Asymmetric Magnetic Reconnection in Coronal Mass Ejection Current Sheets

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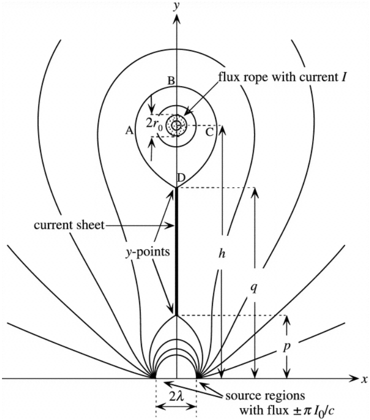
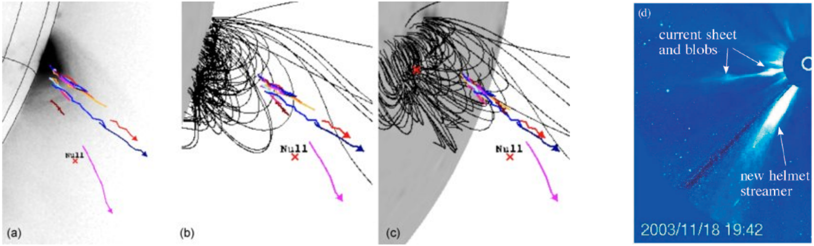
Flux rope models of CMEs predict the formation of an elongated CS behind the rising plasmoid



- Sunward outflow $\Longrightarrow$ 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

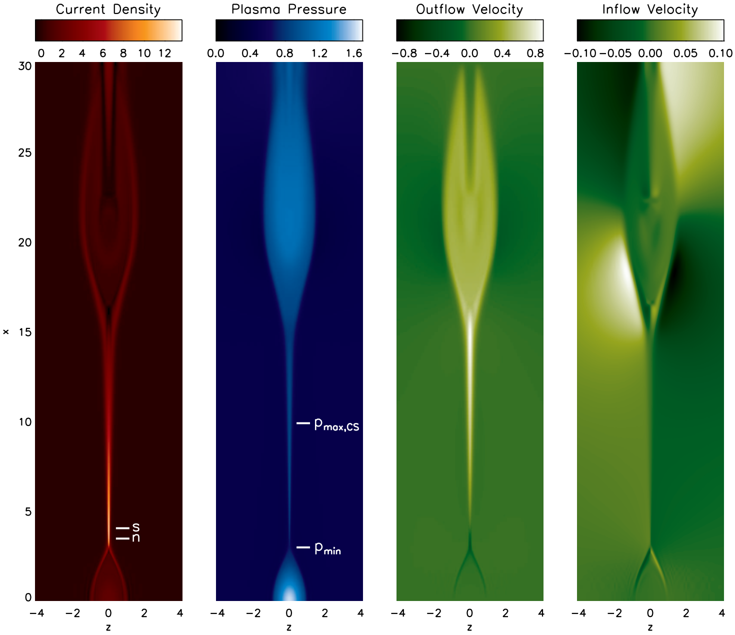


- Are post-eruption current sheets actively reconnecting?
- Are these current sheets energetically important to the eruption as a whole?
- Where is the principal X-line? $\Longleftrightarrow$ Where does the energy go?
- Are CME CSs responsible for mass input and plasma heating in CMEs? (e.g., Murphy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

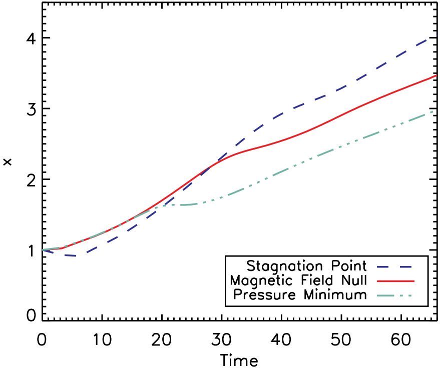
We perform resistive MHD simulations of two initial X-lines which retreat from each other as reconnection develops (Murphy, Phys. Plasmas, 17, 112310, 2010)

- 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

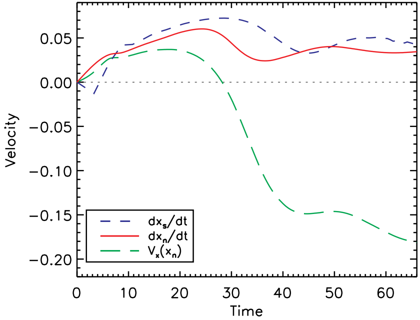


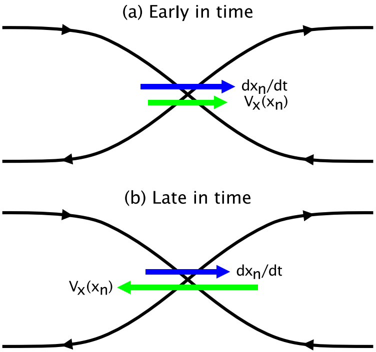
The flow stagnation point and X-line are not colocated



- 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 $\frac{dx_n}{dt}$ 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:

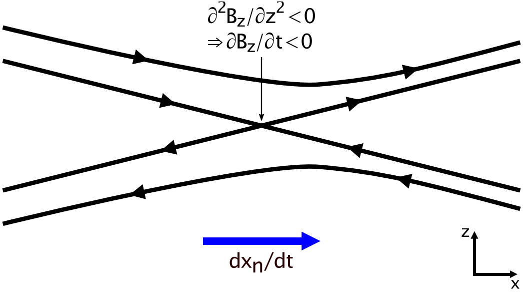
$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = \left.\frac{\partial E_y/\partial x}{\partial B_z/\partial x}\right|_{x_n} \quad (3)$$

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

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

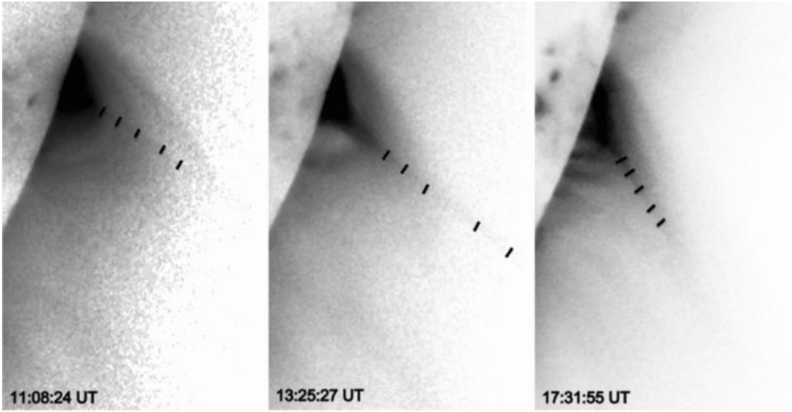
- $\frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2}$, so X-line retreat is caused by diffusion of the normal component of the magnetic field along the inflow direction
- This result can be extended to 3D nulls and to include additional terms in the generalized Ohm's law

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



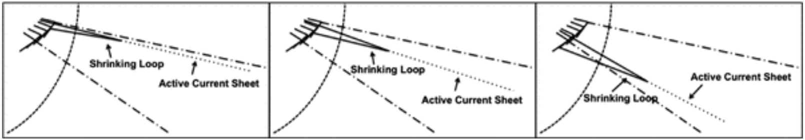
- X-line retreat occurs through a combination of:
  - Advection by the bulk plasma flow
  - Diffusion of the normal component of the magnetic field
- X-line motion depends intrinsically on <u>local parameters</u> evaluated at the X-line
  - X-lines are not (directly) pushed by pressure gradients

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

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

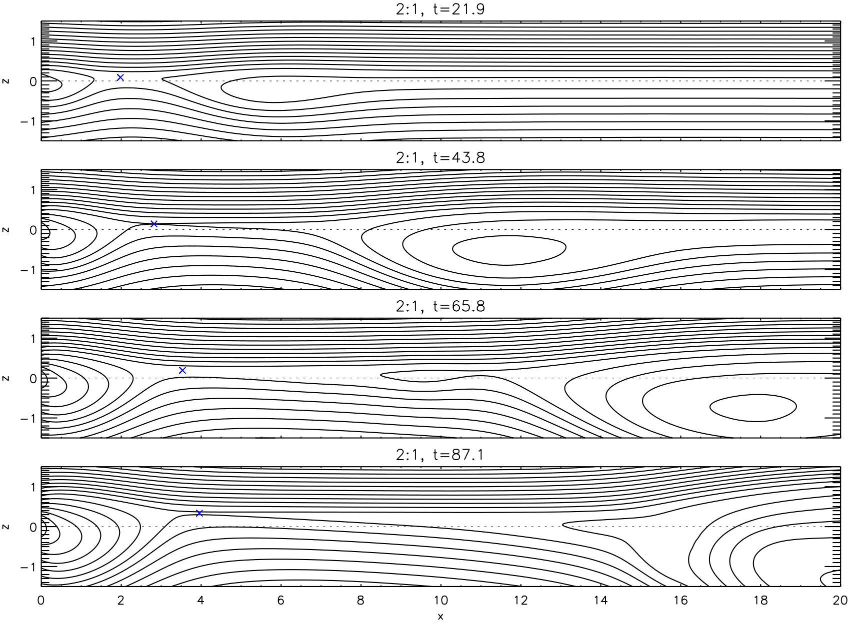
NIMROD simulations of line-tied asymmetric reconnection

- Initial equilibrium is a modified Harris sheet

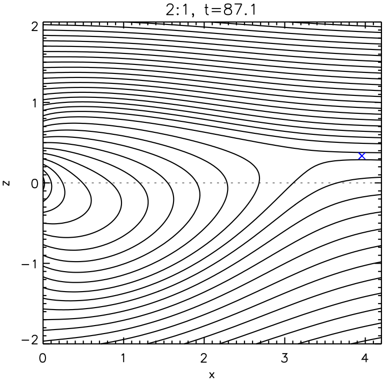
$$B_z(x) = \frac{B_0}{1+b} \tanh\left(\frac{x}{\delta_0} - b\right) \tag{5}$$

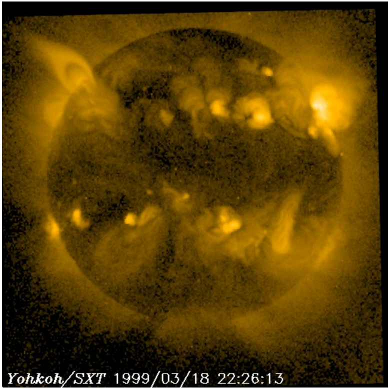
- $0 \leq x \leq 25$, $-7.5 \leq z \leq 7.5$; conducting wall BCs
  - High resolution needed over a much larger area
- Magnetic field ratios: 1.0, 0.5, 0.25, and 0.125
- $\beta_0 = 0.25$ in higher magnetic field upstream region
- Caveats: 1-D initial equilibrium, outer conducting wall BCs, and we do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

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



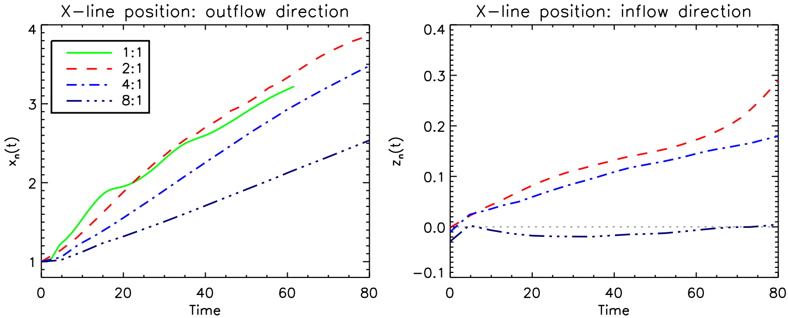
The line-tied lower boundary condition leads to skewing of the post-flare loops





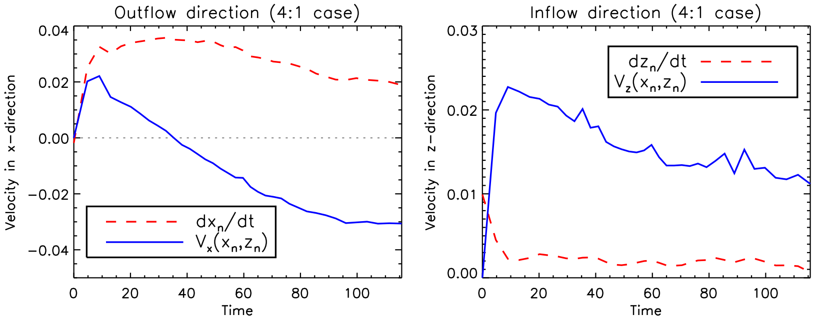
- This skewing occurs because flux contours are not evenly spaced along the photospheric boundary
- Post-flare loops observed by Yohkoh/SXT and Hinode/XRT may show such a distortion

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

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