Non-Adiabatic Electron Heating in the Magnetic Islands During Magnetic Reconnection

Keizo Fujimoto\textsuperscript{1,2} and Jin-Bin Cao\textsuperscript{1,2}

\textsuperscript{1}School of Space and Environment, Beihang University, Beijing, China, \textsuperscript{2}Key Laboratory of Space Environment Monitoring and Information Processing, Ministry of Industry and Information Technology, Beijing, China

Abstract  The present study proposes a new mechanism to cause a strong electron heating in the magnetic islands ejected from the reconnection current layer. A large-scale full kinetic simulation in three-dimensional system demonstrates that the electrons are effectively accelerated by the non-ideal electric field generated through the electromagnetic turbulence excited in the magnetic islands. It is found that the high-energy electrons are efficiently scattered by the turbulence, resulting in the strong electron heating. The existence of turbulence and the associated non-ideal electric field in the magnetic islands is consistent with recent satellite observations in the Earth’s magnetosphere.

Plain Language Summary  Observed velocity distribution of space plasmas often contains high-energy components overlapping the ambient thermal component, implying the existence of local explosive processes producing energetic particles. Magnetic reconnection is one of such the processes, converting the magnetic field energy into plasma kinetic energies. In this study, we propose a new mechanism to cause a strong electron heating in the magnetic islands generated during magnetic reconnection. By means of a large-scale computer simulation, where both electrons and ions are treated as particles, we found that the electrons are effectively accelerated by turbulence-induced electric field. The high-energy electrons are efficiently scattered by the turbulence, resulting in the strong electron heating. The existence of turbulence and the associated induction electric field is consistent with recent satellite observations in the Earth’s magnetosphere.

1. Introduction

Origin of high-energy particles is a key issue in space plasmas as a source of cosmic rays and non-thermal plasmas in space and astrophysical environments (Fermi, 1949; Sarris et al., 1976). Magnetic reconnection is one of the promising processes that can produce energetic particles through the release of magnetic field energy. The reconnection process is ubiquitous in space, triggering dynamical phenomena such as solar flares and magnetospheric substorms of the Earth. In particular, it has been suggested that a significant fraction of the energy released goes to the electrons during magnetic reconnection in solar flares (Lin & Hudson, 1976; Lin et al., 2003). However, our understanding on the electron energization through magnetic reconnection still remains poor.

Recent satellite observations in the Earth’s magnetosphere have suggested that magnetic islands generated in the course of the reconnection process can be an important agent for the electron acceleration (Chen et al., 2008; Huang et al., 2012; Retinò et al., 2008). Theoretical modeling has been examined using fully kinetic simulations, demonstrating that most electrons are accelerated adiabatically, that is, by the Fermi-type and betatron-type accelerations, in the magnetic islands (Dahlin et al., 2014; Drake et al., 2006). On the other hand, there are a number of observational evidences that significant magnetic dissipation occurs inside the magnetic islands in association with intense wave activities (Fu et al., 2017; Huang et al., 2019). These observations imply that the frozen-in condition is locally broken for the electrons and they are strongly accelerated in non-adiabatic ways inside the magnetic islands. Non-adiabatic acceleration can take place inside the islands due to the out-of-plane induction electric field as shown in two-dimensional (2D) kinetic simulations (Oka et al., 2010). The induction field is significant, when the islands are located within or very close to the electron diffusion region (EDR), where the islands evolve quickly. However, once the islands are ejected from the EDR, the electric field is drastically weakened (Oka et al., 2010), contrary to the observations where significant dissipation occurs even far downstream of the EDR (Huang et al., 2019). In this
Letter, it is demonstrated by a three-dimensional (3D) particle-in-cell (PIC) simulation that electromagnetic turbulence is responsible for the generation of the non-ideal electric field at the core of magnetic islands and causes strong electron acceleration and heating.

2. Simulation Model

The 3D PIC simulation model employs the adaptive mesh refinement (AMR) that achieves efficient high-resolution kinetic simulation of multi-scale processes (Fujimoto, 2011). The simulation is performed for a Harris-type current sheet (Harris, 1962) with the magnetic field \( B(z) = -B_0 \tanh(z/\delta) \) and the number density \( n(z) = n_0 \sech^2(z/\delta) + n_b \tanh^2(z/\delta) \), where \( \delta \) is the half width of the current sheet and the subscript \( b \) indicates the background parameter. We choose \( \delta = 0.5\lambda_e \) and \( n_b = 0.044n_0 \) with \( \lambda_e \) the ion inertia length based on \( n_0 \). The refinement criteria of the AMR are provided by the local electron Debye length \( \lambda_{De} \) and the electron flow velocity \( V_{ce} \) defined at the center of each computational cell. Each cell is subdivided when \( \Delta_L \geq 2.0\lambda_{De} \) or \( V_{ce} \geq 2.0V_e \) are satisfied, otherwise the child cells are removed, if any, where \( \Delta_L \) is the size of the square computational cells and \( V_A \) is the Alfvén velocity based on \( B_0 \) and \( n_b \). The system boundaries are periodic in the \( x \) and \( y \) directions and the conducting wall in the \( z \) direction. The ion-to-electron mass ratio and velocity of light are \( m_i/m_e = 100 \) and \( c/V_A = 27 \), respectively, corresponding to \( \omega_{pe}/\omega_A = 2.7 \), where \( \omega_{pe} \) and \( \omega_A \) are the electron plasma frequency and cyclotron frequency based on \( n_b \) and \( B_0 \), respectively. The temperature ratios are \( T_i/T_e = 5.0 \), \( T_i/T_b = 1.0 \), and \( T_b/T_e = 1.0 \), so that the background ions are colder than the plasma sheet ions. The system size is \( L_x \times L_y \times L_z = 81.9\lambda_e \times 41.0\lambda_e \times 81.9\lambda_e \), which is entirely covered by base-level cells (coarsest cells) with \( \Delta_L = 0.08\lambda_e \) and can be subdivided locally into finer cells up to the dynamic range level (finest level) with \( \Delta_L = 0.02\lambda_e \). Therefore, the highest spatial resolution is 4096 \( \times \) 2048 \( \times \) 4096 and the maximum number of particles used is \( 4 \times 10^{11} \) for each species. The normalization parameters are \( m_i \) for mass, \( e \) for charge, \( \lambda_e \) for length, and \( V_A \) for velocity, unless otherwise noted. For comparison, a 2D simulation in the \( xz \) plane is conducted with the same setup.

3. Results

Magnetic reconnection is initiated with a small perturbation to the magnetic field \( B_x \) and \( B_z \) so that the magnetic X-line is initially produced at the center of the computational domain. Figure 1a shows a magnetic island ejected downstream from the current layer. The magnetic island is characterized by coiled magnetic field lines and high plasma density. In 3D system, magnetic islands are distorted and fragmented along the \( y \) axis with a typical scale of \( \sim 10\lambda_e \) due to an electron Kelvin-Helmholtz instability excited in the current layer (Fujimoto, 2016). Figures 1a–1c indicate strong electron heating inside the magnetic island. The electron temperature reaches \( T_e = 20T_{e0} \) inside the island, which is much higher than \( T_e = T_{eb} = T_{e0} \) in the inflow region and \( T_e = 7T_{e0} \) in the outflow region surrounding the island, where \( T_e = (T_{ex} + T_{ey} + T_{ez})/3 \) with \( T_{ej} = (m_i/m_e)\int_{y}^{y_j} (\nu_j - V_{ej})^2 f_j(v_j) d^3v_j \) for \( j = x, y, \) and \( z \). It is also interesting to notice that intense electromagnetic turbulence is generated on the scale smaller than the fragmentation scale in the magnetic island as seen in the fluctuation of the neutral sheet in Figure 1b (green curve). The turbulence is mainly driven by the current sheet shear instability (CSSI) with a characteristic scale of \( k\lambda_i \approx (m_i/m_e)^{1/4} \), where \( \lambda_i \) is the local ion inertia length (Fujimoto & Sydora, 2017). Because of the higher density inside the magnetic island (Figure 1d), the wavenumber \( k \) is shifted to higher value when it is normalized to \( \lambda_i \).

Figure 2 compares the results in the 3D and 2D simulations. In the 2D simulation, the variations along the \( y \) axis are not incorporated in principle. The quantities in the 3D simulation are averaged over the magnetic island from \( y/\lambda_i \approx 2.9 \) to 13.1 that is indicated by red shadow in Figures 1b–1e. The averaged quantities are represented by \( \langle \cdot \rangle \), such as \( \langle A \rangle = \int (y_2 - y_1) f_{y} A d\nu \) with \( y_1 = 2.9 \) and \( y_2 = 13.1 \). The gray curves in Figures 2a and 2b stand for the contours of the approximate magnetic flux function \( \Phi \) defined by \( \nabla^2 \Phi = -\mu_0 J_z \), where \( \nabla^2 \approx 0 \) is assumed. In 2D, the \( y \) gradient is rigorously zero, while, in 3D, \( \Phi \) is averaged from \( y_1 \) to \( y_2 \), so that the kinetic scale fluctuations are eliminated. The snapshot in the 2D simulation is taken at a time step where the magnetic island is located at almost the same distance from the X-line as in the 3D simulation. The electron temperature in Figures 2a and 2b indicates that the electrons are more strongly heated in the
Figure 1. Electron heating in a magnetic island. (a) 3D view of the plasma sheet with an isosurface of the electron density at $n_e/n_0 = 0.10$, yellow tubes indicating the magnetic field lines, electron temperature (color contour) and electron flow (green arrows) on the $xy$ plane at $z/l_i = 0$, and 2D profiles of $n_e$ at $x/l_i = 37.2$ and $y/l_i = 8.0$. (b) Electron temperature on the $yz$ plane at $x/l_i = 37.2$ with the neutral line where $B_x = 0$ in green curve. (c–e) Line profiles at $z/l_i = 0.24$, as indicated by white dashed line in panel (b), of panel (c) temperature $T_e = (T_{ex} + T_{ey} + T_{ez})/3$ in black curve with $T_{ex}$ in green curve, $T_{ey}$ in blue curve, and $T_{ez}$ in orange curve, of panel (d) electron density, and of panel (e) magnetic field fluctuations from the averages over the magnetic island ($\delta B_x$ in green, $\delta B_y$ in blue, and $\delta B_z$ in orange). Red and green shadows in panels (b–e) represent the typical regions inside and outside the magnetic island, respectively.

Figure 2. Comparisons between 3D (left panels) and 2D (right panels) simulations. (a and b) Electron temperature on the $xz$ plane. (c and d) 1D profile at $z = 0$ (indicated by white dashed line in panels [a and b], respectively) of the magnetic field components $B_x$ (green), $B_y$ (blue), and $B_z$ (orange), and (e and f) non-ideal electric field, $-\nabla \rho + \mathbf{J} \times \mathbf{B}/\epsilon$, normalized to the upstream quantities (black curve) with each component of the generalized Ohm’s law: $\nabla \cdot \mathbf{J} = \epsilon (n_e) (\mathbf{m}_e/e) \Delta V_x/\Delta t$ (magenta), $(\delta n_e \Delta V_x)/(n_e)$ (red), $(\delta n_e \Delta V_y)/(n_e)$ (water blue), and $(m_e/(n_e) \mathbf{V} \cdot \mathbf{n}_e \Delta V_y/\Delta t)$ (orange). Gray curves in panels (a and b) represent the contours of the approximate magnetic flux function. The 3D results are averaged over $y/l_i = 2.9 - 13.1$. The $x$ locations of the magnetic island cores and the interior regions are indicated by black dashed lines and gray shadows, respectively.
3D magnetic island than in the 2D island. In fact, the electron temperature in the core region is at most $T_e/T_{e0} \approx 10$ in the 2D case, which is less than half of that in the 3D case.

As shown in Figures 2c and 2d, the magnetic field profiles around the magnetic island are similar between the 2D and 3D cases with negligible out-of-plane component. However, the island in 3D is significantly broadened in the $x$ direction as indicated by gray shadows, implying strong magnetic diffusion within the island. The strong diffusion is also manifested by large amplitude of the non-ideal electric field (comparable to the reconnection electric field with $E_y \approx 0.1$) in the magnetic island (black curve in Figure 2e). The non-ideal field causes the magnetic diffusion through the Faraday’s law $\epsilon B \times \tau = -\nabla \times \mathbf{E}$, and results in the non-ideal electron acceleration. The mechanism to generate the non-ideal field is evaluated through the generalized Ohm’s law in the form

$$\mathbf{E} = \langle \mathbf{V}_e \rangle \times \langle \mathbf{B} \rangle - \frac{1}{e \langle n_e \rangle} \nabla \cdot \langle \mathbf{P}_e \rangle + \frac{m_e}{e} \frac{d\langle V_{Te} \rangle}{dt} + \frac{1}{\langle n_e \rangle} \langle \delta n_e \delta V_e \rangle + \frac{m_e}{e} \nabla \cdot \langle \delta n_e \delta \mathbf{V}_e \rangle \delta V_{Te},$$

where $n_e$, $\mathbf{V}_e$, and $\mathbf{P}_e$ are the electron density, electron bulk velocity, and electron pressure tensor, respectively, and $\delta A = A - \langle A \rangle$ denotes the fluctuation of a quantity $A$. Each term in Equation 1 is normalized to the upstream values of the reconnection region, that is, $\mathbf{V}_{in} = B_0/\sqrt{\mu_0 m_e n_e}$, the Alfvén velocity, $B_0$ the magnetic field magnitude, and $n_e$ the plasma density. The first and second terms on the right-hand side are originated from the average electron inertia (Vasyliunas, 1975), while the other terms are generated by turbulence. The third term represents the contribution from electromagnetic turbulence, the fourth term is raised by electrostatic turbulence, and the last term is caused by the eddy viscosity due to turbulence. It is found in Figure 2e that the non-ideal electric field mainly balances the electromagnetic turbulence term (red curve) in the magnetic island. The turbulence driven by the CSSI generates the momentum transfer of the electrons that induces the DC electric field, resulting in the magnetic diffusion and dissipation (Fujimoto & Sydora, 2017).

On the other hand, in the 2D magnetic island, the non-ideal electric field is found to be much smaller than the reconnection electric field (Figure 2f). At the core of the island, the electric field is sustained by the electron inertia term through $\delta V_{Te}/\delta t$ in association with the evolution of the island. As the field lines contract around the island, the magnetic field gradient is intensified at the island core, which induces $E_y$, so as to accelerate the electrons in the $y$ direction. This term is much larger because of the quick evolution, when the island is located within or in close vicinity of the EDR (see one example at $x/\lambda_i = 40.8$), consistent with the previous simulations (Oka et al., 2010). However, once the island has been ejected from the electron current layer, the non-ideal field is drastically decreased, so that the magnetic diffusion and associated electron acceleration are weak. The results in the 2D simulation are contrary to the recent observations where significant dissipation and wave activities were detected in the magnetic islands (Huang et al., 2019).

The strong electron acceleration in the 3D magnetic island is also demonstrated by the energy spectrum density in Figure 3a, where $\int_{\mathcal{E}}^\infty f(\mathcal{E}) d\mathcal{E} = n_e$ with $\mathcal{E} = m_e/(v_x^2 + v_y^2 + v_z^2)/2$. The electrons in the 3D island (red curve) obtain much more energy, not only than the surrounding electrons in the outflow region (green curve, and the $y$ extent is indicated by green shadow in Figures 1b-1e), but also than those in the corresponding 2D island (black curve). In particular, high-energy electrons with $\mathcal{E}/T_{e0} \gtrsim 20$ are produced 2–3 times more in the 3D island than in the 2D island. This is surprising, because the magnetic field intensity forming the 3D island (Figure 2c) is about two times smaller than that of the 2D island (Figure 2d), indicating that the adiabatic acceleration is less effective in 3D. Instead, the non-ideal electric field generated by the turbulence leads to efficient non-adiabatic acceleration of the electrons. Figures 3b and 3c show a typical distribution function of the electrons in the 3D magnetic island. Compared to that in the 2D island in Figures 3d and 3e, one can see that high-energy electrons are more produced in the 3D island and they are well thermalized to form nearly isotropic distribution function. Since the electron density at the island core is almost the same between the 2D and 3D cases, the distribution functions in Figures 3b–3e indicate the strong electron heating in the 3D island.
The electron acceleration processes in the 3D and 2D islands are further examined by means of the test particle simulations. The electron trajectories are started at the core of the magnetic islands and are traced in accordance with the electric and magnetic fields obtained in the 3D and 2D PIC simulations. Figures 3f and 3g show the typical electron trajectories in the velocity space. In the 3D case (Figure 3f), the electrons are efficiently accelerated along the island core by the non-ideal electric field. As discussed below, the high-energy electrons tend to be scattered due to the electromagnetic turbulence, leading to the strong electron heating. Meanwhile, in the 2D island (Figure 3g), the electrons are accelerated mainly by the in-plane electric fields (i.e., $E_x$ and $E_y$) so as to satisfy locally $\vec{E} + \vec{V}_i \times \vec{B} \approx 0$. Most electrons carry out the bouncing motions inside the magnetic island, repeating acceleration and deceleration due to the in-plane fields directing toward the core of the island. Such the electron motions result in the isotropic distribution function seen in Figures 3d and 3e. Because of weak $E_y$, further acceleration in the $y$ direction hardly occurs. Note that the in-plane fields almost satisfy the frozen-in condition, so that these fields have little impact on the magnetic diffusion and dissipation.

The electron thermalization in the 3D island is caused by the scattering of the high-energy electrons due to the electromagnetic turbulence. The power spectrum of $\delta B_y$ in Figure 4 indicates that intense electromagnetic turbulence is established in the magnetic island (red curve). It is clearly shown that the turbulence intensity in the island is significantly higher than in the other regions such as in the outflow region surrounding the island (green curve) and in the electron current layer formed around the $x$-line (blue curve). The electromagnetic turbulence can affect the electron heating. Meanwhile, the in-plane electric fields (i.e., $E_x$ and $E_y$) cause the strong electron heating. As discussed below, the high-energy electrons tend to be scattered due to the electromagnetic turbulence, leading to the strong electron heating.

The power spectrum of $\delta B_y$ in Figure 4 indicates that intense electromagnetic turbulence is established in the magnetic island (red curve). It is clearly shown that the turbulence intensity in the island is significantly higher than in the other regions such as in the outflow region surrounding the island (green curve) and in the electron current layer formed around the $x$-line (blue curve). The electromagnetic turbulence can affect the electron heating. Meanwhile, the in-plane electric fields (i.e., $E_x$ and $E_y$) cause the strong electron heating.

The typical gyro-radius associated with each Fourier component is estimated as $\rho_{x,k} = (m_e\epsilon \delta B_y)/|v| \approx (m_e |e| \delta B_{y,k})/|v|$ with $\delta B_y = \delta B_{y,k} dk$, where it is assumed that the turbulence is dominated by $\delta B_y$. (Figure 1e). It is reasonable to expect that efficient scattering due to the turbulence occurs, when the diameter of the gyro-motion is comparable to half the wavelength, so that

$$2\rho_{x,k} \sim \frac{\pi}{k}.$$  (2)
The argument determines $|\delta B_{x,k}|$ that is optimal for the electron scattering for a given velocity $v$. The corresponding wave power is derived from

$$P_{w,k} dk = |\delta B_{x,k}|^2 \sim \left( \frac{2m_v}{\pi e} \right)^2 k^2,$$

where $P_{w,k}$ is the power spectrum density.

Unlike the turbulence spectra in Figure 4, the wave power in Equation 3 increases with the wavenumber $(\propto k^2)$. Thus, one can determine a unique wavenumber and the corresponding turbulence power responsible for the electron scattering for a given velocity $v$. In Figure 4 (black lines), the power spectra calculated by Equation 3 are overwritten for the cases of $v/V_A = 20, 10, and 5$. The efficient wave-particle interactions can occur at the intersections with the turbulence spectra. One can see that the wave power at the intersections is much larger for the turbulence in the magnetic island (red curve) than in the other regions, suggesting that the strong electron scattering and the associated electron heating can occur in the 3D magnetic island. In particular, higher-energy electrons are expected to have stronger interactions with the turbulence. The electron scattering also induces the non-ideal electric field in addition to the contribution from the momentum transfer of the fluid electron (Fujimoto & Sydora, 2017). In fact, the particle trajectory in Figure 3f demonstrates the electron scattering due to the Lorentz force imposed by the turbulence. One can see that the kinetic energy is almost conserved during the scattering because of the Lorentz force. However, the velocity direction is significantly diverted, which can result in the momentum transport leading to the generation of the non-ideal electric field. The generation of the non-ideal electric field enhances the magnetic diffusion and dissipation in the magnetic island, consistent with the recent observations (Fu et al., 2017; Huang et al., 2019).

4. Conclusions

The present study has shown, using a large-scale PIC simulation in 3D system, that the electrons are effectively accelerated in the magnetic island by the non-ideal electric field generated through the electromagnetic turbulence. It is found that the high-energy electrons are efficiently scattered by the turbulence, resulting in strong electron heating. The large non-ideal electric field in the magnetic island causes strong magnetic diffusion and dissipation, consistent with recent satellite observations in the Earth’s magnetosphere. The present results are in contrast to those in the previous 2D simulations where the non-ideal electric field inside the magnetic island was very small outside the EDR (Oka et al., 2010) and most part of the electron acceleration was explained by the adiabatic processes (Dahlin et al., 2014; Drake et al., 2006). The curvature drift acceleration discussed, for example, in Dahlin et al. (2014) and Huang et al. (2020), does not effectively work for the electrons around the magnetic island core, since they are mostly unmagnetized.

Several electron acceleration models through turbulence in magnetic reconnection have been recently proposed (e.g., Ergun et al., 2020; Lapenta et al., 2020; Lazarian et al., 2020). Ergun et al. (2020) introduced a theoretical model based on the magnetotail observations, where the electrons are efficiently accelerated by high-frequency ($\omega > \omega_A$) electric field in a magnetic depletion region. Their model differs from ours where the electrons are mainly accelerated by the DC electric field induced by electromagnetic turbulence. Lapenta et al. (2020) performed a 3D PIC simulation for investigation of the electron acceleration in the turbulent outflow jets. They found that a strong energization occurs in adiabatic ways at the jet fronts with increased magnetic field. The mechanisms are contrary to our model where the non-adiabatic acceleration is dominant at the magnetic island core with little magnetic field. Finally, Lazarian et al. (2020) provided a review of 3D turbulent reconnection in which effective particle acceleration takes place in contracting magnetic field in 3D in the same manner as the Fermi acceleration similar to that in Drake et al. (2006) and Dahlin et al. (2014). As such, our model in the 3D magnetic island is essentially different from these earlier models based on turbulence in reconnection.

Data Availability Statement

The simulation data and analysis tools used for this research are available via https://doi.org/10.12176/01.99.00401.
Acknowledgments
K. Fujimoto is grateful to R. D. Sydora for useful discussions. The simulations were carried out by the K computer at the RIKEN Advanced Institute for Computational Science through the HPCI Research project (hp140129 and hp150123). The data analyses were partly performed on analysis servers at Center for Computational Astrophysics (CICA), NAOJ. This research was supported by the National Natural Science Foundation of China under Grant Nos. 41874189 and 41821003.

References
Chen, L.-J., Bhattacharjee, A., Puhl-Quinn, P. A., Yang, H., Bessho, N., Imada, S., et al. (2008). Observation of energetic electrons within magnetic islands. Nature Physics, 4, 19–23. https://doi.org/10.1038/nphys777
Dahlin, J. T., Drake, J. F., & Swisdak, M. (2014). The mechanisms of electron heating and acceleration during magnetic reconnection. Physics of Plasmas, 21, 092304. https://doi.org/10.1063/1.4894484
Drake, J. F., Swisdak, M., Che, H., & Shay, M. (2006). Electron acceleration from contracting magnetic islands during reconnection. Nature, 443, 553–556. https://doi.org/10.1038/nature05116
Ergun, R. E., Ahmadi, N., Kromyda, L., Schwartz, S. J., Chasapis, A., Hoilijoki, S., et al. (2020). Particle acceleration in strong turbulence in the Earth’s magnetotail. The Astrophysical Journal, 898, 153. https://doi.org/10.3847/1538-4357/ab9ba5
Fermi, E. (1949). On the origin of the cosmic radiation. Physical Review, 75, 1169–1174. https://doi.org/10.1103/physrev.75.1169
Fu, H. S., Vaivads, A., Khotyaintsev, Y. V., André, M., Cao, J. B., Olshovsky, V., et al. (2017). Intermittent energy dissipation by turbulent reconnection. Geophysical Research Letters, 44, 37–43. https://doi.org/10.1002/2016GL071787
Fujimoto, K. (2011). A new electromagnetic particle-in-cell model with adaptive mesh refinement for high-performance parallel computation. Journal of Computational Physics, 230, 8508–8526. https://doi.org/10.1016/j.jcp.2011.08.002
Fujimoto, K. (2016). Three-dimensional outflow jets generated in collisionless magnetic reconnection. Geophysical Research Letters, 43, 10557–10564. https://doi.org/10.1002/2016GL070810
Fujimoto, K., & Sydora, R. D. (2017). Linear theory of the current sheet shear instability. Journal of Geophysical Research, 122, 5418–5430. https://doi.org/10.1002/2017JA024079
Harris, E. G. (1962). On a plasma sheath separating regions of oppositely directed magnetic field. Il Nuovo Cimento, 23, 115–121. https://doi.org/10.1007/bf02733547
Huang, S. Y., Jiang, K., Yuan, Z. G., Zhou, M., Sahraoui, F., Fu, H. S., et al. (2019). Observations of flux ropes with strong energy dissipation in the magnetotail. Geophysical Research Letters, 46, 580–589. https://doi.org/10.1029/2018GL081099
Huang, S. Y., Vaivads, A., Khotyaintsev, Y. V., Zhou, M., Fu, H. S., Retinó, A., et al. (2012). Electron acceleration in the reconnection diffusion region: Cluster observations. Geophysical Research Letters, 39, L11103. https://doi.org/10.1029/2012GL051946
Huang, S. Y., Zhang, J., Sahraoui, F., Yuan, Z. G., Deng, X. H., Jiang, K., et al. (2020). Observations of magnetic field line curvature and its role in the space plasma turbulence. The Astrophysical Journal Letters, 898, L18. https://doi.org/10.3847/2041-8213/aba263
Lapenta, G., Berchem, J., Alaoui, M. E., & Walker, R. (2020). Turbulent energization of electron power law tails during magnetic reconnection. Physical Review Letters, 125, 225101. https://doi.org/10.1103/PhysRevLett.125.225101
Lazarian, A., Eynik, G. I., Jafari, A., Kowal, G., Li, H., Xu, S., & Vishniac, E. T. (2020). 3D turbulent reconnection: Theory, tests, and astrophysical implications. Physics of Plasmas, 27, 012305. https://doi.org/10.1063/1.5110603
Lin, R. P., & Hudson, H. S. (1976). Nonthermal processes in large solar-flares. Solar Physics, 50, 153–178. https://doi.org/10.1007/bf00206199
Lin, R. P., Krucker, S., Hurford, G. J., Smith, D. M., Hudson, H. S., Holman, G. D., et al. (2003). RHESSI observations of particle acceleration and energy release in an intense solar gamma-ray line flare. The Astrophysical Journal, 595, L69–L76. https://doi.org/10.1086/378932
Oka, M., Fujimoto, M., Shinohara, I., & Phan, T. D. (2010). “Island surfing” mechanism of electron acceleration during magnetic reconnection. Journal of Geophysical Research, 115, A08223. https://doi.org/10.1029/2010JA015392
Retinó, A., Nakamura, R., Vaivads, A., Khotyaintsev, Y., Hayakawa, T., Tanaka, K., et al. (2008). Cluster observations of energetic electrons and electromagnetic fields within a reconnecting thin current sheet in the Earth’s magnetotail. Journal of Geophysical Research, 113, A12215. https://doi.org/10.1029/2008ja013511
Sarris, E. T., Krimigis, S. M., & Armstrong, T. P. (1976). Observations of magnetospheric bursts of high-energy protons and electrons at ~35 Re with Imp 7. Journal of Geophysical Research, 81, 2341–2355. https://doi.org/10.1029/ja081i03p02341
Vasyliunas, V. M. (1975). Theoretical models of magnetic field line merging. Review of Geophysics, 13, 303–336. https://doi.org/10.1029/rg013i001p00303