing
 368 MFRs.

369 3. The primary electron acceleration mechanisms differed between the coalescing and non-
 370 coalescing MFRs. In coalescing MFRs, Fermi and E_{\parallel} mechanisms were prominent, with E_{\parallel}
 371 acceleration being the dominant process in non-coalescing MFRs. Notably, in coalescing MFRs,
 372 active E_{\parallel} acceleration was concentrated in the proximity of the reconnection site, and it exhibited
 373 a more localized nature compared to Fermi acceleration. These findings highlight that MFR
 374 coalescence significantly enhances the efficiency of Fermi acceleration due to field line
 375 contraction. Conversely, the relatively weak contraction in non-coalescing MFRs restricts the
 376 effectiveness of Fermi acceleration.

377 4. Although the integrated betatron acceleration rate was negative in both coalescing and non-
 378 coalescing MFRs, it was positive in the merging region between the two large-scale MFRs,
 379 corresponding to the compression of the large core field and enhanced electron flux around a 90°
 380 pitch angle, as previously reported by Zhou et al. (2017).

381

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388

389 **Data Availability Statement**

390 The data used in this study was obtained from the MMS Science Data Center
391 (<https://lasp.colorado.edu/mms/sdc/public/about/browse-wrapper/>).

392

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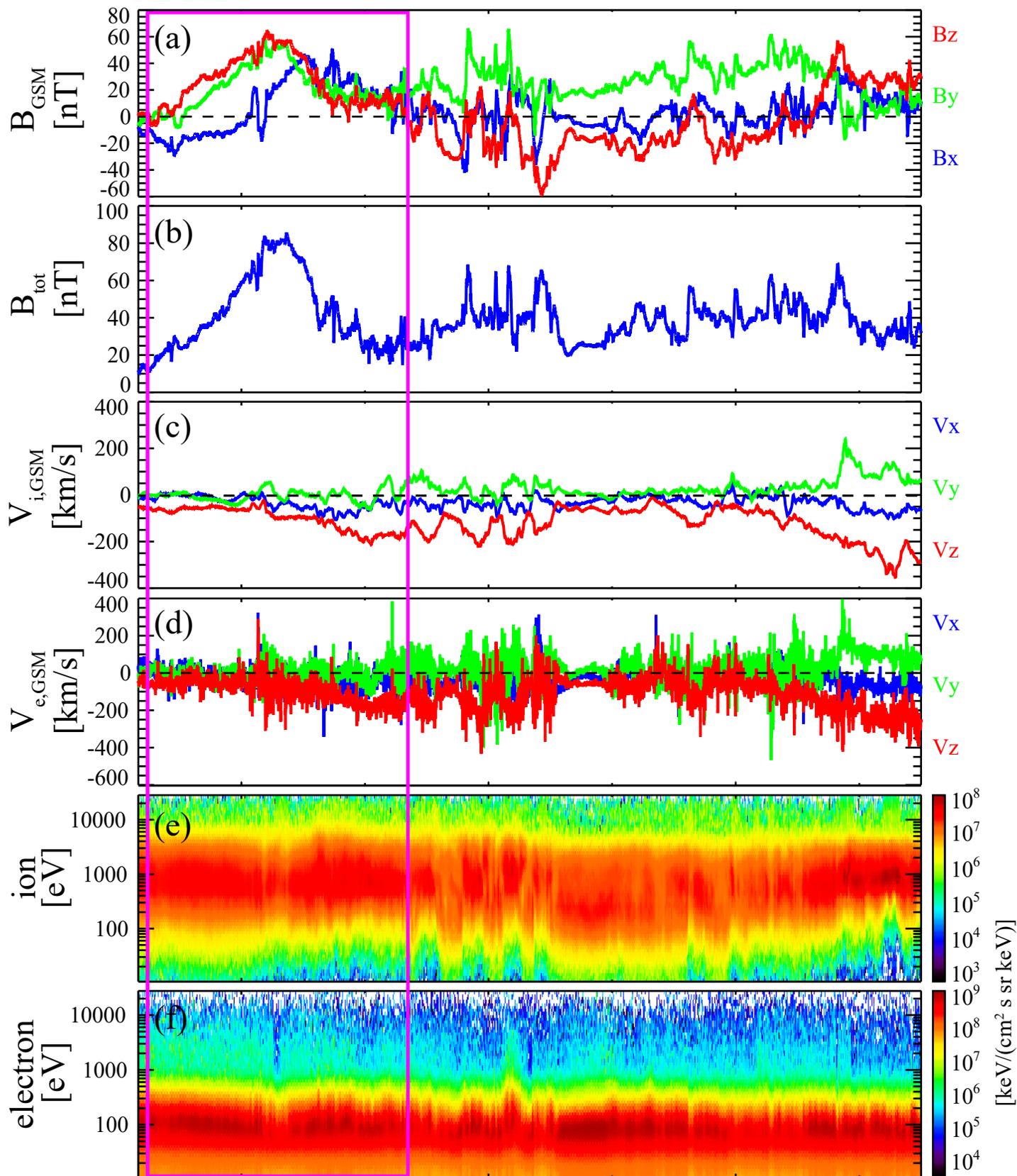
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Figure 1.

MMS2



X_{GSM}	9.7	9.7	9.8
Y_{GSM}	-0.9	-0.9	-0.8
Z_{GSM}	-0.3	-0.3	-0.3
hhmm	0216	0218	0220
2015 Nov 17			

Figure 2.

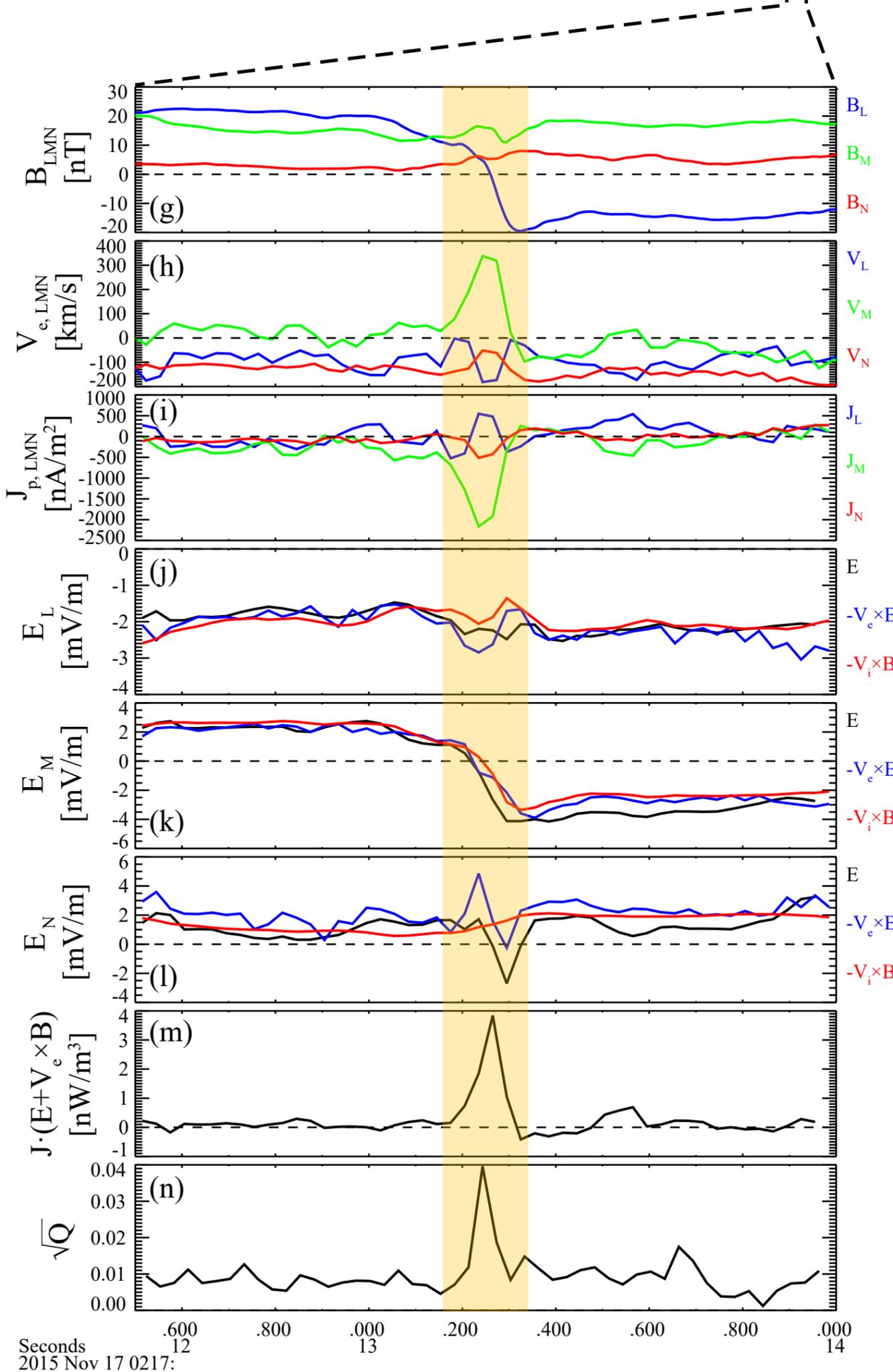
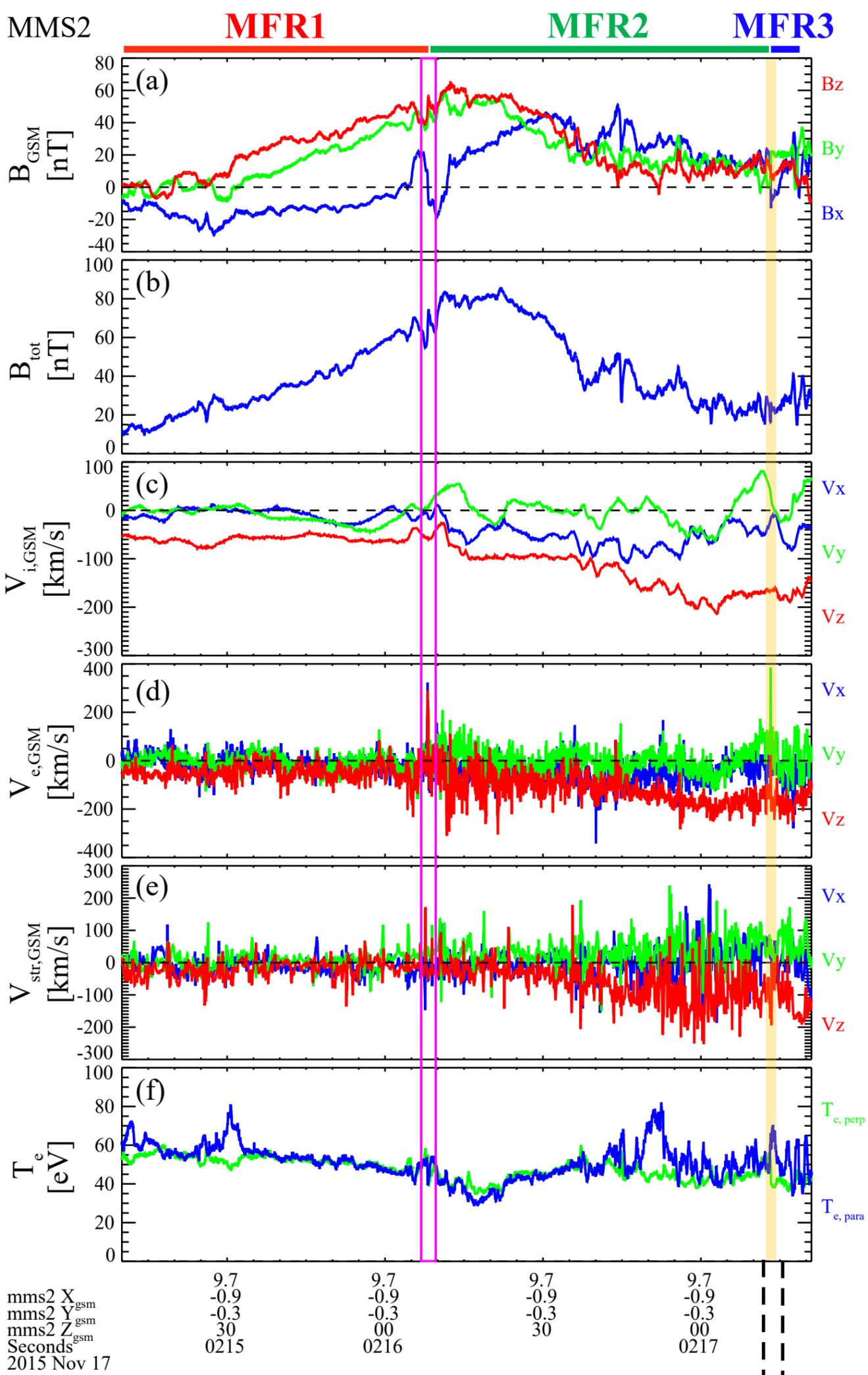
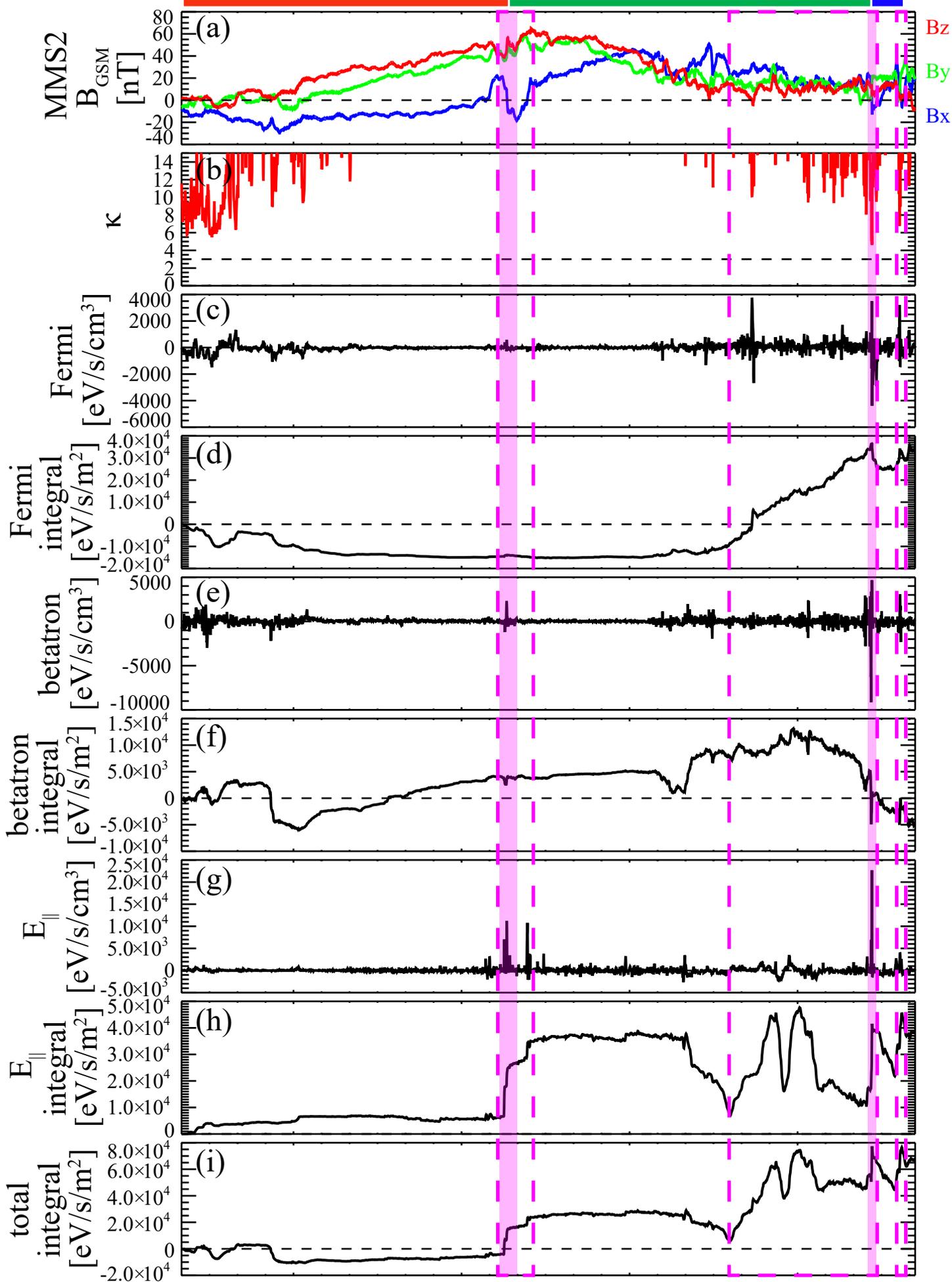


Figure 3.

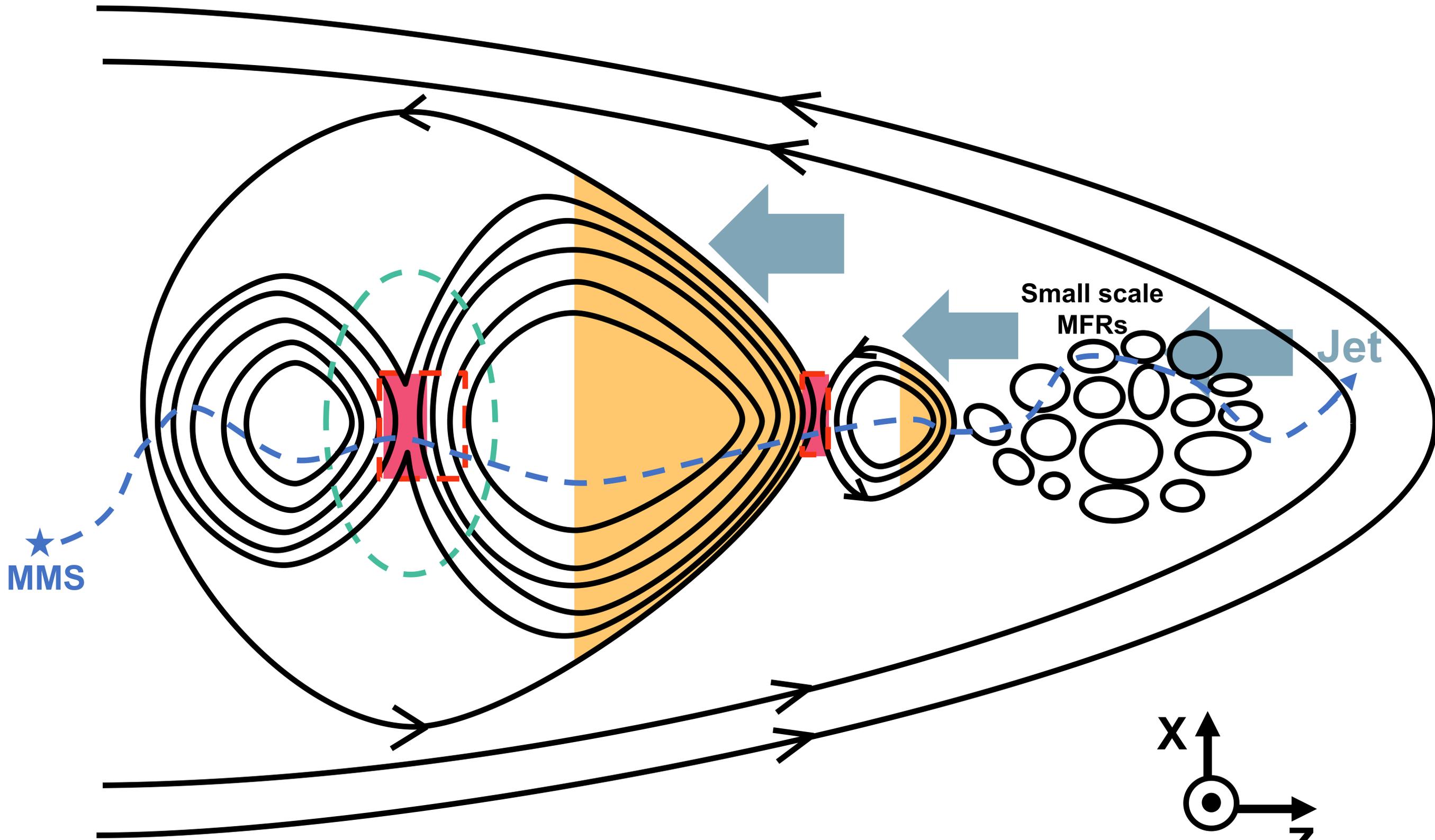
MFR1**MFR2****MFR3**

mms2 X ^{gsm}	9.7	9.7	9.7	9.7
mms2 Y ^{gsm}	-0.9	-0.9	-0.9	-0.9
mms2 Z ^{gsm}	-0.3	-0.3	-0.3	-0.3
Seconds ^{gsm}	30	00	30	00
	0215	0216		0217

2015 Nov 17

Figure 4.

Magnetosheath



Magnetosphere

 : Reconnection region

 : Fermi acceleration region

 : Betatron acceleration region

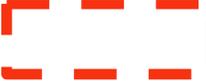
 : E_{\parallel} acceleration region

Figure 5.

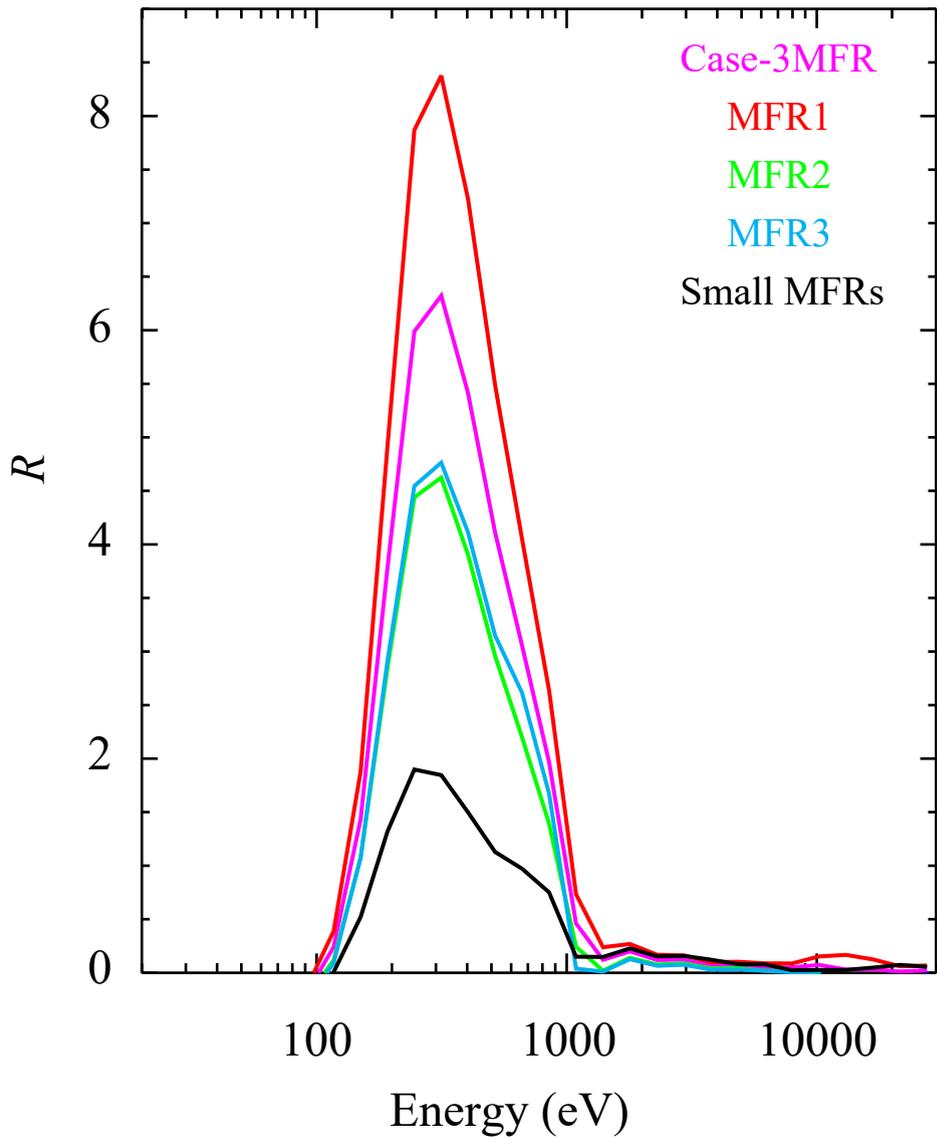


Figure 6.

