AIP Physics of Plasmas

Kinetic simulations of the structures of magnetic island in multiple X line guide field reconnection

Can Huang, Quanming Lu, Hui Zhang, Mingyu Wu, Quanli Dong et al.

Citation: Phys. Plasmas **19**, 042111 (2012); doi: 10.1063/1.4704799
View online: http://dx.doi.org/10.1063/1.4704799
View Table of Contents: http://pop.aip.org/resource/1/PHPAEN/v19/i4
Published by the American Institute of Physics.

Related Articles

Numerical simulations of separatrix instabilities in collisionless magnetic reconnection
Phys. Plasmas 19, 042110 (2012)

Magnetic reconnection and stochastic plasmoid chains in high-Lundquist-number plasmas
Phys. Plasmas 19, 042303 (2012)

Magnetic reconnection in high-energy-density laser-produced plasmas
Phys. Plasmas 19, 056309 (2012)

Observations of electron phase-space holes driven during magnetic reconnection in a laboratory plasma
Phys. Plasmas 19, 032118 (2012)

Energy transformation in a reconnection site
Phys. Plasmas 19, 032904 (2012)

Additional information on Phys. Plasmas

Journal Homepage: http://pop.aip.org/
Journal Information: http://pop.aip.org/about/about_the_journal
Top downloads: http://pop.aip.org/features/most_downloaded
Information for Authors: http://pop.aip.org/authors

ADVERTISEMENT

Kinetic simulations of the structures of magnetic island in multiple X line guide field reconnection

Can Huang,[1] Quanming Lu,[1,a)] Hui Zhang,[2] Mingyu Wu,[1] Quanli Dong,[3] San Lu,[1] and Shui Wang[1]
[1]*CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Science, University of Science and Technology of China, Hefei 230026, China*
[2]*Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California 90095, USA*
[3]*Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China*

(Received 29 January 2012; accepted 29 March 2012; published online 19 April 2012)

Magnetic reconnection is one of the most important processes in astrophysical, space, and laboratory plasmas, and magnetic island is an important feature in reconnection. Therefore, identifying the structures of magnetic island is crucial to improving our understanding of magnetic reconnection. Using two-dimensional (2-D) particle-in-cell (PIC) simulations, we demonstrate that the out-of-plane magnetic field has a dip in the center of magnetic island, which is formed during multiple X line guide field reconnection. Such structures are considered to be produced by the current system in the magnetic island. At the edge of the magnetic island, there exists a current anti-parallel to the in-plane magnetic field, while the current is parallel to the in-plane magnetic field inside the magnetic island. Such a dual-ring current system, which is attributed to the electron dynamics in the magnetic island, leads to the dip of the out-of-plane magnetic field in the center of the island. The relevance between our simulations and crater flux transfer events (C-FTEs) is also discussed. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4704799]

I. INTRODUCTION

Magnetic reconnection is a basic physical process which provides an effective mechanism for fast energy conversion from magnetic energy to plasma kinetic energy. Such conversion process is manifested by plasma heating and jetting in the reconnection outflow regions.[1–3] Electron behaviors are considered to play an important role in collisionless magnetic reconnection. In anti-parallel reconnection, at a scale length below the ion inertial length $\lambda_i = c/\omega_{pi}$ (where ω_{pi} is the ion plasma frequency) around the X line, ions are demagnetized while electrons are magnetized and frozen in the magnetic field lines.[4–6] The electrons first move towards the X-line along the separatrices and then are directed away from the X line along the magnetic field lines just inside the separatrices after they are accelerated in the vicinity of the X-line by the reconnection electric field.[7–9] Therefore, the resulting in-plane currents, which are carried mainly by the magnetized electrons, produce the quadrupole structures of the out-of-plane magnetic field in the ion diffusion region.[4,10–12] In guide field reconnection, the electrons move towards the X line along one pair of separatrices and are away from the X line along the other pair of separatrices. The out-of-plane magnetic field is enhanced in the center of the current sheet by the resulting in-plane currents, and the symmetry of the out-of-plane magnetic field is substantially distorted.[13–15]

In multiple X line reconnection, magnetic island will be formed between X lines. Magnetic island is considered to play an important role in the production of energetic electrons in reconnection.[16–20] Therefore, investigating the structures of magnetic island and their relations to the electron dynamics is essential to know the acceleration mechanism of energetic electrons in reconnection. Both simulations and observations have shown that quadrupole structures of the out-of-plane magnetic field are also formed in magnetic island during multiple X line anti-parallel reconnection, and their generation mechanism is the same as that in single X reconnection.[21–25] In multiple X line guide field reconnection, both simulations and observations have found that the out-of-plane magnetic field is enhanced in magnetic island.[17,26–28] The magnetic flux added by the plasma inflow has been thought to make a most important contribution to the growth of the out-of-plane magnetic field in magnetic island. Using two-dimensional (2-D) particle-in-cell (PIC) simulations, we find that the out-of-plane magnetic field has a dip in the center of magnetic island formed during multiple X line guide field reconnection. We demonstrate that the formation for such structures of magnetic island is attributed to the in-plane currents, which are dominated by electron behaviors in magnetic island. The relevance between our simulations and crater flux transfer events (C-FTEs) is also discussed. FTE has a characteristic magnetic field of a transient bipolar variation of the component along the normal to the local magnetopause, typically associated with the enhancement of magnetic field strength.[29,30] C-FTE is one kind of FTE, whose field magnitude enhancement shows a crater-like dimple in the center of the magnetic island.[31–33]

II. SIMULATION MODEL

A 2-D PIC code is used to investigate the structures of magnetic island formed during multiple X line guide field

a)Author to whom correspondence should be addressed. Electronic mail: qmlu@ustc.edu.cn.

 © 2012 American Institute of Physics

reconnection. In the simulations, the electromagnetic fields are defined on the grids and updated by solving the Maxwell equations with a full explicit algorithm. The initial configuration is a one-dimensional Harris current sheet in the (x, y) plane, and the initial magnetic field is given by[34]

$$\mathbf{B}_0(y) = B_0 \tanh(y/\delta)\mathbf{e}_x + B_{z0}\mathbf{e}_z, \tag{1}$$

where δ is the half-width of the current sheet. B_0 is the asymptotical magnetic strength. B_{z0} is the strength of the guide field. The corresponding number density is

$$n(y) = n_b + n_0 \operatorname{sech}^2(y/\delta), \tag{2}$$

where n_b represents the density of the background plasma and n_0 is the peak Harris density. The distribution functions for the ions and electrons are Maxwellian, and their drift speeds in the z direction satisfy $V_{i0}/V_{e0} = -T_{i0}/T_{e0}$, where $V_{i0}(V_{e0})$ and $T_{i0}(T_{e0})$ are the initial drift speed and temperature for ions (electrons), respectively. In our simulations, the temperature ratio is $T_{i0}/T_{e0} = 4$ and $n_0 = 5n_b$. The current sheet width is $\delta = 0.5c/\omega_{pi}$, where c/ω_{pi} is the ion inertial length defined by n_0. The mass ratio is set to $m_i/m_e = 100$ (where m_e is the rest mass of the electron). The light speed is $c = 15v_A$, where v_A is the Alfvén speed defined by B_0 and n_0. An initial guide field $B_{z0} = B_0$ is used in the simulations.

The computation is carried out in a rectangular domain in the (x, y) plane with dimension $L_x \times L_y = (51.2c/\omega_{pi}) \times (12.8c/\omega_{pi})$. An $N_x \times N_y = 1024 \times 256$ grid system is employed in the simulations, so the spatial resolution is $\Delta x = \Delta y = 0.05\ c/\omega_{pi} = 0.5\, c/\omega_{pe}$. The time step is $\Omega_i \Delta t = 0.001$, where Ω_i is the ion gyrofrequency. We employ more than 1.0×10^7 particles per species in the simulations. The periodic boundary conditions are used along the x direction, while the ideal conducting boundary conditions for electromagnetic fields are employed in the y direction. In order to make the system enter the nonlinear stage quickly, an initial flux perturbation with the form $\psi(x, y) = \psi_0 \cos(2\pi x/L_x)\cos(\pi z/L_z)$ (where ψ is the vector potential component A_z and the value of ψ_0 is chosen as $\psi_0/(B_0 c/\omega_{pi}) = 0.05$) is introduced, which is useful to reach the stage of rapid growth of reconnection.

III. SIMULATION RESULTS

Magnetic island can be formed between X lines in multiple X line reconnection as shown in our 2-D PIC simulations. Figure 1 shows the time evolution of the out-of-plane magnetic field $(B_z - B_{z0})/B_0$ at $\Omega_i t = 22$, 26, 30, and 34, respectively. The magnetic field lines are also plotted in the figure for reference. As time goes on, the width of the magnetic island increases in the y direction, and it is about 6 c/ω_{pi} at the saturation stage. Unlike in anti-parallel reconnection, where the out-of-plane magnetic field exhibits quadrupole structures,[6–9] now it is obviously enhanced in the magnetic island from $\Omega_i t = 30$ due to the presence of an initial guide field. Similar results have also been obtained by other Hall MHD and kinetic simulations, and the enhancement of the out-of-plane magnetic field was found to be dependent strongly on the presence or absence of an initial guide field.[17,26–28] However, from the figure, we can further find that at the saturation stage the out-of-plane magnetic field shows a dip in the center of the magnetic island, and it means that the out-of-plane magnetic field in the center of the magnetic island is smaller than that at the edge of the magnetic island.

Such structures of the out-of-plane magnetic field in the magnetic island can be explained based on the in-plane current system, which are shown in Fig. 2. Figure 2 depicts the ion current along the in-plane magnetic field $j_{||i} = \mathbf{J}_i \cdot \mathbf{B}'/B'$ (Figure 2(a), where $\mathbf{B}' = B_x\mathbf{e}_x + B_y\mathbf{e}_y$ is the in-plane magnetic field, $\mathbf{J}_i$ is the ion current), the electron current along the in-plane magnetic field $j_{||e} = \mathbf{J}_e \cdot \mathbf{B}'/B'$ (Figure 2(b), where $\mathbf{J}_e$ is the electron current), the total current along the in-plane magnetic field $j_{||} = j_{||i} + j_{||e}$ (Figure 2(c)) at $\Omega_i t = 34$, while Figure 2(d) shows the profiles of the total current along the in-plane magnetic field $j_{||}$, the electron current along the in-plane magnetic field $j_{||e}$, and the ion current along the in-plane magnetic field $j_{||i}$. The currents in Fig. 2(d) are obtained along the line $x = 24.5c/\omega_{pi}$ with $-3.5c/\omega_{pi} \le y \le 0$, which is denoted by the dashed lines in Figs. 2(a)–2(c). At the edge of the magnetic island, there exists an electron current anti-parallel to the in-plane magnetic field. The anti-parallel electron current is generated by the energetic electrons directed away from the X lines after

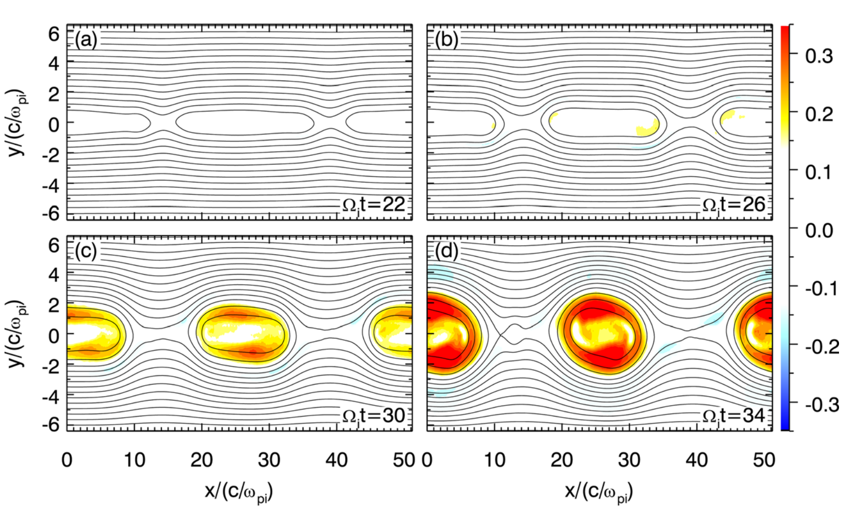

FIG. 1. The time evolution of the out-of-plane magnetic field $(B_z - B_{0z})/B_0$ at $\Omega_i t = 22$, 26, 30, and 34. The solid lines represent the in-plane magnetic field lines.

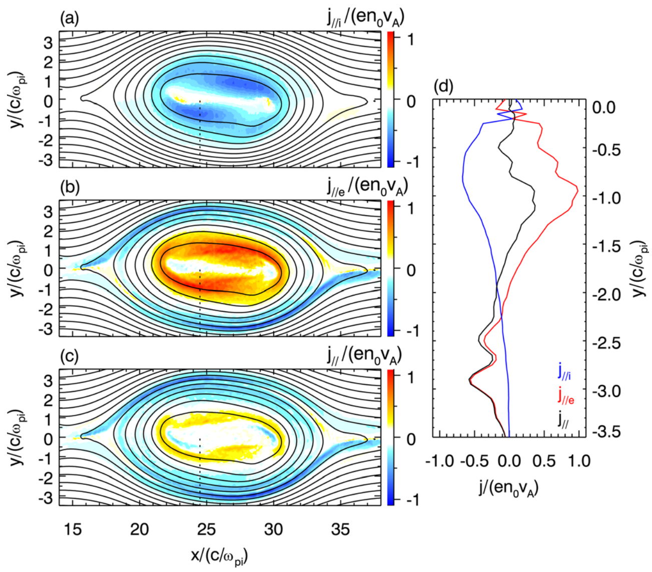

FIG. 2. The currents in the magnetic island at $\Omega_i t = 34$. (a) The ion current along the in-plane magnetic field $j_{||i} = \mathbf{J}_i \cdot \mathbf{B}'/B'$ (where $\mathbf{B}' = B_x\mathbf{e}_x + B_y\mathbf{e}_y$ is the in-plane magnetic field, $\mathbf{J}_i$ is the ion current), (b) the electron current along the in-plane magnetic field $j_{||e} = \mathbf{J}_e \cdot \mathbf{B}'/B'$ (where, $\mathbf{J}_e$ is the electron current), (c) the total current along the in-plane magnetic field $j_{||} = j_{||i} + j_{||e}$. The solid lines in (a)-(d) represent the in-plane magnetic field lines. (d) shows the profiles of the total current along the in-plane magnetic field $j_{||}$ (black line), the electron current along the in-plane magnetic field $j_{||e}$ (red line), and the ion current along the in-plane magnetic field $j_{||i}$ (blue line). The currents in (d) are obtained along the line $x = 24.5c/\omega_{pi}$ with $-3.5c/\omega_{pi} \le y \le 0$, which are denoted by the dashed lines in (a)-(c).

they are accelerated in the vicinity of the X lines.[8,9] Inside the magnetic island, the electron current is parallel to the in-plane magnetic field, while the ion current is anti-parallel to the in-plane magnetic field. However, the electron and ion currents cannot be cancelled totally, and there exists a net current parallel to the in-plane magnetic field inside the magnetic island. Therefore, the total current is anti-parallel to the in-plane magnetic field at the edge of the magnetic island, and it is parallel to the in-plane magnetic field inside the magnetic island. The contributions of electron and ion currents to the total current along the in-plane magnetic field can be demonstrated more clearly in Fig. 2(d). The anti-parallel current at the edge of the magnetic island, which is contributed mainly by the electrons, is around $y = 2.8c/\omega_{pi}$. The net parallel current inside the magnetic island is around $y = -1.0c/\omega_{pi}$. It is worth noting that the directions of the in-plane currents will also be reversed if the sign of the initial guide field is changed. However, this does not change the generation mechanism of the dip of the out-of-plane magnetic field in the center of the island proposed in this paper.

The generation mechanism for such a current system inside the magnetic island is also related to electron dynamics in magnetic reconnection. Inside the magnetic island, both the electrons and ions suffer electric field drift and move along the magnetic field lines. A typical electron trajectory at the edge of the magnetic island and its evolution of kinetic energy are plotted in Fig. 3. Figures 3(a)–3(c) describe the electron trajectory during $24 \le \Omega_i t \le 27.5$, $27.5 \le \Omega_i t \le 30.8$, and $30.8 \le \Omega_i t \le 32.5$, respectively. The three periods correspond to the stages when the electron is in the inflow, the vicinity of the right X line, and the outflow regions. Figure 3(d) shows the parallel electric field suffered by the electron, Fig. 3(e) plots the evolution of the corresponding electron kinetic energy ε (where $\varepsilon = (\gamma - 1)m_e c^2$ and γ is the relativistic factor), and Fig. 3(f) describes the velocity of its gyrocenter. The electron drift velocity is anti-parallel to the in-plane magnetic field. The electrons can still be accelerated due to the

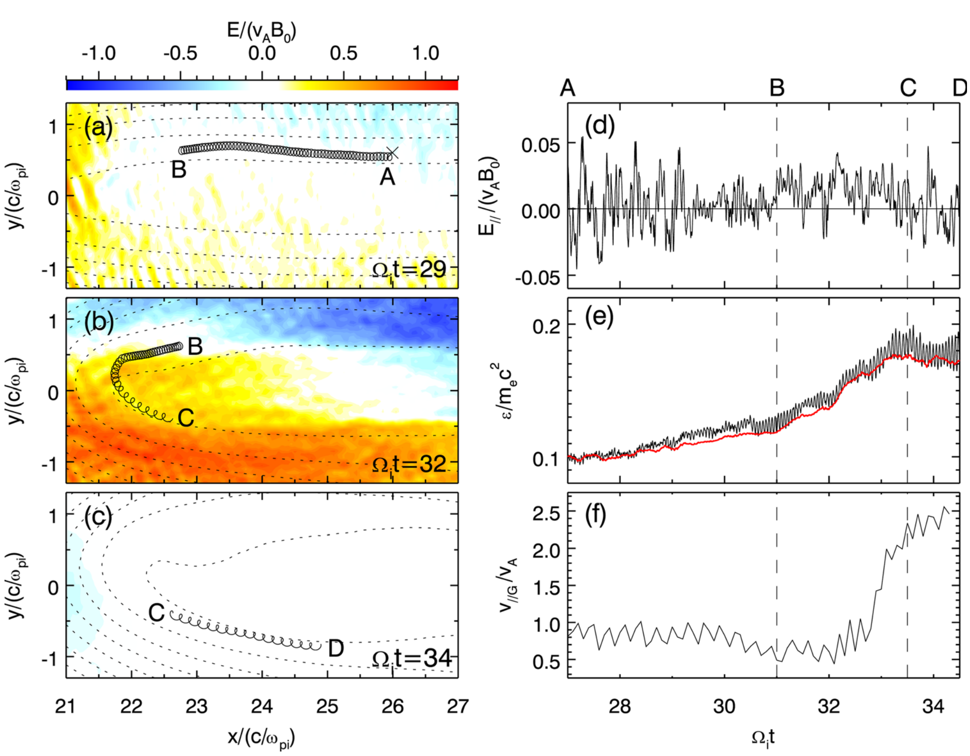

FIG. 3. A typical electron trajectory and its time evolution of kinetic energy during $24 \le \Omega_i t \le 27.5$, $27.5 \le \Omega_i t \le 30.8$, and $30.8 \le \Omega_i t \le 32.5$, respectively. The three periods correspond to the stages when the electron is in the inflow, the vicinity of the right X line, and the outflow regions. (a)-(c) describe its trajectory, and contours of the electric field E_x, E_y, and E_z are also plotted in (a)-(c), respectively. (d) shows the parallel electric field suffered by the electron, (e) plots the evolution of the corresponding electron kinetic energy ε (where $\varepsilon = (\gamma - 1)m_e c^2$ and γ is the relativistic factor), and (f) describes the velocity of its gyrocenter. In (a)-(c), the dashed lines represent the in-plane magnetic field lines.

existence of the parallel electric field in the pileup region. The acceleration process is similar to the mechanism proposed by Fu *et al.*[12] and Drake *et al.*[16] They proposed that the electrons are accelerated by the inductive electric field at the end of the island, which resembles a single "kick" from a contracting island. However, the ions cannot be obviously accelerated by the electric field due to their large mass, which results in a net current parallel to the in-plane magnetic field inside the magnetic island.

IV. CONCLUSIONS AND DISCUSSION

In summary, by performing 2-D PIC simulations, we found that the out-of-plane magnetic field is enhanced in a magnetic island, however, there exists a dip in the center of the island. At the edge of magnetic island, the electron current anti-parallel to the in-plane magnetic field is generated by the energetic electrons, which are accelerated in the vicinity of the X lines and then directed away from the X lines. Inside the magnetic island, the current inside the magnetic island is the combined results of the electric field drift and acceleration by the inductive electric field, as proposed previously by Fu *et al.*[12] and Drake *et al.*[16] There exist both the ion and electron currents. The electron current is parallel to the in-plane magnetic field, while the ion current is anti-parallel to the in-plane magnetic field. A net current parallel to the in-plane magnetic field is formed inside the magnetic island, because the electrons can be accelerated by the parallel electric field and get larger currents than that of the ions and have larger current than that of the ions. Such a dual-ring current system leads to a dip of the out-of-plane magnetic field in the center of the island. The simulation results are consistent with the observational characteristics of a typical C-FTE.[33] Therefore, our simulations may provide an explanation for the generation mechanism of C-FTE. One thing we should notice is that in three-dimensional (3-D) flux ropes, the interaction between them makes the structures intrinsically turbulent.[28] It may change the structures of the currents and then the out-of-plane magnetic field as described in this paper, which is beyond the scope of this paper and is our future work.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation of China, Grant Nos. 40931053, 41174124, 973 program (2012CB825602), Ocean Public Welfare Scientific Research Project, State Oceanic Administration People's Republic of China (No. 201005017), and the Fundamental Research Funds for the Central Universities (WK2080000010).

[1] P. A. Sweet, in *Electromagnetic Phenomena in Cosmical Physics*, edited by B. Lehnert (Cambridge University Press, London, 1958), p. 123.
[2] E. N. Parker, J. Geophys. Res. **62**, 509, doi:10.1029/JZ062i004p00509 (1957).
[3] D. Biskamp, *Magnetic Reconnection in Plasmas* (Cambridge University Press, Cambridge, 2000).
[4] B. U. Ö. Sonnerup, "Magnetic field reconnection," in *Solar System Plasma Physics*, edited by L. J. Lanzèerotti, C. F. Kennel, and E. N. Parker (North-Holland, New York, 1979), Vol. 3, p. 46.
[5] J. Birn *et al.*, J. Geophys. Res. **106**, 3715, doi:10.1029/1999JA900449 (2001).
[6] T. Nagai, I. Shinohara, M. Fujimoto *et al.*, J. Geophys. Res. **106**, 25929, doi:10.1029/2001JA900038 (2001).
[7] P. L. Pritchett, J. Geophys. Res. **106**, 3783 (2001).
[8] R. S. Wang, Q. M. Lu, C. Huang, and S. Wang, J. Geophys. Res. **115**, A01209, doi:10.1029/2009JA014553 (2010).
[9] Q. M. Lu, C. Huang, J. L. Xie *et al.*, J. Geophys. Res. **115**, A11208, doi:10.1029/2010JA015713 (2010).
[10] M. Øieroset, T. D. Phan, M. Fujimoto *et al.*, Nature **412**, 414 (2001).
[11] Z. W. Ma and A. Bhattacharjee, J. Geophys. Res. **106**, 3773, doi:10.1029/1999JA001004 (2001).
[12] X. R. Fu, Q. M. Lu, and S. Wang, Phys. Plasmas **13**, 012309 (2006).
[13] P. L. Pritchett and F. V. Coroniti, J. Geophys. Res. **109**, A01220, doi:10.1029/2003JA009999 (2004).
[14] C. Huang, Q. M. Lu, and S. Wang, Phys. Plasmas **17**, 072306 (2010).
[15] S. Lu, Q. M. Lu, Y. Cao *et al.*, Chin. Sci. Bull. **56**, 48 (2011).
[16] J. F. Drake, M. Swisdak, H. Che, and M. A. Shay, Nature **443**, 553 (2006).
[17] L. J. Chen *et al.*, Nat. Phys. **4**, 19 (2007).
[18] R. S. Wang, Q. M. Lu, A. M. Du, and S. Wang, Phys. Rev. Lett. **104**, 175003 (2010).
[19] M. Oka, T. D. Phan, S. Krucker, M. Fujimoto, and I. Shinohara, Astrophys. J. **714**, 915 (2010).
[20] K. G. Tanaka, M. Fujimoto, S. V. Badman, and I. Shinohara, Phys. Plasmas **18**, 022903 (2011).
[21] H. Karimabadi, D. Krauss-Varban, N. Omidi, and H. X. Vu, J. Geophys. Res. **104**, 12313, doi:10.1029/1999JA900089 (1999).
[22] H. Karimabadi, J. D. Huba, D. Krauss-Varban, and N. Omidi, Geophys. Res. Lett. **31**, L07806, doi:10.1029/2004GL019553 (2004).
[23] X. H. Deng, H. Matsumoto, H. Kojima *et al.*, J. Geophys. Res. **109**, A05206, doi:10.1029/2003JA010031 (2004).
[24] C. X. Liu, S. P. Jin, F. S. Wei, Q. M. Lu, and H. A. Yang, J. Geophys. Res. **114**, A10208, doi:10.1029/2009JA014257 (2009).
[25] Q. H. Zhang, M. W. Dunlop, R. Y. Liu *et al.*, Ann. Geophys. **29**, 1827 (2011).
[26] Z. W. Ma, A. Otto, and L. C. Lee, J. Geophys. Res. **99**, 6125, doi:10.1029/93JA03480 (1994).
[27] J. F. Drake, M. Swisdak, K. M. Schoeffler *et al.*, Geophys. Res. Lett. **33**, L13105, doi:10.1029/2006GL025957 (2006).
[28] W. Daughton, V. Roytershteyn, H. Karimabadi *et al.*, Nat. Phys. **7**, 539 (2011).
[29] C. T. Russell and R. C. Elphic, Space Sci. Rev. **22**, 681 (1978).
[30] Q. H. Zhang, M. W. Dunlop, M. Lockwood *et al.*, J. Geophys. Res. **115**, A10237, doi:10.1029/2010JA015526 (2010).
[31] J. LaBelle, R. A. Treumann, G. Haerendel *et al.*, J. Geophys. Res. **92**, 5827, doi:10.1029/JA092iA06p05827 (1987).
[32] C. J. Farrugia, R. P. Rijnbeek, M. A. Saunders *et al.*, J. Geophys. Res. **93**, 14465, doi:10.1029/JA093iA12p14465 (1988).
[33] H. Zhang *et al.*, J. Geophys. Res. **115**, A08229, doi:10.1029/2009JA015013 (2010).
[34] E. G. Harris, Nuovo Cimento Soc. Ital. Fis. **23**, 115 (1962).