Asymmetric Magnetic Reconnection in the Solar Atmosphere

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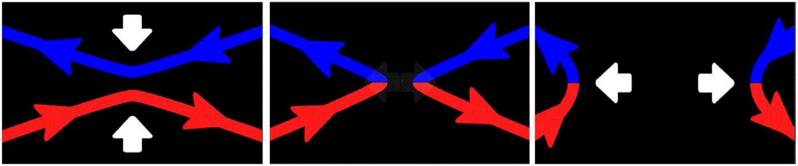
Outline

- Basic physics of magnetic reconnection
- Magnetic reconnection in different environments
  - Solar atmosphere
  - Earth's magnetosphere
  - Laboratory plasmas
- Asymmetric magnetic reconnection in the solar atmosphere
  - Observational signatures of asymmetric flare reconnection
  - The plasmoid instability during asymmetric reconnection
  - Asymmetric reconnection in the weakly ionized chromosphere

Basic Physics of Magnetic Reconnection

Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma



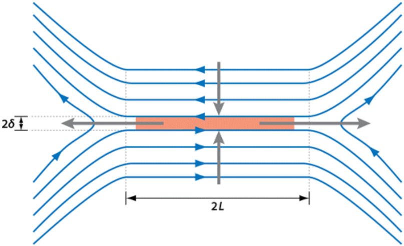
- Occurs in regions of strong magnetic shear
- Changes the magnetic topology
- Releases magnetic energy into kinetic and thermal energy
- Often efficiently accelerates particles
- Typically produces bidirectional Alfvénic outflow jets
- Often *fast* after a slow buildup phase

Open questions in magnetic reconnection

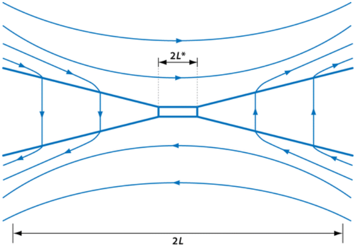
- What sets the reconnection rate in different environments?
- What leads to a sudden onset of fast reconnection?
- What is the interplay between small-scale physics and global dynamics?
- How are particles accelerated and heated?
  - How does efficient particle acceleration feed back on reconnection?
- What role does reconnection play in astrophysical dynamos, turbulence, and instabilities?
- How does reconnection occur in 3D?
- How does reconnection behave in astrophysical environments?

Classical picture: Sweet-Parker (slow) vs. Petschek (fast)

Sweet-Parker

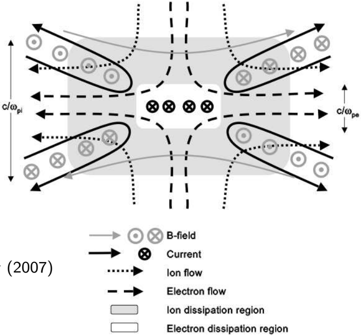


Petschek



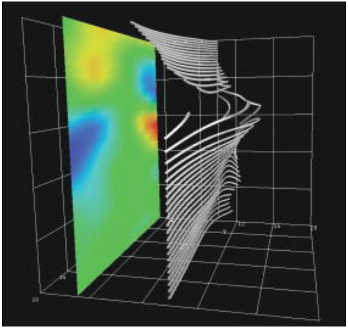
- The Sweet-Parker vs. Petschek dichotomy ignores important advances in our understanding of high Lundquist number and collisionless reconnection (Zweibel & Yamada 2009)

Fundamentals of collisionless reconnection



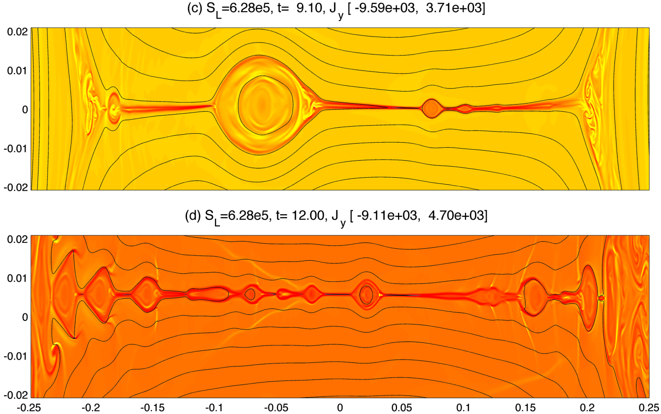
Drake & Shay (2007)

Yamada et al. (2006)



- On scales shorter than the ion inertial length, electrons and ions decouple. The magnetic field is carried by the electrons.
- The electrons pull the magnetic field into a much smaller diffusion region
  - $\Rightarrow$ X-point geometry $\Rightarrow$ fast reconnection
- The in-plane magnetic field is pulled by electrons in the out-of-plane direction $\Rightarrow$ quadrupole magnetic field

Elongated current sheets are susceptible to the tearing-like plasmoid instability (Loureiro et al. 2007)

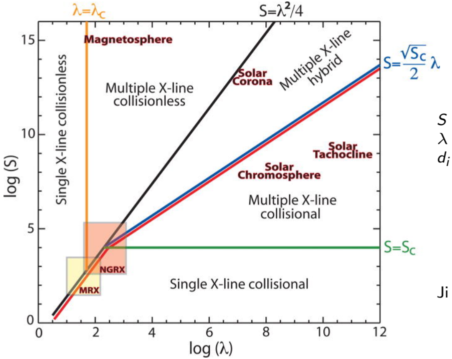


Bhattacharjee et al. (2009)

$S = \mu_0 L V_A / \eta$ is the Lundquist number

- Breaks up 2D current sheets into alternating X-points and islands when $S \gtrsim 10^4$; reconnection becomes sort of fast!
- The Sweet-Parker model is not applicable to astrophysical reconnection where S is orders of magnitude larger!

Emerging phase diagram for collisionless vs. plasmoid dominated reconnection



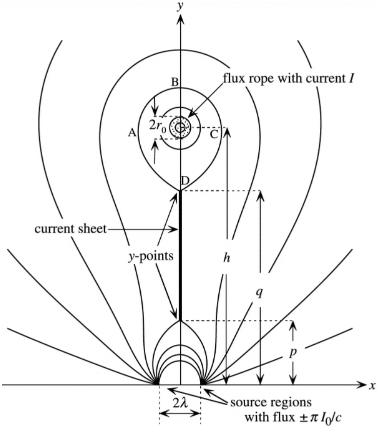
$S = \mu_0 L V_A / \eta$
$\lambda \equiv L/d_i$
$d_i =$ ion inertial length

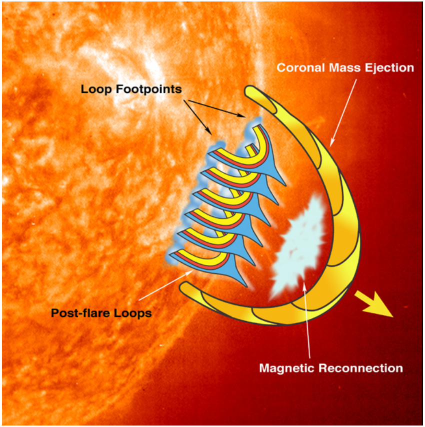
Ji & Daughton (2011)

- Caveats:
  - Extrapolation for $S \gtrsim 10^7$
  - 3D effects/scaling not well understood
- Next-generation reconnection experiments could test this parameter space diagram

Magnetic Reconnection in Different Environments

The ‘standard model’ of solar flares and CMEs predicts a reconnecting current sheet behind a rising flux rope





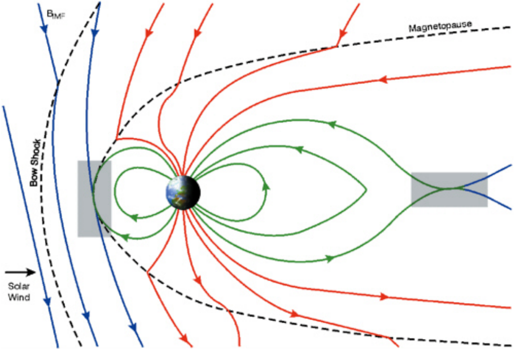
The standard model includes several observational signatures of flare reconnection

- The observational signatures of flare reconnection include
  - Growing arcade of flare loops
  - Apparent motion of footpoints of newly reconnected loops
  - Hard X-ray (HXR) emission at loop footpoints
  - Sheet-like structures behind rising flux ropes
  - Inflow/outflow pattern in reconnection region
- More complete story when multiple signatures are observed simultaneously
- These signatures are modified by magnetic asymmetry

Learning about reconnection in solar/astrophysical plasmas

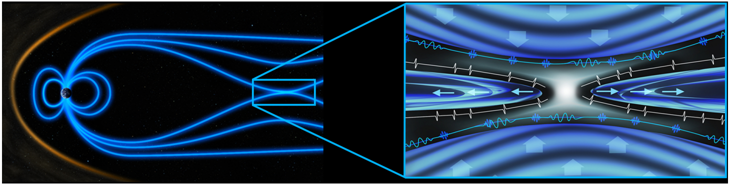
- Advantages:
  - Observations of large-scale dynamics
  - Parameter regimes inaccessible by experiment or simulation
  - Detailed information on thermal properties of plasma
- Disadvantages:
  - No experimental control
  - Limited to remote sensing
  - Cannot directly observe small-scale physics
  - Difficult to diagnose magnetic field
- Examples:
  - Solar/stellar flares and coronal mass ejections
  - Chromospheric jets (and type II spicules?)
  - Interstellar medium and star formation regions
  - Accretion disks
  - Neutron star magnetospheres
  - Magnetized turbulence

Magnetic reconnection in Earth's magnetosphere



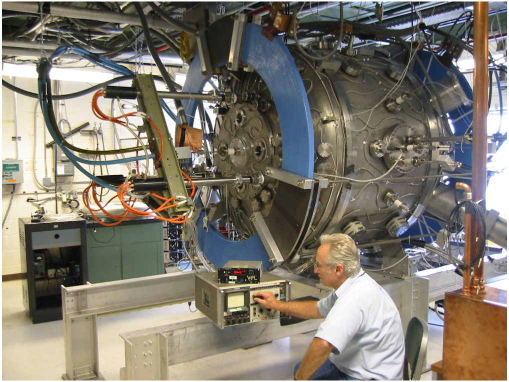
- Magnetic reconnection occurs in two primary locations in Earth's magnetosphere in response to driving from solar wind
  - Dayside magnetopause: solar wind plasma reconnecting with magnetospheric plasma
  - Magnetotail: in response to magnetic energy building up in lobes due to solar wind driving
- Collisionless physics become important

Learning about reconnection in space plasmas



- Advantages:
  - Extremely detailed data at a small number of points
  - Parameter regimes inaccessible to experiment
  - Excellent for studying collisionless physics
- Disadvantages:
  - Difficult to connect observations to global dynamics
  - Difficult to disentangle cause and effect
  - No experimental control
- Missions:
  - Cluster, THEMIS, Geotail, ACE, Wind, Ulysses, Voyagers 1&2, STEREO A/B, DSCOVR
  - Launched 16 hours ago: Magnetospheric Multiscale Mission

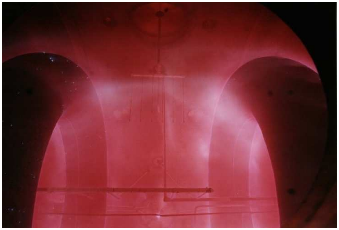
Magnetic reconnection in laboratory plasmas



MRX

- Dedicated experiments on reconnection allow direct observations of reconnection under controlled conditions
- Complements observations of solar/space/astrophysical reconnection!

Learning about reconnection from laboratory experiments



MRX

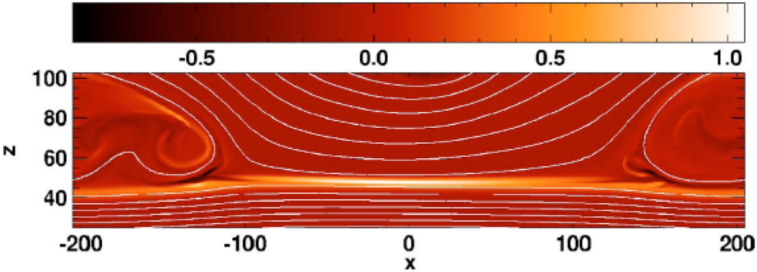
- Advantages:
  - Can insert probes directly (especially for $T \lesssim 20$ eV)
  - Study small-scale physics and global dynamics simultaneously
  - Controlled experiments
- Disadvantages:
  - Relatively modest parameter regimes
  - Modest separation of scales
  - Results influenced by BCs/experimental method
- Examples:
  - Tokamaks, spheromaks, reversed field pinches
  - MRX, VTF, TS-3/4, SSX, RSX, CS-3D

Asymmetric Magnetic Reconnection in the Solar Atmosphere

Asymmetric Magnetic Reconnection

- Most models of reconnection assume symmetry
- However, asymmetric magnetic reconnection occurs in the solar atmosphere, solar wind, space/astrophysical plasmas, and Laboratory experiments
- *Asymmetric inflow reconnection* occurs when the upstream magnetic fields and/or plasma parameters differ
  - Solar jets: emerging flux interacting with overlying flux
  - Earth's dayside magnetopause
  - Tearing modes in tokamaks and other confined plasmas
- *Asymmetric outflow reconnection* occurs when conditions in the outflow regions are different
  - Solar flare and CME current sheets
  - Earth's magnetotail
  - Spheromak merging experiments
- There are also 3D asymmetries (e.g., patchy reconnection)

Cassak & Shay (2007) consider the scaling of asymmetric inflow reconnection



- Assume Sweet-Parker-like reconnection with different upstream magnetic fields (B_L, B_R) and densities (ρ_L, ρ_R)
- The outflow velocity scales as a hybrid Alfvén velocity:

$$V_{out} \sim V_{Ah} \equiv \sqrt{\frac{B_L B_R (B_L + B_R)}{\rho_L B_R + \rho_R B_L}} \tag{1}$$

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

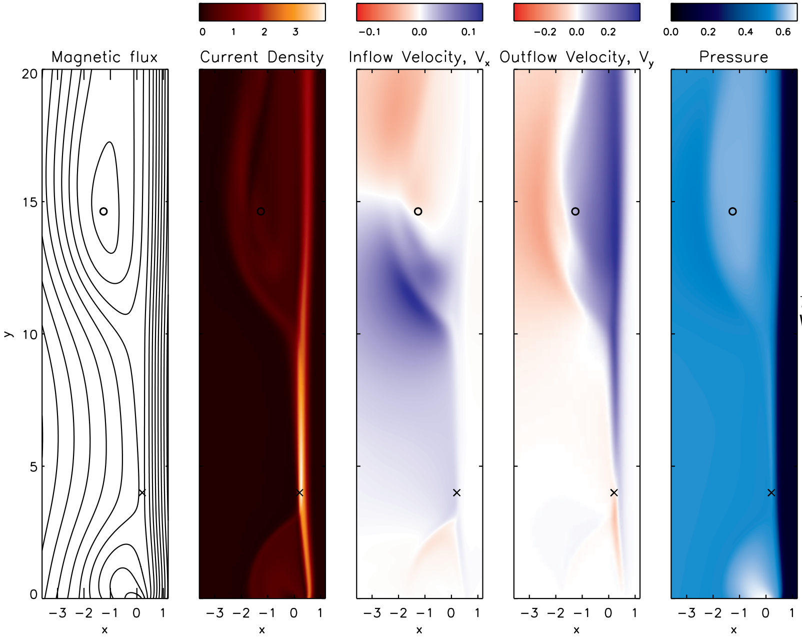
How does magnetic asymmetry impact the standard model of two-ribbon solar flares?

- We use NIMROD to perform resistive MHD simulations of line-tied asymmetric reconnection (Murphy et al. 2012)
- Asymmetric upstream magnetic fields

$$B_y(x) = \frac{B_0}{1+b} \tanh\left(\frac{x}{\delta_0} - b\right) \tag{2}$$

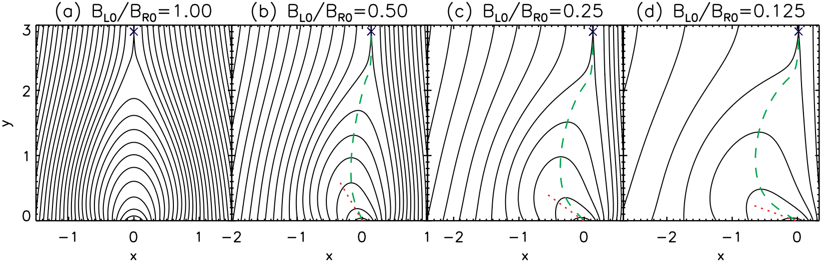
  - Magnetic asymmetries of $B_L/B_R \in \{0.125, 0.25, 0.5, 1\}$
- Initial X-line near lower wall makes reconnection asymmetric
- Caveats: β larger than reality; unphysical upper wall BC (far from region of interest); no vertical stratification, 3D effects/guide field, or collisionless effects
- This setup allows us to:
  - Isolate the effects of magnetic asymmetry
  - Investigate the basic physics of asymmetric reconnection

The X-point is low so most released energy goes up



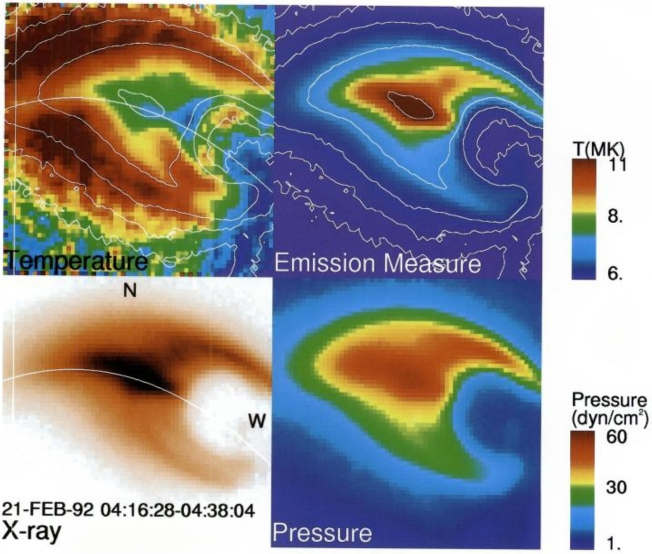
$$\frac{B_L}{B_R} = 0.25$$
$$V_{Ah} = 0.5$$

The flare loops develop a skewed candle flame shape



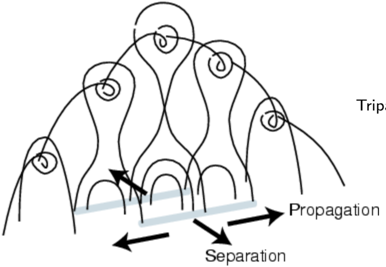
- Dashed green line: loop-top positions from simulation
- Dotted red line: analytic asymptotic approximation using potential field solution

The Tsuneta (1996) flare is a famous candidate event



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

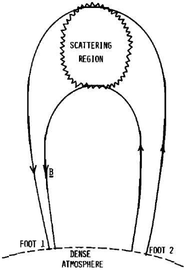
Asymmetric speeds of footpoint motion



Tripathi et al. (2006)

- The footpoints of newly reconnected loops show apparent motion away from each other as more flux is reconnected
- Equal amounts of flux reconnected from each side
  $\Rightarrow$ Weak **B** footpoint moves faster than strong **B** footpoint
- Because of the patchy distribution of flux on the photosphere, more complicated motions frequently occur

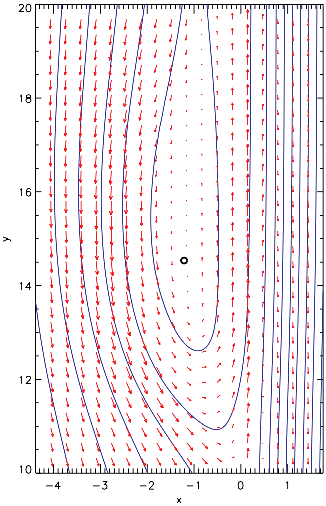
Asymmetric hard X-ray (HXR) footpoint emission



Melrose & White (1979, 1981)

- HXR emission at flare loop footpoints results from energetic particles impacting the chromosphere
- Magnetic mirroring is more effective 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. 2004)

The outflow plasmoid develops net vorticity because the reconnection jet impacts it obliquely rather than directly



- Velocity vectors in reference frame of O-point
- Rolling motion observed in many prominence eruptions

Take away points

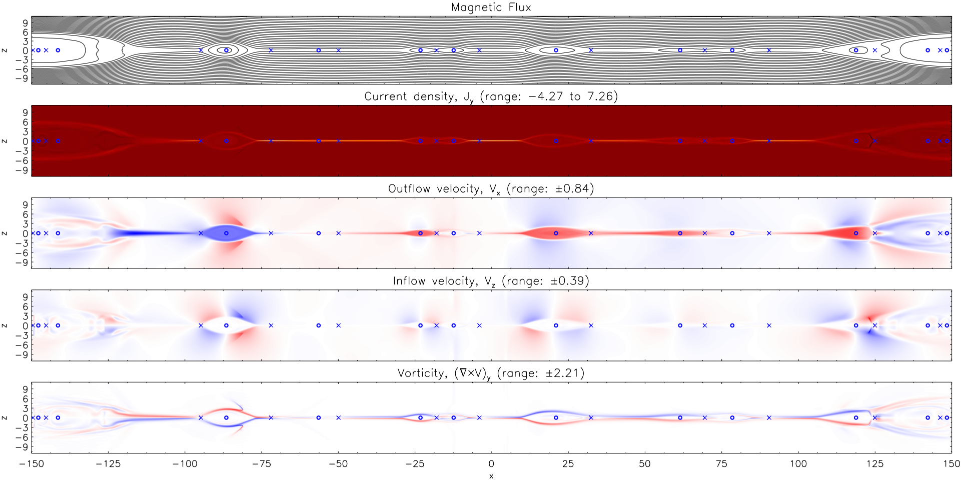
- Magnetic asymmetry leads to observational consequences during solar reconnection
  - Flare loops with skewed candle flame shape
  - Asymmetric footpoint motion and hard X-ray emission
  - Drifting of current sheet into strong field region
  - Rolling motions in rising flux rope
- Important effects not included in these simulations:
  - Realistic 3D magnetic geometry
  - Patchy distribution of photospheric flux
  - Vertical stratification of atmosphere
  - Collisionless effects
- Open question:
  - How can we use observation and simulation to test these predictions and determine the roles of 3D effects?

The Plasmoid Instability During Asymmetric Magnetic Reconnection

What are the dynamics of the plasmoid instability during asymmetric inflow reconnection?

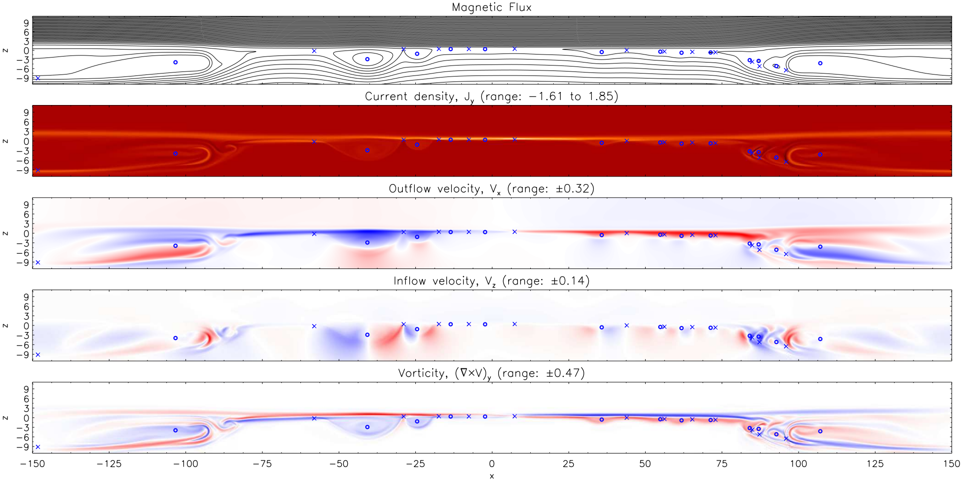
- Most simulations of the plasmoid instability assume reconnection with symmetric upstream fields
  - Simplifies computing and analysis
  - Plasmoids and outflows interact in one dimension
- In 3D, flux ropes twist and writhe and sometimes bounce off each other instead of merging
  - Asymmetric simulations offer clues to 3D dynamics
- We perform NIMROD simulations of the plasmoid instability with asymmetric magnetic fields (Murphy et al. 2013)
  - (Hybrid) Lundquist numbers up to 10^5
  - Two uneven initial X-line perturbations along $z = 0$
  - $B_L/B_R \in \{0.125, 0.25, 0.5, 1\}$; $\beta_0 \geq 1$; periodic outflow BCs
  - Caveats: simple Harris sheet equilibrium; no guide field or 3D effects; resistive MHD

Plasmoid instability: symmetric inflow ($B_{L0}/B_{R0} = 1$)



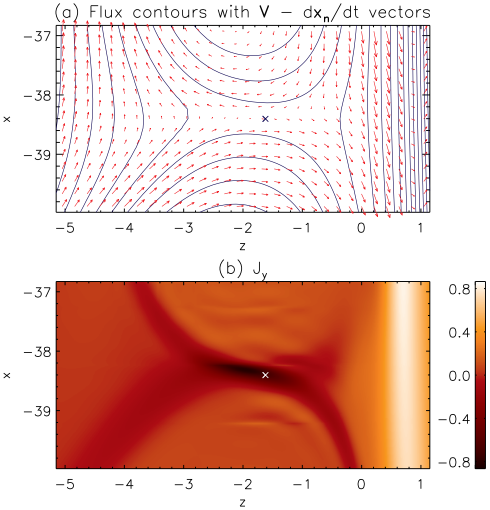
- X-points and O-points are located along symmetry axis
- X-points often located near one exit of each current sheet
- No net vorticity in islands

Plasmoid instability: asymmetric inflow ($B_{L0}/B_{R0} = 0.25$)



- Displacement between X-point and O-points along z direction
- Islands develop preferentially into weak field upstream region
- Islands have vorticity and downstream regions are turbulent

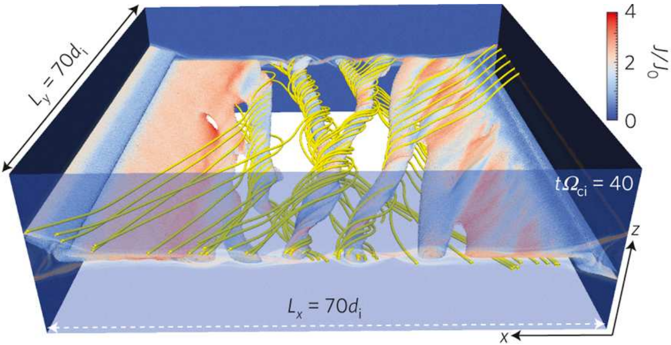
Secondary merging is doubly asymmetric



- Bottom island is much larger $\Rightarrow$ island merging is not head-on
- Flow pattern dominated by shear flow associated with island vorticity $\Rightarrow$ Partial stabilization of secondary reconnection

Three-dimensional effects in fully kinetic simulations of reconnection

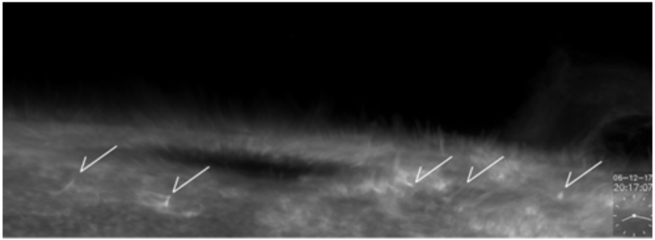
Daughton et al. (2011)



- Instead of nice 2D islands, there are highly twisted irregular flux rope structures
- Open question: how is the plasmoid instability affected?

Asymmetric Magnetic Reconnection in the Partially Ionized Solar Chromosphere

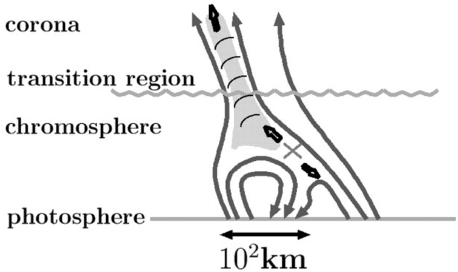
Magnetic reconnection is ubiquitous in the chromosphere



Hinode/SOT
Shibata et al. (2007)

- Plasma in the solar corona is typically $\sim$fully ionized
- The chromospheric ionization fraction ranges from $\lesssim$0.01–0.5
- Reconnection time scales $\lesssim$ ionization/recombination time scales $\Rightarrow$ plasma often not in ionization equilibrium
- We perform simulations of asymmetric magnetic reconnection in partially ionized chromospheric plasmas
- Motivating questions:
  - How does asymmetry impact chromospheric reconnection?
  - What are the dynamics of the plasmoid instability?

Asymmetric reconnection in chromospheric jets



Shibata et al. (2007)

- Asymmetric inflow reconnection often occurs at the boundaries between different domains of plasma
  - Example: Earth's dayside magnetopause
- Chromospheric jets occur when newly emerged flux reconnects with pre-existing overlying flux
  - Naturally asymmetric!
- The chromosphere is a dynamic magnetized environment
  - Asymmetric reconnection should be the norm

We use the plasma-neutral module of the HiFi framework (Meier & Shumlak 2012; Leake et al. 2012, 2013)

- Separate continuity, momentum, and energy equations for ions and neutrals
  - Ionization and recombination (non-equilibrium ionization)
  - Momentum/energy transfer between species
  - Charge exchange
  - Resistivity
  - Hall effect
  - Optically thin radiative losses
  - Isotropic neutral thermal conduction
  - Anisotropic ion thermal conduction
- Leake et al. (2012, 2013) simulate symmetric chromospheric reconnection
  - Reconnecting field drags ions into current sheet $\rightarrow$ enhancement of ion density
  - Recombination helps remove ions from current sheet

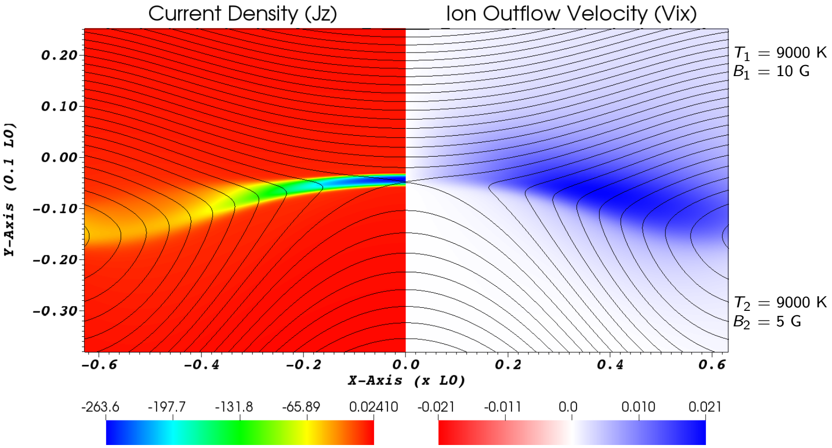
We perform simulations with symmetric and asymmetric upstream temperatures and magnetic field strengths

- Specify $\mathbf{B}$ and T on each side
- Calculate n_i and n_n so there is approximate total pressure balance ($\beta \gtrsim 3$) while assuming initial ionization equilibrium
- Need initial ion-neutral drift so forces acting on ions can balance forces acting on neutrals
- Focus on single case with symmetric T and asymmetric $\mathbf{B}$:[1]

$$T_1 = T_2 = 9000 \text{ K}$$
$$B_1 = 10 \text{ G}, B_2 = 5 \text{ G}$$

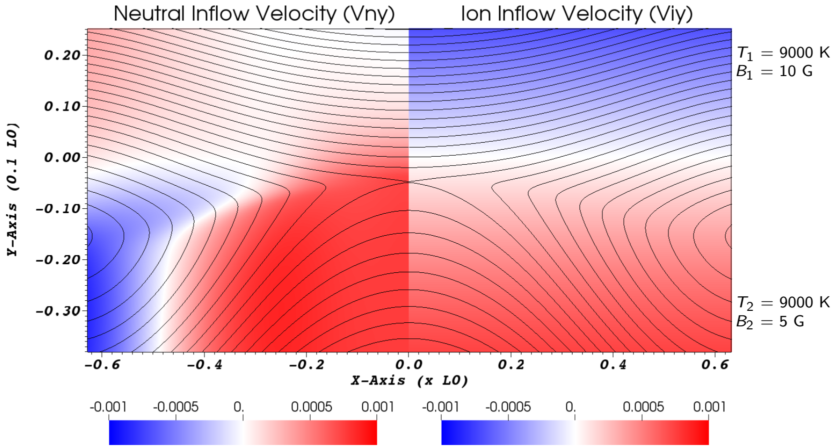
[1]The normalizations are $B_0 = 10$ G, $L_0 = 10$ km, $V_0 = 126$ km s^{-1}, and $n_0 = 3 \times 10^{16}$ m^{-3}. For details, see Murphy & Lukin (submitted to ApJ)

Current sheet structure: Symmetric T, Asymmetric **B**



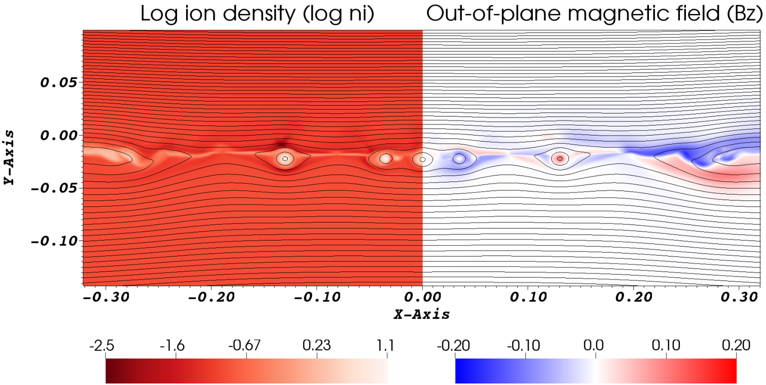
- The ion and neutral outflows are tightly coupled
- Slightly arched current sheet; X-point on weak **B** side

Comparing inflow velocities: Symmetric T, Asymmetric **B**



- Asymmetric decoupling between ions and neutrals in inflow
- Higher neutral pressure on bottom $\rightarrow$ neutrals flow upward

Dynamics of the plasmoid instability



- Plasmoids bulge into weak field upstream region
- High ion density in plasmoids
- Hall fields locally a large fraction of reconnecting field
  - Beginning of transition to Hall reconnection?
  - Core fields in some plasmoids after merging

Connecting to solar observations and experiment

- Connecting to solar observations (e.g., *IRIS*)
  - Challenges
    - Non-equilibrium ionization of minor elements
    - Radiative transfer
    - Very short length scales
    - Confusion along line-of-sight
  - Opportunities
    - Predicting spectral signatures, velocities, physical conditions
    - Statistical properties of reconnection events (e.g., jets)
- Connecting to experiment (e.g., MRX; Lawrence et al. 2013)
  - Challenges
    - Limited separation of scales
    - Relatively modest plasma parameters
  - Opportunities
    - *In situ* diagnostic capabilities
    - Improved understanding of basic physics
    - Validation of simulation results

Summary and Conclusions

- Magnetic reconnection is a fundamental process in laboratory, space, and astrophysical plasmas
- Emerging phase diagram: plasmoid-dominated vs. collisionless reconnection
- Understanding reconnection requires cross-disciplinary efforts
- Magnetic asymmetry during flares leads to skewed candle flame shaped flare loops, asymmetric footpoint motion and HXR emission, and rolling motions in the rising flux rope
- Magnetic asymmetry qualitatively changes the dynamics of the plasmoid instability
- Simulations of partially ionized chromospheric reconnection show neutral flows through current sheets and other effects not present in symmetric cases