

1 **Title : Electron-Scale Dynamics of the Diffusion Region during Symmetric Magnetic**
2 **Reconnection in Space**

3
4 R. B. Torbert^{1,2}, J. L. Burch², T. D. Phan³, M. Hesse^{4,2}, M. R. Argall¹, J. Shuster⁵, R. E. Ergun⁶,
5 L. Alm⁷, R. Nakamura⁸, K. J. Genestreti⁸, D. J. Gershman⁵, W.R. Paterson⁵, D. L. Turner⁹, I.
6 Cohen¹⁰, B. L. Giles⁵, C. J. Pollock⁵, S. Wang¹¹, L.-J. Chen¹¹, J. E. Stawarz¹², J. P. Eastwood¹², K.-
7 J. Hwang², C. Farrugia¹, I. Dors¹, H. Vaith¹, C. Mouikis¹, A. Ardakani¹, B. H. Mauk¹⁰, S. A.
8 Fuselier^{2,13}, C. T. Russell¹⁴, R. J. Strangeway¹⁴, T.E. Moore⁵, J. F. Drake¹¹, M. A. Shay¹⁵, Yuri V.
9 Khotyaintsev⁷, P.-A. Lindqvist¹⁶, W. Baumjohann⁸, F. D. Wilder⁶, N. Ahmadi⁶, J. C. Dorelli⁵, L.
10 A. Avanov⁵, M. Oka³, D. N. Baker⁶, J. F. Fennell⁹, J. B. Blake⁹, A. N. Jaynes¹⁷, O. Le Contel¹⁸, S.
11 M. Petrinen¹⁹, B. Lavraud²⁰, Y. Saito²¹

12
13 **Affiliations:**

14 ¹ University of New Hampshire, Durham, New Hampshire, USA

15 ² Southwest Research Institute, San Antonio TX, USA

16 ³ University of California, Berkeley, USA

17 ⁴ University of Bergen, Norway

18 ⁵ NASA, Goddard Space Flight Center, Greenbelt, Maryland, USA

19 ⁶ University of Colorado Laboratory for Atmospheric and Space Physics, Boulder, Colorado, USA

20 ⁷ Swedish Institute of Space Physics, Uppsala, Sweden

21 ⁸ Space Research Institute, Austrian Academy of Sciences, Graz, Austria

22 ⁹ Aerospace Corporation, El Segundo, California

23 ¹⁰ Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA

24 ¹¹ University of Maryland, College Park, Maryland, USA

25 ¹² Blackett Laboratory, Imperial College London, London, UK

26 ¹³ The University of Texas at San Antonio, San Antonio, Texas, USA

27 ¹⁴ University of California, Los Angeles, Los Angeles, California, USA

28 ¹⁵ University of Delaware, Newark, Delaware, USA

29 ¹⁶ Royal Institute of Technology, Stockholm, Sweden

30 ¹⁷ University of Iowa, Iowa City, Iowa

31 ¹⁸ Laboratoire de Physique des Plasmas, Centre National de la Recherche Scientifique/Ecole

32 Polytechnique/Sorbonne Université/Univ. Paris Sud/Observatoire de Paris, Paris, France.

33 ¹⁹ Lockheed Martin Advanced Technology Center, Palo Alto, California

34 ²⁰ Institut de Recherche en Astrophysique et Planétologie, Centre National de la Recherche

35 Scientifique, Centre National d'Etudes Spatiales, Université de Toulouse, France

36 ²¹ Institute for Space and Astronautical Sciences, Sagami-hara, Japan

37 Japan

38
39 **One Sentence Summary:** NASA's Magnetospheric Multiscale mission detected fast magnetic
40 reconnection and high-speed electron jets in the Earth's magnetotail.

41
42 **Abstract:** Magnetic reconnection is an energy conversion process which occurs in many

43 astrophysical contexts including the Earth's magnetosphere, where the process can be investigated

44 in-situ by spacecraft. We present the encounter of a reconnection site in Earth's magnetotail by the

45 Magnetospheric Multiscale spacecraft, where reconnection involves symmetric inflow conditions.
46 The electron-scale plasma measurements revealed i) super-Alfvénic electron jets reaching 15,000
47 km/s, ii) electron meandering motion and acceleration by the electric field, producing multiple
48 crescent-shaped structures in the velocity distributions, iii) the spatial dimensions of the electron
49 diffusion region with an aspect ratio of 0.1-0.2, consistent with fast reconnection . The well-
50 structured multiple layers of electron populations indicate that, despite the presence of turbulence
51 near the reconnection site, the dominant electron dynamics are mostly laminar.

52
53 **Main Text:** Magnetic reconnection is a large-scale plasma process which converts electromagnetic
54 energy to particle energy, and the dominant mechanism by which solar wind energy enters the
55 Earth’s magnetosphere. This energy is subsequently dissipated by geomagnetic substorms and
56 aurorae (1,2). Although the consequences of reconnection are large scale, the process starts at the
57 small ion-scale, and even smaller, the electron-scale diffusion region (EDR). Studying the physical
58 processes that cause magnetic reconnection requires determining structures and dynamics inside the
59 EDR with sufficiently high resolution plasma and field measurements (3), beyond the capabilities
60 of previous spacecraft missions that have encountered the EDR (4-6).

61 The Magnetospheric Multiscale (MMS) mission focuses on investigating two reconnection regions
62 known to exist around the Earth, the dayside magnetopause and the nightside magnetotail, which
63 host very different plasma parameter regimes. During its first phase (2015-2016), the four MMS
64 spacecraft investigated reconnection in the dayside magnetopause (3), where the inflow conditions
65 are highly asymmetric, with different plasma and magnetic pressures in the two inflow regions. In
66 dayside reconnection, magnetic energy conversion processes occur in two separated regions--the X-
67 line, where the magnetic field reverses, and the electron flow stagnation point (7-8). In its second

68 phase (2017), MMS explored the kinetic processes of reconnection in the Earth's magnetotail where
 69 the inflow conditions are nearly symmetric, the available magnetic energy per particle is more than
 70 an order of magnitude higher than on the dayside, and the X-line and stagnation point are coincident
 71 (9). The amount of magnetic energy per particle in the magnetotail is comparable to that of the solar
 72 corona, where magnetic reconnection also occurs.

73 On 11 July 2017, at ~22:34 Universal Time (UT) MMS encountered an EDR when it
 74 detected tailward-directed ion and electron jets (negative ion and electron bulk velocities, V_{iL} and
 75 V_{eL} , Figures 1f,g) followed by earthward-directed jets, spanning a reversal of essentially the north-
 76 south component of the magnetotail magnetic field B_N (Figure 1d) in an intense current sheet (large
 77 V_{eM} . We adopt an (LMN) coordinate system to orient the data to the usual 2D view of the magnetic
 78 field near a reconnection X-line (Figure 1j), with L in the outflow direction, M along the X-line, and
 79 N normal to the current sheet (I_0). The out-of-plane guide field ratio, B_M/B_L , for this event is
 80 estimated to be small ($< 10\%$) (I_0). The spacecraft were in the magnetotail at a radial distance from
 81 Earth of 22 Earth radii. Four-spacecraft timing of the flow and field reversals indicate that the
 82 structure moved away from Earth with velocity $V_L \sim -170$ km/s. These are signatures of a tailward
 83 retreat of the reconnection X-line past the spacecraft, as indicated by the MMS path in Figure 1j
 84 (5,6,11-16). Except for a brief excursion to the edge of the inflow region, seen in a small
 85 perturbation in magnetic field components beginning at 22:34:00UT (due to a flapping of the current
 86 sheet), the spacecraft stayed close to the neutral sheet ($B_L = 0$ plane), indicated by small values of
 87 $|B_L|$ ($\sim 0-2$ nT), during the flow and field reversal. These observations are consistent with crossing
 88 both ion and electron diffusion regions, an identification which is supported by the profiles of the ion
 89 and electron flows: the out-of-plane electron velocity, V_{eM} , peaked at $\sim -15,000$ km/s, within an order
 90 of magnitude of the electron Alfvén speed ($B/\sqrt{2\mu_0 m_e n_e}$), where m_e and n_e are electron mass and

91 density), approximately 20-25,000 km/s. Starting from the X-line (at the V_{eL} and \mathbf{B} reversal location)
 92 and going left and right in Figure 1h, the electron perpendicular outflow speed $|V_{e\perp L}|$ increased and
 93 greatly exceeded the ion speed. While the ion outflow speed ($|V_{iL}|$, Figure 1f) increased with
 94 increasing distance from the X-line, $|V_{e\perp L}|$ reached a peak ($\sim 7,000$ km/s) before slowing and
 95 approaching the ion flow speed at $\sim 22:33:50$ before, and $\sim 22:34:20$ after, the X-line. Thus, the ends
 96 of the ion diffusion region, where the ion and electron outflow velocities are expected to match, are
 97 encountered likely near these times. The end of the electron diffusion region, on the other hand,
 98 marked by the departure of $V_{e\perp}$ from $\mathbf{E} \times \mathbf{B} / B^2$, was confined to a much smaller interval around the
 99 X-line, where the electron density reached a symmetric minimum of 0.03 cm^{-3} (electron inertial
 100 length, $d_e \sim 30$ km).

101 Figures 2a-j (and 3a-e) display MMS3 data in and around the EDR, again in LMN
 102 coordinates. Figures 2(k-n) show reduced electron distribution functions (DFs) during the strong
 103 reconnecting current (J_M) at times before, and during, the peak of the quantity $\mathbf{J} \cdot \mathbf{E}'$ (where $\mathbf{E}' = \mathbf{E} +$
 104 $\mathbf{V}_e \times \mathbf{B}$), which is the electromagnetic energy conversion rate in the plasma frame, a signature of the
 105 EDR (15). Although $\mathbf{J} \cdot \mathbf{E}'$ is mostly positive throughout the period shown in Figure 2, there are
 106 some regions with negative values, indicating that the electrons are transferring energy to the
 107 electromagnetic field, as seen also in simulations (17-19). Figure 3c shows that, at all spacecraft, the
 108 signs of E_N and B_L were opposite, consistent with E_N converging toward the neutral sheet ($B_L = 0$)
 109 from both hemispheres, as expected for symmetric reconnection with a minimal guide field
 110 (13, 15, 20, 21). MMS2 (and 4) remained below the neutral sheet ($B_L < 0$ and $E_N > 0$) in the vicinity of
 111 the EDR crossing, while MMS1 and 3, located at higher N, made excursions above the sheet, where
 112 $B_L > 0$ and $E_N < 0$. This E_N field accelerates the neutral sheet electrons towards the inflow region

113 where they are accelerated along meandering trajectories (22) by the reconnection field, $E_M \sim 1-2$
 114 mV/m (Figures 3c,e and (10)). The electrons were eventually turned towards the L, or exhaust,
 115 direction by B_N as they exited the EDR, forming the electron jet seen in figures 2c and 3b on either
 116 side of the X-line.

117 The electron temperature profile in panel 2f shows strong anisotropy from 22:34:01.0 to
 118 02.8 due to magnetic field-aligned electrons in the in-flow region (4). During the EDR crossing,
 119 there was only a small rise (few 100eV) in parallel or perpendicular temperature (parallel,
 120 perpendicular pressure divided by n_e), unlike the case of asymmetric reconnection (3), implying that
 121 a substantial fraction of the energy conversion went into the strong electron flows in the M and L
 122 directions.

123 The aspect ratio of the EDR is an approximate measure of the reconnection rate that has not
 124 been determined experimentally but has been studied theoretically and with simulations (4,20,23).
 125 Four-spacecraft timing analysis of the B_N reversal near 22:34:02.2 (see Figure 2a) indicates that the
 126 X-line structure was moving tailward (V_{XL} , L component of the X-line velocity, ~ -170 km/s). The
 127 EDR length can be estimated by multiplying V_{XL} by the $1/e$ width of V_{eM} (~ 3 s, Figure 2c), or by the
 128 $|V_{eL}|$ peak-to-peak time (~ 2 s, Figure 2d), yielding a full length of 350-500 km (12-17 d_e). MMS also
 129 made a brief excursion into the EDR inflow region (beginning at $\sim 22:34:01.0$), indicated by the
 130 increase in $|B_L|$ and confirmed by the cooler electrons (Figure 2b). By 22:34:02.2, the change in B_L
 131 and the timing analysis ($V_{XN} \sim -70$ km/s) show the structure moving southward, giving MMS also a
 132 normal motion into the EDR, reaching the neutral sheet and the peak of the cross-tail current by
 133 22:34:03.0. Using Ampere's Law (10), dividing the change in B_L during this normal motion into the
 134 EDR (Figure 2a, $\sim 22:34:02.0$ to 03.0) by the average of J_M , yields a simple estimate of the normal

135 half-width of 30 km, $\sim 1 d_e$ (10). Thus, the aspect ratio is $\sim 0.1 - 0.2$, implying a reconnection rate
 136 consistent with fast reconnection (24).

137 Multiple crescent and triangular-shaped features in the DF's (Figures 2(k-n) and lower
 138 panels of Figure 3) are the result of electron meandering motion in the electromagnetic field
 139 structure of the EDR. Figure 2l shows a DF taken at a location below (in N) the EDR, which
 140 features multiple crescents, seen as enhanced phase space density at increasing velocities, similar to
 141 predictions (25-27) and shown in Figure 2q from the simulation of Figure 2o (10). Contrary to
 142 magnetopause observations and models (3,28), we find more than one crescent. The observations
 143 show that crescents at higher $V_{\perp 1}$ are broader in $V_{\perp 2}$ than models predict, i.e., particles with a larger
 144 range of $V_{\perp 2}$ bounce twice more than predicted by the model. A likely explanation is that the
 145 current sheet electron distribution is more energetic than in the model, but the distributions may be
 146 sensitive to even a very small guide field (29). Models show that these crescents are generated by
 147 the interaction of bouncing electrons with both the normal (E_N) and the reconnection electric field
 148 (E_M), and their existence is consistent with canonical momentum conservation. The observation of
 149 multiple crescents indicates that the rather complex electron orbits are relatively unperturbed by
 150 high frequency fluctuations in the electromagnetic fields. This implies that turbulent effects, which
 151 would scatter electrons and hence eliminate distinct phase space features like crescents, do not
 152 dominate the particle dynamics in the EDR.

153 Figures 2(m,n) display a second DF, taken near the X point, which features a pronounced
 154 triangular shape in the plane containing B , broader at higher energies. Figure 2n shows two
 155 enhancements at lower $V_{\perp 1}$ (seen at $\pm V_{\perp 2}$, which is within $\sim 20^\circ$ of V_N) corresponding to inflowing
 156 populations from both above and below the X-line. These enhancements are similar to those

157 predicted from the simulation shown in figure 2(o-s). In figure 2m, the triangular shape narrows in
 158 width as the energy increases, which also appears in the simulation (figure 2r). Bouncing electrons
 159 account for this feature: for each bounce, electrons gain successively more energy from acceleration
 160 by the reconnection electric field. If electrons have a finite V_L , they eventually interact with the
 161 magnetic field in the outflow, and are ejected from the immediate vicinity of the X-line. The
 162 acceleration by the reconnection electric field and this ejection explain the triangular shape of the
 163 distribution: only electrons with very small V_L remain near the X point long enough to execute
 164 multiple bounces and be accelerated to higher energies.

165 The electron DFs of Figure 3 (lower panels) show the evolution of the above features as
 166 MMS entered the EDR. From signatures of the inflow region (4), with DFs elongated along B ,
 167 (MMS1 and 2, first column, at 22:34:02.514), the spacecraft, with MMS3 leading, penetrated
 168 farther into the current layer and saw accelerated and gyrating electrons growing in energy as time
 169 (and N position) increased, showing a perpendicular crescent with energy >1 keV (2×10^4 km/s). By
 170 22:34:02.724, all spacecraft were showing the perpendicular crescents, enhanced flow along the
 171 $E \times B$ direction, and also beaming features in the parallel directions. The parallel beams may be
 172 responsible for the high frequency electrostatic noise near the upper hybrid frequency (~ 1200 Hz),
 173 seen at this time in Figure 2i (30). When the spacecraft were fully within the reconnecting current
 174 layer (panel b, 22:34:02.694 -02.757), there were higher energy features rotating into both the $V_{\perp 1}$
 175 ($\sim M$) and the V_{\parallel} directions along with persistent counter-streaming, low energy ($\sim 10,000$ km/s)
 176 field-aligned beams. By 22:34:02.757, MMS3, which was deepest in the EDR, saw very energetic
 177 electrons in $V_{\perp 1}$, and also in the $-V_{\parallel}$ direction: i.e., these accelerated electrons were rapidly leaving
 178 the EDR region. The evolution of many such features can be seen in movie S1.

179 We presented MMS observations of the magnetotail reconnection electron diffusion region,
180 which differs from that on the dayside as it involves symmetric inflow. MMS determined the aspect
181 ratio of the diffusion region (0.1-0.2), which is consistent with simulations of fast reconnection
182 (7,15,17,24). The MMS observations of electron dynamics in the diffusion region match predictions
183 made by one class of theories and models – nearly laminar ones that assume the effects of
184 turbulence and associated fluctuations on the electron dynamics are small. Unlike the magnetopause
185 results (3), we find that electrons can be accelerated up to three successive times by the
186 reconnection electric field- possibly a consequence of longer confinement in the symmetric
187 magnetic structure. Taken together with MMS observations at the magnetopause, these results
188 provide confirmation that reconnection is an efficient mechanism for the release of magnetic
189 energy, for both geomagnetic substorms and auroral phenomena, and also discriminate between
190 competing theories of reconnection. The energy width of the electron crescents differs from model
191 predictions.

192

193

194 **References**

- 195 1. T. Nagai *et al.*, Structure and dynamics of magnetic reconnection for substorm onsets with
 196 Geotail observations, *J. Geophys. Res.* 103,A3(1998) doi:10.1029/97JA02190.
- 197 2. V. Angelopoulos *et al.*, Tail Reconnection Triggering Substorm Onset, *Science* 321 (5891), 931-
 198 935(2008) DOI: 10.1126/science.1160495.
- 199 3. J.L. Burch *et al.*, Electron-scale measurements of magnetic reconnection in space, *Science*
 200 10.1126/science.aaf2939 (2016).
- 201 4. L.J. Chen, *et al.*, Evidence of an extended electron current sheet and its neighboring magnetic
 202 island during magnetotail reconnection, *J. Geophys. Res. Sp. Phys.*, 113(12), 1–19(2008)
 203 doi:10.1029/2008JA013385.
- 204 5. T. I. Nagai, *et al.*, Construction of magnetic reconnection in the near-Earth magnetotail with
 205 Geotail, *J. Geophys. Res.*, 116, A04,222(2011),doi:10.1029/2010JA016283 (2011).
- 206 6. M. Oka, *et al.*, In situ evidence of electron energization in the electron diffusion region of
 207 magnetotail reconnection, *J. Geophys. Res.*, 21(3)(2016), doi: 10.1002/2015JA022040.
- 208 7. J.L. Burch, T.D. Phan, Magnetic Reconnection at the Dayside Magnetosphere: Advances with
 209 MMS, *Geophys. Res. Lett.*, 43(2016), doi:10.1002/2016GL069787(2016).
- 210 8. K.J. Genestreti, *et al.*, The effect of a guide field on local energy conversion during asymmetric
 211 magnetic reconnection: MMS observations, *J. Geophys. Res.: Space Phys.*, 122,
 212 (2017),doi:10.1002/2017JA024247.
- 213 9. P.A. Cassak, M.A. Shay Scaling of asymmetric magnetic reconnection: General theory and collisional
 214 simulations. *Physics of Plasmas*, 14(10), 102114(2007),doi:10.1063/1.2795630.
- 215 10. Materials and methods are available as supplementary material.
- 216 11. M. Øieroset, *et al.*, In situ detection of collisionless reconnection in the Earth's magnetotail, *Nature*,
 217 412, 414–417(2001), doi: 10.1038/35086520.
- 218 12 A. Runov, *et al.*, Current sheet structure near magnetic X-line observed by Cluster, *Geophys. Res.*
 219 *Lett.*, 30, 1579(2003), doi: 10.1029/2002GL016730 (2003).
- 220 13. A.L. Borg *et al.*, Cluster encounter of a magnetic reconnection diffusion region in the near-Earth
 221 magnetotail on September 19, 2003, *Geophys. Res. Lett.*, 32(19), 32–35(2005),
 222 doi:10.1029/2005GL023794.
- 223 14. V. Angelopoulos, *et al.*, Tail reconnection triggering substorm onset, *Science*, 321(5891), 931–
 224 935(2008) , doi:10.1126/science.1168045.
- 225 15. J.P. Eastwood, *et al.*, Average properties of the magnetic reconnection ion diffusion region in the
 226 Earth's magnetotail: The 2001-2005 Cluster observations and comparison with simulations, *J.*
 227 *Geophys. Res.*, 115(A8), A08,215(2010), doi:10.1029/2009JA014962.
- 228 16. D.N. Baker, *et al.*, Timing of magnetic reconnection initiation during a global magnetospheric
 229 substorm onset, *Geophys. Res. Lett.*, 29, 2190(2002), doi:10.1029/2002GL015539,
- 230 17. S. Zenitani, *et al.*, New Measure of the Dissipation Region in Collisionless Magnetic
 231 Reconnection, *Phys. Rev. Lett.* **106**, issue 19 (2011).
- 232 18. M.A. Shay, Kinetic signatures of the region surrounding the X line in asymmetric
 233 (magnetopause) reconnection, *Geophys. Res. Lett.*, 43, 4145–4154(2016), doi:10.1002/
 234 2016GL069034. ^[1]_{SEP}
- 235 19. P.A. Cassak, *et al.*, The effect of a guide field on local energy conversion during asymmetric
 236 magnetic reconnection: Particle-in-cell simulations. *Journal of Geophysical Research: Space*
 237 *Physics*, 122(2017), doi:10.1002/2017JA024555.
- 238 20. Shay, M. A. Et al. Structure of the dissipation region during collisionless magnetic
 239 reconnection, *J. Geophys. Res.*, **103**, A5, 9165-9176 (1998).

- 240 21. J.R.Wygant, *et al.*, Cluster observations of an intense normal component of the electric field at a
 241 thin reconnecting current sheet in the tail and its role in the shock-like acceleration of the ion
 242 fluid into the separatrix region, *J. Geophys. Res.*, 110, A09206(2005), doi:10.1029/
 243 2004JA010708
- 244 22. R. Horiuchi, T. Sato, Particle simulation study of driven magnetic reconnection in a
 245 collisionless plasma, *Physics of Plasmas* 1, 3587 (1994), doi:10.1063/1.870894.
- 246 23. P. A. Sweet, The Neutral Point Theory of Solar Flares. In B. Lehnert (Ed.), *Electromagnetic*
 247 *Phenomena in Cosmical Physics* (Vol. 6, p. 123) (1958).
- 248 24. H.E. Petschek, Magnetic Field Annihilation. *NASA Special Publication*, 50, 425.
 249 Adsabs.harvard.edu/abs/1964NASSP..50..425P(1964).
- 250 25. J. Ng, *et al.*, Kinetic Structure of the Electron Diffusion Region in Antiparallel Magnetic
 251 Reconnection. *Phys. Rev. Lett.*, 106(6), 65002(2011), doi:10.1103/PhysRevLett.106.065002
- 252 26. N. Bessho, N., *et al.*, Electron distribution functions in the electron diffusion region of magnetic
 253 reconnection: Physics behind the fine structures. *Geophysical Research Letters*, 41(24), 8688–
 254 8695(2014), doi:10.1002/2014GL062034
- 255 27. J. R. Shuster, *et al.*, Spatiotemporal evolution of electron characteristics in the electron diffusion
 256 region of magnetic reconnection: Implications for acceleration and heating, *Geophys. Res. Lett.*
 257 **42**, 2586-2593(2015).
- 258 28. M. Hesse, *et al.*, On the electron diffusion region in planar, asymmetric systems. *Geophys. Res.*
 259 *Lett.* **41**, 8673–8680 [SEP](2014).
- 260 29. J. Ng, *et al.*, Phase space structure of the electron diffusion region in reconnection with weak
 261 guide fields, *Physics of Plasma*, 19, 112108 (2012).
- 262 30. W.M. Farrell, *et al.*, The role of upper hybrid waves in magnetic reconnection, *Geophys. Res.*
 263 *Lett.*, 30(24)(2003), 2259, doi:10.1029/2003GL017549.
- 264 31. M Hesse, *et al.*, [The Physical Foundation of the Reconnection Electric Field](#), *Phys. Plasmas*, 25,
 265 032901 (2018); doi: 10.1063/1.5021461
- 266 32. Dunlop, M. W., *et al.*, Analysis of multipoint magnetometer data, *Adv. Sp. Res.*, 8(9-10), 273–277,
 267 doi:10.1016/0273-1177(88)90141-X (1988).

269
 270

271 Acknowledgements

272
 273

The dedicated efforts of the entire MMS team are greatly appreciated. We are especially
 274 grateful to the leadership of the GSFC Project Manager, the late Craig Tooley, his Deputy, Brent
 275 Robertson, and the SwRI Payload Project Manager, Ron Black.

276 Funding

277 This work was supported by NASA prime Contract No. NNG04EB99C at SwRI, by STFC(UK)
 278 grant ST/N000692/1, by CNES, CNRS-INSIS and CNRS-INSU in France, by the Austrian
 279 Research Promotion Agency FFG, by NASA Grant NNX14AC78G at the University of Maryland,

280 by NASA grant NNX08A083G-MMS IDS at the University of California and the University of
281 Delaware, and by the Swedish National Space Board.

282

283

284 Author contributions

285 Analysis and writing were contributed by (RBT,JLB,TDP,MH,MRA), analysis by

286 (JS,REE,LA,RN,KJG,DLT,SW,LJC,JES,JPE,KJH,CF,ID,CM,AA,CTR,RJS,TEM,JFD,MAS,YVK,

287 MO,ANJ,SMP), electric field data by (RBT,REE,HV,PAL,YVK,FDW,NA), plasma data by

288 (DJG,WRP,BLG,CJP,LJC,SAF,JCD,LAA,BL,YS), magnetic field data by

289 (CTR,RJS,WB,OLC,HV,RBT), and energetic particle data by (DLT,IC,BHM,DNB,JFF,JBB,ANJ).

290 **Data and Materials Availability**

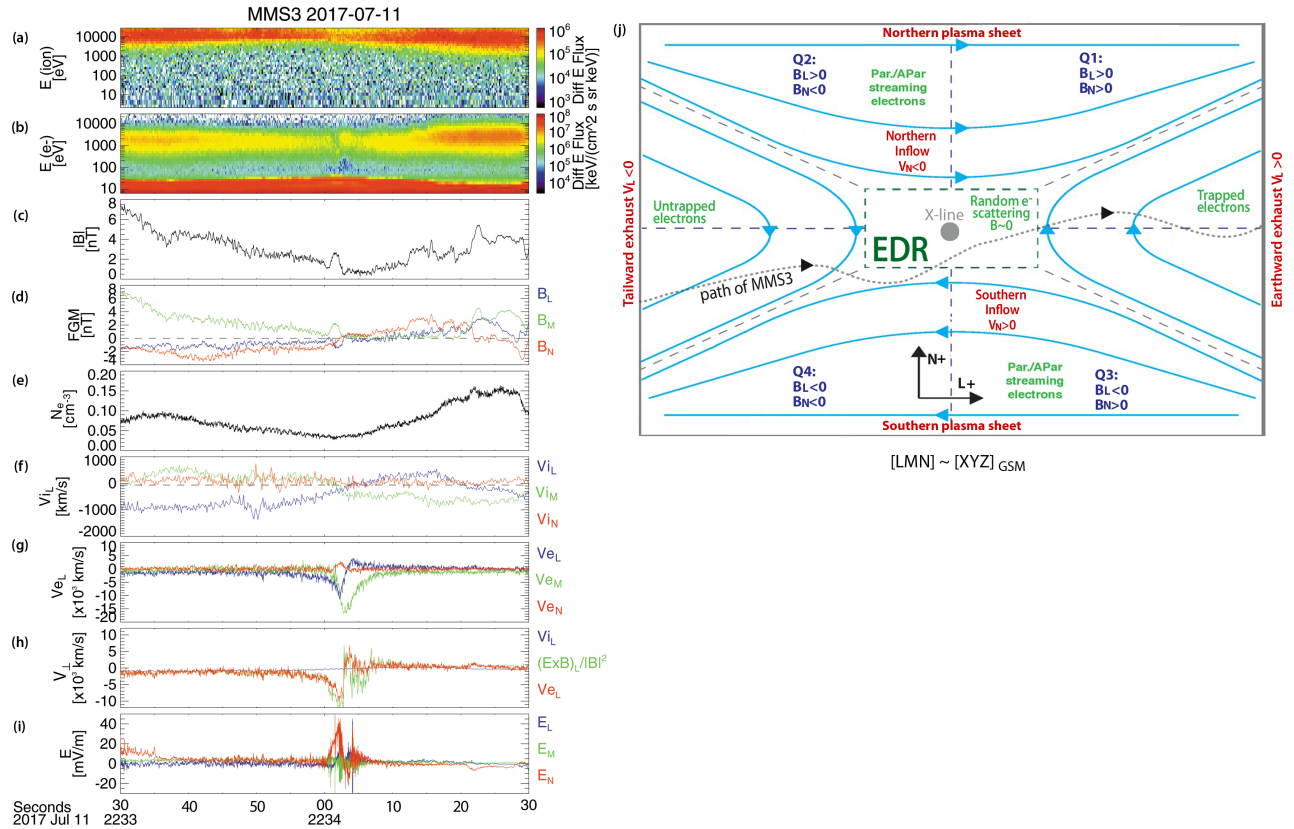
291

292 All data from MMS are archived at <https://lasp.colorado.edu/mms/sdc/public/links/>, We used

293 data from the period of 22:29 to 22:37 UT on July 11, 2017, modified as described in (10).

294

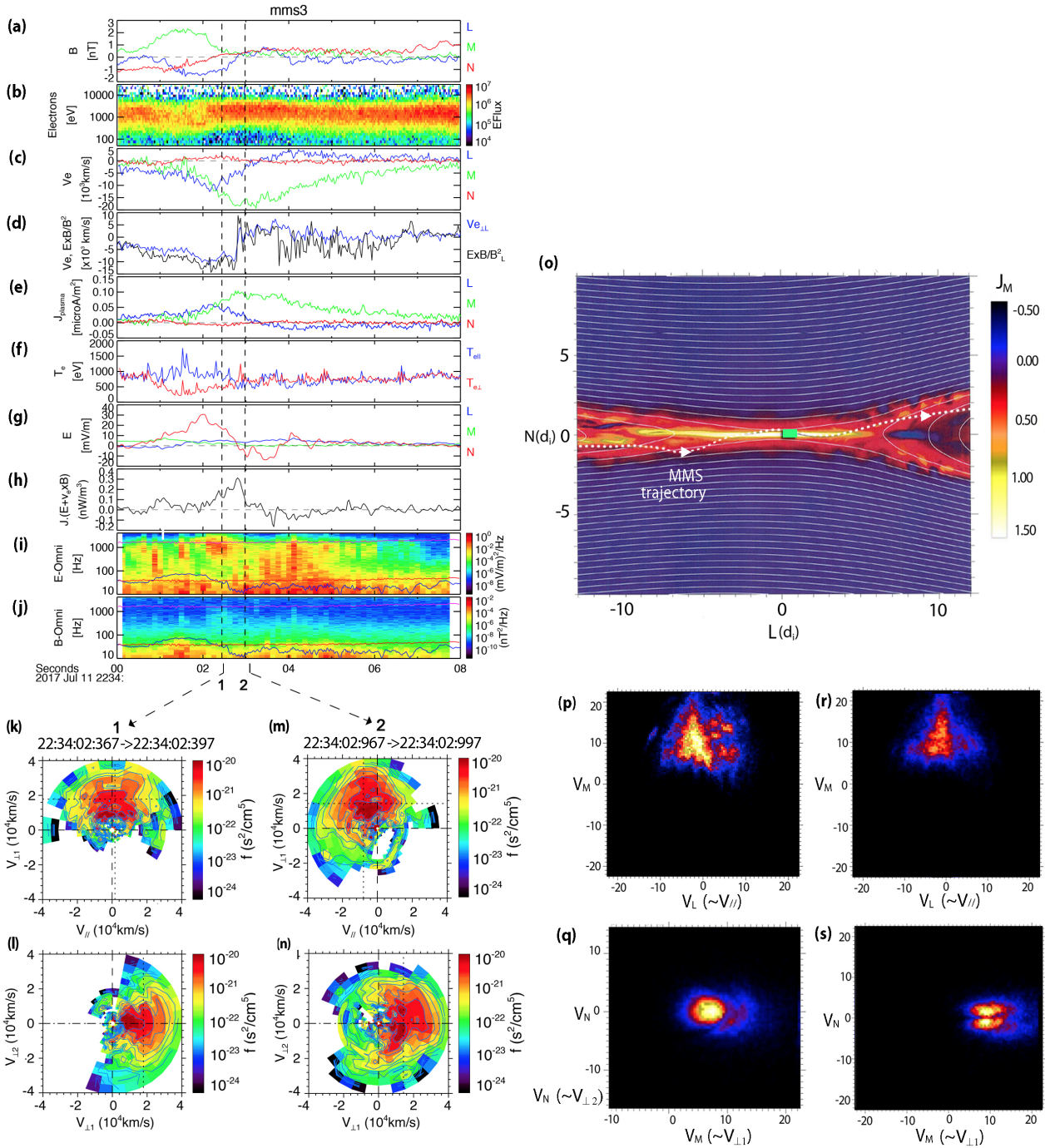
295 **Figures**
 296



297
 298 **Figure 1. MMS3 summary data near the crossing of the EDR at 223403 on 2017 July 11. (a,b)**
 299 energy-time spectrograms of ion and electron energy flux, respectively; (c) magnetic field
 300 magnitude, and (d) components in the LMN coordinate system, which is very close to the usual
 301 Geocentric Solar Magnetospheric (GSM) system (10); (e) electron density; (f) ion bulk velocity
 302 vector; (g) electron bulk velocity vector; (h) the L-component of ion and electron flow
 303 perpendicular to \mathbf{B} , and of $\mathbf{E} \times \mathbf{B} / B^2$; (i) \mathbf{E} , electric field; (j) an illustration of a typical symmetric
 304 EDR in the LMN coordinate system, and the expected properties in various quadrants (Q), together
 305 with the inferred relative path of the MMS satellites as the X-line retreated tailward.

306

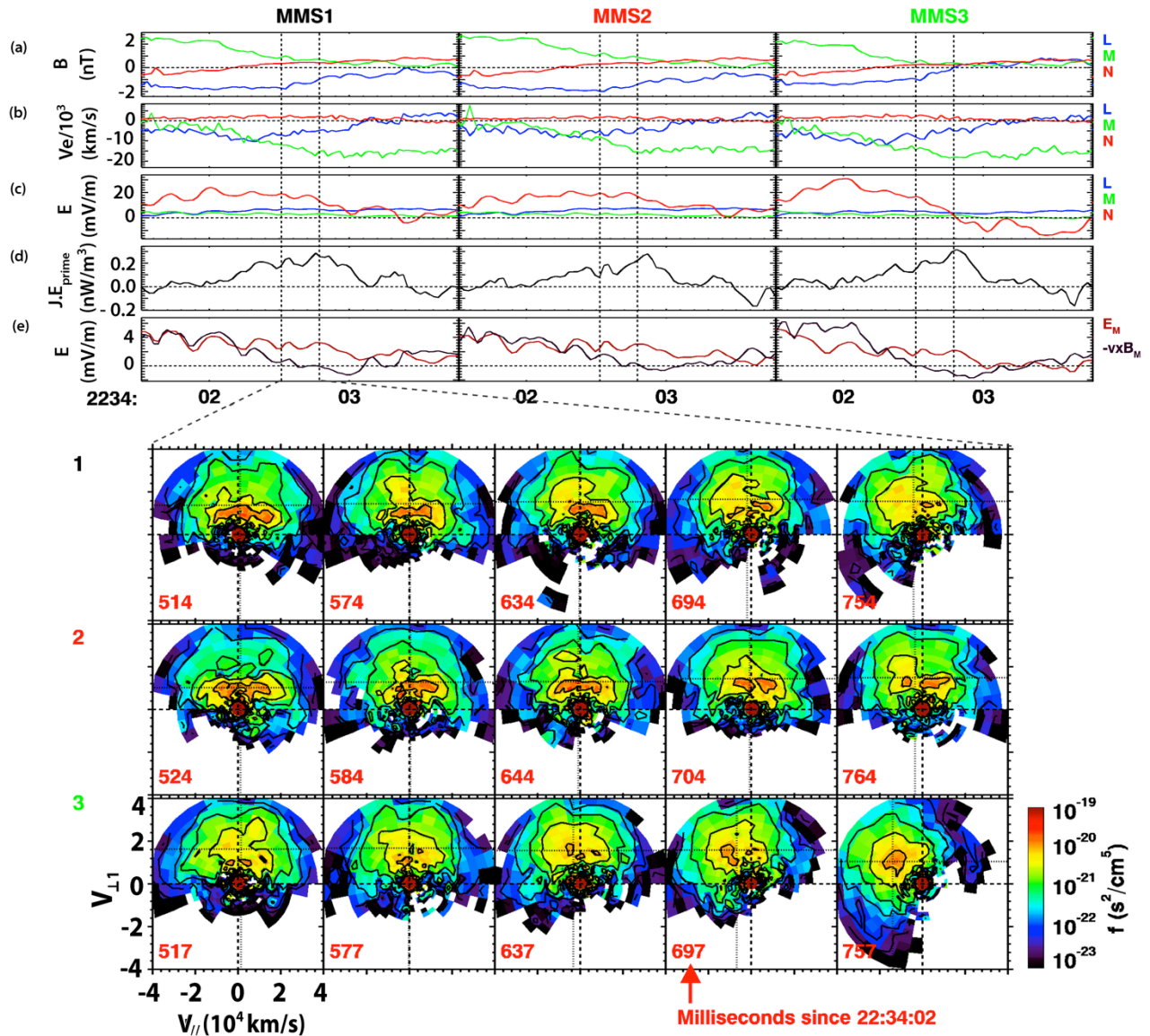
307



310 **Figure 2. MMS3 plasma and field data for 8s from Figure 1 on 2017 July 11. Panel (a)**

311 **Magnetic field components in LMN coordinate system; (b) electron omni-directional**

312 spectrogram, with minimum energy set at 50eV to avoid the lower energy spacecraft
 313 photoelectrons seen in Figure 1b; (c) electron bulk velocity; (d) L components of $\mathbf{V}_{e\perp}$ and
 314 $\mathbf{E}\times\mathbf{B}/B^2$; (e) Current from plasma measurements; (f) $T_{e\parallel}$ and $T_{e\perp}$; (g) Electric field; (h) $\mathbf{J}\cdot\mathbf{E}'$;
 315 (electric (i), magnetic (j)) omni-directional frequency spectrograms, showing the power
 316 spectral density of electric or magnetic field fluctuations; (k,l,m,n) electron velocity
 317 distribution functions at the times indicated, $V_{\perp 1}$ is $(\mathbf{b}\times\mathbf{v})\times\mathbf{b}$, where \mathbf{b} and \mathbf{v} are unit vectors of
 318 \mathbf{B} and \mathbf{V}_e ; $V_{\perp 2} = \mathbf{v}\times\mathbf{b}$; and V_{\parallel} is the parallel electron velocity. $V_{\perp 1}$ is essentially the $\mathbf{E}\times\mathbf{B}$
 319 direction and the bulk flow component in that direction is indicated by the dashed vertical
 320 lines; (o) Magnetic configuration of a computer simulation (10), with color-coded reconnection
 321 current (J_M) and the inferred MMS trajectory overlain; (p,q,r,s) Reduced distribution f_e near the
 322 green box in (o) from that simulation, with velocity axes (in ion Alfvén speed units) corresponding
 323 to those of the data in panels k-n. The color code is the same as panel (o), but with simulation units
 324 representing phase space density, like those of panels (k-n).
 325
 326
 327
 328



329
 330 **Figure 3. Field data and electron DFs for three MMS spacecraft on 2017 July 11, for ~2**
 331 **seconds around the EDR.** Upper panels, for each spacecraft: (a) components of \mathbf{B} ; (b) Electron
 332 bulk velocity; (c) \mathbf{E} , where the reversal in E_N is seen on MMS3 and briefly MMS1, but not MMS2
 333 ; (d) $\mathbf{J} \cdot \mathbf{E}'$; (e) M-component of \mathbf{E} and $-(\mathbf{V}_e \times \mathbf{B})$; Lower panels, from 2.604s to 2.784s are the
 334 reduced (summed over $V_{\perp 2}$) electron 30ms DFs in $(V_{||}, V_{\perp 1})$ for each spacecraft at the times
 335 between the dotted lines in the upper panels.

336 **Supplementary Materials**

337 Materials and Methods

338 Figures S1 - S4

339 Movie S1



Supplementary Materials for

Electron-Scale Dynamics of the Diffusion Region during Symmetric Magnetic Reconnection in Space

R. B. Torbert^{1,2}, J. L. Burch², T. D. Phan³, M. Hesse^{4,2}, M. R. Argall¹, J. Shuster⁵, R. E. Ergun⁶, L. Alm⁷, R. Nakamura⁸, K. J. Genestreti⁸, D. J. Gershman⁵, W.R. Paterson⁵, D. L. Turner⁹, I. Cohen¹⁰, B. L. Giles⁵, C. J. Pollock⁵, S. Wang¹¹, L.-J. Chen¹¹, J.E. Stawarz¹², J. P. Eastwood¹², K.-J. Hwang², C. Farrugia¹, I. Dors¹, H. Vaith¹, C. Mouikis¹, A. Ardakani¹, B. H. Mauk¹⁰, S. A. Fuselier^{2,13}, C. T. Russell¹⁴, R. J. Strangeway¹⁴, T.E. Moore⁵, J. F. Drake¹¹, M. A. Shay¹⁵, Yuri V. Khotyaintsev⁷, P.-A. Lindqvist¹⁶, W. Baumjohann⁸, F. D. Wilder⁶, N. Ahmadi⁶, J. C. Dorelli⁵, L. A. Avanov⁵, M. Oka³, D. N. Baker⁶, J. F. Fennell⁹, J. B. Blake⁹, A. N. Jaynes¹⁷, O. Le Contel¹⁸, S. M. Petrinec¹⁹, B. Lavraud²⁰, Y. Saito²¹

Affiliations:

¹ University of New Hampshire, Durham, New Hampshire, USA

² Southwest Research Institute, San Antonio TX, USA

³ University of California, Berkeley, USA

⁴ University of Bergen, Norway

⁵ NASA, Goddard Space Flight Center, Greenbelt, Maryland, USA

⁶ University of Colorado Laboratory for Atmospheric and Space Physics, Boulder, Colorado, USA

⁷ Swedish Institute of Space Physics, Uppsala, Sweden

⁸ Space Research Institute, Austrian Academy of Sciences, Graz, Austria

⁹ Aerospace Corporation, El Segundo, California

¹⁰ Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA

¹¹ University of Maryland, College Park, Maryland, USA

¹² Blackett Laboratory, Imperial College London, London, UK

¹³ The University of Texas at San Antonio, San Antonio, Texas, USA

¹⁴ University of California, Los Angeles, Los Angeles, California, USA

¹⁵ University of Delaware, Newark, Delaware, USA

¹⁶ Royal Institute of Technology, Stockholm, Sweden

¹⁷ University of Iowa, Iowa City, Iowa

¹⁸ Laboratoire de Physique des Plasmas, Centre National de la Recherche Scientifique/Ecole Polytechnique/Sorbonne Université/Univ. Paris Sud/Observatoire de Paris, Paris, France.

¹⁹ Lockheed Martin Advanced Technology Center, Palo Alto, California

²⁰ Institut de Recherche en Astrophysique et Planétologie, Centre National de la Recherche Scientifique, Centre National d'Etudes Spatiales, Université de Toulouse, France

²¹ Institute for Space and Astronautical Sciences, Sagami-hara, Japan

Japan

Correspondence to: roy.torbert@unh.edu

This PDF file includes:

Materials and Methods
Supplementary Text
Figs. S1 to S4
Captions for Movies S1.

Other Supplementary Materials for this manuscript include the following:

Movies S1.

Materials and Methods

Location and Configuration of MMS at 22:34:00 UT on 11 July 2017.

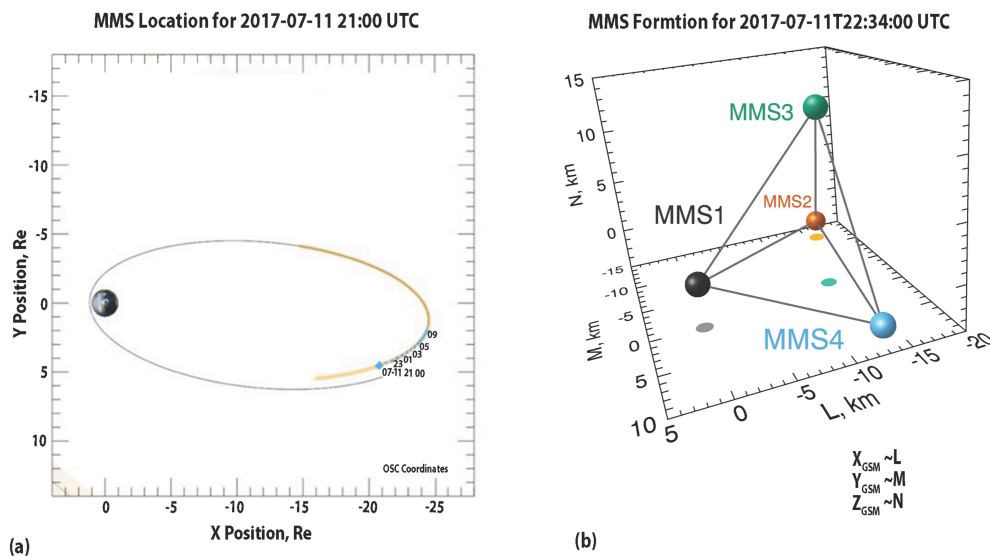


Fig- S1. Location and Configuration of MMS at 22:34:00 UT on 11 July 2017. Panel (a) shows an ecliptic-plane projection of the MMS orbit in geocentric-solar-ecliptic (GSE, nearly inertial) coordinates on 2017 July 11. Times in the orbit are labeled in UT, starting at 21:00. Between 21:00 and 22:00 on this date, mild magnetospheric substorm activity began in the magnetotail. The beige area is the MMS region of interest where high resolution data are taken. **Panel (b)** shows the MMS spacecraft tetrahedral formation in an LMN coordinate system which is very close to the GSM (Geocentric Solar Magnetospheric) coordinates that are typically used to display data in the magnetotail: **X** towards Sun; **Y** perpendicular to Earth’s magnetic dipole and **X**, pointing towards dusk; and **Z** = **X** x **Y**.

The LMN coordinate system for the EDR encounter was established by first determining **N** in the direction of the maximum directional derivative in **B** at 22:34:02s, then determining the **M** vector perpendicular to this **N**, which maximizes the magnitude of the reconnecting current, as seen in Figure 2e, and **L** then is given by $\mathbf{N} \times \mathbf{M}$. For this event, [L;M;N] in GSE coordinates are

[0.971, 0.216, -0.106; -0.234, 0.948, -0.215; 0.054, 0.233, 0.971] and, in GSM coordinates, [0.971, 0.219, -0.098; -0.234, 0.956, -0.180; 0.054, 0.197, 0.979]. The LMN unit vectors are all within ~ 15 degrees of the GSM unit vectors, with $X_{\text{GSM}} \sim L$; $Y_{\text{GSM}} \sim M$; and $Z_{\text{GSM}} \sim N$, as indicated in the figure. An LMN system can be determined in many different ways, and the several that have been applied for this case are all somewhat similar to the above, but vary by 5-10 degrees. This has a large impact on only one quantity, E_M . Figure 3c shows a normal electric field, E_N , ~ 30 mV/m, whereas E_M (in figures 2g, 3c, and 3e) is ~ 1 -2 mV/m. Thus, a change in the N-M axes by only 4 degrees can change E_M by 100%. Due to this fact and the underlying uncertainty of the electric field measurement of ~ 1 mV/m, an estimate of the reconnection rate from the value of E_M is not reliable. Therefore, we have relied on the scalar quantity, $\mathbf{J} \cdot \mathbf{E}'$ (figures 2h and 3d), which shows that electromagnetic energy is being converted to plasma energy, independent of a particular LMN system.

Guide field (B_M/B_L) estimation

Ideally, the guide field would be determined from the relative angle between the magnetic fields of the two inflow regions. However, this could not be done because MMS did not encounter both lobe regions near the time of X-line crossing. However, it is possible to obtain an estimate of the guide field for this event. The lobe-like magnetic field $|B_L|$ (near 22:31 UT, shown in Figure S2) was ~ 13 nT, and $|B|$ in the EDR was as low as 0.4 nT (Figure 1c, and in Figure 3(a) at $\sim 22:34:02.8$ for MMS3), which implies that the guide field B_M was of the order of 0.4 nT, but may be somewhat higher due to the effects of the Hall magnetic field. Thus, the normalized guide field $|B_M|/|B_L|$ may be $\sim 4\%$, but certainly less than 10%.

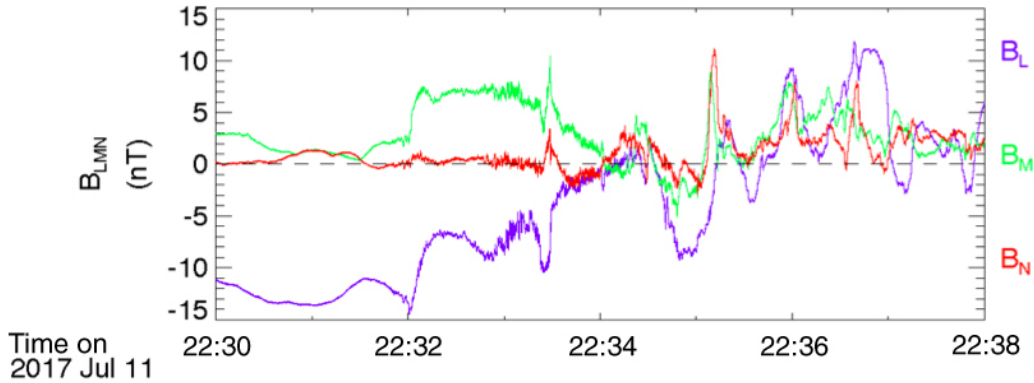


Fig-S2: Magnetic field components in LMN coordinates. Coordinates for this plot were determined using a longer interval (22:31:00 – 22:34:00 UT) than those in the main text. Because of the flapping motion of the current sheet (see in B_L variations) in this interval, the LMN coordinate system is only approximate for data over this long interval.

Computation Details and Calibration Corrections

The ion velocities in figure 1f have been corrected for the fact that the fast plasma instrument (FPI) does not cover a sufficient energy range to account for high energy ion phase space when the ion temperature is greater than about 10 keV, as seen in figure 1a. Comparisons over 5 minutes around 22:34:00 with the other ion spectrometer, the Hot Plasma Composition Analyzer, which goes to higher energies, and with the $\mathbf{E} \times \mathbf{B} / B^2$ velocity show that, during the interval of figure 1, a correction by multiplying the MMS Science Data Center (SDC) data repository values for FPI by a factor of 2, gives values of V_{ion} that are accurate to within about 20%. In addition, the low density of this EDR encounter resulted in spacecraft potential values greater than 50V. The local photoelectrons from the spacecraft can therefore be seen in figure 1b,

at energies below this value. These electrons were removed in the data of figure 2b by plotting energies only greater than 50eV, and in the computation of the DFs in figures 2 and 3. This same high spacecraft potential affects the offsets of the axial electric field sensor, which then drifts on time scales ~ 10 seconds, the same time scale as the electron density in figure 1e. With running medians over 8 seconds, the offsets of the median electric field were recalibrated to agree with the median of $-\mathbf{V}_e \times \mathbf{B}$. The electric field was low-pass filtered with a 3 dB point of 8 Hz to correspond to the approximate time dependence of the electron moments.

Using plasma moments, the time profiles of the current peak, from 22:34:01.8 to $\sim 22:34:04.0$ in Figure 2e are nearly identical for all four spacecraft, and agree with the curlometer calculation (32) of the current from the four spacecraft (\mathbf{J}_{curl}) at the barycenter of the MMS tetrahedron, except that \mathbf{J}_{curl} is a constant fraction (0.8) of the plasma \mathbf{J} . Because all the profiles are the same in time, the current width must have been greater than the spacecraft separation (~ 15 km). The factor of largest uncertainty is the electron density, which therefore is adjusted to be 0.8 of the SDC value in the calculations below.

A more detailed estimate of the normal half-width of the EDR follows from Ampere's Law:

$$\mu_0 J_M = (\text{curl}(\mathbf{B}))_M = (\partial_N B_L - \partial_L B_N).$$

where ∂_N is the partial derivative in the N direction. In our case, B_N is small compared to the other components, and $\partial_L B_N$ even smaller, so we ignore this term. We can thus compute the N position as an integral,

$$N = \int \frac{dB_L}{\mu_0 J_M}$$

over ~ 1 second from both the rise of the cross-tail current and the appearance of accelerated electrons ($\sim 22:34:02.0$, Figures 2e,b) to the midplane crossing (i.e. neutral sheet and also current

maximum) at 22:34:03.0. This gives a value of 25 km, a little less than the simple division in the main text. A less reliable estimate follows from timing. As mentioned above, the timing analysis at 22:34:02.2s shows the structure with a normal velocity $V_{XN} \sim -70$ km/s, but then falls to zero by 22:34:03.0. An average of these two normal velocities (35 km/s), multiplied by the time elapsed above, ~ 1 s, yields an estimate of the EDR normal half-width of ~ 35 km. We therefore place bounds on this normal width ranging from greater than 15 km (from current profiles) to a higher estimate of 35 km, from timing, with the two estimates from Ampere's Law, 25-30 km, falling in the middle. We have adopted the simple Ampere value of 30 km for the half-width.

Simulation parameters

The 2D Particle-In-Cell (PIC) simulation shown in figures 2o-r was computed over 3200×3200 grid, a mass ratio $m_i/m_e=100$, and 7×10^{10} particles, of the simulation type described with complete details in (31). The initial configuration is a Harris current sheet, with a customary superposed X-type perturbation and a background density of 0.2 in both inflow regions. The ion-electron temperature ratio is 5, and the initial temperature is constant throughout the modeled system. The actual locations of the DFs from this simulation in Figure 2 are: (L=-0.5, N=0.1 for (p,q) and L= 0.5 ,N=0 for (r,s)).

Supplementary Text

Reconnection Topology

The topology of the field lines around the EDR is confirmed by examining pitch angle distributions of the (very) energetic electrons (40-130 keV, Figure S3). These data cover 40 seconds around the EDR, which is clearly prominent in the electron velocity peak in Fig. S3 (c). At 22:34:07UT, just Earthward of the EDR, MMS3 detected a burst of energetic electrons in the anti-parallel direction, presumably accelerated in the reconnection process and streaming out along the separatrices. This would be consistent with the return of MMS3 below the neutral sheet on the earthward side of the EDR. Later and further into the exhaust, these electrons are seen filling in the pitch angles (although with enhanced fluxes in the anti-parallel direction) and are now trapped in the Earthward extent of the magnetic field. Tailward of the EDR, before 22:34:00, these electrons are not visible, indicating that they had escaped along field lines connected at both ends to the solar wind. This is evidence of magnetic reconnection on-going at the EDR, and the ability of the reconnection process to accelerate electrons to very high energies, as seen in reconnection in solar flares.

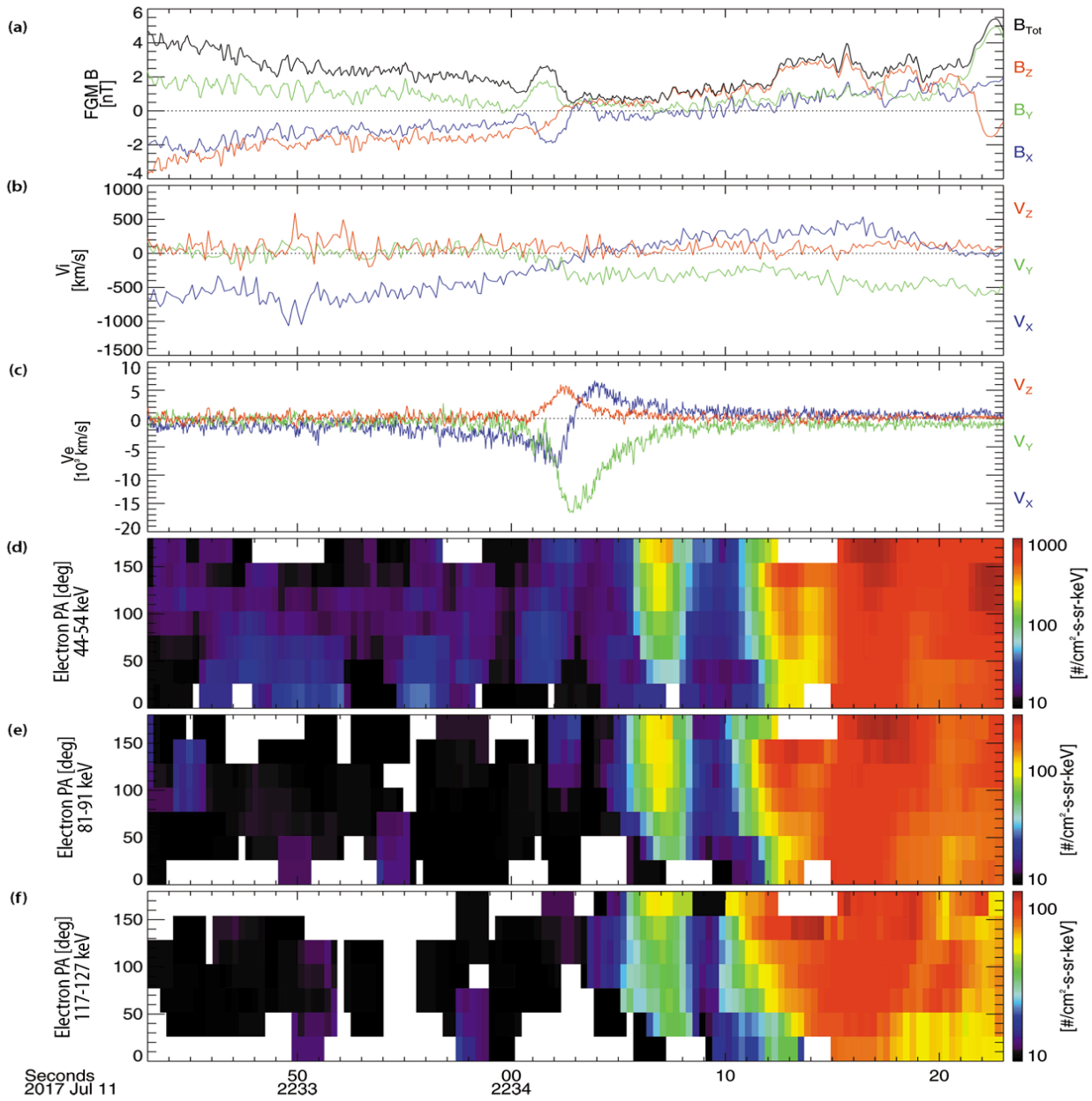


Fig-S3. MMS3 Energetic Particle and Magnetic Fields. Magnetic field (a), ion (b) and electron (c) velocities, and electron pitch-angle distributions (d-f) for three selected high energies.

Movie S1.

Electron Velocity-space Distributions. A 6-second segment of burst-mode electron distributions is keyed to a plot of plasma and field data covering the same time period as Figure 2, but from all MMS spacecraft. These distributions are accumulated over four 30ms electron distribution functions to bring out detailed features when the density is as low as 0.03cm^{-3} , as in this case. The velocity axes are in the same LMN coordinate system as described above. Figure S4 shows one pane from the animated Movie S1.

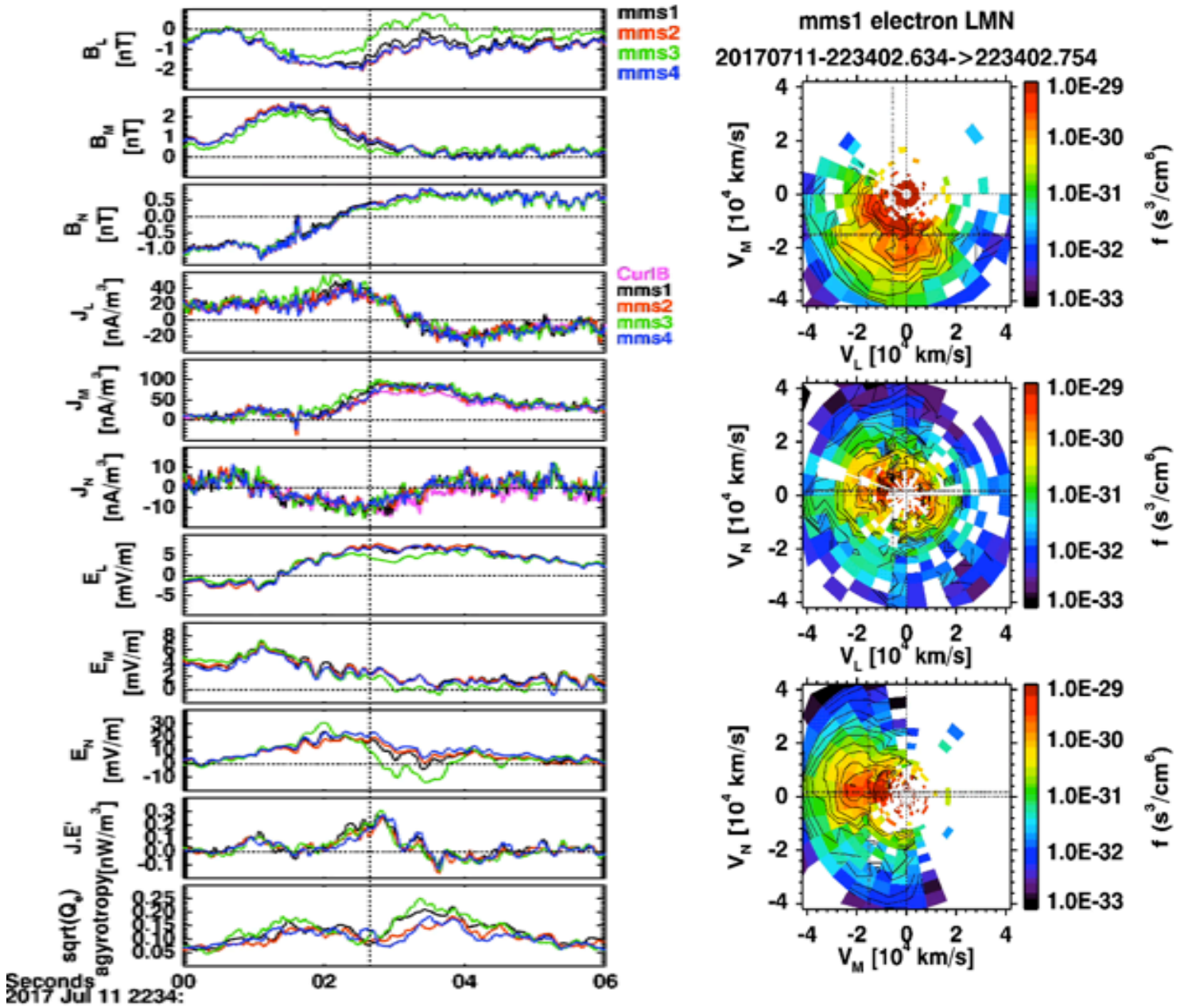


Figure S4, one pane of Movie S1. In the left panel, the time history (from top to bottom) of: B_L , B_M , B_N , J_L , J_M , J_N , E_L , E_M , E_N , $J \cdot E'$, and the Swisdak agyrotropy index, a numerical index indicating agyrotropic features like crescents, for all four spacecraft. The right panel shows the first of four columns (that for MMS1, which is repeated for the other three spacecraft, MMS2-4) that shows the reduced electron distributions for each spacecraft along the indicated LMN velocities at the time of the vertical dash line in the left panel.