Asymmetric Magnetic Reconnection in Coronal Mass Ejection Current Sheets

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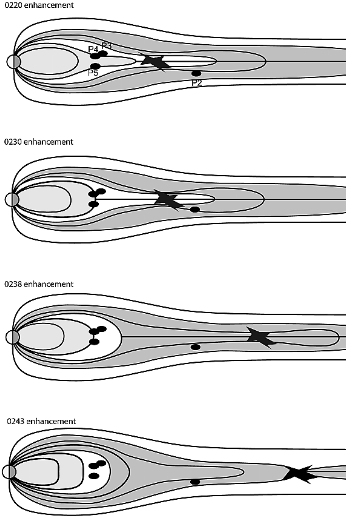
Outline

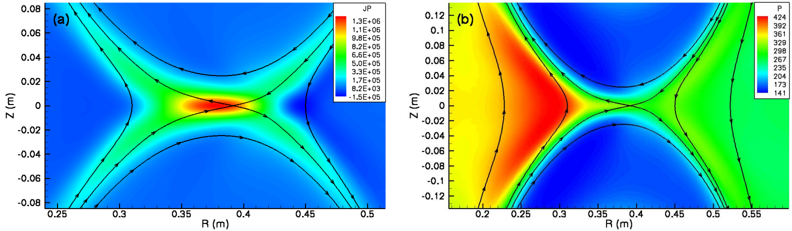
- Examples of asymmetric outflow reconnection
- Post-eruption current sheets (CSs) in the wakes behind coronal mass ejections (CMEs)
- A scaling model for asymmetric outflow reconnection
- Resistive MHD simulations of X-line retreat
- What does it mean for an X-line to move?
- Line-tied asymmetric reconnection during solar eruptions
- Multiple X-line reconnection

In planetary magnetotails, earthward outflow must overcome a steep plasma + magnetic pressure gradient



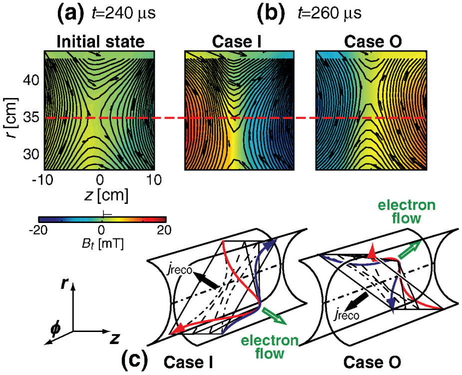
- Tailward X-line retreat during the recovery phase of substorms (figure from R. Nakamura et al. 2011)

During spheromak merging, pressure builds up near low radii because of the lesser available volume



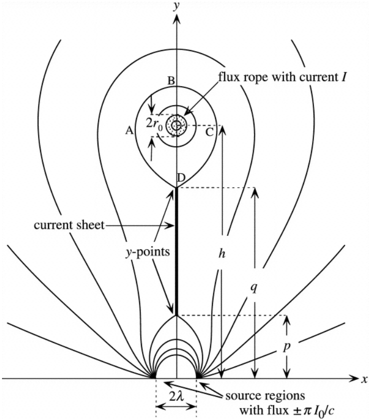
- The position of the X-point near the outboard side of the reconnection layer allows a stronger inward-directed tension force to overcome the steeper pressure gradient
- Above: resistive MHD simulations of push reconnection in MRX (Murphy & Sovinec 2008)

X-point motion is observed during two-fluid counter-helicity push reconnection in MRX



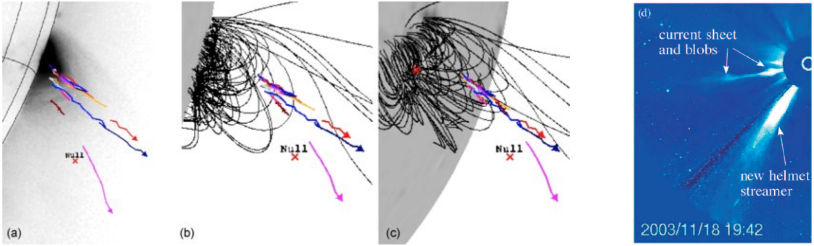
- The electron flow associated with the reconnection current has a component along the radial direction
- The X-line is pulled by the radial component of the electron flow, resulting in an asymmetric outflow pattern (Inomoto et al. 2006; Murphy & Sovinec 2008)

Flux rope models of CMEs predict the formation of an elongated CS behind the rising plasmoid



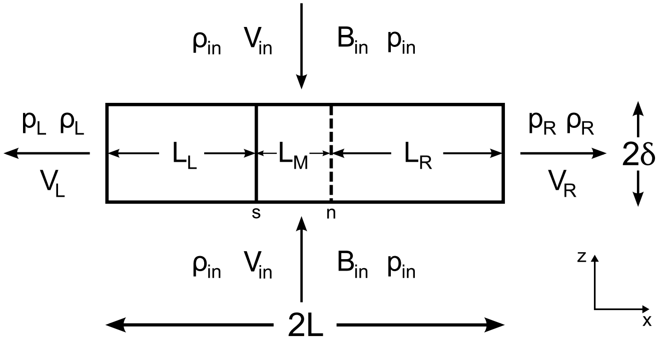
- Sunward outflow $\Longrightarrow$ post-flare loops, low solar atmosphere
- Anti-sunward outflow $\Longrightarrow$ rising flux rope
- Significant gradients for upstream density, pressure, and magnetic field strength

Open questions



- Are post-eruption current sheets actively reconnecting?
- Are these current sheets energetically important to the eruption as a whole?
- Where is the principal X-line? $\Longleftrightarrow$ Where does the energy go?
- Are CME CSs responsible for mass input and plasma heating in CMEs? (e.g., Murphy et al. 2011)
- Are large-scale blobs due to the plasmoid instability?
  - Perhaps, but some show C III and other cool lines

Scaling relations for asymmetric outflow reconnection (Murphy, Sovinec, & Cassak 2010)



- The above figure represents a long and thin reconnection layer with asymmetric downstream pressure. Reconnection is assumed to be steady in an inertial reference frame.
- 'n' denotes the magnetic field null and 's' denotes the flow stagnation point

Scaling relations for asymmetric outflow reconnection (Murphy, Sovinec, & Cassak 2010)

- Following Cassak & Shay (2007), we integrate over this control volume and find relations approximating conservation of mass, momentum, and energy

$$
\begin{aligned}
2\rho_{in} V_{in} L &\sim \rho_L V_L \delta + \rho_R V_R \delta \\
\rho_L V_L^2 + p_L &\sim \rho_R V_R^2 + p_R \\
2 V_{in} L \left(\alpha p_{in} + \frac{B_{in}^2}{\mu_0} \right) &\sim V_L \delta \left(\alpha p_L + \frac{\rho_L V_L^2}{2} \right) \\
&\quad + V_R \delta \left(\alpha p_R + \frac{\rho_R V_R^2}{2} \right)
\end{aligned}
$$

where $\alpha \equiv \gamma/(\gamma - 1)$ and we ignore upstream kinetic energy/downstream kinetic energy and assume the contribution from tension along the boundary is small or even.

Deriving the outflow velocity and reconnection rate

- In the incompressible limit

$$V_{L,R}^2 \sim \sqrt{4\left(c_{in}^2 - \frac{\bar{p}}{\rho}\right)^2 + \left(\frac{\Delta p}{2\rho}\right)^2} \pm \frac{\Delta p}{2\rho}$$

  using $\bar{p} \equiv \frac{p_L + p_R}{2}$, $\Delta p \equiv p_R - p_L$, and $c_{in}^2 = \frac{B_{in}^2}{\mu_0 \rho_{in}} + \frac{\alpha p_{in}}{\rho_{in}}$

- By assuming resistive dissipation, the electric field is then given by

$$E_y \sim B_{in}\sqrt{\frac{\eta\left(V_L + V_R\right)}{2\mu_0 L}}$$

Implications of scaling model

- The scaling relations show that the reconnection rate is weakly sensitive to asymmetric downstream pressure
  - If one outflow jet is blocked, reconnection is almost as quick
  - Reconnection slows down greatly only when both outflow jets are blocked
  - The CS responds to asymmetric downstream pressure by changing its thickness or length
- However, this analysis makes three major assumptions:
  - The CS is stationary
  - The CS thickness is uniform
  - Magnetic tension contributes symmetrically along the boundaries
- To make further progress, we must do <u>numerical simulations</u>

We perform resistive MHD simulations of two initial X-lines which retreat from each other as reconnection develops (Murphy, Phys. Plasmas, 17, 112310, 2010)

- The 2-D simulations start from a periodic Harris sheet which is perturbed at two nearby locations ($x = \pm 1$)
- Domain: $-30 \leq x \leq 30$, $-12 \leq z \leq 12$
- Simulation parameters: $\eta = 10^{-3}$, $\beta_\infty = 1$, $\mathrm{S} = 10^3$–10^4, $\mathrm{Pm} = 1$, $\gamma = 5/3$, $\delta_0 = 0.1$
- Define:
  - x_n is the position of the X-line
  - x_s is the position of the flow stagnation point
  - $V_x(x_n)$ is the velocity *at* the X-line
  - $\frac{\mathrm{d}x_n}{\mathrm{d}t}$ is the velocity *of* the X-line
- $\hat{\mathbf{x}}$ is the outflow direction, $\hat{\mathbf{y}}$ is the out-of-plane direction, and $\hat{\mathbf{z}}$ is the inflow direction
- We show only $x \geq 0$ since the simulation is symmetric

NIMROD solves the equations of extended MHD using a finite element formulation (Sovinec et al. 2004)

- In dimensionless form, the equations used for these simulations are

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\eta \mathbf{J} - \mathbf{V} \times \mathbf{B}) + \kappa_{divb} \nabla\nabla \cdot \mathbf{B} \tag{1}$$

$$\mathbf{J} = \nabla \times \mathbf{B} \tag{2}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{3}$$

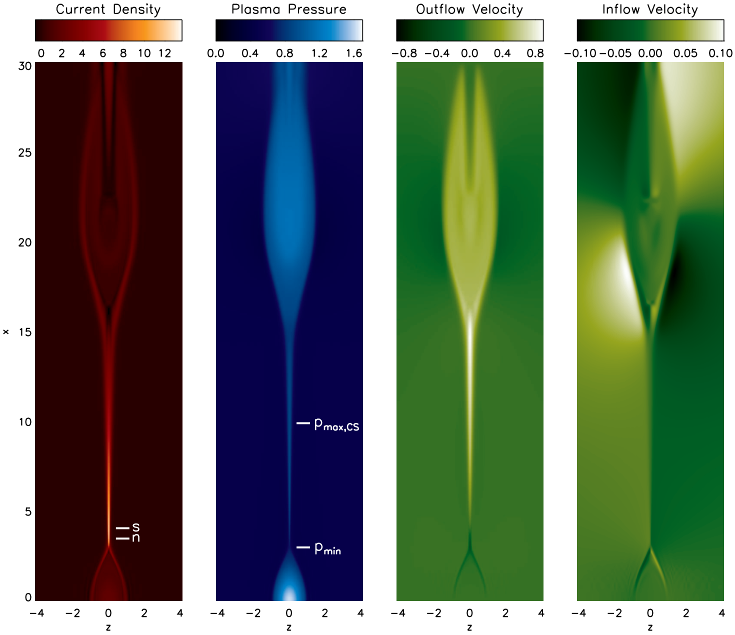
$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \rho \nu \nabla \mathbf{V} \tag{4}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = \nabla \cdot D \nabla \rho \tag{5}$$

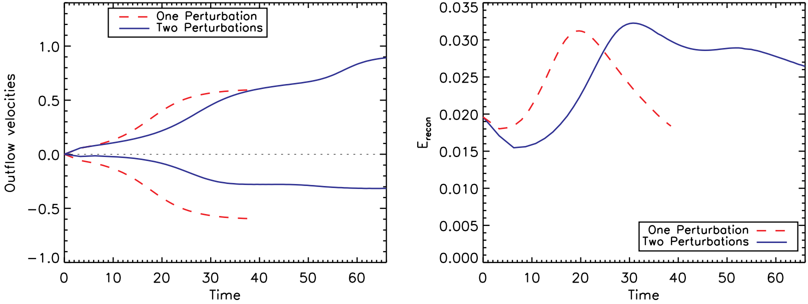
$$\frac{\rho}{\gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -\frac{p}{2} \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + Q \tag{6}$$

- Divergence cleaning is used to prevent the accumulation of divergence error

The CSs have characteristic single wedge shapes

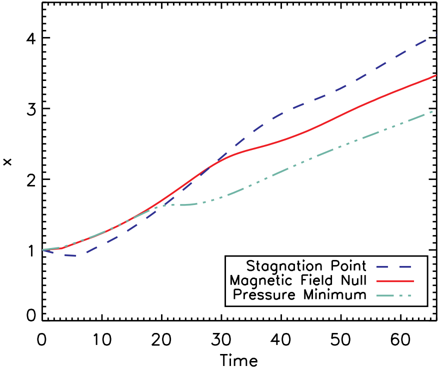


The outflow away from the obstruction is much faster



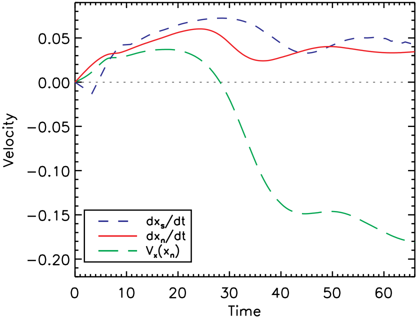
- Most of the energy goes away from the obstructed exit (see also Seaton 2008; Reeves et al. 2010; Roussev et al. 2001)
- Eventually, reconnection proceeds more quickly in retreat simulations than in otherwise equivalent symmetric cases
- The comparison with the single perturbation case is halted around $t \approx 40$ because of the formation of an island at $x = 0$

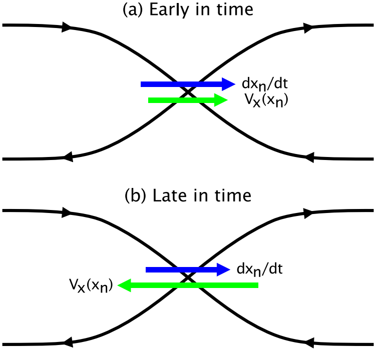
The flow stagnation point and X-line are not colocated



- Surprisingly, the relative positions of the X-line and flow stagnation point switch!
- This occurs so that the stagnation point will be located near where the tension and pressure forces cancel
- Reconnection develops slowly because the X-line is located near a pressure minimum early in time

Late in time, the X-line diffuses against strong plasma flow





- The stagnation point retreats more quickly than the X-line
- Any difference between $\frac{\mathrm{d}x_n}{\mathrm{d}t}$ and $V_x(x_n)$ must be due to diffusion (e.g., Seaton 2008, Murphy 2010)
- The velocity *at* the X-line is not the velocity *of* the X-line!

What sets the rate of X-line retreat?

- The inflow (z) component of Faraday's law for the 2D symmetric inflow case is

$$\frac{\partial B_z}{\partial t} = -\frac{\partial E_y}{\partial x} \tag{7}$$

- The convective derivative of B_z at the X-line taken at the velocity of X-line retreat, $\mathrm{d}x_n/\mathrm{d}t$, is

$$\left.\frac{\partial B_z}{\partial t}\right|_{x_n} + \frac{\mathrm{d}x_n}{\mathrm{d}t}\left.\frac{\partial B_z}{\partial x}\right|_{x_n} = 0 \tag{8}$$

  The RHS of Eq. (8) is zero because $B_z(x_n, z = 0) = 0$ by definition for this geometry.

Deriving an exact expression for the rate of X-line retreat

- From Eqs. 7 and 8:

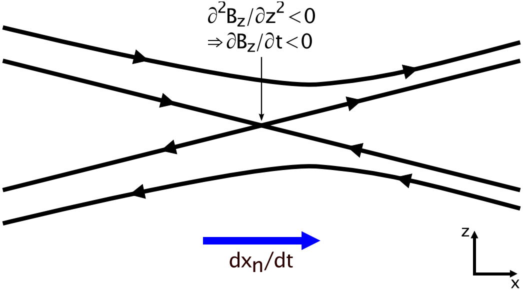
$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = \left.\frac{\partial E_y/\partial x}{\partial B_z/\partial x}\right|_{x_n} \tag{9}$$

- Using $\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J}$, we arrive at

$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = V_x(x_n) - \eta \left[\frac{\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2}}{\frac{\partial B_z}{\partial x}} \right]_{x_n} \tag{10}$$

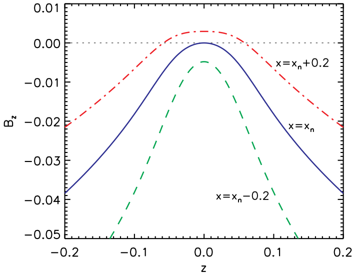
- $\frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2}$, so X-line retreat is caused by diffusion of the normal component of the magnetic field along the inflow direction
- This result can be extended to 3D nulls and to include additional terms in the generalized Ohm's law

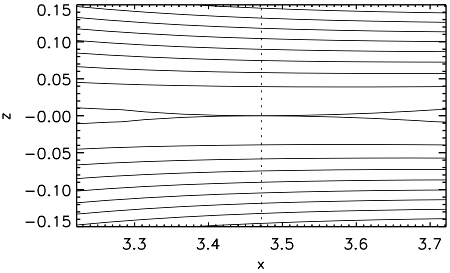
The X-line moves in the direction of increasing total reconnection electric field strength



- X-line retreat occurs through a combination of:
  - Advection by the bulk plasma flow
  - Diffusion of the normal component of the magnetic field
- X-line motion depends intrinsically on <u>local parameters</u> evaluated at the X-line
  - X-lines are not (directly) pushed by pressure gradients

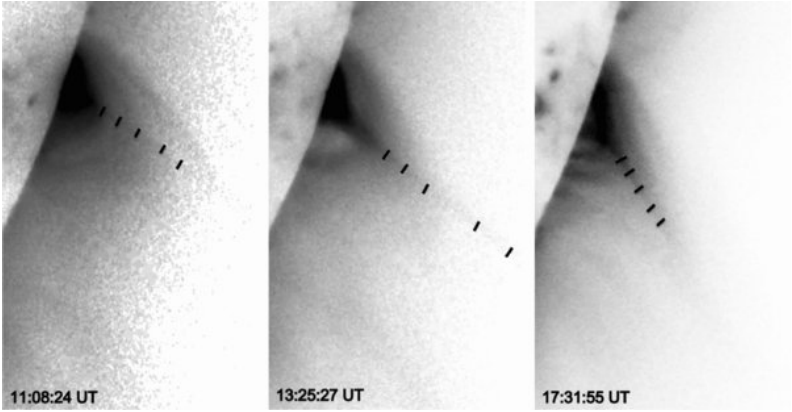
The magnetic field structure near the X-line is characteristic of this mechanism for X-line retreat





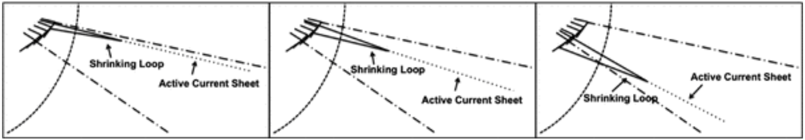
- Negative B_z diffuses from above and below into the region of the X-line
- *Left:* $B_z(z)$ along three locations near the X-line.
- *Right:* Magnetic flux contours near the X-line.

CME CSs are frequently observed to drift with time



- Above: Hinode/XRT observations in the wake behind the 'Cartwheel CME' (from Savage et al. 2010)
- Apparent drift velocity: $\sim$5–10 km s^{-1} at $\rho \sim 1.1$–$1.2 R_\odot$
- Estimate from solar rotation alone: $\sim$0.1 km s^{-1}

The are at least four possible explanations for this drift



- Different parts of CS become active at different times (above, from Savage et al. 2010)
- The reconnecting field lines are pulled along with the rising flux rope at an angle
- Reconnection is very strongly driven behind the CME, and the plasmas come in at different velocities
- The drift is associated with line-tied asymmetric reconnection

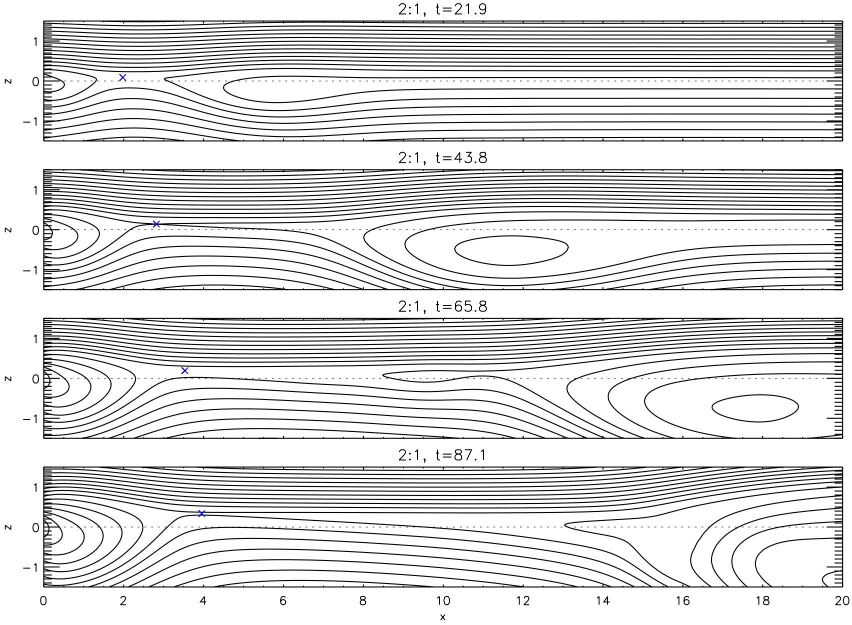
NIMROD simulations of line-tied asymmetric reconnection

- Initial equilibrium is a modified Harris sheet

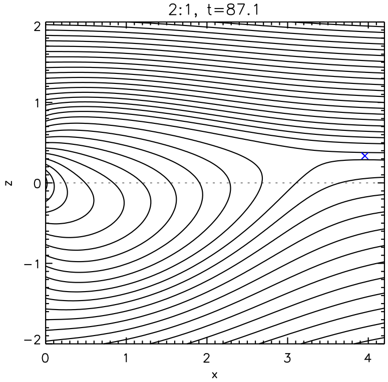
$$B_z(x) = \frac{B_0}{1+b} \tanh\left(\frac{x}{\delta_0} - b\right) \tag{11}$$

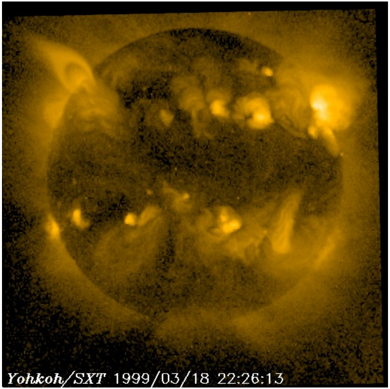
- $0 \leq x \leq 25$, $-7.5 \leq z \leq 7.5$; conducting wall BCs
  - High resolution needed over a much larger area
- Magnetic field ratios: 1.0, 0.5, 0.25, and 0.125
- $\beta_0 = 0.25$ in higher magnetic field upstream region
- Caveats: 1-D initial equilibrium, outer conducting wall BCs, and we do not consider the rising flux rope in detail

X-line drift is away from wall and toward stronger **B**



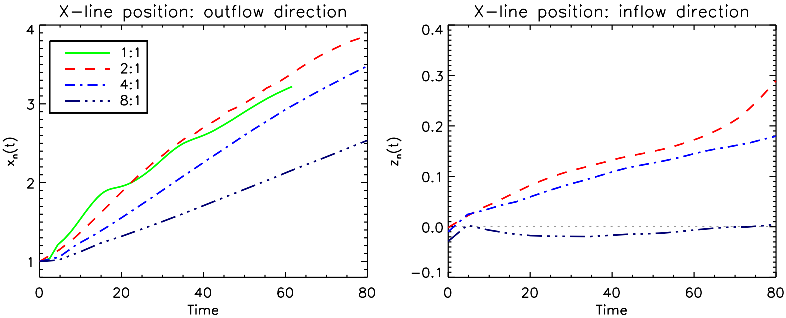
The line-tied lower boundary condition leads to skewing of the post-flare loops





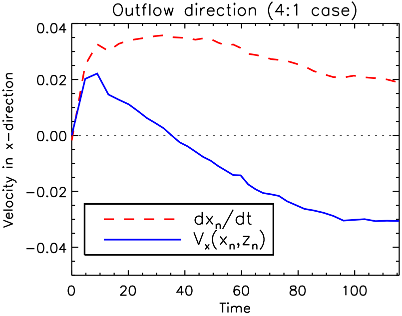
- This skewing occurs because flux contours are not evenly spaced along the photospheric boundary
- Post-flare loops observed by Yohkoh/SXT and Hinode/XRT may show such a distortion

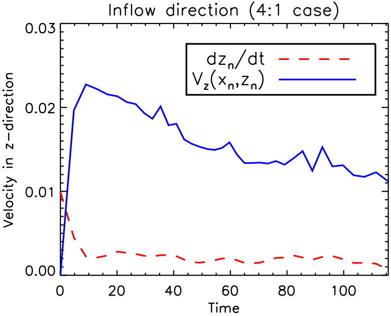
Decreasing B for one upstream region leads to a decrease in the rate of X-line motion



- Hinode/EIS observations of the Cartwheel CME CS provide densities of $\sim 2 \times 10^8$ cm^{-3} using a Fe XIII density diagnostic (Landi et al., submitted)
- Assuming $B \sim 10$–15 G, the 2:1 inflow drift rate is comparable to obsevations

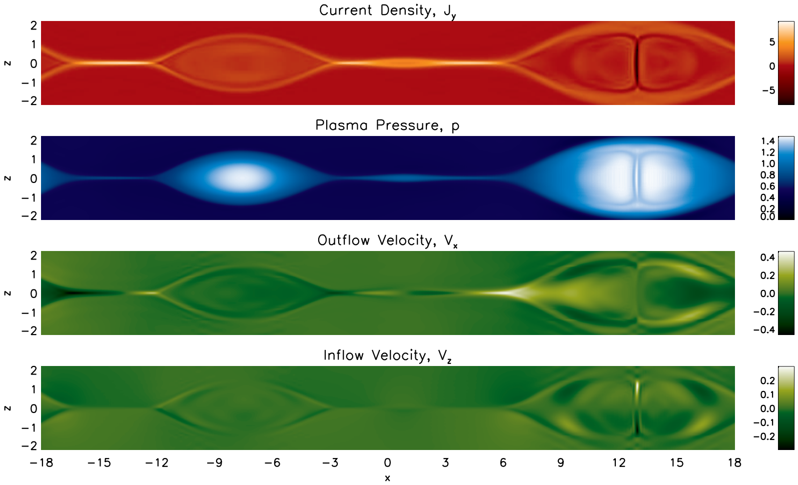
Again, the plasma velocity at the X-line differs greatly from the rate of X-line motion





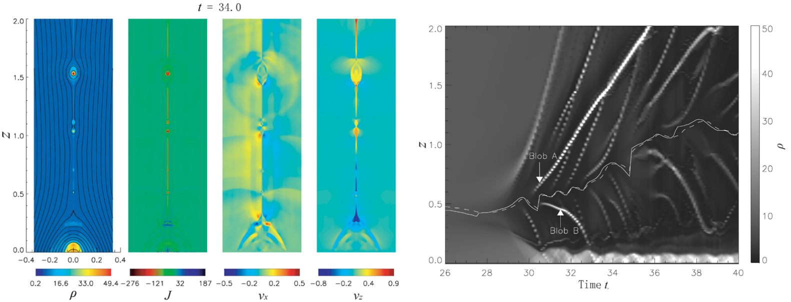
- $V_x(x_n, z_n)$ and $V_z(x_n, z_n)$ give the velocity at the X-line
- $\mathrm{d}x_n/\mathrm{d}t$ and $\mathrm{d}z_n/\mathrm{d}t$ give the rate of X-line motion
- No flow stagnation point within the CS

NIMROD simulations of multiple X-line reconnection were analyzed by A. K. Young



- When an X-line is located near one exit of a current sheet, the flow stagnation point is located between the X-line and a central plasma pressure maximum

SHASTA simulations using adaptive mesh refinement show plasmoid formation in line-tied current sheets



- Reconnection becomes faster when plasmoid formation onsets (Shen, Lin, & Murphy 2011)
- The flow stagnation point (*dashed line*) and principal X-point (*solid line*) frequently switch relative positions
- Newly formed islands move upward (downward) if the flow stagnation point is above (below) the principal X-point

In resistive MHD when inflow is symmetric, the number of X-lines can only change by resistive diffusion of B_z

- The induction equation is

$$\frac{\partial \mathbf{B}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{V} - \mathbf{B} \left(\nabla \cdot \mathbf{V} \right) + \eta \nabla^2 \mathbf{B}, \tag{12}$$

where in our 2-D geometry,

$$\left[\eta \nabla^2 \mathbf{B} \right]_z = \eta \left[\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right]. \tag{13}$$

- The term $\eta \frac{\partial^2 B_z}{\partial x^2}$ acts to smooth out the $B_z(x)$ profile. This term can move or reduce the number of X-lines (where $B_z = 0$), but not create new X-lines.
- The term $\eta \frac{\partial^2 B_z}{\partial z^2}$ brings in B_z along the inflow direction. This term can move or increase the number of X-lines, but by symmetry cannot cause pre-existing X-lines to disappear.

Conclusions

- Asymmetric outflow reconnection occurs in planetary magnetotails, laboratory plasmas, solar eruptions, and elsewhere in nature and the laboratory
- The primary X-line in CME CSs is probably near the lower base of the CS (see also Seaton 2008; Shen et al. 2011)
  - Most of the energy is directed upward
- Late in time there is significant flow across the X-line in the opposite direction of X-line retreat
- X-line retreat is due to advection by the bulk plasma flow and diffusion of the normal component of the magnetic field
- The observational signatures of line-tied asymmetric reconnection include:
  - Skewing/distortion of post-flare loops
  - Slow drifting to stronger magnetic field side
  - Plasmoid preferentially propagates into low-field region

Future Work

- Extend X-line retreat analysis to include additional terms in Ohm's law
- 3-D simulations of X-line retreat
- Develop a suite of time-dependent ionization routines to predict observational signatures of CME CSs from simulations (with J. Raymond and C. Shen)
- Quantify drifting in a sample of CME CSs and look for observational signatures of line-tied asymmetric reconnection (with M. P. Miralles, K. Reeves, D. Webb, D. Seaton)
- Investigate energetics of CME current sheets
  - Contributor to plasma heating in CMEs?