Asymmetric Magnetic Reconnection in the Solar Atmosphere

Nick Murphy

Harvard-Smithsonian Center for Astrophysics

Pre-Hurricane NIMROD Team Meeting
Providence, Rhode Island
October 27, 2012

Collaborators: Mari Paz Miralles, John Raymond, Drake Ranquist, Crystal Pope, Kathy Reeves, Chengcai Shen, Jun Lin, Trae Winter, Dan Seaton, Aad van Ballegooijen, Clare Parnell, Andrew Haynes, Lijia Guo, & Yi-Min Huang
SDO/AIA takes $4096^2$ observations of the Sun in eight EUV wavelengths with a 12 second cadence
Overall science goal: To understand the dynamics and consequences of reconnection in the solar atmosphere

- NIMROD simulations of asymmetric reconnection (this talk)
- Analytic theory on appearance, disappearance, and motion of magnetic nulls (one slide)
- Non-equilibrium ionization modeling of coronal mass ejections (Murphy et al. 2011)
  - Ionization/recombination timescales are comparable to expansion time scales
  - Charge state distribution contains temperature history information
  - Evidence of significant heating, but mechanism(s) unclear
- Reconnection in partially ionized chromospheric plasmas
  - New collaboration with V. Lukin & J. Leake using HiFi code
  - Topics: inflow asymmetry, elemental fractionation, Hall effect
- Solar observations of reconnection (including asymmetry)
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
- The plasmoid instability during asymmetric inflow reconnection
Flux rope models of CMEs predict a current sheet behind the rising flux rope

Signatures of reconnection: ‘current sheet’ structures

- White light, X-ray, and EUV observations show sheet-like structures between the post-flare loops and the rising flux rope
- Much thicker than expected; the current sheets may be embedded in a larger-scale plasma sheet
- Current sheets often drift considerably \(\rightarrow\) asymmetry?
Signatures of reconnection: inflows, upflows, downflows

- High cadence observations show reconnection inflows and sunward/anti-sunward exhaust
- Supra-arcade downflows (SADs) re-interpreted as wakes behind contracting loops (Savage et al. 2012)
- Downflows often sub-Alfvénic: due to asymmetry? (Reeves et al. 2010; Murphy 2010; Murphy et al. 2010, 2012)
Open questions in solar/astrophysical reconnection

- What sets the reconnection rate?
- What are the small-scale physics of reconnection?
- What is the interplay between small and large scales?
- Why is there a sudden onset to fast magnetic reconnection?
- Is the 3D plasmoid instability enough for fast reconnection, or are collisionless effects required?
- How are particles accelerated and heated?
- What sets the observed thickness of current sheets?
- How does 3D reconnection occur?
- What are the roles of turbulence, instabilities, and asymmetry?
- How does magnetic reconnection occur in partially ionized plasmas such as the chromosphere?
Part I: Line-tied asymmetric reconnection in the solar atmosphere
NIMROD simulations of line-tied asymmetric reconnection

- Reconnecting magnetic fields are asymmetric:
  \[ B_y(x) = \frac{B_0}{1 + b} \tanh \left( \frac{x}{\delta_0} - b \right) \]  

- 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
  - \(\beta\) larger than reality
- 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 (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.
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.
- $\frac{dx_n}{dt}$ and $\frac{dy_n}{dt}$ 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.
Fitting simulated asymmetric loops to multi-viewpoint observations constrains the asymmetry

- Most important constraints
  - Location of looptop relative to footpoints
  - Different perspectives from \textit{STEREO A/B} and \textit{SDO}
- Results for two events: asymmetries between 1.5 and 4.0
- Next step: compare to photospheric magnetograms
Asymmetric speeds of footpoint motion

- 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.
- The footpoint on the strong $B$ side will move slower than the footpoint on the weak $B$ side.
- Because of the patchy distribution of flux on the photosphere, more complicated motions frequently occur.
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.
The outflow plasmoid develops net vorticity because the CS outflow impacts it at an angle.

▶ Velocity vectors in reference frame of O-point
Part II: The plasmoid instability during asymmetric inflow reconnection
NIMROD simulations of asymmetric plasmoid instability

- Reconnecting magnetic fields are asymmetric:
  \[ B_y(x) = \frac{B_0}{1 + b} \tanh \left( \frac{x}{\delta_0} - b \right) \]  

- A small number of localized initial magnetic perturbations placed asymmetrically along \( z = 0 \) near center of domain

- Symmetric case: \( \{ B_1, B_2 \} = \{ 1, 1 \} \); \( S_{Ah} \sim 10^5 \) \( V_{Ah} = 1.0 \)

- Asymmetric case: \( \{ B_1, B_2 \} = \{ 0.25 \} \); \( S_{Ah} \sim 5 \times 10^4 \), \( V_{Ah} = 0.5 \)

- Uniform initial density

- \( \beta_0 = 1 \) in higher magnetic field upstream region

- Domain: \( -150 \leq x \leq 150, -16 \leq z \leq 16 \)

- Boundary conditions: periodic along outflow direction and conducting wall along inflow direction

- No mesh packing along outflow direction, and modest resolution requirements in strong \( B \) upstream region
Numerical considerations

- Mesh packing required over longer stretch along inflow direction
  - X-lines drift toward strong magnetic field upstream region
  - Somewhat less resolution required along outflow direction than in symmetric case
  - Higher resolution required in weak $\mathbf{B}$ upstream region than in strong $\mathbf{B}$ upstream region

- Preliminary simulations showed sloshing/oscillatory behavior
  - Symmetric perturbations led to asymmetric magnetic pressure imbalance
  - Resolved by using weak, localized perturbations and increasing the size of the domain along the inflow direction
Plasmoid instability: symmetric inflow

Magnetic Flux

Current density, $J_y$ (range: $-3.36$ to $7.31$)

Outflow velocity, $V_x$ (range: $\pm 0.84$)

Inflow velocity, $V_z$ (range: $\pm 0.36$)

Vorticity, $(\nabla \times V)_y$ (range: $\pm 1.64$)
Plasmoid instability: asymmetric inflow
Key features of symmetric inflow simulation

- X-points and O-points all located along $z = 0$
  - Makes it easy to find nulls
- X-lines often located near one exit of each current sheet
  - Characteristic single-wedge shape
- There is net plasma flow across X-lines
  - Flow stagnation points not co-located with X-line
  - The velocity of each X-line differs from the plasma flow velocity at each X-line (see Murphy 2010)
- Outflow jets impact islands directly
  - No net vorticity in islands and downstream regions
  - Less noticeable turbulence in downstream regions
- Outflow velocity $\sim 5/6$ of Alfvén speed
Key features of asymmetric inflow simulation

- Maximum outflow velocity is $\sim 2/3$ of $V_{Ah}$
- Current sheets thicker than symmetric case
- X-lines vary in position along inflow direction
- Islands develop preferentially into weak $B$ upstream region
- Outflow jets impact islands obliquely
  - Islands advected outward less efficiently
  - Net vorticity develops in each magnetic islands
- Downstream region is turbulent
  - Plasmoids impacting and merging with downstream island
  - Several X-points and O-points
- Very little happening in strong $B$ upstream region
  - Less resolution needed than in weak $B$ upstream region
- Secondary reconnection events (when islands merge) have asymmetric inflow and outflow
The asymmetric case shows little enhancement in the reconnection rate from the predicted value

Use formulae from Cassak & Shay (2007); Birn et al. (2011):

\[ E_{\text{predict}} = \sqrt{\frac{\eta V_{Ah}}{L}} B_L B_R \]
\[ t_{Ah} = \frac{L}{V_{Ah}} \]
\[ L = 100 \]

Note: \( S_{Ah} \) is lower by a factor of two for the asymmetric case
Murphy (2010) derived an exact expression for the rate of X-line retreat when it is restricted to 1D

\[
\frac{dx_n}{dt} = \frac{\partial E_y}{\partial x} \bigg|_{x_n} = \frac{\partial E_y}{\partial B_z} \bigg|_{x_n} = V_x(x_n) - \eta \left[ \frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right]_{x_n} \tag{3}
\]

The 3D equivalent for the motion of isolated magnetic nulls is

\[
\frac{dx_n}{dt} = (\nabla B)^{-1} \nabla \times E = V(x_n) - \left[ \eta (\nabla B)^{-1} \nabla^2 B \right]_{x_n} \tag{4}
\]

This provides insight into how nulls form, move, and disappear

- Plasma flow across nulls allowed by resistive diffusion
- When the Jacobian matrix \( \nabla B \) is singular, nulls are either appearing or disappearing
- Newly formed null-null pairs initially move apart very quickly
- Allows convenient tracking of nulls in 2D and 3D simulations
Conclusions

The observational signatures of asymmetric reconnection during solar eruptions include:

- Skewing/distortion of post-flare loops into a skewed candle flame shape
- The weak field footpoint moves more quickly and has stronger hard X-ray emission
- The X-line drifts slowly into the strong field region
- Net vorticity in the rising flux rope

Features of the asymmetric plasmoid instability include:

- X-line positions not all at same location along inflow direction
- Islands develop into the weak $B$ upstream region
- Outflow jets impact islands obliquely
  - Less efficient outward advection of islands
  - Circulation within each island
- Turbulence in the downstream region
- Broader current sheets than the symmetric case
- The reconnection rate is not greatly enhanced above the predicted value for asymmetric reconnection without plasmoids
Simulations are performed using NASA’s Pleiades cluster.
Main limitation is memory management for large 2D simulations.
- Running largest jobs on 9 of 12 cores on nodes with 48 GB.
Future work with NIMROD (recent NSF/DOE proposal)

- Topics in recent NSF/DOE proposal with J. King and M. Oka
  - Compare dynamics of X-line retreat using two-fluid NIMROD and PIC simulations (with Mitsuo Oka)
  - Plasmoid instability during asymmetric inflow reconnection
  - Scaling behavior of X-line retreat in resistive MHD
    - How do global conditions affect local dynamics of X-line retreat?
  - 3D simulations of two competing reconnection sites
    - Provide insight into

- How do energetic particles affect the reconnection process?
  - Huge fraction of available electrons are accelerated
  - We sorta know how particles are accelerated, but don’t know how energetic particles feed back on the reconnection process
What sets the rate of X-line retreat?

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

  \[
  \frac{\partial B_z}{\partial t} = - \frac{\partial E_y}{\partial x} \quad (5)
  \]

- The convective derivative of $B_z$ at the X-line taken at the velocity of X-line retreat, $dx_n/dt$, is

  \[
  \frac{\partial B_z}{\partial t} \bigg|_{x_n} + \frac{dx_n}{dt} \frac{\partial B_z}{\partial x} \bigg|_{x_n} = 0 \quad (6)
  \]

The RHS of Eq. (6) 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. 5 and 6:

\[
\frac{dx_n}{dt} = \frac{\partial E_y/\partial x}{\partial B_z/\partial x} \bigg|_{x_n} \tag{7}
\]

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

\[
\frac{dx_n}{dt} = V_x(x_n) - \eta \left[ \frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right] \bigg|_{x_n} \tag{8}
\]

\[\frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2}, \text{ so X-line retreat is caused by diffusion of the normal component of the magnetic field along the inflow direction}\]

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
Different approaches for studying reconnection

- **Laboratory experiments**
  - *Advantages*: experimental control, fantastic diagnostic capabilities, simultaneous view of small and large scales
  - *Disadvantages*: modest dimensionless parameters/separation of scales, boundary conditions affecting results

- **In situ** measurements in near-Earth space plasmas
  - *Advantages*: extremely detailed data at a small number of points, great for studying collisionless effects
  - *Disadvantages*: difficult to connect to global dynamics or distinguish between cause and effect

- **Solar observations**
  - *Advantages*: large-scale dynamics, parameter regimes inaccessible elsewhere, detailed thermal information
  - *Disadvantages*: cannot observe small scales, magnetic field difficult to diagnose