Lower hybrid drift waves driving electron nongyrotropic heating and vortical flows in a magnetic reconnection layer

L.-J. Chen[1], S. Wang[1,2], O. Le Contel[3], A. Rager[1], M. Hesse[4], J. Drake[2], J. Dorelli[1], J. Ng[1,2], N. Bessho[1,2], D. Graham[5], L. B. Wilson III[1], T. Moore[1], B. Giles[1], W. Paterson[1], B. Lavraud[6], K. Genestreti[7], R. Nakamura[8], Yu. V. Khotyaintsev[5], R. E. Ergun[9], R. B. Torbert[7], J. Burch[10], C. Pollock[11], C. T. Russell[12], P.-A. Lindqvist[13], L. Avanov[1,2]

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[2]University of Maryland, College Park, Maryland, USA
[3]CNRS/Ecole Polytechnique/Sorbonne Université/Univ. Paris Sud/Observatoire de Paris, Paris, France
[4]University of Bergen, Bergen, Norway
[5]Swedish Institute of Space Physics, Uppsala, Sweden
[6]Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse (UPS), CNRS, CNES, Toulouse, France
[7]University of New Hampshire, Durham, New Hampshire, USA
[8]Space Research Institute, Austrian Academy of Sciences, Graz, Austria.
[9]University of Colorado, Boulder, Colorado, USA
[10]Southwest Research Institute, San Antonio, TX, USA
[11]Denali Scientific, Healy, AK, USA
[12]University of California, Los Angeles, Los Angeles, California, USA
[13]KTH Royal Institute of Technology, Stockholm, Sweden

Abstract

We report measurements of lower-hybrid drift waves driving electron heating and vortical flows in an electron-scale reconnection layer under a guide field. Electrons accelerated by the electrostatic potential of the waves exhibit perpendicular and nongyrotropic heating. The vortical flows generate magnetic field perturbations comparable to the guide field magnitude. The measurements reveal a new regime of electron-wave interaction and how this interaction modifies the electron dynamics in the reconnection layer.

The lower hybrid drift instability (LHDI) is thought to be effective in plasma transport [e.g. 1-5], heating [6-7], and current dissipation [8-10] in systems where binary collisions are unimportant. It is driven by currents across the magnetic field in inhomogeneous plasmas [10]. During magnetic reconnection as the stored magnetic energy is released [11-12], both cross-field currents and spatial inhomogeneities are particularly strong in the core region of reconnection characterized by an intense electron current layer [13-16]. This region is referred to as the electron-scale reconnection layer. Such an environment is in principle conducive to the LHDI.

The role of LHDI in the electron-scale reconnection layer has not been experimentally established. The LHDI is widely considered to be important in magnetic reconnection by theories and simulations (see review by Fujimoto et al. [17]). However, detecting the LHDI in the electron-scale reconnection layer is highly challenging. Earlier laboratory [18-19] and space [20-21] measurements have only observed waves produced by the LHDI at the outer edge of the ion-scale reconnection current layers. One laboratory work showing waves in the lower hybrid

frequency range inside ion-scale reconnection layers only measured the magnetic field [22-23] and was not able to address the electrostatic aspect of the waves nor the electron response. In the laboratory experiment in [22-23], the probe is larger than the width of the electron-scale reconnection layer (~ a few electron skin depths), and hence not able to resolve whether the waves could occur inside the layer. For space experiments, even though probe dimensions are orders of magnitude smaller than the electron skin depth, crossings of an electron-scale reconnection layer typically last for only a fraction of a second. Owing to the measurement time resolution, detection of the electron response to the waves could not be made until the Magnetospheric Multiscale (MMS) mission [24-25]. Our recent work suggests the presence of lower hybrid drift waves (LHDW) in the electron-scale reconnection layer but the analyzed measurements (30 ms/sample) was insufficient to resolve the electron response [26]. In this paper, we analyze the multi-dimensional structure of the wave electric field and its influence on electron distribution functions (7.5 ms/sample [27]). The measurements reveal a new regime of electron-wave interaction and the strong modification of electron dynamics in the reconnection layer.

Fully kinetic simulations predict that LHDWs can modify ion-scale current sheet properties and lead to onset of collisionless reconnection [7,28-31]. Electron heating preferentially perpendicular to the magnetic field is shown to enhance the growth rate of the tearing instability responsible for reconnection onset by orders of magnitude [7,31]. Furthermore, the perpendicular heating is found to be nongyrotropic in a simulation [7]. These predictions have found no experimental evidence so far. On the other hand, the two-dimensional (2D) electric field structure of the LHDWs, predicted in the instability analysis [28,32-33] and simulations of

ion-scale current sheets [34], has been observed at a plasma boundary without magnetic reconnection [35].

Here we discuss LHDWs driving electron heating and flow vortices in an electron-scale reconnection layer observed by multiple MMS spacecraft. The size of the flow vortices is comparable to the width of the electron layer. In the layer, the magnetic field component anti-parallel to the direction of the current (known as the guide field) dominates. The waves have a strong electrostatic component. The wave electric field perpendicular to the magnetic field results in vortical flow patterns that produce magnetic field perturbations comparable to the guide field magnitude. Electron acceleration by the wave electric field results in perpendicular and nongyrotropic heating. The measurements used in this paper are taken by the following instruments: DC-coupled magnetic fields by the Flux Gate Magnetometer [36], AC-coupled magnetic fields the Search Coil Magnetometer [37], electric fields the Electric Double Probes [38-39], and plasma measurements the Fast Plasma Investigation [40].

The electron-scale reconnection current layer is encountered by MMS on the night side of the terrestrial magnetosphere at ~18 R_E from the Earth at approximately 05:27:07 UT on July 3, 2017. A key signature of magnetic reconnection is the correlated reversals of the reconnected magnetic field B_N and the plasma outflows V_L, as illustrated in Figure 1a, where L is along the outflow, M is the direction of the reconnection current, and N completes the third orthonormal direction [26]. The correlated reversals are captured by MMS1 as shown in Figures 1b-c. In the two-second interval, B_N evolves from +3 nT to -4 nT (Figure 1b), and the reversal is in concert with reversals of the electron and ion outflows, V_{eL} and V_{iL} (Figure 1c). At the location of the correlated reversals, the current is mainly carried by the electron flow, indicative of the electron-

scale reconnection layer. The half width of the electron current layer is estimated to be 25 km ~

$2.8 d_e$, where $d_e = c/\omega_{pe} \sim 8.8$ km is the electron skin depth, c is the speed of light and

ω_{pe} is the electron plasma frequency. The estimate is based on $B_L/(\Delta B_L/\Delta N)$. Two ways to

obtain the gradient $\Delta B_L/\Delta N$ are based on: (a) B_L and N from the MMS1 and 3 spacecraft (relative

locations along N illustrated as the origins of arrows in Figures 3a-b); (b) $\mu_0 J_M$ (with

negligible $\Delta B_N/\Delta L$) measured by MMS1 before the B_N reversal when the spacecraft enters the

most intense V_{eM} layer. The two estimates yield consistent results.

Large-amplitude waves in the lower hybrid frequency range are observed in the electron

current layer in the interval 052707.15 - 052707.75 UT (marked by a horizontal blue bar in

Figure 1d). In this interval, B_M is the dominant magnetic component, known as the guide field,

estimated to be ~30% of the asymptotic reconnecting component [26]. The fluctuation profiles of

the electron flow components V_{eL} and V_{eN} are correlated with those of the electric field

components E_N and E_L, respectively, indicative of wave-driven flows through the $E \times B$ drift (

$V_{E \times B}$). However, the electron flow velocity perpendicular to the magnetic field ($V_{e\perp}$)

exhibits finite deviations from $V_{E \times B}$ (Figure 1e) in correlation with largest amplitude E

fluctuations. The physics behind these deviations will be further studied in Figure 4. The ion

velocity $V_{i\perp}$ is much smaller than $V_{e\perp}$ and $V_{E \times B}$ (Figure 1e), implying that ions are

unmagnetized and decoupled from electrons. The decoupling gives rise to a strong ion-electron

relative drift perpendicular to the magnetic field. This condition in combination with the density

and magnetic field gradients along N is conducive to the LHDI [10]. The spectral powers in the

electric (Figure 1f) and magnetic (Figure 1g) fields are enhanced by more than one order of

magnitude in the lower hybrid frequency range, $f_{lh} = \sqrt{f_{ci} f_{ce}}$ ~3-8 Hz in the interval.

The frequency-wave number relation measured by MMS is consistent with the local

dispersion relation predicted by the LHDI theory [10]. The MMS data points are observed at

around the predicted maximum growth rate. The theoretical dispersion and the growth rate

curves (Figure 2) are obtained by inputting the parameters measured by MMS to equation 5 in

Ref. [10] in the $T_e \ll T_i$ limit (the observed T_e/T_i ~ 0.1). The parameters (averaged over the

wave interval) are: the background $E \times B$ drift speed 4300 km/s, ion thermal speed 760 km/s,

magnetic field magnitude 8.1 nT, plasma density 0.36 cm^{-3}, magnetic field gradient along N 0.20

nT/km, and density gradient along N -0.00075 cm^{-3}/km. The ion bulk velocity $V_{i\perp}$ is negligible

(See Figure 1e) compared to the perpendicular wave speed $\omega/k_\perp$ ~1500 km/s. The wave

vector k for the f_{lh} range of 3-8 Hz (corresponding to the range of ω/ω_{lh} covered by the MMS

data points in Figure 2) is computed from the Fourier components of the measured magnetic

field and current density at each frequency bin, $k(\omega) = i\mu_0 J(\omega) \times B^*(\omega)/|B(\omega)|^2$ (where $B^*(\omega)$ is

the complex conjugate of $B(\omega)$), assuming traveling waves and no displacement current in

Ampere's law [41]. The average direction of propagation is [-0.995, -0.071, 0.068] in the LMN

coordinates, and average phase speed $\omega/k = 1450$ km/s.

Simultaneous multi-point measurements of the wave electric fields perpendicular to B,

$\delta E_\perp$, reveal an alternating converging and diverging pattern (an example is shown in Figure

3a). This pattern bears a high degree of similarity to the electric field structure of LHDW

observed at a plasma boundary without reconnection [35]. The band-pass (2-50 Hz) filtered

$\delta E_\perp$ vectors measured by MMS1-3 are projected onto the *L-N* plane using the propagation

velocity $V_p \sim$ -1450 km/s $\hat{L}$ to convert from time to distance along *L* (Figure 3a). The *N*

coordinates are based on the spacecraft relative locations with zero set to be at the estimated $B_L =$

$B_N = 0$ line (the reconnection X-line).

In the presence of the guide field B_M, a vortical electron-flow pattern is formed on the *L-N*

plane due to the $\delta E \times B$ drift. Here the vortical $\delta V_{e\perp}$ flows are directly detected for the first

time by the electron instrument on MMS and shown in Figure 3b. Such a flow pattern gives rise

to a circulating perpendicular current and results in a magnetic perturbation δB along *M*. This

δB is comparable to the guide field B_M, and can be visually discerned as the localized

enhancement in B_M at 052707.7 UT (marked by a magenta arrow in Figure 1c). The spatial scales

of this vortical structure are approximately the half width of the electron current layer ($\sim 2.8\ d_e$).

The estimated half width of the vortical structure is 30 km (3.4 d_e) along *L*, and 15 km along *N*

(Figures 3a-b). The *N* size is constrained by the spacecraft separation.

The LHDW dramatically impacts the electron dynamics in the reconnection layer. Electrons

with gyroradius comparable with the half width of the vortex are accelerated by the wave electric

field, resulting in perpendicular heating and a possibility to enhance the tearing growth rate

predicted by simulations [e.g., 7]. The electrostatic potential, $\Phi_E = \int \delta E \cdot V_p\, dt$, reaches 560 V

from the exterior to the center region of the vortical structure at 052707.7 UT (Figure 3c). To

determine V_p, the potential can be written as $\Phi_B = \dfrac{B \cdot \delta B}{en\,\mu_0}$ [35,42] using Ampere's law

$\nabla \times \delta B = \mu_0 e n \nabla \Phi_B \times B / |B|^2$, where B is the instantaneous magnetic field, and the magnetic

field perturbation δB (parallel to the average magnetic field over the vortex) is from the

electron $\delta \boldsymbol{E} \times \boldsymbol{B}$ drift current. By maximizing the correlation between Φ_E and Φ_B profiles (correlation coefficient 0.97), the structure propagation velocity $\boldsymbol{V_p}$ is obtained to be -1430 km/s $\hat{L}$, consistent with the phase velocity obtained earlier. Figure 3d shows that the maximum increase in $T_{e\perp}$ is 205 eV in contrast to 96 eV for $T_{e\parallel}$. The potential provides a ~560 eV kinetic energy gain for the electrons passing from the equipotential of location A (locations are labeled on the data points in Figure 3d) to that of location C within one gyro-orbit. In contrast, the average T_e for the interval 052707.15-.75 UT is 360 eV, significantly lower than the T_e inside the potential structure.

The perpendicular heating is nongyrotropic as revealed by the distribution functions. At the potential maximum, the electron distribution function in the velocity plane perpendicular to the magnetic field, the $v_{E \times B} - v_{E \perp}$ plane, exhibits a nongyrotropic crescent structure (distribution C in Figure 4). The energy corresponding to the inner velocity boundary of the crescent population indicates the acceleration potential energy for electrons with negligibly small energy outside the potential structure [e.g., 43]. In this case, the inner boundary is at a cutoff speed of approximately 14,000 km/s (~558 eV), consistent with the potential energy difference 560 eV between locations A and C based on the electrostatic potential computed from the measured $\boldsymbol{E}$ and $\boldsymbol{B}$ (Figure 3c). This agreement indicates direct acceleration of the crescent electrons by the LHDW electrostatic potential. The crescent population has an angular spread with respect to $v_{E \perp} = 0$ due to finite gyroradius effects of non-uniformly distributed electrons that have been accelerated [e.g., 43-45]. Distribution A, located outside the potential, does not exhibit a crescent structure, supporting that the crescent distribution in Figure 3 is a consequence of energization during electron gyration across the wave potential and not a mere product of the larger-scale

reconnection process. In the wave interval, multiple vortices exhibiting nongyrotropic heating are observed.

As the spacecraft travels through the 2D potential structure along L, the maximally achievable kinetic energies at locations A-C differ by the corresponding potential energy increments (Figure 4), further supporting that the crescent electrons are demagnetized and accelerated by the LHDW potential. The phase-space density integrated over $v_{\parallel}$ and averaged over an angular range within $30°$ from the $+v_{E \times B}$ direction (approximately $-\hat{L}$) in the $v_{\perp}$ plane is plotted as a function of the electron perpendicular energy $W_{\perp} = m_e v_{\perp}^2/2$ (Figure 4b). The potential energy difference between time A (B) and time C (marked in Figure 3d) deduced from Φ_E (Figure 3c) is added to the spectra from distribution A (B) and plotted as the magenta (light blue) dotted curve. The agreement with spectra C between ~0.7-1.2 keV further substantiates that the crescent electrons are accelerated by the potential difference, implying that these electrons are demagnetized. The crescent electrons have an average energy ~800 eV. The gyro-radius of these electrons from the edge (|B| ~ 6 nT) to the center (|B| ~ 10 nT) of the potential structure is 16-9 km. Electrons from outside of the potential could reach the peak potential region in one gyro-orbit, as the half-width of the potential is comparable to twice the gyroradius. We note that while the crescent electrons are demagnetized, the motion of lower energy electrons is predominantly the $\delta E_{\perp} \times B_M$ drift, and gives rise to the vortical flows.

The guide field plays a pivotal role in allowing LHDI to occur in the electron-scale reconnection layer. In the wave interval, the guide field (B_M) is the dominant magnetic field component (Figure 1a), giving rise to a strong electron outflow jet V_{eL} through the $E_N \times B_M$ drift in the high Hall electric field E_N region (Figures 1c-e). The background drift velocity is

toward -*L* with an averaged magnitude of 4300 km/s (~ 15 V_A, based on local |B|), placing the system in a high drift regime as this electron-ion relative drift is significantly larger than the ion thermal speed of 750 km/s. The guide field keeps the electron beta (ratio of the electron thermal energy to the magnetic energy) in the range of ~0.3-2 during the LHDW interval, such that the finite-beta stabilization [10] does not come into effect. The relatively high electron-ion drift and moderate beta due to the guide field provide an environment for LHDI to take place.

In summary, LHDWs are observed to cause electron nongyrotropic heating and vortical flows in an electron-scale reconnection layer with a finite guide field. The waves have a spatial scale comparable to the half width of the electron layer, and primarily propagate along the outflow direction. Electron preferential perpendicular heating and nongyrotropy predicted by simulations [7] are observed for the first time, providing a potentially fertile ground for further reconnection to occur on the wave spatial scales. The strong electron vortical flows lead to δB comparable to the guide field magnitude. The measurements reveal a new regime of LHDW interaction with electrons.

Can the preferential perpendicular heating further trigger secondary tearing at the LHDW scale? Pursuit of this open question will transform our current picture of turbulent reconnection and guide-field reconnection. Existing analysis of tearing instabilities considers primarily current sheets much thicker than the electron scale. To address the question of reconnection-onset on the LHDW scale, fully kinetic simulations and state-of-the-art laboratory reconnection experiments that resolve the plasma response in the LHDW spatiotemporal scales are required.

Captions

Figure 1. Large-amplitude LHDWs driving electron flow bursts in an electron-scale reconnection layer detected by the MMS1 spacecraft. (a) Schematic showing MMS1 trajectory in an electron-scale current layer (the colored region where warmer colors represent stronger current densities) during reconnection with a guide field. Gray curves represent magnetic field lines. Note that the region where the outflow V_L is positive (negative), the magnetic field B_N is also positive (negative). (b) Three components of the magnetic field $\boldsymbol{B}$. (c) Electron flows V_{eLMN} and 20 times the ion outflow, $20V_{iL}$. (d) Electric field components E_{LMN}. (e) Electron (red) and ion (green) flow velocities along the $\boldsymbol{E} \times \boldsymbol{B}$ direction and the $\boldsymbol{E} \times \boldsymbol{B}$ drift speed (blue). (f) The electric field power spectral density. (g) The magnetic field power spectral density. The lower hybrid wave frequency is displayed as a curve in panels f-g. The wave interval is marked by a light blue bar in Figure 1d.

Figure 2. The dispersion relation measured by MMS (solid black circles) and predicted by theory (blue curve) [10]. The MMS data points are observed at around the maximum growth rate (red) with an average $k_\perp \rho_e$ about 0.15. The electron thermal gyroradius $\rho_e = v_{te}/\omega_e \sim 8$ km, where the electron thermal speed $v_{te} = \sqrt{2T_e/m_e}$ is based on the average electron temperature T_e and the electron gyrofrequency ω_e based on the average magnetic field. The average lower hybrid frequency $\omega_{lh} = 34$ rad/s.

Figure 3. One outstanding example of an LHDW structure (marked by the magenta arrow in Figure 1) with its resulting electron vortical flow and heating. (a) Electric field vectors perpendicular to $\boldsymbol{B}$ projected onto the L-N plane from three MMS spacecraft. (b) Electron flows $\delta V_{e\perp}$ from three spacecraft showing a vortical pattern. (c) The electrostatic potentials Φ_E

(blue) and Φ_B (red) computed based on integrating the measured $\delta E_\perp$ along $\boldsymbol{k}$ and based

on δB, respectively. (d) Electron temperatures parallel (red) and perpendicular (blue) to $\boldsymbol{B}$

showing preferential perpendicular heating. The quantities $\delta E_\perp$, $\delta V_{e\perp}$, and δB are

band-pass filtered at 2-50 Hz, extending beyond the range of the local f_{lh} to cover most of the

enhanced $\boldsymbol{E}$ spectral power (Figure 1f) while removing the DC component.

Figure 4. Reduced electron distribution functions in the background $\boldsymbol{E} \times \boldsymbol{B}$ (low pass filtered

fields below 1 Hz) drift frame showing nongyrotropic perpendicular heating and direct

acceleration by the LHDW potential. (a) Distributions ABC (corresponding to the data points

marked in Figure 3d) in the $v_{\boldsymbol{E} \times \boldsymbol{B}}$ - $v_{\boldsymbol{E}\perp}$ plane, where $v_{\boldsymbol{E} \times \boldsymbol{B}}$ and $v_{\boldsymbol{E}\perp}$ are along the

$\boldsymbol{E} \times \boldsymbol{B}$ and perpendicular electric field directions, respectively. (b) Phase-space densities of the

reduced distributions ABC as a function of the perpendicular energy $W_\perp$ along the direction of

$v_{\boldsymbol{E} \times \boldsymbol{B}}$. The dotted magenta (light-blue) curve is distribution A (B) shifted by the potential

energy difference between time A (B) and time C, and agrees with distribution C within

uncertainties (± 150 eV given by the instrument's energy bin width and/or the potential energy

change over the distribution sampling time).

References

[1] J. F. Drake, J. Gerber, and R. G. Kleva, J. Geophys. Res., 99 (A6), 11211, (1995)

[2] R. G. Kleva and J. F. Drake, Phys. Fluids, 27, 1686, (1984).

[3] A. Le, W. Daughton, L.-J. Chen, and J. Egedal, Geophys. Res. Lett., 44, 2096, (2017).

[4] A. Le, W. Daughton, O. Ohia, L.-J. Chen, Y.-H. Liu, S. Wang, W. D. Nystrom, and R. Bird, Phys. Plasmas, 25, 062103, (2018)

[5] Graham, D. B., et al., J. Geophys. Res. Space Physics, 122, (2016)

[6] I. H. Cairns and B. F. McMillan, Phys. Plasmas, 12, 102110, (2005).

[7] P. Ricci, et al., Phys. Plasmas, 11, 4489, (2004).

[8] J. D. Huba, N. T. Gladd, and K. Papadopoulos, Geophys. Res. Lett., 4, 3, (1977).

[9] J. D. Huba, N. T. Gladd, and K. Papadopolulos, J. Geophys. Res., 83, A11, (1978).

[10] R. C. Davidson, N. T. Gladd, C. S. Wu, and J. D. Huba, Phys. Rev. Lett., 37, (12) 750, (1976).

[11] L.-J. Chen, A. Bhattacharjee, P. A. Puhl-Quinn, H. Yang, N. Bessho, S. Imada, S. Muhlbachler, P. W. Daly, B. Lefebvre, Y. Khotyaintsev, et al., Nature Phys., 4, 19-23, (2008).

[12] M. Yamada, L.-J. Chen, J. Yoo., S. Wang, W. Fox, J. Jara-Almonte, H. Ji, W. Daughton, A. Le, J. Burch, et al., Nat Commun, 9, 5223, (2018)

[13] L.-J. Chen, N. Bessho, B. Lefebvre, H. Vaith, A. Fazakerley, A. Bhattacharjee, P. A. Puhl-Quinn, A. Runov, Y. Khotyaintsev, A. Vaivads, E. Georgescu, and R. Torbert, J. Geophys. Res., 113, A12213, (2008).

[14] L.-J. Chen, N. Bessho, B. Lefebvre, H. Vaith, A. Asnes, O. Santolik, A. Fazakerley, P. Puhl-Quinn, A. Bhattacharjee, Y. Khotyaintsev, P. Daly, and R. Torbert, Phys. Plasmas, 16, 056501, (2009).

[15] L.-J. Chen, W. S. Daughton, B. Lefebvre, and R. B Torbert, Phys. Plasmas, 18, 012904, (2011).

[16] L.-J. Chen, W. Daughton, A. Bhattacharjee, R. B. Torbert, V. Roytershteyn, and N. Bessho, Phys. Plasmas, 19, 112902, (2012).

[17] M. Fujimoto, I. Shinohara, and H. Kojima, Space Sci. Rev., 160, 123, (2011).

[18] T. A. Carter, M. Yamada, H. Ji, R. M. Kulsrud, and F. Trintchouk, Phys. Plasmas, 9, 8, (2002a).

[19] T. A. Carter, H. Ji, F. Trintchouk, M. Yamada, and R. M. Kulsrud, Phys. Rev. Lett., 88, 1, (2002b).

[20] I. Shinohara, T. Nagai, M. Fujimoto, T. Terasawa, T. Mukai, K. Tsuruda, and T. Yamamoto, J. Geophys. Res., 103 (A9), 20, 365, (1998)

[21] S. D. Bale, F. S. Mozer, T. Phan, Geophys. Res. Lett., 29, 24, 2180, (2002).

[22] H. Ji, S. Terry, M. Yamada, R. Kulsrud, A. Kuritsyn, and Y. Ren, Phys. Rev. Lett., 92, 11, (2004)

[23] H. Ji, R. Kulsrud, W. Fox, and M. Yamada, J. Geophys. Res., 110, A08212, (2005).

[24] J. L. Burch, R. B. Torbert, T. D. Phan, L.-J. Chen, T. E. Moore, R. E. Ergun, J. P. Eastwood, D. J. Gershman, P. A. Cassak, M. R. Argall, et al., Science, 352, aaf2939 (2016).

[25] D. B. Graham, Y. V. Khotyaintsev, C. Norgren, A. Vaivads, M. Andre, J. F. Drake, J. Egedal, M. Zhou, O. Le Contel, J. M. Webster, et al., J. Geophys. Res: Space Physics, 124, 8727-8760, (2019).

[26] L.-J. Chen, S. Wang, M. Hesse, R. E. Ergun, T. Moore, B. Giles, et al., Geophys. Res. Lett., 46, (2019).

[27] A. C. Rager, J. C. Dorelli, D. J. Gershman, V. Uritsky, L. A. Avanov, R. B. Torbert, et al., Geophys. Res. Lett., 45, 578, (2018).

[28] W. Daughton, Phys. Plasmas, 10, 3103, (2003).

[29] W. Daughton, G. Lapenta, and P. Ricci, Phys. Res. Lett., 93, 105004, (2004)

[30] I. Shinohara and M. Fujimoto, Cospar Colloquia Series, 16, 123, (2005).

[31] K. G. Tanaka, I. Shinohara, and M. Fujimoto, Geophys. Res. Lett., 32, (2005).

[32] P. H. Yoon, A. T. Y. Lui, and M. I. Sitnov, Phys. Plasmas, 9, 1526, (2002).

[33] J. Ng, A. Hakim, J. Juno, and A. Bhattacharjee, J. Geophys. Res., 124, 3331, (2019)

[34] M. Tanaka, and T. Sato, J. Geophys. Res., 86, A7, (1981)

[35] C. Norgren, A. Vaivads, Yu. V. Khotyaintsev, and M. Andre, Phys. Rev. Lett., 109, 055001, (2012)

[36] C. T. Russell, B. J. Anderson, W. Baumjohann, K. R. Bromund, D. Dearborn, D. Fischer, et al., Space Sci. Rev., 199, 189-256 (2016).

[37] O. LeContel, P. Leroy, A. Roux, C. Coillot, D. Alison, A. Bouabdellah, et al., Space Sci. Rev., 199, 257-282, (2016).

[38] R. E. Ergun, S. Tucker, J. Westfall, K. A. Goodrich, D. M. Malaspina, D. Summers, et al., Space Sci. Rev., 199, 167-188, (2016).

[39] P.-A. Lindqvist, G. Olsson, R. B. Torbert, B. King,M. Granoff, D. Rau, et al., Space Sci. Rev., 199, 137-165, (2016).

[40] C. Pollock, T. Moore, A. Jacques, J. Burch, U. Gliese, Y. Saito, et al., Space Sci. Rev., 19, 331-406, (2016).

[41] P. M. Bellan, J. Geophys. Res., 121, 8589, (2016)

[42] A. Divin, Yu. V. Khotyaintsev, A. Vaivads, and M. Andre, J. Geophys. Res.: Space Physics, 120, 1124-1132, (2015).

[43] N. Bessho, L.-J. Chen, and M. Hesse, Geophys. Res. Lett., 43, 1828, (2016).

[44] J. R. Shuster, L.-J. Chen, M. Hesse, M. R. Argall, W. Daughton, R. B. Torbert, et al., Geophys. Res. Lett., 42, 2586, (2015).

[45] L.-J. Chen, M. Hesse, S. Wang, N. Bessho, and W. Daughton, Geophys. Res. Lett., 43, 2405, (2016)