Breaking magnetic field lines during reconnection

H. Che¹, J. F. Drake², M. Swisdak²

¹University of Colorado, Boulder, CO, 80309
²University of Maryland, College Park, MD 20742

During magnetic reconnection, the field lines must break and reconnect to release the energy that drives solar and stellar flares¹,² and other explosive events in nature³ and the laboratory⁴. Specifically how this happens has been unclear since dissipation is needed to break magnetic field lines and classical collisions are typically weak. Ion-electron drag arising from turbulence⁵, dubbed ‘anomalous resistivity’, and thermal momentum transport⁶ are two mechanisms that have been widely invoked. Measurements of enhanced turbulence near reconnection sites in space⁷,⁸ and in the laboratory⁹,¹⁰ lend support to the anomalous resistivity idea but there has been no demonstration from measurements that this turbulence produces the necessary enhanced drag¹¹. Here we report computer simulations that conclusively show that neither of the two previously favored mechanisms control how magnetic field lines reconnect in the plasmas of greatest interest, those in which the magnetic field dominates the energy budget. Rather, we find that when the current layers that form during magnetic reconnection become too intense, they disintegrate and spread into a complex web of filaments that causes the rate of reconnection to increase abruptly. This filamentary web can be explored in the laboratory or in space with satellites that can measure electric and magnetic field fluctuations with frequencies up to the electron cyclotron frequency.

Particle-in-cell (PIC) simulations reveal that at late time the rate of reconnection in a 3-D reconnecting system jumps sharply above the rate measured in 2-D (Fig. 1a). The jump is a consequence of the development of turbulence in 3-D. To understand why this happens it is necessary to explore how magnetic fields break and reconnect. Magnetic reconnection (Fig. 2a) produces large electric fields that are parallel to the local magnetic field in the vicinity of the x-line (Fig. 2b). In the absence of finite electron mass or other dissipative processes, such a parallel electric field would produce an infinite current and reconnection would cease. The mechanisms that limit the electron response to parallel electric fields can be understood from the electron momentum equation in the direction perpendicular to the plane of reconnection (the z direction),¹²

\[
\frac{\partial \tilde{p}_e}{\partial t} + \nabla \cdot \tilde{P}_e v_{ze} = -e n_e E_z + \frac{1}{c} \left( \mathbf{j}_e \times \mathbf{B} \right)_z - \nabla \cdot \tilde{P}_e, \quad (1)
\]

where \( \tilde{p}_e \) is the momentum density, \( \mathbf{j}_e \) is the electron current density and \( \tilde{P}_e = \tilde{P}_e \cdot \mathbf{\hat{z}} \) with \( \tilde{P}_e \) the pressure tensor. In a 3-D system where the intense current layers produced during reconnection (Fig. 2c) drive short-scale turbulence with wavevectors along the z direction, the impact of this turbulence can be quantified by averaging Eq.
The comparison of the time development of the rate of reconnection between 2-D and 3-D reveals that for a system that initially has low $\beta_\perp$, the rate of reconnection rises in time with the two simulations matching until $\Omega_t t \approx 3.0$ when the rate in the 3-D case abruptly increases above that in 2-D (Fig. 1a). The reconnection electric field $E_z$ drives a strong current around the x-line that strengthens and narrows in time (Fig. 1a). At late time the current layer in the 3-D case abruptly broadens. A cut of the current density $J_{ez}$ in the plane of reconnection at late time reveals that the current layer in 3-D is not laminar (Fig. 2c), suggesting that the broadening of the current layer is a result of turbulence. The transition between the nearly laminar current layer at $\Omega_t t \approx 3.0$ and the highly filamented current layer at $\Omega_t t \approx 3.75$ is shown in Figs. 3a, b. The sharp jump in the strength of the magnetic field perturbation (Figs. 3c, d) and the wavelength of the electric field perturbations (Figs. 3e, f) indicate that this current filamentation instability
is distinct from the Buneman, electron-hole and lower-hybrid instabilities explored earlier in observations and modeling. This instability did not appear in earlier simulations because the computational domains along z were too short to capture its long wavelength parallel to \( \mathbf{B} \). The variances in the electric fields around the x-line (Fig. 1b) further demonstrate the strong correlation between the onset of the turbulence at late time and the abrupt increase in the rate of reconnection in the 3-D simulation.

While the development of turbulence in Figs. 1-3 is clear, the role of this turbulence in reconnection, and whether it facilitates the breaking of field lines, requires the evaluation of Ohm’s law in Eq. (2) around the x-line. Cuts of important terms in Ohm’s law along the y direction through the x-line from 2-D and 3-D simulations appear in Fig. 4. In the 2-D case the reconnection electric field is balanced by the electron inertia even at late time. Heating of electrons within the dissipation region in this case is insufficient to enable the thermal momentum transport to increase to balance the reconnection electric field. The data in Fig. 4 for the 3-D case documents a rapid evolution in the mechanisms controlling how the magnetic field lines are broken during reconnection. At \( \Omega_t t \approx 3.0 \) the reconnection electric field is still mostly balanced by the electron inertia with turbulence induced drag playing a modest role. By \( \Omega_t t \approx 3.35 \) the turbulence induced drag has increased sufficiently to reach parity with the inertia. By \( \Omega_t t \approx 3.75 \) in Fig. 4c the filamentation instability is dominating the dynamics and the resulting turbulent momentum transport almost completely balances the reconnection electric field. The positive spike in \( \hat{\mathbf{V}} \cdot \hat{\mathbf{J}}_{\text{ce}} \) at the x-line with negative minima upstream demonstrates that momentum is being transported away from the x-line. The sudden broadening of the current layer (Fig. 1a) by the filamentation instability at this time causes the electron streaming velocity and the inertia term in Ohm’s law to decrease sharply at the x-line but increase upstream where the momentum is transported. Similarly, the sudden decrease in the streaming velocity at the x-line reduces the turbulent drag. This chain of events can be seen in the time sequence of the inertia, drag and transport terms in Fig. 1c. The dominance at late time of the turbulent transport of momentum in Ohm’s law is evident. The spatial structure of turbulent momentum transport (Fig. 2d) maps that of the current layer (Fig. 2c), where white denotes a decrease in the local momentum and black indicates an increase.

The spatial structure of the drag (Fig. 2e) is very different. Since it does not correlate with the region of high current density, it is incorrect to denote this as an “anomalous resistivity”. The drag maps the region of high electron streaming velocity and large parallel electric field (Fig. 2b), which both peak within the density cavity that is intrinsic to collisionless reconnection with a guide field. Because the drag does not act directly on the current, which controls the magnetic structure of the dissipation region and associated outflows, Fig. 2 provides further evidence that at late time the drag is less important as a facilitator of reconnection than the turbulent momentum transport.

What is the nature of the instability that drives the filamentation of the current shown in Fig. 3? In the frame of the simulation, the time-dependence of the transverse electric fields reveal that it is a right-hand circularly polarized electromagnetic wave and hence is part of the whistler/electron-cyclotron branch. The spatial correlation between the current density and transport in Fig. 2 suggests that it is driven by the current density
gradient. The measured phase speed of $10c_{As}$ is close to the electron drift speed, suggesting that the coupling to the ions is weak. A simple fluid description of electromagnetic waves in this regime is given by the electron MHD equation,\(^\text{23, 24}\)

$$
\frac{\partial}{\partial t} \mathbf{PB} = \frac{1}{ne} \tilde{\nabla} \times \left( \left( \mathbf{P} \tilde{B} \right) \times \tilde{J} \right); \quad P = 1 - d_e^2 \nabla^2,
$$

(3)

where $d_e = c / \omega_{pe}$ is the electron skin depth. Linearization of this equation in the presence of a local current density gradient $J_{ec}' = dJ_{ec}' / dy$ with growth rate $\gamma$ and wavevectors $k_e$ and $k_x$ along and across $\tilde{B}$ yields the dispersion relation,

$$
\tilde{\varphi} \left( \gamma - \frac{ik_e v_{ce}}{P_k} \right) = \Omega_{ce}^2 \frac{k_e^2}{P_k^2} \left( -k_e k_x^2 d_e^2 + P_k \frac{k_e J_{ec}'}{ne \Omega_{ce}} \right); \quad P_k = 1 + k_e^2 d_e^2,
$$

(4)

where $\varphi = \gamma + ik_e v_{ce}$, $k_e^2 = k_x^2 + k_e^2$ and $v_{ce} = -J_{ec}' / ne e$ is the local electron streaming velocity. In the absence of $J_{ec}'$, this dispersion relation yields whistler/electron-cyclotron waves. The current gradient causes instability. Defining the small parameter $\varepsilon = J_{ec}' / ne \Omega_{ce}$, the growth rate peaks at $\gamma = \Omega_{ce} \varepsilon / 2$ for $k_e d_e \geq 1$ with $k_e d_e = \varepsilon$. Analysis of the simulation data reveals that $k_e d_e \approx 2$ with $k_e d_e = 0.4$, which is close to the prediction. Of course, a kinetic treatment will be required to fully understand this filamentation instability.

The measurement of the filamentary structure of the electron current layer should be possible with existing magnetospheric satellites\(^\text{11}\) or in laboratory experiments\(^\text{10}\). The filaments are streaming at the electron drift speed, which is around the electron Alfvén speed, $c_{Aec} = B_e / \sqrt{4 \pi n_e m_e}$, when its width is $d_e$. With this scaling, $\varepsilon \approx B_e / B$ so that $k_e d_e \approx \varepsilon \approx B_e / B$ and $\omega \approx k_e c_{Aec} \approx \Omega_e B_e^2 / B^2$. The planned Magnetospheric Multiscale Mission (mms.space.swri.edu), whose instruments will measure all components of the electric field, will provide the most complete sets of data describing this complex region.


**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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**Author Information** The authors declare that they have no competing financial interests. Correspondence and requests for materials should be addressed to H. C. (email: Haihong.Che@colorado.edu).
Figure 1: The time evolution of reconnection. Particle-in-cell simulations using the p3d code\textsuperscript{25} are performed in doubly periodic 2-D and 3-D geometry starting with two Harris current sheets with a uniform plasma density \( n_0 \). The reconnection magnetic field is
\[
\frac{B_x}{B_0} = \tanh\left(\frac{y - L_y/4}{w_0}\right) - \tanh\left(\frac{y - 3L_y/4}{w_0}\right) - 1,
\]
where \( w_0 = 0.5d_i, L_x = 4.0d_i, L_y = 2.0d_i \) and \( L_z = 8.0d_i \) are the half-width of the initial current sheets and the box size in the \( x, y \) and \( z \) directions. The electron and ion temperatures, \( T_e = T_i = 0.04 \), are initially uniform. The initial out-of-plane “guide” field \( B_y/B_0 = 5.0 \) outside of the current layers and increases within the current layers so that the total magnetic field \( B \) is a constant. The cyclotron time is \( \Omega_c^{-1} = m_e/eB_0 \), the Alfvén speed is \( c_A = B_0/\sqrt{4\pi m_i n_0} \) and the ion inertial length is \( d_i = c_A/\Omega_c \). The electron mass is 0.01\( m_i \) and the velocity of light \( c = 20c_A \). The 3-D spatial grid consists of 512 x 256 x 1024 cells with 20 particles per cell while in 2-D it is 2048 x 1024 with 100 particles per cell. Reconnection is initiated with a large-scale magnetic perturbation. In (a) are the rates of reconnection \( \langle E_z \rangle \) and the half-widths of the z-averaged electron current layer at the x-line (see Fig. 2a) in 3-D (solid) and 2-D (dashed), in (b) are the electric field variances \( \langle \delta E_z^2 \rangle \) (solid), \( \langle \delta E_x^2 \rangle \) (dot-dashed) and \( \langle \delta E_y^2 \rangle \) (dashed) and in (c) are the dominant components of Ohm’s law, the electron inertia \( -(m_e/e)\partial < v_{ce} > / \partial t \) (dot-dashed orange), the drag \( D_z = -< \delta n_e \delta E_z > / < n_e > \) (dashed blue), the \( y \)-directed turbulent momentum transport, \( T_{yz} = -(1/e < n_e >)\partial < \delta P_{ye} \delta v_{ce} > / \partial y \) (solid red), and the thermal momentum transport \( -\nabla_{\perp} \cdot < \vec{P} > / < n_e > e \) (triple dots-dashed green).
with four times the initial electron and ion temperatures (not shown), no turbulence develops and thermal momentum transport balances $\langle E_z \rangle$.

Figure 2: The geometry of magnetic reconnection at late time. In the $x$-$y$ plane at $t = 3.75\Omega_{ci}^{-1}$ from the 3-D simulation of Fig. 1. In (a) the reconnected magnetic field lines (averaged over $z$). In (b) the field line motion toward and away from the $x$-line induces an electric field that produces the parallel (to $B$) electric field $\langle E \parallel \rangle$ that drives the intense electron current layer around the $x$-line in (c). The irregular structure of the current layer indicates that it is turbulent (see also Fig. 3). The filamentation of the current layer transports electron momentum $p_{e z}$ away from the center of the current layer. The rate of momentum transport $T_{yz}$ is shown in (d). The turbulence also produces a net electron-ion drag $D_z$ shown in (e). Note that the spatial distribution of $D_z$ differs from that of $T_{yz}$, which suggests that distinct turbulent processes are active.
Figure 3: The filamentary structure of the electron current layer. In the y-z plane in a cut through the x-line at \( t = 3.0 \Omega_{ci}^{-1} \) (a, c, e) and \( t = 3.75 \Omega_{ci}^{-1} \) (b, d, f) are the electron current \( j_{ex} \) (a, b), the magnetic field perturbations \( \delta B_z \) in (c, d) and the electric field perturbations \( \delta E_z \) in (e, f).

Figure 4: Breaking magnetic field lines: the dominant components of Ohm’s law. At \( t = 3.0 \Omega_{ci}^{-1} \), \( t = 3.35 \Omega_{ci}^{-1} \) and \( t = 3.75 \Omega_{ci}^{-1} \) from the 3-D simulation and \( t = 3.75 \Omega_{ci}^{-1} \) from the 2-D simulation, the dominant contributions to Ohm’s law in cuts along the inflow direction (y) through the x-line. Shown are \( <E_z> \) (solid black), \( -<v_{ey}><B_z>/c \) (dashed black), electron inertia (dot-dashed black), the thermal momentum transport \( -(1/n_e)\partial <P_{eyz}>/\partial y \) (dot-dashed green), the drag \( D_z \) (solid blue) and turbulent transport \( T_{yz} \) (dashed red). The solid grey line shows the sum of all of the contributions to Ohm’s law, which should lie on top of \( <E_z> \).
In 2-D the electron inertia continues to balance the reconnection electric field at late time, a solution that is not consistent with steady reconnection. In 3-D the turbulent drag and inertia dominate at $t = 3.0 \Omega_i^{-1}$. By $t = 3.35 \Omega_i^{-1}$ the turbulent drag and the rate of reconnection both sharply increase, suggesting a causal relation. By $t = 3.75 \Omega_i^{-1}$ the current layer is becoming filamentary and turbulent momentum transport completely dominates force balance at the x-line. Momentum is transported upstream away from the x-line, producing a positive $T_{yz}$ at the x-line and negative values upstream corresponding to a momentum transfer and not a momentum sink. At the x-line the drag drops sharply as the dynamics of the filaments dominates.