Asymmetric Magnetic Reconnection in the Solar Atmosphere

Nick Murphy

Harvard-Smithsonian Center for Astrophysics

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Introduction

- Most models of reconnection assume symmetry
- *Asymmetric inflow reconnection* occurs when the upstream magnetic fields and/or plasma parameters differ
  - Dayside magnetopause
  - Tearing in tokamaks, RFPs, and other confined plasmas
  - Merging of unequal flux ropes
  - 'Pull' reconnection in MRX
- *Asymmetric outflow reconnection* occurs, for example, when outflow in one direction is impeded
  - Flare/CME current sheets
  - Planetary magnetotails
  - Spheromak merging
  - 'Push' reconnection in MRX
- This talk covers reconnection with both asymmetric inflow and outflow during solar eruptions

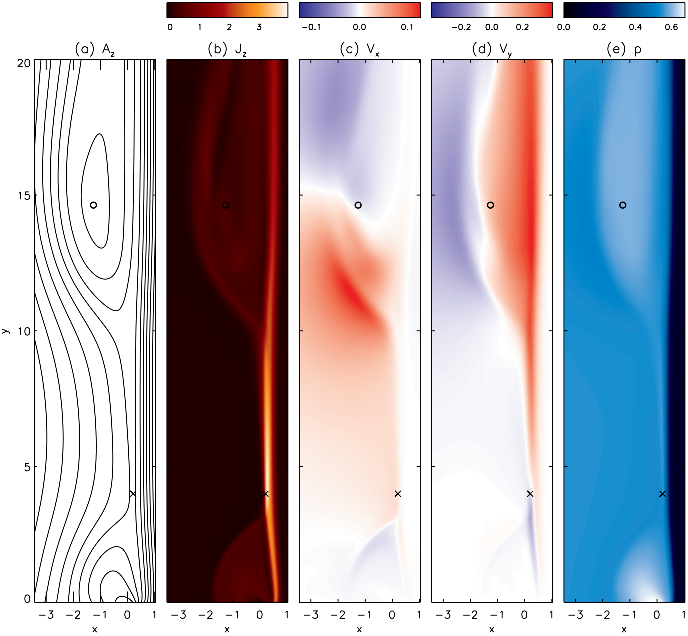
NIMROD simulations of line-tied asymmetric reconnection

- Reconnecting magnetic fields are asymmetric:

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

- Initial X-line located at $(x, y) = (0, 1)$ near lower wall
- Magnetic field ratios: 1.0, 0.5, 0.25, and 0.125
- $\beta_0 = 0.18$ in higher magnetic field upstream region
- $-7 \leq x \leq 7$, $0 \leq y \leq 30$; conducting wall BCs
- High resolution needed over a larger area
- Caveats:
  - 1-D initial equilibrium with no vertical stratification
  - Single X-line in resistive MHD
  - Neglect 3-D effects
  - Unphysical upper conducting wall BC
- See Murphy et al. (2012, ApJ) for details

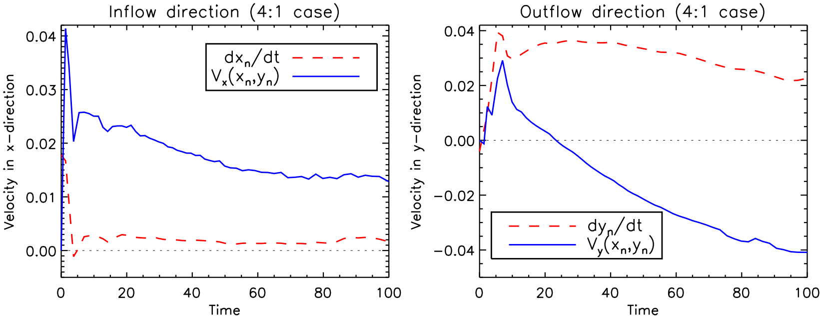
Reconnection with both asymmetric inflow and outflow



The location of the principal X-line helps determine where released energy goes

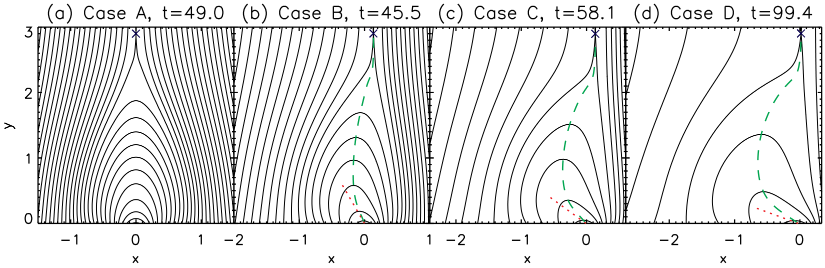
- The principal X-line is generally located near the lower base of the current sheet
  - Most of the released energy is directed upward
  - Consistent with numerical and analytical results by Seaton (2008), Reeves et al. (2010), Murphy (2010), & Shen et al. (2011)
  - However, during one guide field simulation the X-line drifted to the top of the current sheet
- The X-line usually drifts slowly into the strong field region
- X-line motion is tied intrinsically to derivatives of the out-of-plane electric field (Murphy 2010)

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



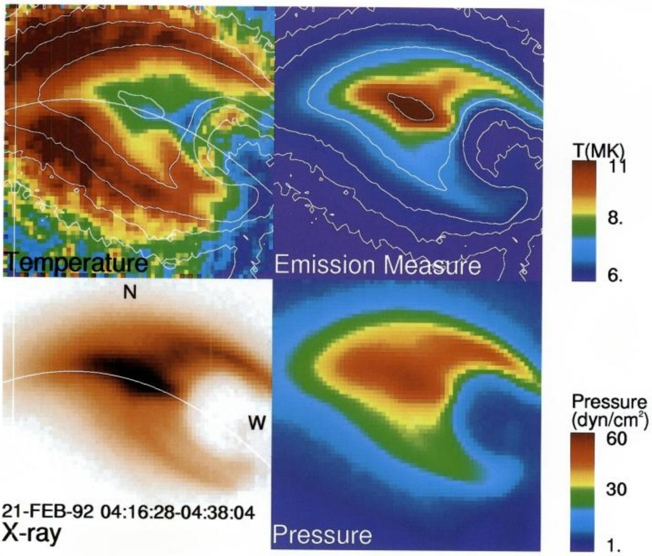
- $V_x(x_n, y_n)$ and $V_y(x_n, y_n)$ give the flow velocity at the X-line
- $\mathrm{d}x_n/\mathrm{d}t$ and $\mathrm{d}y_n/\mathrm{d}t$ give the rate of X-line motion
- X-line motion results from a combination of:
  - Advection by the bulk plasma flow
  - Diffusion of the magnetic field
- No flow stagnation point within the CS in simulation frame

The post-flare loops develop a skewed candle flame shape



- Magnetic flux contours for $B_L/B_R \in \{1,\ 0.5,\ 0.25,\ 0.125\}$ when $y_n \approx 2.9$
- Dashed green line: loop-top positions
- Dotted red line: analytic asymptotic approximation

The Tsuneta (1996) flare is a famous candidate event



- Shape suggests north is weak **B** side

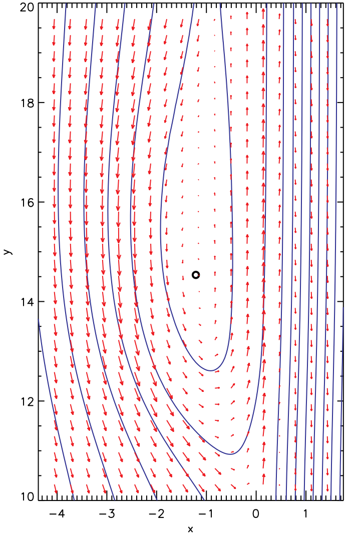
Asymmetric speeds of footpoint motion

- In 2-D models, the footpoints of newly reconnected loops show apparent motion away from each other as more flux is reconnected
- In 2-D, 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

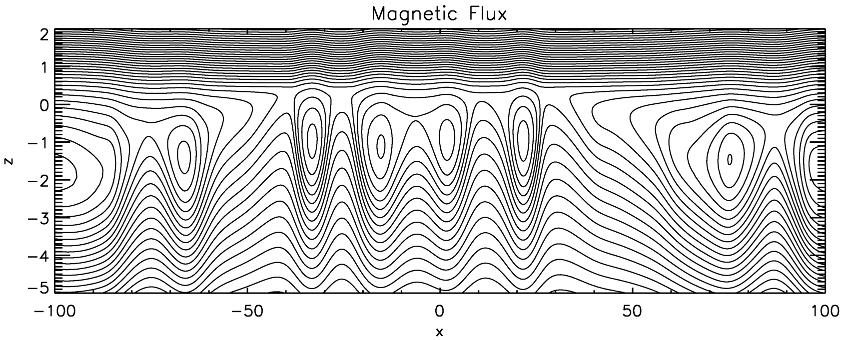
- The standard model of flares predicts HXR emission at the flare footpoints from energetic particles (EPs) impacting the chromosphere
- Magnetic mirroring reflects energetic particles (EPs) preferentially on the strong **B** side
- More particles should escape on the weak **B** side, leading to greater HXR emission
- This trend is observed in $\sim 2/3$ of events (Goff et al.)
  - Additional factors include:
    - Asymmetry in initial pitch angle distributions of EPs
    - Directionality of the reconnecting electric field (Hamilton et al. 2005; Li & Lin 2012)
    - Different column densities (cf. Saint-Hilaire et al. 2008)
  - More detailed energetic particle modeling is required

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



- Velocity vectors in reference frame of O-point

Preliminary results: asymmetric inflow plasmoid instability



- Above simulation seeded with several initial X-lines
- The plasmoids develop preferentially into the weak field region
- Few new X-lines form
- Outward advection of plasmoids is inefficient
- How do the onset criterion, linear/nonlinear growth rates, and dynamics change with increasing Lundquist number?

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
  - Test against observations from SDO/AIA, Hinode/XRT, and RHESSI
  - Plasmoid instability during asymmetric inflow reconnection