# Asymmetric Magnetic Reconnection in Coronal Mass Ejection Current Sheets

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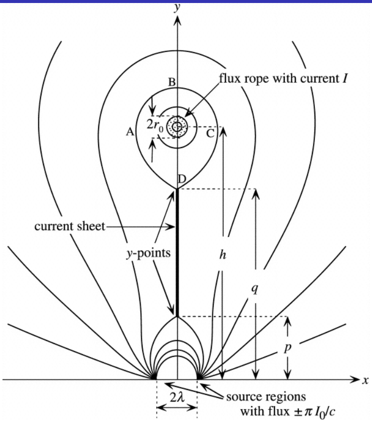
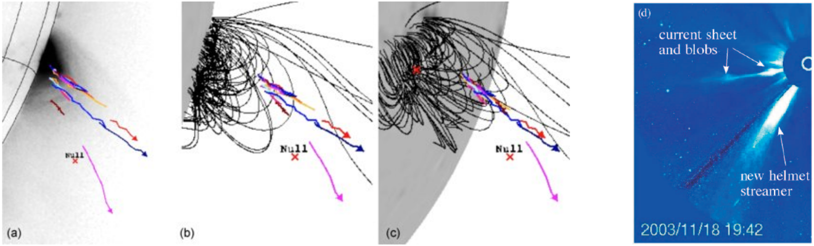
# Flux rope models of CMEs predict the formation of an elongated CS behind the rising plasmoid




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

# Open questions

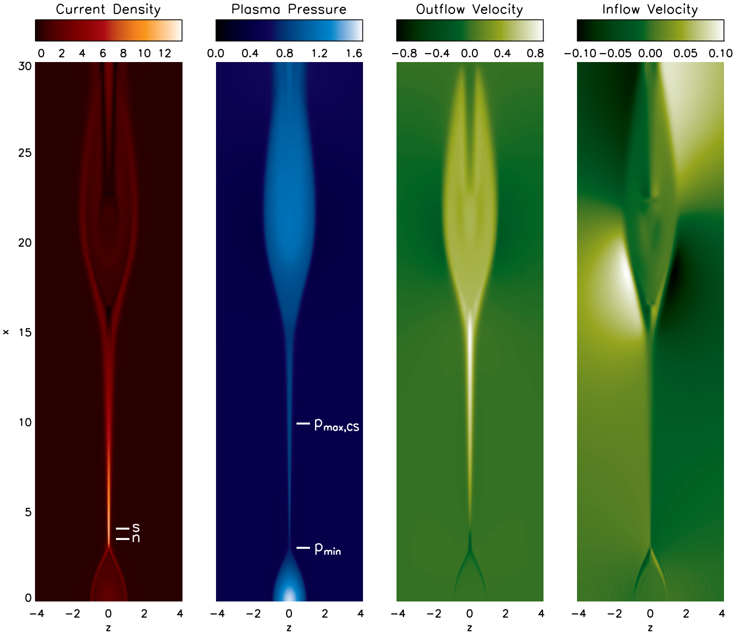



- Are post-eruption current sheets actively reconnecting?
- Are these current sheets energetically important to the eruption as a whole?
- Where is the principal X-line? $\Longleftrightarrow$ Where does the energy go?
- Are CME CSs responsible for mass input and plasma heating in CMEs? (e.g., Murphy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

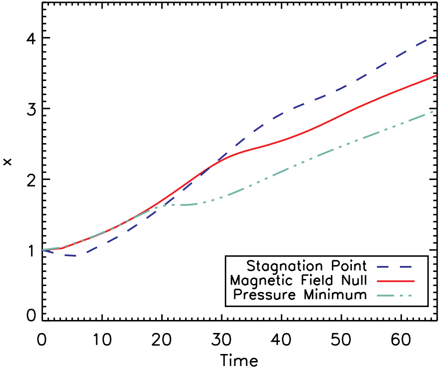
# We perform resistive MHD simulations of two initial X-lines which retreat from each other as reconnection develops (Murphy, Phys. Plasmas, 17, 112310, 2010)

- The 2-D simulations start from a periodic Harris sheet which is perturbed at two nearby locations ($x = \pm 1$)
- Use the NIMROD extended MHD code (Sovinec et al. 2004)
- 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

# The CSs have characteristic single wedge shapes

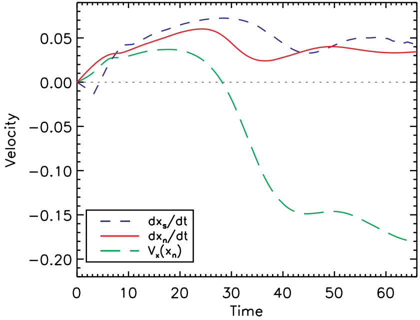


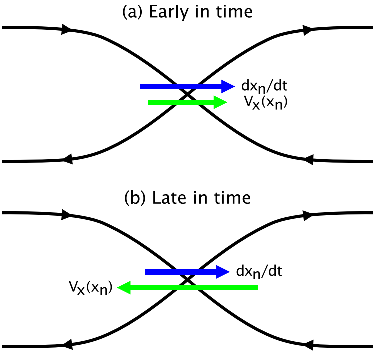
# The flow stagnation point and X-line are not colocated




- 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

$$\frac{\partial B_z}{\partial t} = -\frac{\partial E_y}{\partial x} \tag{1}$$

- 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

$$\left.\frac{\partial B_z}{\partial t}\right|_{x_n} + \frac{\mathrm{d}x_n}{\mathrm{d}t} \left.\frac{\partial B_z}{\partial x}\right|_{x_n} = 0 \tag{2}$$

  The RHS of Eq. (2) 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. 1 and 2:

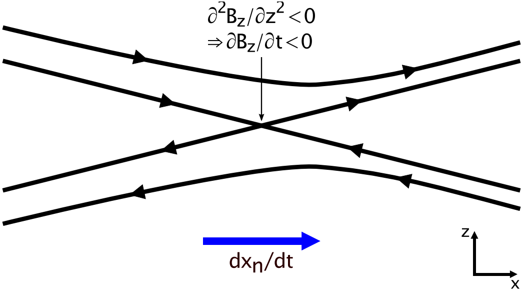
$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = \left.\frac{\partial E_y/\partial x}{\partial B_z/\partial x}\right|_{x_n} \tag{3}$$

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

$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = V_x(x_n) - \eta \left[ \frac{\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2}}{\frac{\partial B_z}{\partial x}} \right]_{x_n} \tag{4}$$

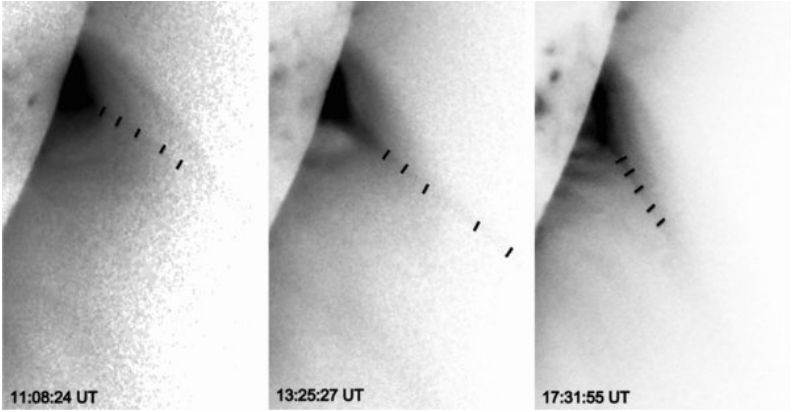
- $\frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2}$, so X-line retreat is caused by diffusion of the normal component of the magnetic field along the inflow direction
- This result can be extended to 3D nulls and to include additional terms in the generalized Ohm's law

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



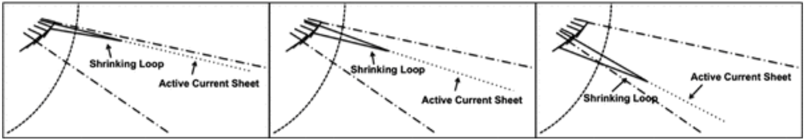

- X-line retreat occurs through a combination of:
  - Advection by the bulk plasma flow
  - Diffusion of the normal component of the magnetic field
- X-line motion depends intrinsically on <u>local parameters</u> evaluated at the X-line
  - X-lines are not (directly) pushed by pressure gradients

# CME CSs are often observed to drift with time




- Above: Hinode/XRT observations after the ‘Cartwheel CME’ show a CS drift of 4 deg hr$^{-1}$ (Savage et al. 2010)
- The CS observed by Ko et al. (2003) drifts at $\sim$1 deg hr$^{-1}$
- CSs observed by AIA or XRT that show drifts include the 2010 Nov 3, 2011 Mar 8, and 2011 Mar 11 events

# There are several 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 drifting is in response to post-eruption magnetic field lines becoming more potential
- The drift arises from line-tied asymmetric reconnection

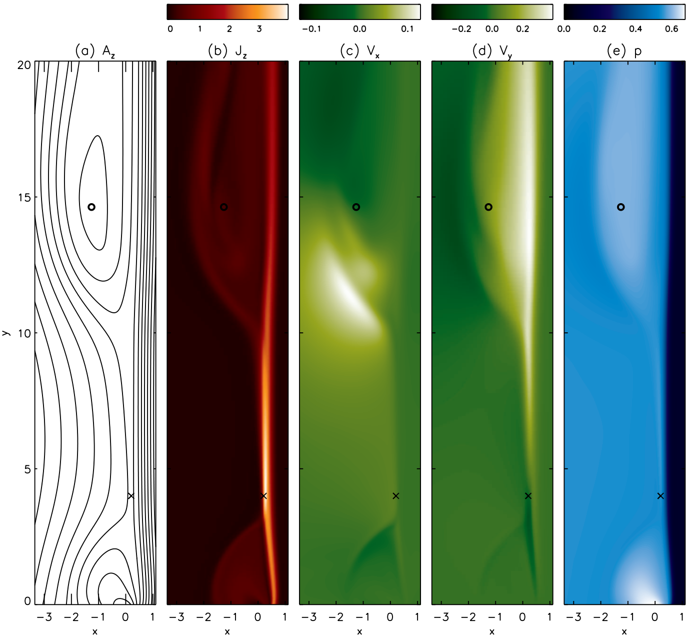
# NIMROD simulations of line-tied asymmetric reconnection

- Reconnecting magnetic fields are asymmetric:

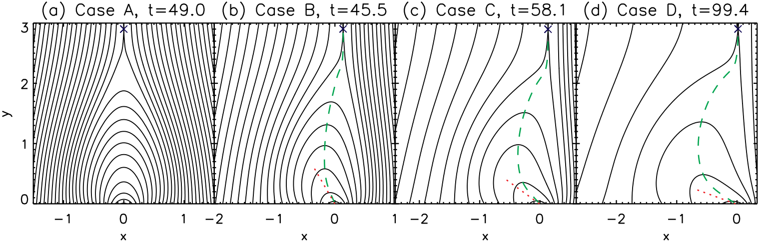
$$B_y(x) = \frac{B_0}{1+b} \tanh\left(\frac{x}{\delta_0} - b\right) \tag{5}$$

- $-7 \leq x \leq 7$, $0 \leq y \leq 30$; conducting wall BCs
  - High resolution needed over a much larger area
- Magnetic field ratios: 1.0, 0.5, 0.25, and 0.125
- $\beta_0 = 0.18$ 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

# Reconnection with both asymmetric inflow and outflow

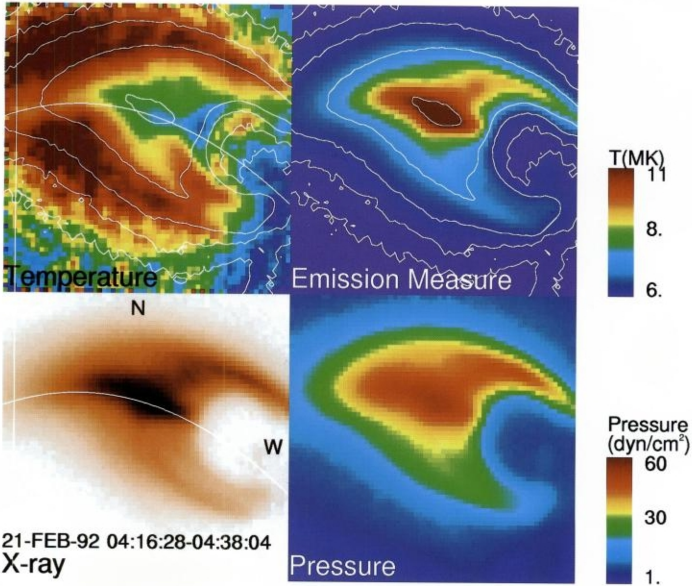


# The post-flare loops develop a characteristic candle flame structure

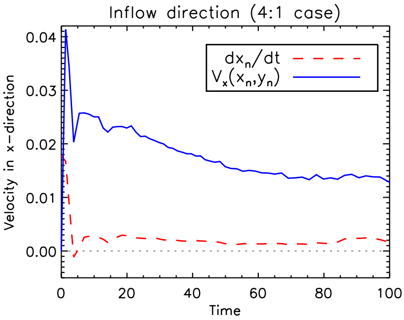


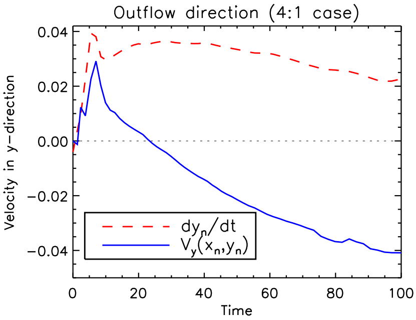

- Above: magnetic flux contours for four different asymmetries ($B_L/B_R = 1,\ 0.5,\ 0.25,\ 0.125$)
- The loop-top positions (dashed green line) are a function of height
- Analytic theory predicts the asymptotic slope near the field reversal reasonably well (dotted red line)

# The Tsuneta (1996) flare is a famous candidate event



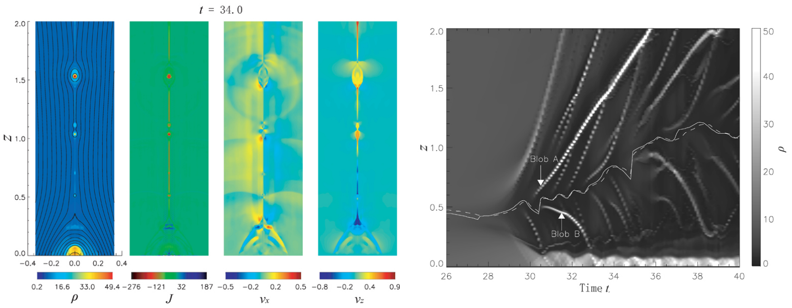
# Again, the plasma velocity at the X-line differs greatly from the rate of X-line motion



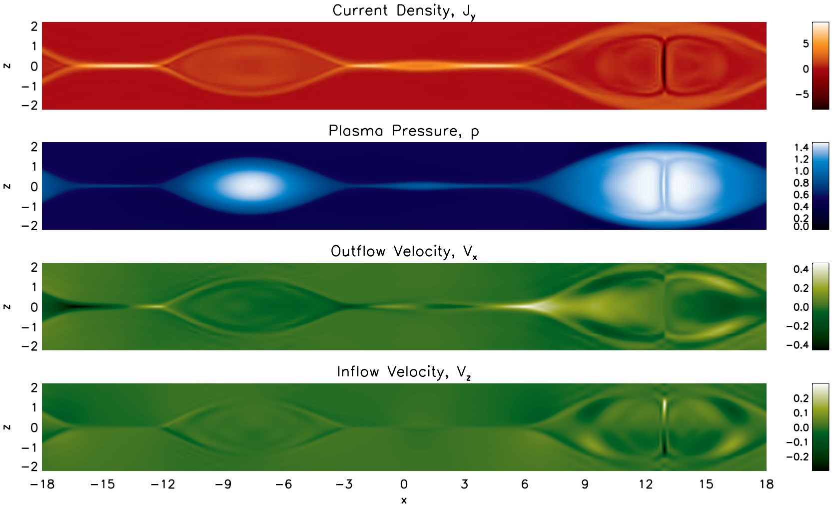

- $V_x(x_n, y_n)$ and $V_y(x_n, y_n)$ give the velocity at the X-line
- $\mathrm{d}x_n/\mathrm{d}t$ and $\mathrm{d}y_n/\mathrm{d}t$ give the rate of X-line motion
- No flow stagnation point within the CS

# 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

# NIMROD simulations of multiple X-line reconnection




- 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

# 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

$$\frac{\partial \mathbf{B}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{V} - \mathbf{B} \left( \nabla \cdot \mathbf{V} \right) + \eta \nabla^2 \mathbf{B}, \qquad (6)$$

where in our 2-D geometry,

$$\left[ \eta \nabla^2 \mathbf{B} \right]_z = \eta \left[ \frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right]. \qquad (7)$$

- 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
  - Net vorticity in the rising flux rope
  - Plasmoid preferentially develops into low-field region