Observational Signatures of Asymmetric Magnetic Reconnection During Solar Eruptions

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Introduction

- Most models of reconnection assume symmetry
- However, asymmetric magnetic reconnection occurs in the solar atmosphere, the solar wind, space plasmas, laboratory experiments, and elsewhere
- *Asymmetric inflow reconnection* occurs when the upstream magnetic fields and/or plasma parameters differ
  - Dayside magnetopause, sawteeth in tokamaks, merging of unequal flux ropes
- *Asymmetric outflow reconnection* occurs when outflow in one direction is impeded or the X-line is displaced towards one end of the current sheet
  - Earth's magnetotail, flare/CME current sheets
- What happens during doubly asymmetric reconnection?
  - Application: line-tied reconnection in flare/CME current sheets

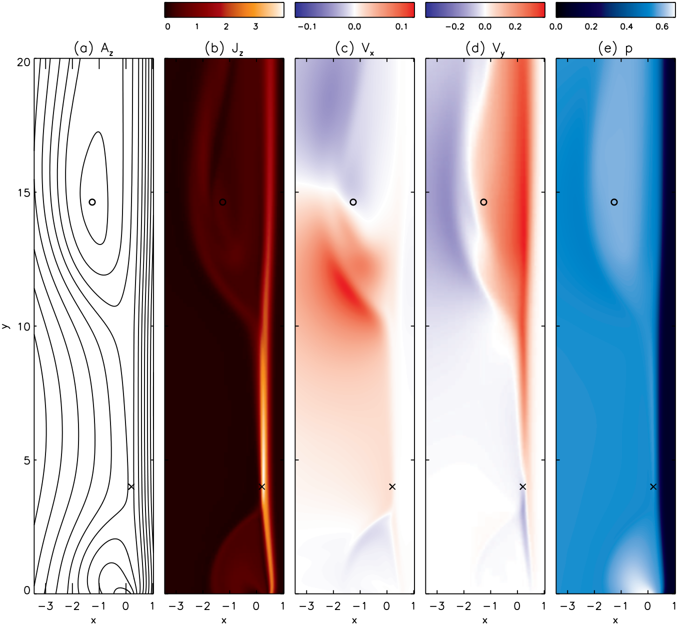
NIMROD simulations of line-tied asymmetric reconnection

- Reconnecting magnetic fields are asymmetric:

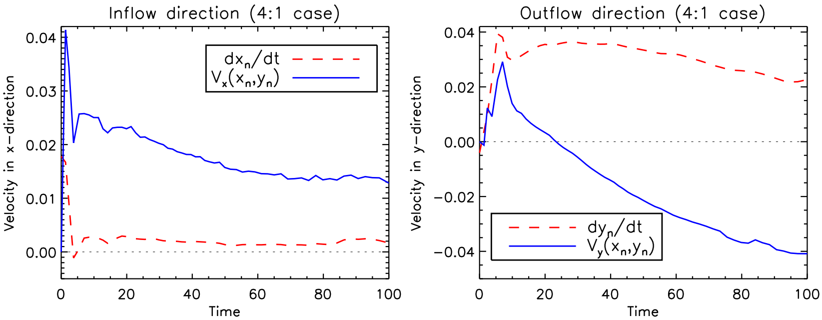
$$B_y(x) = \frac{B_0}{1+b} \tanh\left(\frac{x}{\delta_0} - b\right) \tag{1}$$

- $-7 \leq x \leq 7$, $0 \leq y \leq 30$; conducting wall BCs
    - High resolution needed over a much larger area
- Center initial X-line perturbation at $(x, y) = (0, 1)$, near the lower wall
- 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 with no vertical stratification, unphysical upper conducting wall BC, and we do not consider the rising flux rope in detail

Reconnection with both asymmetric inflow and outflow

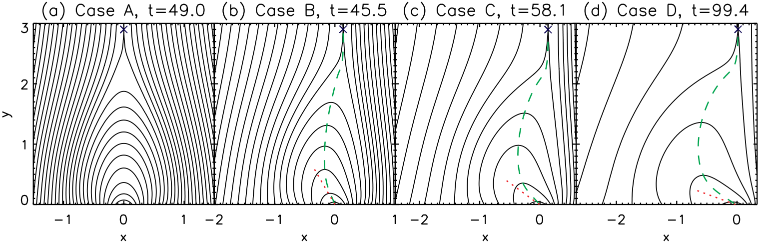


There is significant plasma flow across the X-line in both the inflow and outflow directions (see also Murphy 2010)



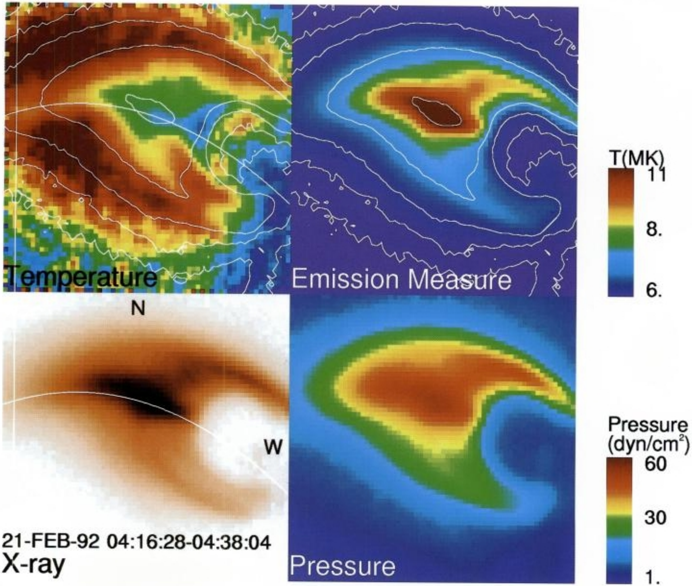
- $V_x(x_n, y_n)$ and $V_y(x_n, y_n)$ give the velocity at the X-line
- $\mathrm{d}x_n/\mathrm{d}t$ and $\mathrm{d}y_n/\mathrm{d}t$ give the rate of X-line motion
- Differences between $\mathbf{V}(x_n, y_n)$ and $\mathrm{d}\mathbf{x}_n/\mathrm{d}t$ result from diffusion
- No flow stagnation point within the CS

The post-flare loops develop a skewed candle flame shape



- 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



The location of the principal X-line

- During most simulations, the principal X-line is located near the lower base of the current sheet
  - Consistent with numerical and analytical results by Seaton (2008), Reeves et al. (2010), Murphy (2010), & Shen et al. (2011)
- However, during one guide field simulation the X-line drifted to the top of the current sheet
- X-line motion is tied intrinsically to derivatives of the out-of-plane electric field (Murphy 2010)
- Discussion question: What sets the location of the principal X-line?

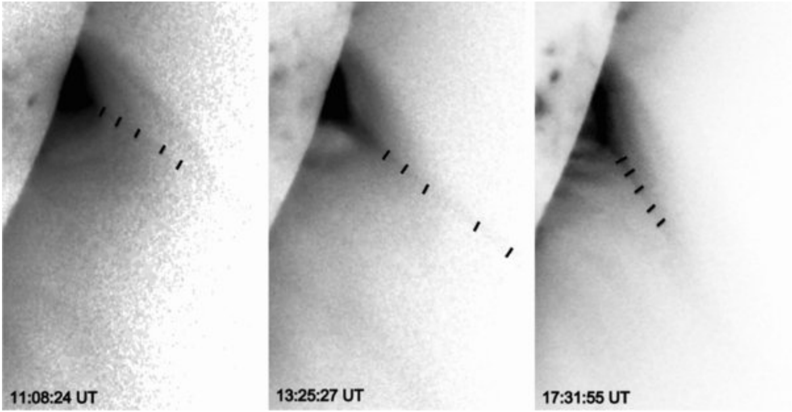
Asymmetric speeds of footpoint motion

- In two-dimensional models, the footpoints of newly reconnected loops move away from each other as more flux is reconnected
- In two-dimensions, the amount of flux reconnected on each side of the loop must be equal to each other
- When the magnetic fields are asymmetric, the footpoint on the strong **B** side will move slowly compared to the footpoint on the weak **B** side
- Because of the patchy distribution of flux on the photosphere, more complicated motions frequently occur (e.g., Bogachev et al. 2005; Grigis & Benz 2005; Su et al. 2007; Yang et al. 2009)

Asymmetric hard X-ray (HXR) footpoint emission

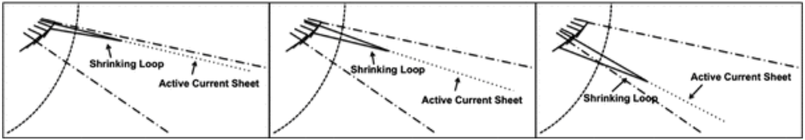
- The standard model of flares predicts HXR emission at the flare footpoints from energetic particles (EPs) impacting the chromosphere
- Magnetic mirroring reflects energetic particles (EPs) preferentially on the strong **B** side
- More particles should escape on the weak **B** side, leading to greater HXR emission
- This trend is observed in ∼2/3 of events (Goff et al.)
  - Additional factors include:
    - Asymmetry in initial pitch angle distributions of EPs
    - Particle drifts in the presence of a guide field (Hamilton et al. 2005; Li & Lin, submitted)
    - Different column densities (cf. Saint-Hilaire et al. 2008)
  - More detailed energetic particle modeling is required

CME CSs are often observed to drift with time



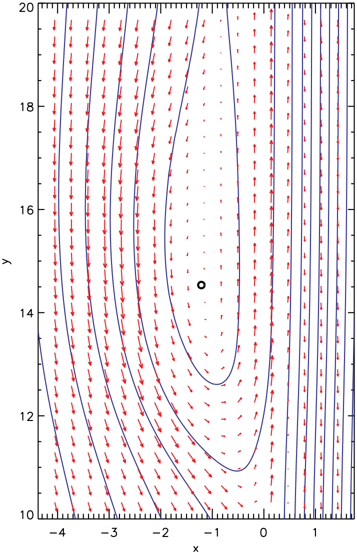
- Above: Hinode/XRT observations after the 'Cartwheel CME' show a CS drift of 4 deg hr^{-1} (Savage et al. 2010)
- The CS observed by Ko et al. (2003) drifts at $\sim$1 deg hr^{-1}
- CSs observed by AIA or XRT that show drifts include the 2010 Nov 3, 2011 Mar 8, and 2011 Mar 11 events

There are several possible explanations for this drift



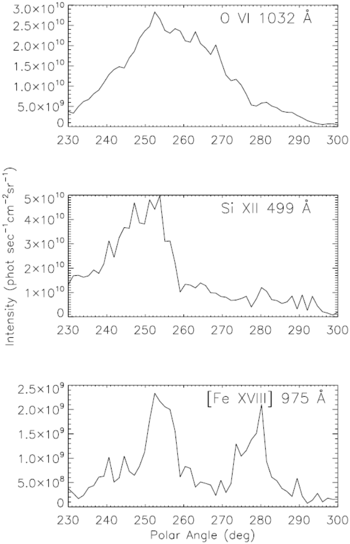
- Different parts of CS become active at different times (above, from Savage et al. 2010)
- The reconnecting field lines are pulled along with the rising flux rope at an angle
- Reconnection is very strongly driven behind the CME, and the plasmas come in at different velocities
- The drifting is in response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

Circulation in the outflow plasmoid



- The outflow plasmoid develops net vorticity because the CS outflow impacts it at an angle

UVCS observations of the 2003 Nov 4 CME CS show a temperature gradient along the inflow direction



- From Ciaravella & Raymond (2008)

Conclusions

- We simulate 2D reconnection in a line-tied asymmetric current sheet
  - Both the inflow and outflow are asymmetric
- The observational signatures of asymmetric reconnection during solar eruptions include:
  - Skewing/distortion of post-flare loops into a skewed candle flame shape
  - The footpoint in the weak field region moves more quickly and has stronger HXR emission than the footpoint in the strong field region
  - The X-line drifts slowly into the strong field region
  - Net vorticity in the rising flux rope
- Future work on this problem:
  - Energetic particle modeling of skewed post-flare loops with HyLoop
  - Plasmoid instability during asymmetric inflow reconnection

Discussion Questions

- How asymmetric is reconnection in flare/CME current sheets?
- What sets the location of the principal X-line?
- What causes some CME current sheets to drift?
- What are the consequences of 3D reconnection and the patchy distribution of flux at the photosphere?
- How can we observationally determine how important CME current sheets are to the eruption as a whole?

Extra Slides

What sets the rate of X-line retreat?

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

$$\frac{\partial B_z}{\partial t} = -\frac{\partial E_y}{\partial x} \tag{2}$$

- 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

$$\left.\frac{\partial B_z}{\partial t}\right|_{x_n} + \frac{\mathrm{d}x_n}{\mathrm{d}t}\left.\frac{\partial B_z}{\partial x}\right|_{x_n} = 0 \tag{3}$$

The RHS of Eq. (3) 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. 2 and 3:

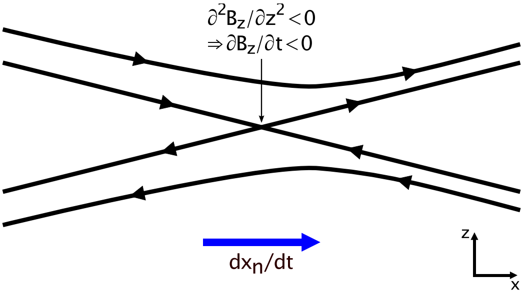
$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = \left.\frac{\partial E_y/\partial x}{\partial B_z/\partial x}\right|_{x_n} \tag{4}$$

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

$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = V_x(x_n) - \eta \left[\frac{\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2}}{\frac{\partial B_z}{\partial x}} \right]_{x_n} \tag{5}$$

- $\frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2}$, 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 local parameters evaluated at the X-line
  - X-lines are not (directly) pushed by pressure gradients