Enhanced electron mixing and heating in 3-D asymmetric reconnection at the Earth’s magnetopause

A. Le1, W. Daughton1, L.-J. Chen2,3, and J. Egedal4

1Plasma Theory and Applications, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 2Astronomy Department, University of Maryland, College Park, Maryland, USA, 3NASAGoddard Space Flight Center, Greenbelt, Maryland, USA, 4Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin, USA

Abstract Electron heating and mixing during asymmetric reconnection are studied with a 3-D kinetic simulation that matches plasma parameters from Magnetospheric Multiscale (MMS) spacecraft observations of a magnetopause diffusion region. The mixing and heating are strongly enhanced across the magnetospheric separatrix compared to a 2-D simulation. The transport of particles across the separatrix in 3-D is attributed to lower hybrid drift turbulence excited at the steep density gradient near the magnetopause. In the 3-D simulation (and not the 2-D simulation), the electron temperature parallel to the magnetic field within the mixing layer is significantly higher than its upstream value in agreement with the MMS observations.

1. Introduction

Magnetic reconnection transports plasma and energy from the shocked solar wind of the magnetosheath across the magnetopause into Earth’s magnetosphere [Paschmann et al., 1979]. The Magnetospheric Multiscale (MMS) mission [Burch et al., 2014] has enabled detailed multipoint observations of this process with instruments that resolve plasma kinetic scales. The first phase of the mission focused on the magnetopause, which is characterized by large asymmetries in conditions between the sheath and magnetospheric plasmas. Particle-in-cell simulation has been used to study the kinetic signatures of asymmetric reconnection [Pritchett, 2008; Mozer and Pritchett, 2009; Malakit et al., 2010; Egedal et al., 2011; Pritchett et al., 2012; Hesse et al., 2014; Shay et al., 2016; Chen et al., 2016a], primarily in two-dimensional (2-D) systems, and many key particle and field signatures agree favorably with observations [Chen et al., 2016b; Egedal et al., 2016].

An important class of fluctuations is suppressed in 2-D, however. Drift waves and instabilities, particularly the lower hybrid drift instability (LHDI) [Krall and Liewer, 1971], entail variations out of the 2-D plane and may interact with reconnecting current sheets [Hultqvist et al., 1977; Hoshino, 1991; Lapenta et al., 2003; Daughton et al., 2004]. There have been numerous observations of lower hybrid fluctuations at magnetospheric reconnection sites [Gary and Eastman, 1979; André et al., 2001; Bale et al., 2002; Vaivads et al., 2004; Zhou et al., 2009; Norgren et al., 2012; Graham et al., 2016, 2017] and in laboratory reconnection experiments [Carter et al., 2001; Fox et al., 2010]. Initial studies focused on the possibility that LHDI fluctuations could contribute to anomalous resistivity [Davidson and Gladd, 1975] and thereby help explain fast reconnection rates. Under typical magnetospheric conditions with $T_e\geq T_i$, however, LHDI does not significantly alter the reconnection rate or gross dynamics of reconnecting current sheets [Roytershteyn et al., 2012; Zeller et al., 2002; Pritchett, 2013].

We reconsider here the role of drift fluctuations using fully kinetic simulations that match the upstream plasma conditions of a reconnection event observed by the MMS spacecraft [Burch et al., 2016; Price et al., 2016]. For this recent MMS event, simulations indicate that 3-D instabilities do indeed contribute to average electron momentum balance through so-called anomalous viscosity [Price et al., 2016], although the overall reconnection rate is nevertheless similar to 2-D. The lower hybrid range fluctuations are found to enhance the transport of plasma across the magnetospheric separatrix. The plasma transport is then linked with parallel (to the local magnetic field) heating of the electrons near the magnetopause, as observed by MMS. In the 2-D simulation, the observed electron heating scales with previously derived equations of state for adiabatically trapped electrons [Le et al., 2009; Egedal et al., 2013] on both sides of the current sheet. In 3-D, lower hybrid fluctuations with fast parallel dynamics cause the magnetosphere side electron temperature to follow Chew-Goldberger-Low (CGL) scalings [Chew et al., 1956].
2. Particle-in-Cell Simulations

Asymmetric reconnection is studied with fully kinetic simulations in 2-D and 3-D geometries using the code VPIC [Bowers et al., 2008]. The upstream plasma conditions are very similar to those considered in previous numerical modeling [Price et al., 2016] of the MMS diffusion region encounter on 16 October 2015 reported by Burch et al. [2016]. The density asymmetry between the sheath and magnetosphere plasmas for this event is a factor of ~16. In order to resolve this relatively large asymmetry, macroparticles from the two sides are loaded as separate populations with different numerical weights, selected so that each population is resolved with ~150 particles per species per cell. Besides ensuring reasonable resolution of the low-density plasma, modeling the sheath and magnetosphere plasmas as separate populations also allows the mixing of plasma over time to be diagnosed and quantified [Daughton et al., 2014].

The initial conditions include a drifting Harris sheet population superposed on an asymmetric Maxwellian background [Roytershteyn et al., 2012]. For each quantity $Q$ with asymptotic upstream values $Q_o$ and $Q_i$ on the sheath and magnetosphere sides, we define the following 1-D profile depending on coordinate $z$ (note that $x$ and $z$ are reversed compared to typical GSM coordinates at the magnetopause):

$$F(Q_o, Q_i) = (1/2) \left[ (Q_i + Q_o) + (Q_i - Q_o) \tanh(z/\lambda) \right],$$

with $\lambda = d_{io}$ ($d_{io}$ is the ion inertial length based on sheath density $n_o$). The initial reconnecting magnetic field component is $B_y = F (B_o, B_i)$ with $B_i/B_o = -1.7$, and the uniform guide field is $B_z/B_o \approx 0.1$. The temperature profile for each species is taken as $T_i = F (T_{io}, T_{1i})$ with $T_{1i}/T_{io} \approx 3.4$ and $T_{1i}/T_{io} \approx 11.4$. The density profile is then chosen to satisfy hydrodynamic force balance:

$$n = n_{iH} \sech^2(z/\lambda) + \frac{F(n_{iH}T_{io}, n_{iH}T_{1i})}{F(T_{io}, T_{1i})},$$

where the density of the current-carrying Harris population $n_{iH} = n_o \mu_e (|B_y| + |B_z|)^2 / 8T_{io}$ with temperature $T_{io}$ taken as the higher magnetosphere temperature of each species. The density ratio is $n_{iH}/n_i \approx 0.062$. The computational domain for the 3-D run is $L_x \times L_y \times L_z = 4096 \times 1024 \times 2048$ cells = $40d_{io} \times 10d_{io} \times 20d_{io}$, requiring a total of $\sim 2.6$ trillion numerical particles. The $z$ boundaries are conducting and reflect particles, while the domain is periodic in $x$ and $y$, which limits how long the simulation may be run before boundary effects become important [Daughton et al., 2006]. An initial magnetic perturbation seeds reconnection with a single dominant $X$ line. The corresponding 2-D run is identical except that it is reduced to a single cell in the $y$ direction. Other parameters are a reduced ion-to-electron mass ratio of $m_i/m_e = 100$ and frequency ratio $\omega_{peo}/\omega_{ceo} = 1.5$ (based on sheath conditions). In the following, simulation results are plotted at time $t \times \omega_{peo} = 50$, when reconnection is quasi steady. The features of our simulation are similar to those of Price et al. [2016], evidence that the fully developed state of the reconnecting layer depends mainly on the asymptotic boundary conditions and not on the details of the initial equilibrium [Pritchett and Mozer, 2009; Roytershteyn et al., 2012].

3. Fluctuations, Mixing, and Heating

The strong density gradient across the magnetopause in this event is susceptible to drift instabilities [Price et al., 2016], which include out-of-plane variations and are absent in 2-D models. Based on the typical range of wave vectors with $k \cdot \mathbf{B} \sim 0$ and $k \cdot \mathbf{B}_g \sim 1$, the fluctuations and resulting turbulence are associated with the electrostatic lower hybrid drift instability (LHDI) [Daughton, 2003]. At early time in the simulation (Figures 1a and 1c), a coherent mode that propagates in the electron drift direction is dominant in the simulation with $k \cdot \mathbf{B}_g \sim 0.5$ and $\omega^2 \sim \omega_{peo}^2 (1 + 4 \pi n_{iH} e^2 / B^2)$, in agreement with a local electrostatic LHDI dispersion relation [Krall and Liever, 1971]. The density profile in the $y-z$ plane is plotted in Figure 1 at (a) $x = 0.25d_{io}$ and (b) $x = 20.1d_{io}$ (through $X$ line), and the variations about the mean density along the indicated horizontal cuts are plotted in Figures 1e and 1f. The density is modulated along the magnetopause by the rippling of the density gradient layer.

The LHDI in this low-$\beta$ region is predominantly electrostatic, and the associated electric potential is $\Phi_y = -\int E_y dy$ (although because of the weak guide field, $\mathbf{k}$ is not strictly in the $y$ direction). The waves transiently reach a level with $e\Phi_y \sim T_e$ (Figure 1e), and at later time $e\Phi_y \sim 0.1 - 0.2T_e$ similar to magnetospheric observations.
Figure 1. Contours of density in the $y$ (direction of current flow) and $z$ (across the current layer) plane at $\Omega_{ci} = 10$ at (a) $x = 0.25d_0$ and (b) $x = 20.1d_0$ (X line). (c, d) Same as Figures 1a and 1b at a later time $\Omega_{ci} = 50$. (e, f) Profiles along the $y$ direction from the horizontal cut at time $\Omega_{ci} = 10$ indicated in Figures 1a and 1b, where $\beta_e \sim 0.25$. The density fluctuations result from flute-like rippling. The potential $\Phi_y = -\int E_y dy$, and $\Phi_B$ is defined by Norgren et al. [2012].

(g) The normalized reconnection rate (blue), and $T_e/\parallel$ (red) averaged over the $y$ direction and the segment $z = 11–12d_0$ at $x = 20.1d_0$ (X line).

[Norgren et al., 2012; Graham et al., 2016]. Assuming the reconnection electric field is $E_r \sim 0.1B_\parallel v_\parallel/c$, the ratio of the wave electric field $E_w$ to $E_r$ will be

$$
\frac{E_w}{E_r} \sim \sqrt{\frac{\beta_e m_i}{m_e}},
$$

where we assume $E_w \sim k_\perp \Phi_y \sim \Phi_y/\rho_e$ and $e\Phi_y/T_e \sim 0.1$, and $\beta_e$ is the ratio of electron fluid to magnetic pressure. For our initial conditions, $\beta_e$ has asymptotic values of 0.24 (sheath) and 0.017 (magnetosphere). Under typical conditions with $\beta_e > m_e/m_i$, the fluctuating electric field may therefore be significantly larger than the reconnection field and strongly influence the electrons. The contributions of fluctuations to the $y$-averaged electron momentum balance equation [Royerstheyn et al., 2012; Price et al., 2016] are plotted in Figure 2g along a cut across the X line. We find in agreement with Price et al. [2016] that anomalous viscosity $\alpha < J \times \delta B >$ is comparable to the inertial term near the X line and to the pressure term near the stagnation region. Anomalous resistivity $\alpha < \delta n \delta E_r >$ is large during a transient early phase, but it becomes small as the initially steep gradients relax. This later state is likely more representative of actual conditions in space.
Figure 2. Profiles through the X line at $x = 20.1d_0$ across the reconnection layer of (a) the density, (b) the mix diagnostic $M$, (c) the out-of-plane current, (d) the reconnecting magnetic field component, (e) the parallel electron temperature, and (f) the perpendicular electron temperature. (g) Terms in the averaged Ohm’s law, where $\langle Q \rangle$ is a spatial $y$ average of quantity $Q$ and $\delta Q = Q - \langle Q \rangle$. (h, i) The inflowing sheath electrons display the temperature scalings of Le et al. [2009], and the magnetosphere electrons follow CGL [Chew et al., 1956] scalings. (j) The CGL and trapping equations of state (EoS 2009) for $T_\parallel$ as functions of density for a fixed magnetic field strength $B/B_\infty = 1$ (subscript $\infty$ refers to upstream conditions).
Figure 3. Profiles from particle-in-cell (PIC) simulations of asymmetric reconnection. (a, d) The electron mixing measure is defined as $M = (n_{sh} - n_{sp}) / (n_{sh} + n_{sp})$, where $n_{sh}$ and $n_{sp}$ are the densities of electrons that were initially on the sheath and magnetosphere sides of the domain. The electron parallel temperature $T_{e∥}$ is elevated within the mix layer in the (b) 3-D run, while it remains lower in the (e) 2-D run. The perpendicular electron temperature is moderate in both (c) 3-D and (f) 2-D. In-plane magnetic flux surfaces are drawn for the 2-D simulation.

While the lower hybrid fluctuations here are mainly electrostatic in the edge region, the $\mathbf{E} \times \mathbf{B}$ electron currents in the wave field generate a magnetic perturbation of the local equilibrium (reconnecting) field component. Norgren et al. [2012] developed an analysis method based on the following potential inferred from magnetic fluctuations: $(e \Phi_B/T_e) = (2/\beta_e) (\Delta B_x/B_x)$. This potential $\Phi_B$ is compared to the electric potential $\Phi_y$ in Figure 1e, and they indeed agree well. Note that the magnetic field fluctuation is in phase with the wave electrostatic potential (and thus out of phase with the wave electric field), and $\Delta B_x/B_x$ will be small when $e \Phi_y/T_e < 1$ and $\beta_e < 1$.

At later times, turbulence develops from the fluctuations. The lower hybrid drift waves appear to couple to electron velocity shear-driven modes [Romero et al., 1992], leading to the development of vortices (Figure 1b). The turning over of vortices may also twist magnetospheric field lines into flux ropes that undergo local reconnection [Ergun et al., 2016], but the specific details of this hypothesis remain to be investigated in the present run. In addition, we observe in Figure 1b a kink with the longest wavelength accessible in this system, which based on its wave number of $k_y \sqrt{\rho_i/\rho_e} \sim 0.6$ could be the electromagnetic LHDI that develops in the high-$\beta$ center of reconnecting current sheets [Daughton, 2003; Roytershteyn et al., 2012]. The kinking of the current sheet is largest at the magnetic O line within the exhaust, and it is much weaker near the X line.

Although LHDI under typical magnetospheric conditions does not significantly alter the gross reconnection rate or dynamics [Zeiler et al., 2002; Roytershteyn et al., 2012; Pritchett, 2013], the fluctuations may enhance the transport of plasma across the magnetic field. The electron transport is quantified using a mixing diagnostic plotted in Figure 3 from the (a) 3-D and (d) 2-D simulations, defined as $M = (n_{sh} - n_{sp}) / (n_{sh} + n_{sp})$ [Daughton et al., 2014]. The quantities $n_{sh}$ and $n_{sp}$ are the local densities of electrons that originated on the sheath and magnetosphere sides of the initial current layer. Visible in the 3-D data (Figure 3a) is a layer of width $\sim 1 - 2d_0$ bordering the magnetosphere side separatrix where the electron populations are well mixed, with roughly equal electron densities from each side of the magnetopause. In 2-D (Figure 3d), on the other hand, the mixing of sheath electrons into the magnetosphere is minimal. In 2-D systems, conservation of out-of-plane canonical momentum ties the electron particle orbits to flux surfaces, and particle mixing is therefore limited to a scale on the order of the electron gyroradius (based on the in-plane magnetic field) across the magnetic separatrix.

LHDI initially heats electrons in the perpendicular direction [Daughton et al., 2004], and in large systems it can potentially generate superthermal electrons in the parallel direction [Cairns and McMillan, 2005]. In this simulation, the electron energization is mainly parallel and is linked to enhanced transport in 3-D, particularly
after the reconnection rate peaks (see Figure 1g). The parallel electron temperature $T_{e\parallel}$ is plotted in Figure 3 from the (b) 3-D run and the (e) 2-D run. In the 3-D simulation, the electron parallel temperature is enhanced within the mixing layer, and it reaches peak values of $T_{e\parallel}/T_{e\perp} \sim 4–5$. One of the key observations by MMS during the 16 October 2015 reconnection event was an increased parallel electron temperature near the diffusion region [Burch et al., 2016], with peak anisotropy in the observations of $T_{e\parallel}/T_{e\perp} \sim 3$. Note that the parallel heating is significantly weaker in the 2-D run with a peak of $T_{e\parallel}/T_{e\perp} \sim 1.6$. In both 2-D and 3-D, the perpendicular electron heating is comparatively mild (Figures 3c and 3f).

The differences between 2-D and 3-D mixing and heating are also illustrated in Figure 2, which displays profiles from both the 2-D and the 3-D runs along cuts through the approximate X line. Within the region of strong LHDI fluctuations at $z \sim 11–13d_{01}$ in the 3-D run, there is an enhancement of the total density (Figure 2a). This denser plasma on the magnetosphere side coincides with the region of electron mixing (Figure 2b), which is shifted to the magnetosphere side of both the approximate X line (indicated by the vertical dashed lines) and the peak of the out-of-plane current (Figure 2c) or equivalently the magnetic shear layer (Figure 2d). The increased electron parallel temperature that is evident in Figure 3b is also plotted in Figure 2e. As noted above, the perpendicular electron temperature (Figure 2f) does not display evidence of strong heating in either 2-D or 3-D.

4. Particle and Fluid Pictures

We consider the energization physics both by examining the electron velocity distributions and by considering a fluid description. Electron velocity distributions in $v_{\parallel},v_{\perp}$ space are plotted in Figure 4 from particles in a box of side 0.2$d_{01}$ centered at the cross plotted in Figure 4a. This point, at which $T_{e\parallel}/T_{e\perp} \sim 4$, is deeper into the magnetosphere than the typical location of crescent-shaped electron distributions [Burch et al., 2016] (see Figures 4e–4g), which persist in 3-D [Price et al., 2016] and are typically found within an in-plane gyroradius of the magnetospheric separatrix [Egedal et al., 2016].

Separate velocity distributions are plotted in Figure 4 for electrons originating in (b) the sheath and (c) the magnetosphere, along with (d) the total electron distribution. The sheath electrons that have penetrated into the magnetosphere in Figure 4b display a discontinuous distribution as a function of parallel velocity, with gaps for certain ranges of $v_{\parallel}$, suggesting that the plasma conditions within this flux tube vary faster than the transit time of the electrons across the reconnection region. Similar discontinuities are also visible in the magnetosphere electron distribution in Figure 4c, where, for example, the phase space density is reduced below $v_{\parallel} \sim -v_{\perp-1}$. Interestingly, the combined total distribution in Figure 4e is relatively smooth. It resembles the elongated trapped distributions typical of laminar 2-D current sheets [Egedal et al., 2013] and observed near magnetopause reconnection sites [Graham et al., 2014, 2016].

In this system, electron orbits very near the X line are chaotic [Le et al., 2013; Egedal et al., 2016]. In the inflows, however, the electrons undergo regular magnetized motion with well-conserved adiabatic invariant $\mu$, and those electron populations that remain on one side of the separatrix follow relatively simple equations of state. In Figures 2h and 2i, each electron population (sheath and magnetosphere) is treated as a separate fluid with its own density and temperature moments. The sheath electron density $n_{e\text{sh}}$ and temperature $T_{e\text{sh}}$ within the sheath follow equations of state for electrons that are adiabatically trapped by a localized parallel electric field [Le et al., 2009; Egedal et al., 2013]. The highest parallel temperatures are predicted in regions of weak magnetic field and enhanced ion density. A weaker magnetic field occurs when magnetic flux tubes expand, driving a rarefaction of the electron density. Meanwhile, the quasi-neutrality constraint requires the electron and ion densities to closely match, and this is accomplished by parallel compression (and associated heating). As plotted on the left-hand sides of Figures 2h and 2i, the trapping leads to moderate parallel heating and perpendicular cooling in the sheath inflow with a peak anisotropy of $T_{e\text{sh}||}/T_{e\text{sh}\perp} \sim 3$, similar in 2-D and 3-D. In the 2-D simulation, the electron heating and temperature anisotropy are weaker on the low-$\beta$ magnetosphere side, as opposed to previous simulation studies. This is because the in-plane flow stagnation point is well separated from the X line [Cassak and Shay, 2007] for these parameters, and as a result few magnetosphere electrons enter regions of enhanced density or weak magnetic field that are conducive to strong heating.

The heating within the magnetosphere inflow is substantially enhanced in 3-D, in part because particle transport alters the plasma profiles (as in Figure 2) and magnetosphere electrons enter regions of increased ion density. The heating, however, is stronger than predicted by the adiabatic trapping model, and the magnetosphere electrons (within the magnetosphere inflow) more closely obey CGL scalings [Chew et al., 1956].
Figure 4. (a) The electron temperature anisotropy $T_{e\parallel}/T_{e\perp}$ near the X line in a cut of the 3-D PIC simulation. The magenta contours mark electron mix fractions of 0.1. The distribution in parallel ($v_{\parallel}$) and perpendicular ($v_{\perp}$) velocity space of electrons originating from the (b) sheath and (c) magnetosphere at the green $\times$ in Figure 4a, where $T_{e\parallel}/T_{e\perp} \sim 4$. (d) Plot of the total combined electron distribution. (e–g) Similar plots for the point marked by a red circle in Figure 4a showing perpendicular crescents in $v_{\perp1} - v_{\perp2}$ space.

$T_{e\parallel} \propto n_{sp\parallel}^2/B^2$ and $T_{e\perp} \propto B$, as plotted on the right-hand sides of Figures 2h and 2i. Similar scalings hold within the mixing layer downstream of the X line (not plotted). The CGL model assumes only that the electrons are well magnetized ($\mu$ is invariant) and the parallel thermal heat flux is negligible. In the deeply trapped regime, the trapping model of Le et al. [2009] reduces to the CGL scalings, although the CGL parallel temperature is asymptotically a factor of $\sim 2$ greater (see Figure 2j). The trapping model likely fails because it assumes that trapped electron bounce times are shorter than any other relevant time scale. The ratio of the electron bounce frequency to the lower hybrid frequency, however, is $\sim \omega_{pe}/\omega_{LH} \sim 2\pi \sqrt{\beta}/(L_\parallel/d)$, where a typical parallel length scale $L_\parallel$ is a few $d$. Thus, in low or moderate $\beta$ magnetospheric plasmas, the finite transit time of
Acknowledgments
A.L. received support from the LDRD office at LANL and acknowledges NASA grant NNX14AL38G. W.D.’s work was supported by NASA grant NNH13AW51L. L.-J.C. received support from DOE grant DESC0016278; NSF grants AGS-1202537, AGS-1543598, and AGS-1552142; and the NASA Magnetospheric Multiscale Mission. J.E. acknowledges support through NSF GEM award 1405166 and NASA grant NNX14AC68G. Simulations were performed at LANL on the Trinity machine and with Institutional Computing resources. Archived simulation data are available upon request to the authors.

References
André, M., et al. (2001), Multi-spacecraft observations of broadband waves near the lower hybrid frequency at the earthward edge of the magnetopause, Ann. Geophys., 19, 1471 – 1481.
Bale, S., F. Mozer, and T. Phan (2002), Observation of lower hybrid drift instability in the diffusion region at a reconnecting magnetopause, Geophys. Res. Lett., 29(24), 2180, doi:10.1029/2002GL016113.
Bowers, K., J. Albright, L. Yin, B. Bergen, and T. J. T. Kwan (2008), Ultrahigh performance three-dimensional electromagnetic relativistic kinetic plasma simulation, Phys. Plasmas, 15(5), 055703, doi:10.1063/1.2840133.
Burch, J., T. Moore, R. Torbert, and B. Giles (2014), Magnetospheric multiscale overview and science objectives, Space Sci. Rev., 199, 5–21.
Burch, J. L., et al. (2016), Electron-scale measurements of magnetic reconnection in space, Science, 352(6290), aaaf2939, doi:10.1126/science.aaaf2939.
Cairns, I. H., and B. McMillan (2005), Electron acceleration by lower hybrid waves in magnetic reconnection regions, Phys. Plasmas, 12(10), 102110.
Carter, T., J. I., F. Trinitchouk, M. Yamada, and R. Kulsrud (2001), Measurement of lower-hybrid drift turbulence in a reconnecting current sheet, Phys. Rev. Lett., 88(1), 015001.
Cassak, P. A., and M. A. Shay (2007), Scaling of asymmetric magnetic reconnection: General theory and collisional simulations, Phys. Plasmas, 14(10), 102114, doi:10.1063/1.2795630.
Chen, L.-J., M. Hesse, S. Wang, N. Bessho, and W. Daughton (2016a), Electron energization and structure of the diffusion region during asymmetric reconnection, Geophys. Res. Lett., 43, 2405 – 2412, doi:10.1002/2016GL068243.
Chen, L.-J., et al. (2016b), Electron energization and mixing observed by MMS in the vicinity of an electron diffusion region during magnetopause reconnection, Geophys. Res. Lett., 43, 6036–6043, doi:10.1002/2016GL069215.
Chew, G. F., M. L. Goldberger, and F. E. Low (1956), The Boltzmann equation and the one-fluid hydrodynamic equations in the absence of particle collisions, Proc. R. Soc. A, 236, 112 – 118.
Daughton, W. (2003), Electromagnetic properties of the lower-hybrid drift instability in a thin current sheet, Phys. Plasmas, 10(8), 3103 – 3119, doi:10.1063/1.1594724.
Daughton, W., G. Lapenta, and P. Ricci (2004), Nonlinear evolution of the lower-hybrid drift instability in a current sheet, Phys. Rev. Lett., 93(10), 105004.
Daughton, W., J. Scudder, and H. Karimabadi (2006), Fully kinetic simulations of undriven magnetic reconnection with open boundary conditions, Phys. Plasmas, 13(7), 072101, doi:10.1063/1.2218817.
Daughton, W., T. K. M. Nakamura, H. Karimabadi, V. Roytershteyn, and B. Loring (2014), Computing the reconnection rate in turbulent kinetic layers by using electron mixing to identify topology, Phys. Plasmas, 21(5), 052307, doi:10.1063/1.4875730.
Davidson, R., and N. Gladd (1975), Anomalous transport properties associated with the lower-hybrid-drift instability, Phys. Fluids, 18(10), 1327 – 1333.

electrons must be taken into account for lower hybrid frequency range fluctuations. In fact, a similar CGL scaling held in a simulation of magnetic island merging [Le et al., 2012] within large-amplitude ion cyclotron waves with high parallel phase speeds. This suggests that when the parallel dynamics of fluctuations (with typical frequencies below \( \omega_{ce} \)) are fast enough, the electron heat flux associated with parallel streaming will become unimportant, and the electron fluid will obey CGL scalings to a good approximation.

5. Discussion and Summary
We compared the electron mixing and heating between 2-D and 3-D kinetic simulations of asymmetric reconnection with plasma parameters matching those of an event observed by the MMS spacecraft [Burch et al., 2016]. The primary differences between 2-D and 3-D resulted from the development of lower hybrid range fluctuations [Daughton, 2003]. While the electrostatic lower hybrid drift waves do not strongly influence the overall reconnection rate [Roytershteyn et al., 2012], they enhance cross-field plasma transport from the sheath into the magnetosphere.

For these plasma parameters, the magnetosphere heating is relatively weak in 2-D, as opposed to previous results for asymmetric reconnection [Egedal et al., 2011]. The difference likely stems from the relatively extreme asymmetry of the upstream plasma conditions, which increases the separation between the X line and flow stagnation points [Cassak and Shay, 2007]. In 3-D, the electron parallel heating is strongest on the magnetosphere side. This results from two mechanisms. First, lower hybrid induced transport alters the mean plasma profiles, such that magnetosphere electrons move through regions of increased density and weaker magnetic field, which both tend to increase the level of electron parallel heating and temperature anisotropy [Le et al., 2009; Egedal et al., 2013]. And second, the fast parallel dynamics of the lower hybrid fluctuations leads the electrons to more closely follow CGL temperature scalings, which predict even stronger parallel heating than the adiabatic trapping model (see Figure 2j). The CGL scalings may be pertinent to a variety of situations where fluctuations have typical parallel variations faster than electron orbit times, although in practice they would be difficult to apply to observational data when populations of electrons from different sources mix. It is worth noting, finally, that the transport and heating associated with lower hybrid fluctuations do not depend strongly on the presence or rate of magnetic reconnection, and they could continue to be important throughout the magnetopause boundary layer even in the absence of reconnection [Treumann et al., 1991].
Egedal, J., A. Le, P. L. Pritchett, and W. Daughton (2011), Electron dynamics in two-dimensional asymmetric anti-parallel reconnection, Phys. Plasmas, 18(10), 102901, doi:10.1063/1.3646316.

Egedal, J., A. Le, W. Daughton, B. Wetherton, P. A. Cassak, L.-J. Chen, B. Lavraud, R. B. Torbert, J. Dorelli, D. J. Gershman, and L. A. Avanov (2016), Spacecraft observations and analytic theory of crescent-shaped electron distributions in asymmetric magnetic reconnection, Phys. Rev. Lett., 117, 185101, doi:10.1103/PhysRevLett.117.185101.

Egedal, J., A. Le, and W. Daughton (2013), A review of pressure anisotropy caused by electron trapping in collisionless plasma, and its implications for magnetic reconnection, Phys. Plasmas, 20(6), 061201, doi:10.1063/1.4811092.

Ergun, R. E., et al. (2016), Magnetospheric multiscale satellites observations of parallel electric fields associated with magnetic reconnection, Phys. Rev. Lett., 116, 235102, doi:10.1103/PhysRevLett.116.235102.

Fox, W., M. Porkolab, J. Egedal, N. Katz, and A. Le (2010), Laboratory observations of electron energization and associated lower-hybrid and Trivelpiece-Gould wave turbulence during magnetic reconnection, Phys. Plasmas, 17(7), 072303.

Gary, S. P., and T. E. Eastman (1979), The lower hybrid drift instability at the magnetopause, J. Geophys. Res., 84(A12), 7378–7381.

Graham, D. B., Y. V. Khotyaintsev, A. Vaivads, M. André, and A. Fazakerley (2014), Electron dynamics in the diffusion region of an asymmetric magnetic reconnection, Phys. Rev. Lett., 112(21), 215004.

Graham, D. B., et al. (2016), Electron currents and heating in the ion diffusion region of asymmetric reconnection, Geophys. Res. Lett., 43, 4691–4700, doi:10.1002/2016GL068613.

Graham, D. B., et al. (2017), Lower hybrid waves in the ion diffusion and magnetospheric inflow regions, J. Geophys. Res. Space Physics, 122, 517–533, doi:10.1002/2016JA023572.

Hesse, M., N. Aunai, D. Sibeck, and J. Birn (2014), On the electron diffusion region in planar, asymmetric, systems, Geophys. Res. Lett., 41, 8673–8680, doi:10.1002/2014GL061586.

Hoshino, M. (1991), Forced magnetic reconnection in a plasma sheet with localized resistivity profile excited by lower hybrid drift type instability, J. Geophys. Res., 96(A7), 11,555–11,567.

Huba, J. D., N. T. Gladd, and K. Papadopoulos (1977), The lower-hybrid-drift instability as a source of anomalous resistivity for magnetic field line reconnection, Geophys. Res. Lett., 4, 125–126, doi:10.1029/GL004i003p00125.

Kraß, N. A., and P. C. Lever (1971), Low-frequency instabilities in magnetic pulses, Phys. Rev. A, 4(S), 2094–2103.

Lapenta, G., J. Brackbill, and W. Daughton (2003), The unexpected role of the lower hybrid drift instability in magnetic reconnection in three dimensions, Phys. Plasmas, 10(5), 1577–1587.

Le, A., H. Karimabadi, J. Egedal, V. Roytershteyn, and W. Daughton (2012), Electron energization during magnetic island coalescence, Phys. Plasmas, 19(7), 072120.

Le, A., J. Egedal, O. Ohia, W. Daughton, H. Karimabadi, and V. S. Lukin (2013), Regimes of the electron diffusion region in magnetic reconnection, Phys. Rev. Lett., 110, 135004, doi:10.1103/PhysRevLett.110.135004.

Le, A. J. Egedal, W. Daughton, W. Fox, and N. Katz (2009), Equations of state for collisionless guide-field reconnection, Phys. Rev. Lett., 102(8), 085001, doi:10.1103/PhysRevLett.102.085001.

Malakit, K., M. Shay, P. Cassak, and C. Bard (2010), Scaling of asymmetric magnetic reconnection: Kinetic particle-in-cell simulations, J. Geophys. Res., 115, A10223, doi:10.1029/2010JA015452.

Mozer, F. S., and P. L. Pritchett (2009), Regions associated with electron physics in asymmetric magnetic field reconnection, Geophys. Res. Lett., 36, L07102, doi:10.1029/2009GL037463.

Norgren, C., A. Vaivads, Y. V. Khotyaintsev, and M. André (2012), Lower hybrid drift waves: Space observations, Phys. Rev. Lett., 109(5), 055001.

Paschmann, G., I. Papamastorakis, N. Scopke, G. Haerendel, B. U. O. Sonnerup, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russel, and R. C. Elphic (1979), Plasma acceleration at the Earth’s magnetopause—Evidence for reconnection, Nature, 282, 243–246, doi:10.1038/282243a0.

Price, L., M. Swisdak, J. F. Drake, P. A. Cassak, J. T. Dahlin, and R. E. Ergun (2016), The effects of turbulence on three-dimensional magnetic reconnection at the magnetopause, Geophys. Res. Lett., 43, 6020–6037, doi:10.1002/2016GL069578.

Pritchett, P. (2013), The influence of intense electric fields on three-dimensional asymmetric magnetic reconnection, Phys. Plasmas, 20(6), 061204.

Pritchett, P., F. Mozer, and M. Wilber (2012), Intense perpendicular electric fields associated with three-dimensional magnetic reconnection at the subsolar magnetopause, J. Geophys. Res., 117, A06212, doi:10.1029/2012JA017533.

Pritchett, P. L. (2008), Collisionless magnetic reconnection in an asymmetric current sheet, J. Geophys. Res., 113, A06210, doi:10.1029/2007JA012930.

Pritchett, P. L., and F. S. Mozer (2009), Asymmetric magnetic reconnection in the presence of a guide field, J. Geophys. Res., 114, A11210, doi:10.1029/2009JA014343.

Romero, H., G. Ganguli, Y. Lee, and P. Palmasasso (1992), Electron –ion hybrid instabilities driven by velocity shear in a magnetized plasma, Phys. Fluids B, 4(7), 1708–1723.

Roytershteyn, V., W. Daughton, H. Karimabadi, and F. S. Mozer (2012), Influence of the lower-hybrid drift instability on magnetic line reconnection in asymmetric configurations, Phys. Rev. Lett., 108, 185001, doi:10.1103/PhysRevLett.108.185001.

Shay, M., T. Phan, C. Haggerty, M. Fujiwara, J. Drake, K. Malakit, P. Cassak, and M. Swisdak (2016), Kinetic signatures of the region surrounding the x line in asymmetric (magnetopause) reconnection, Geophys. Res. Lett., 43, 4145–4154, doi:10.1002/2016GL069334.

Treumann, R. A., J. LaBelle, and R. Pottelette (1991), Plasma diffusion at the magnetopause: The case of lower hybrid drift waves, J. Geophys. Res., 96(A9), 16,009–16,013, doi:10.1029/91JA01671.

Vaivads, A., M. André, S. C. Buchert, J.-E. Wahlund, A. N. Fazakerley, and N. Cornilleau-Wehrlin (2004), Cluster observations of lower hybrid turbulence within thin layers at the magnetopause, Geophys. Res. Lett., 31, L03804, doi:10.1029/2003GL018142.

Zeiler, A., D. Biskamp, J. Drake, B. Rogers, M. Shay, and M. Scholer (2002), Three-dimensional particle simulations of collisionless magnetic reconnection, J. Geophys. Res., 107(A9), 1230, doi:10.1029/2001JA000287.

Zhou, M., et al. (2009), Observation of waves near lower hybrid frequency in the reconnection region with thin current sheet, J. Geophys. Res., 114, A02216, doi:10.1029/2008JA013427.