Asymmetric Magnetic Reconnection During Coronal Mass Ejections

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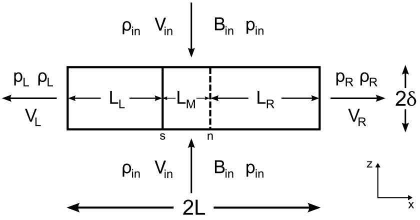
Introduction

- Most theories of magnetic reconnection assume that the current sheet is symmetric in both the inflow and outflow directions
- In CME current sheets, sunward outflow is directed into a region of strong plasma and magnetic pressure, and antisunward outflow is directed towards the rising flux rope
- X-line motion occurs in CME current sheets, the Earth's magnetotail (Runov et al. 2003), and laboratory plasma experiments (Inomoto et al. 2006; Murphy & Sovinec 2008)
  - The X-line location helps determines where the energy goes
- Reconnection between magnetic fields of unequal strength occurs frequently in the solar atmosphere, at the Earth's dayside magnetopause, and in the laboratory
- In this poster we consider asymmetric outflow reconnection, multiple X-line reconnection, and reconnection that is asymmetric in both the inflow and outflow directions

Background: Murphy, Sovinec, & Cassak (2010) developed a scaling model for asymmetric outflow reconnection



- The above figure represents a long and thin reconnection layer with asymmetric downstream pressure
- 'n' denotes the magnetic field null and 's' denotes the flow stagnation point
- The scaling relations suggest that the reconnection rate is weakly sensitive to asymmetric downstream pressure unless both outflow jets are blocked
- This analysis assumes that the current sheet is stationary, the thickness is uniform, and that the surface integral of magnetic tension contributes symmetrically ($\Rightarrow$ simulations)

We perform resistive MHD simulations of two initial X-lines which retreat from each other as reconnection develops (see Murphy 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

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

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

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

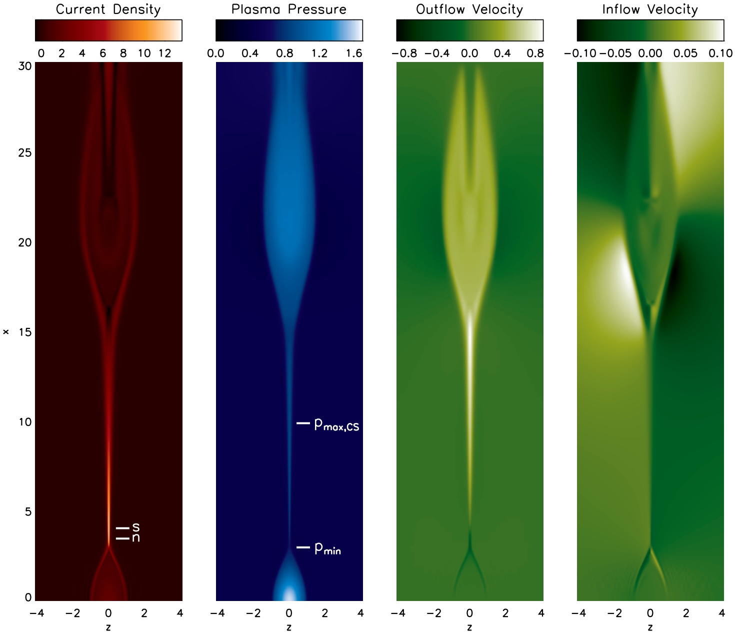
$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \rho \nu \nabla \mathbf{V} \tag{4}$$

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

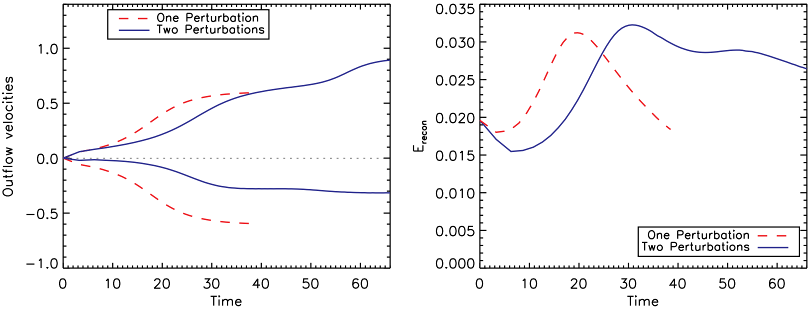
$$\frac{\rho}{\gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -\frac{p}{2} \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + Q \tag{6}$$

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

The current sheets have characteristic single wedge shapes

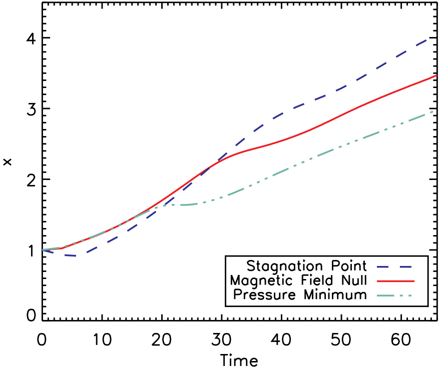


The simulations suggest that most of the outflow energy from CME current sheets is directed upward towards the rising plasmoid



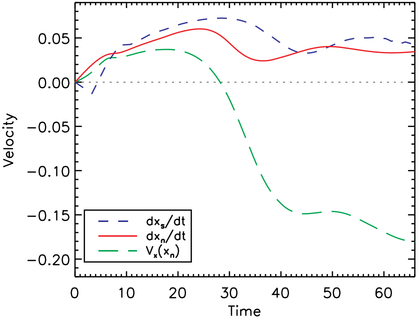
- In agreement with Seaton (2008) and Reeves et al. (2010), most of the energy goes away from the obstructed exit
- Eventually, reconnection proceeds more quickly in retreat simulations than in otherwise equivalent symmetric, non-retreating simulations

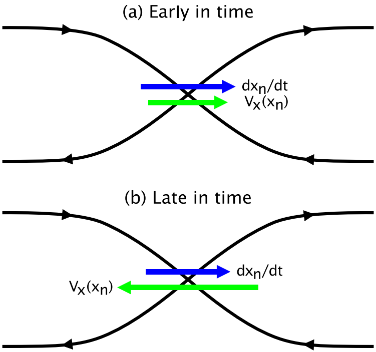
The flow stagnation point and X-line are not colocated



- 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 $\frac{dx_n}{dt}$ and $V_x(x_n)$ must be due to diffusion (e.g., Seaton 2008)
- 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 expression for X-line retreat

- From Eqs. 7 and 8:

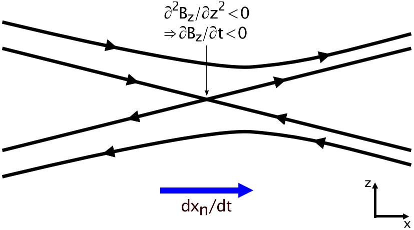
$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = \left.\frac{\partial E_y/\partial x}{\partial B_z/\partial x}\right|_{x_n} \tag{9}$$

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

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

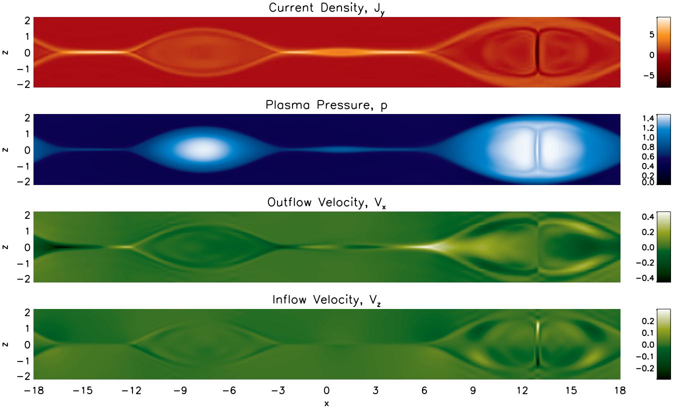
- In the simulations $\frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2}$, so X-line retreat is caused by diffusion of the normal component of the magnetic field along the inflow direction
- Equation (9) can also be evaluated using additional terms in the generalized Ohm's law

Mechanism and implications



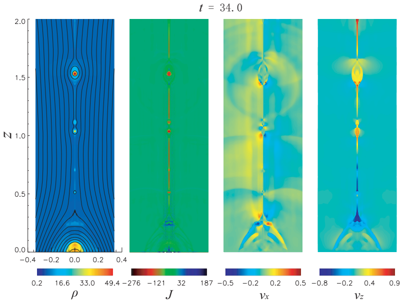
- The X-line moves in the direction of increasing total reconnection electric field strength
- X-line retreat occurs through a combination of advection by bulk plasma flow and diffusion of the normal component of the magnetic field
- X-line motion depends intrinsically on local parameters evaluated at the X-line

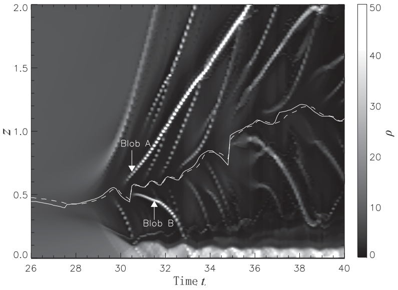
NIMROD simulations of multiple X-line reconnection were analyzed by A. K. Young



- Isolated or strong initial perturbations are more likely to survive (see also Nakamura et al. 2010)
- 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, ApJ, in press)
- 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

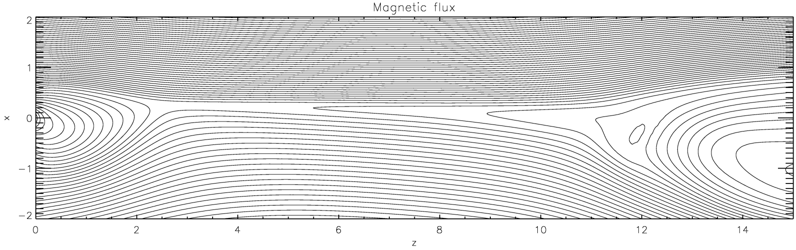
$$\frac{\partial \mathbf{B}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{V} - \mathbf{B} \left(\nabla \cdot \mathbf{V} \right) + \eta \nabla^2 \mathbf{B}, \tag{11}$$

where in our 2-D geometry,

$$\left[\eta \nabla^2 \mathbf{B} \right]_z = \eta \left[\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right]. \tag{12}$$

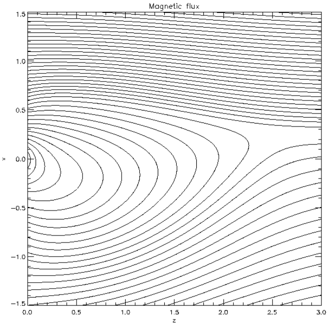
- The term $\eta \frac{\partial^2 B_z}{\partial x^2}$ acts to smooth out the $B_z(x)$ profile. This term can move or reduce the number of X-lines (where $B_z = 0$), but not create new X-lines.
- The term $\eta \frac{\partial^2 B_z}{\partial z^2}$ brings in B_z along the inflow direction. This term can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

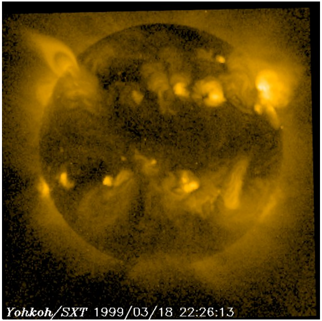
CME current sheets often drift or tilt with time



- The current sheet drifting may be due to asymmetry in the upstream magnetic fields (see Cassak & Shay 2007)
- We are analyzing simulations of line-tied asymmetric reconnection between magnetic fields of different strength
- Other possibilities to explain the drift are that different parts of the current sheet are actively reconnecting at different times (Savage et al. 2010) or that the rising flux rope propagates at an angle and drags along the current sheet behind it

The line-tied lower boundary condition leads to skewing of the reconnected 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

Conclusions

- NIMROD simulations of X-line retreat suggest that most of the outflow energy from CME current sheets is directed upward towards the rising plasmoid
  - 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 either advection by the bulk plasma flow or by diffusion of the normal component of the magnetic field
- NIMROD and SHASTA simulations show faster reconnection after plasmoid formation onsets
  - The flow stagnation point is typically located between the X-line and a central plasma pressure maximum
  - The relative locations of the flow stagnation point and principal X-line correlate with the direction of plasmoid motion
- Line-tied asymmetric reconnection might be responsible for current sheet drifting observed in the 'Cartwheel CME'
  - The structure of reconnection post-flare loops will be skewed when the reconnecting fields are of uneven strength