Magnetic Reconnection in Heliospheric, Laboratory, and Astrophysical Plasmas

Nick Murphy

Harvard-Smithsonian Center for Astrophysics

Astronomy Lunch Talk
Boston University
December 2, 2014

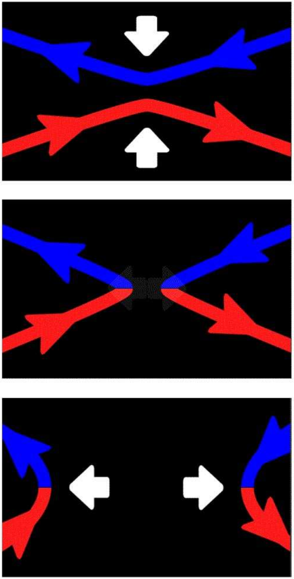
Outline

- Overview of magnetic reconnection
- Reconnection in different environments
  - Solar atmosphere
  - Earth's magnetosphere
  - Laboratory plasmas
  - Interstellar medium
- A dichotomy of dichotomies, and an emerging phase diagram
  - Sweet-Parker vs. Petschek reconnection
  - Plasmoid-dominated vs. collisionless reconnection
- Preliminary announcement of Inclusive Astronomy meeting

Magnetic reconnection is a fundamental process in magnetized plasmas

- Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma
- Reconnection occurs in:
    - Solar atmosphere (flares, coronal mass ejections, jets)
    - Laboratory plasmas (fusion devices, dedicated experiments)
    - Earth's magnetosphere (in response to driving by solar wind)
    - Astrophysical plasmas (star formation regions, accretion disks, jets, ISM/galactic dynamos, stellar chromospheres/coronae)
- A more complete understanding of reconnection requires an interdisciplinary approach

Picturing two-dimensional magnetic reconnection



Credits: Center for Visual computing, Univ. of California Riverside

Missing essential 3D effects!

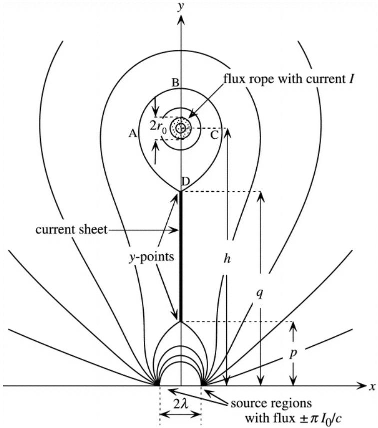
Usual ingredients of magnetic reconnection

- Occurs in regions of strong magnetic shear
- Release of magnetic energy into kinetic and thermal energy
  - Often explosive
  - Energy released on small scales but with global consequences
- Changes in magnetic topology
- Outflow jets at $\sim$Alfvén speed
- Efficient particle acceleration
- Reconnection is often *fast*
- Reconnection often onsets after a slow buildup phase

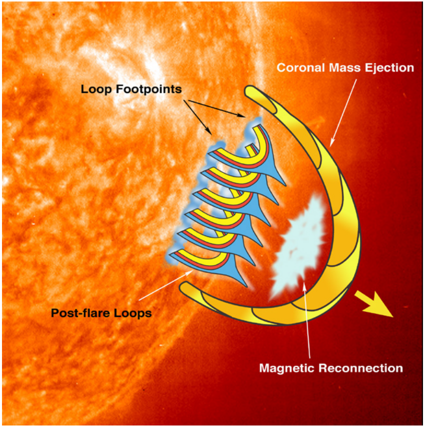
Open questions in magnetic reconnection

- What sets the reconnection rate?
- Why is there often a sudden onset to fast reconnection?
- What is the interplay between small-scale physics and global dynamics?
  - Including collisionless/kinetic effects
- How are particles accelerated and heated?
- What are the roles of turbulence, instabilities, and asymmetry?
- How does 3D reconnection occur?
- How does reconnection behave in extreme astrophysical environments?
  - Neutron star atmospheres, supernovae, gamma ray bursts, black hole accretion disks
  - Weakly ionized plasmas such as the solar chromosphere and protoplanetary disks (e.g., Murphy & Lukin, in prep)

The 'standard model' of solar flares and CMEs predict a reconnecting current sheet behind a rising flux rope



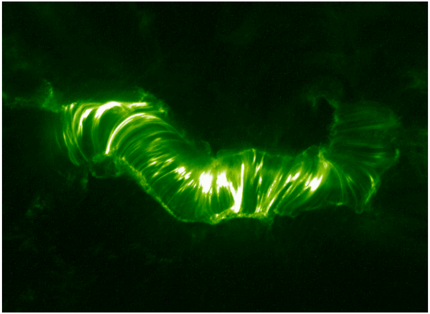
Lin & Forbes (2000)

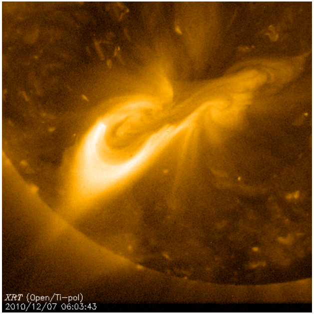


Reconnection is an essential ingredient in solar flares and coronal mass ejections (CMEs)

- Signatures of coronal reconnection include
  - Changes in magnetic topology
  - A growing arcade of flare loop structures
  - 'Current sheet' structures above the flare loops
  - Plasma motions into and out of reconnection region
  - Hard X-ray emission above flare loops

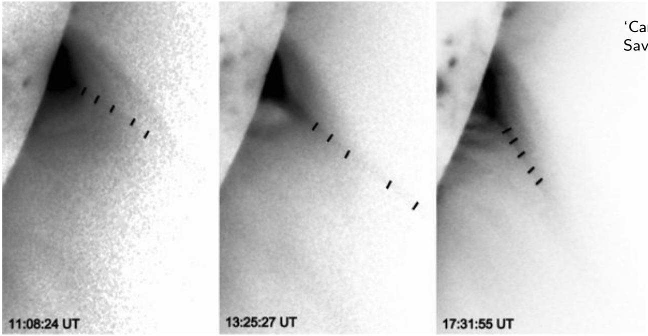
Signatures of reconnection: cuspy post-flare loops





- Shrinkage (contraction) of flare loops after reconnection
- Footpoints of most recently reconnected loops show apparent motion away from the neutral line (field reversal)
- These observations provide information on the energetics, thermodynamics, reconnection rate, and magnetic topology

Signatures of reconnection: ‘current sheet’ structures

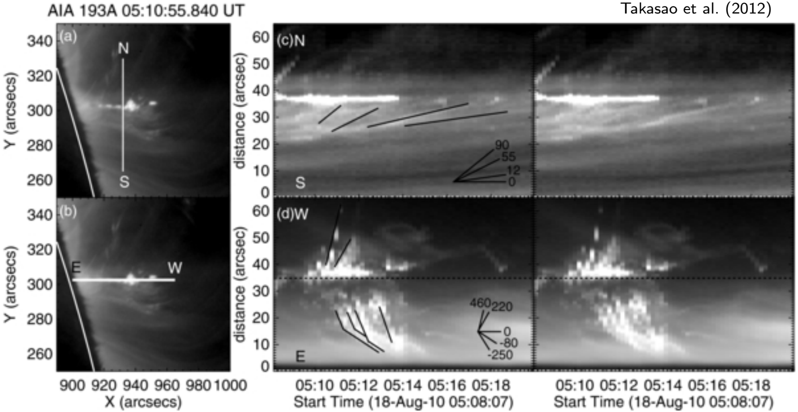


‘Cartwheel CME’
Savage et al. (2012)

- White light, X-ray, and EUV observations show sheet-like structures that develop 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

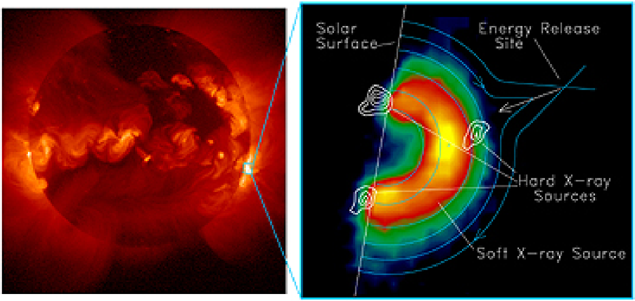
Signatures of reconnection: inflows, upflows, downflows

Takasao et al. (2012)



- High cadence observations show reconnection inflows and sunward/anti-sunward exhaust

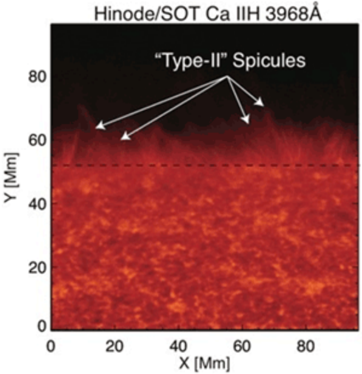
Signatures of reconnection: Above-the-loop-top hard X-ray (HXR) sources (Masuda et al. 1994)



Yohkoh X-ray Image of a Solar Flare, Jan. 13, 1992

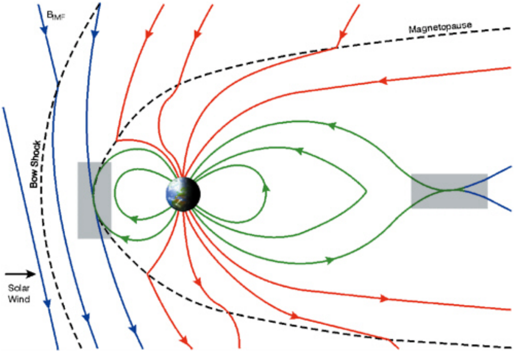
- Evidence for particle acceleration occuring at or above the apex of the post-flare loop
- Lower HXR sources due to energetic particles or a thermal conduction front impacting the chromosphere

Magnetic reconnnection is ubiquitous in the partially ionized solar chromosphere



- Ionization fraction: $\lesssim 0.01$ to ~ 0.5
- Chromospheric jets and Type II spicules may be manifestations of reconnection in partially ionized plasmas
- How does reconnection occur in weakly ionized plasmas?

Magnetic reconnection in Earth's magnetosphere

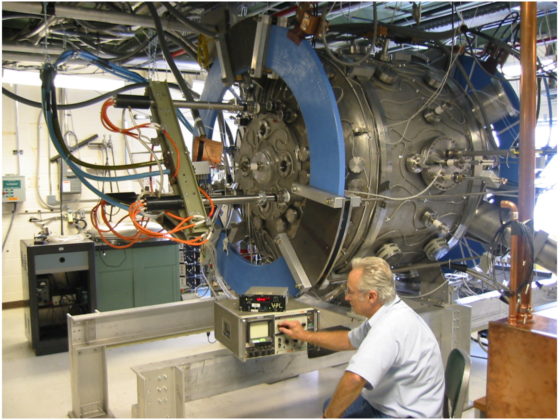


- Magnetic reconnection occurs in two primary locations in Earth's magnetosphere in response to driving from solar wind
  - Dayside magnetopause: solar wind plasma reconnecting with magnetospheric plasma
  - Magnetotail: in response to magnetic energy building up in lobes due to solar wind driving

Magnetic reconnection in Earth's magnetosphere

- MHD not valid; need collisionless physics
- Can be measured *in situ* using magnetometers on spacecraft
  - With multiple spacecraft in a compact formation, you can calculate the curls of quantities! (e.g., *Cluster*)
- Reconnection is an important part of space weather (geomagnetic storms & substorms)
  - Key goal of space weather forecasting: predicting orientation of interplanetary magnetic field
- Analogous physical processes in solar flares and magnetotail

Magnetic reconnection in laboratory plasmas



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

Reconnection during a sawtooth crash allows heat stored in the core plasma of a tokamak to quickly escape

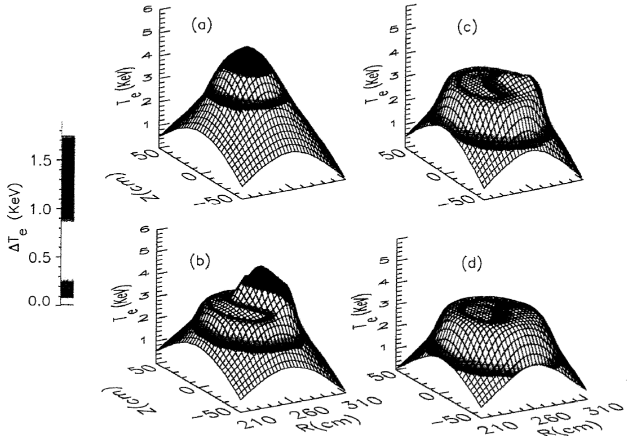


FIG. 1. The $T_e(r,\theta)$ profiles in three dimensions during the crash period of a sawtooth. Heat transfer ΔT_e is superposed with coded color contours. The time intervalbetween each figure is ~ 120 μs.

- Reconnection degrades confinement in magnetically confined fusion plasmas (peaked temperature profile $\rightarrow$ flat profile)

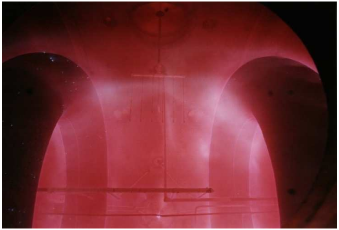
Magnetic reconnection in the ISM

- Occurs on scales too small to observe directly
- Indirect observations: dissipation range of ISM turbulence?
- In absence of reconnection, the number of magnetic field reversals in the Milky Way should $\approx$ the number of galactic rotations
- There are $\sim$5–10 reversals
  - Suggests that reconnection in ISM is fast
  - Linked to problem of forming large-scale field in dynamo theory

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

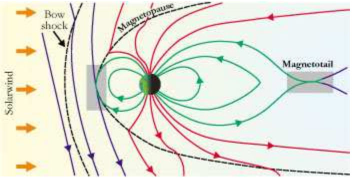
Learning about reconnection from laboratory experiments



MRX

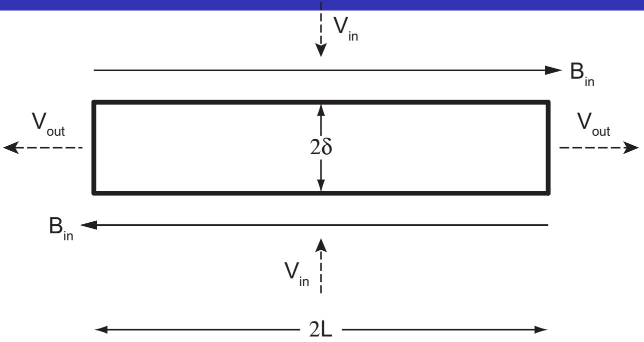
- Advantages:
  - Can insert probes directly (especially for $T \lesssim 20$ eV)
  - Study small-scale physics and global dynamics simultaneously
  - Controlled experiments
- Disadvantages:
  - Relatively modest parameter regimes
  - Modest separation of scales
  - Results influenced by BCs/experimental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

Learning about reconnection in space plasmas



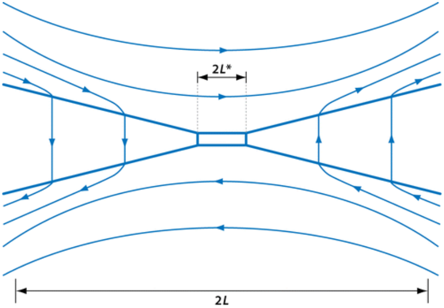
- Advantages:
  - Extremely detailed data at a small number of points
  - Parameter regimes inaccessible to experiment
  - Excellent for studying collisionless physics
- Disadvantages:
  - Difficult to connect observations to global dynamics
  - Difficult to disentangle cause and effect
  - No experimental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

The Sweet-Parker model provides the simplest description of resistive magnetic reconnection



- Assume a long and thin, steady-state current sheet
- The reconnection rate scales as $S^{-1/2}$, where the Lundquist number $S \equiv \frac{LV_A}{\eta}$ for current sheet half-length L, upstream Alfvén speed V_A, and resistivity η
- Predicts extremely low reconnection rates in astrophysical plasmas where $S \ggg\ggg 1$

The Petschek Model predicts fast reconnection for large Lundquist number plasmas

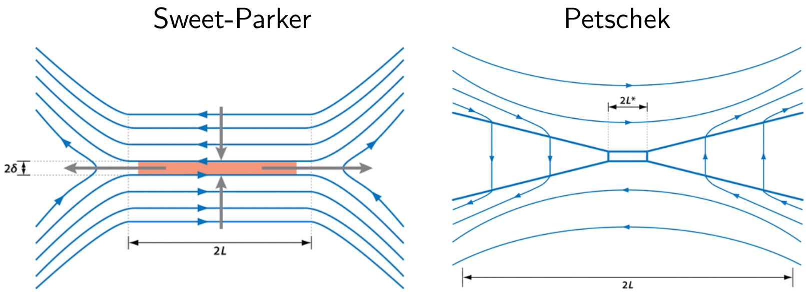


- Petschek (1964) proposed an X-line geometry
- The inflow and outflow are separated by slow mode shocks
- No bottleneck from conservation of mass
- Reconnection rate $\propto \frac{1}{\ln S} \Rightarrow$ fast reconnection!

Problems with the Petschek Model

- Need localized anomalous resistivity to get Petschek reconnection in resistive MHD simulations
- Petschek reconnection not observed in the laboratory or space plasmas
- Anomalous resistivity requires collisionless effects
- However, these effects occur only on short length scales where MHD breaks down
  - $\Rightarrow$ collisionless reconnection, not Petschek
- Therefore, the original Petschek model is not a viable mechanism for fast reconnection
- The key insight from Petschek is that reconnection could be sped up when δ/L is of order unity

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



Zweibel & Yamada (2009)

- The Sweet-Parker vs. Petschek dichotomy ignores important advances in our understanding of high Lundquist number and collisionless reconnection

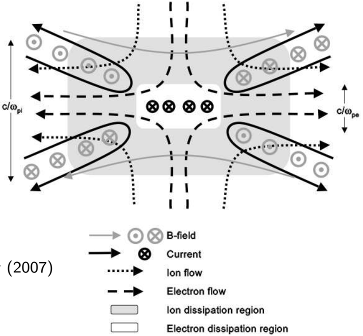
Invoking the generalized Ohm's law

- The generalized Ohm's law is given by

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = \eta \mathbf{J} + \underbrace{\frac{\mathbf{J} \times \mathbf{B}}{e n_e c}}_{\text{Hall}} - \underbrace{\frac{\nabla \cdot \mathbf{P}_e}{n_e e c}}_{\text{elec. pressure}} + \underbrace{\frac{m_e}{n_e e^2} \frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t}}_{\text{elec. inertia}} \tag{1}$$

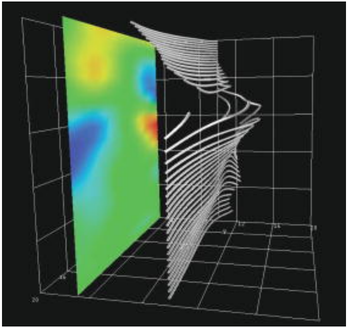
- The frozen-in condition can be broken by
  - The resistive term
  - The divergence of the electron pressure tensor term
  - Electron inertia
- The Hall term causes the magnetic field to be carried by the electron fluid
  - Doesn't break frozen-in condition, but can restructure reconnection region
- These additional terms introduce new physics into the system at short length scales
  - Ion inertial length, ion sound gyroradius

Fundamentals of collisionless reconnection



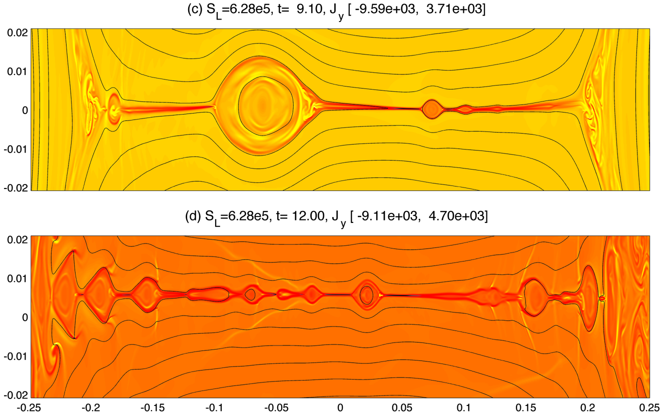
Drake & Shay (2007)

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)



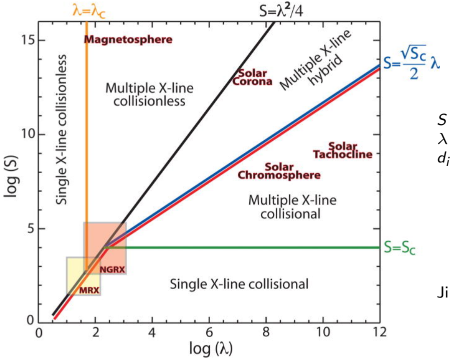
Bhattacharjee et al. (2009)

- Breaks up 2D current sheets into alternating X-points and islands when $S \gtrsim 10^4$
- The Sweet-Parker model is not applicable to astrophysical reconnection!

But does the plasmoid instability lead to fast enough reconnection?

- Simulations of the 2D plasmoid instability find a reconnection rate of $\frac{V_{in}}{V_A} \sim 0.01$ for $10^4 \lesssim S \lesssim 10^7$
- Reconnection rates of $\sim$0.1 are needed to describe flares
- Shepherd & Cassak (2010) argue that this instability leads to the formation of structure on small enough scales for collisionless reconnection to develop
- The collisionless reconnection then gives the fastest reconnection rates

Emerging phase diagram for collisionless vs. plasmoid dominated reconnection

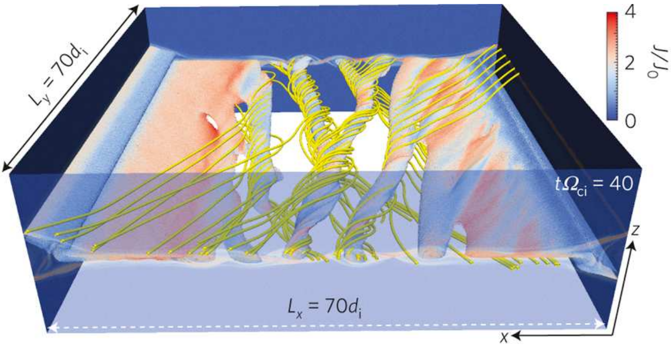


$S = \mu_0 L V_A/\eta$
$\lambda \equiv L/d_i$
d_i = ion inertial length

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

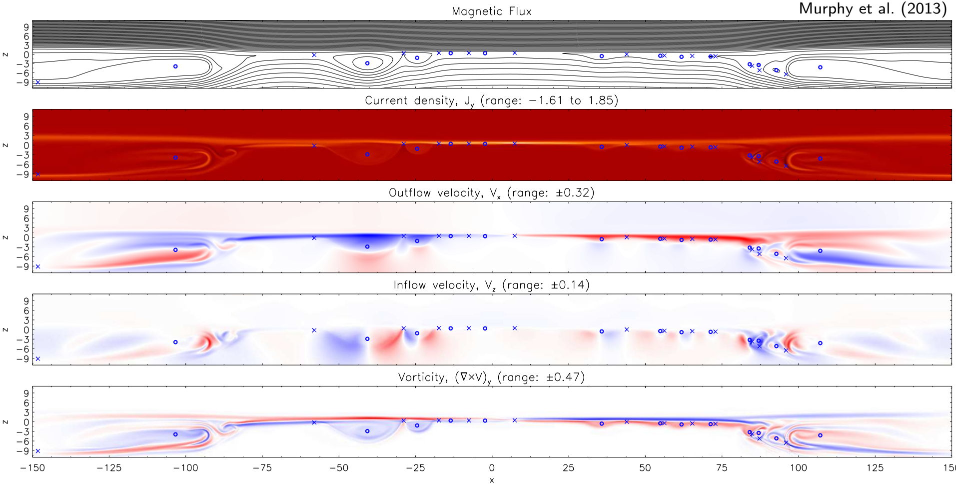
Three-dimensional effects in fully kinetic simulations of reconnection



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

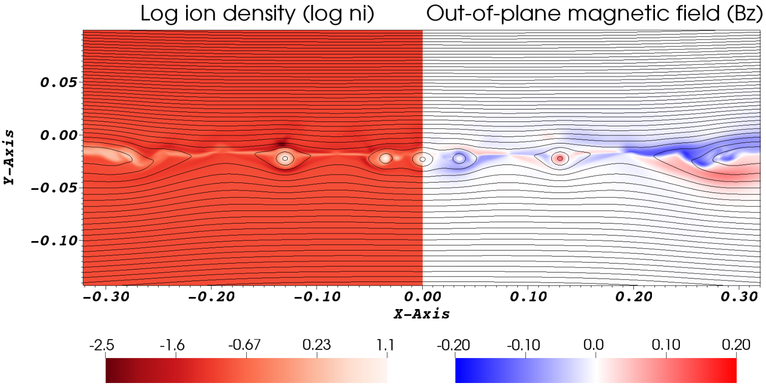
Plasmoid instability as modified by magnetic asymmetry

Murphy et al. (2013)



- Islands develop preferentially into weak field upstream region
- Outflow jets impact islands obliquely rather than directly
- Islands have vorticity and downstream regions are turbulent

Plasmoid instability in the weakly ionized chromosphere



- Two-fluid (plasma-neutral) simulations with HiFi
  - Leake et al. (2012, 2013); Murphy & Lukin (in prep)
- Ions dragged into plasmoids ⇒ efficient recombination
- Higher neutral pressure on weak field side leads to neutral flows through the current sheet
- Beginning of transition to Hall reconnection (!?)

Summary

- Magnetic reconnection is a fundamental process in magnetized plasmas in astrophysical, heliospheric, and laboratory plasmas
- Understanding magnetic reconnection requires complementary, cross-discipline efforts
  - <u>Solar observations</u> show large-scale dynamics in parameter regimes inaccessible in the laboratory, but with limited information on **B** and small-scale dynamics
  - <u>Astrophysical reconnection</u> provides information about extreme regions of parameter space
  - <u>*In situ* measurements</u> in space plasmas provide extremely detailed information, but only at a few spatial locations
  - <u>Laboratory experiments</u> allow controlled studies with detailed measurements at both small and large scales, but at relatively modest plasma parameters
- Emerging phase diagram:
  - Collisionless reconnection (fast)
  - Plasmoid-dominated reconnection (also kind of fast)

Inclusive Astronomy meeting to be held next summer!

- Most work on diversity, equal opportunity, and inclusion in astronomy focuses along a single dimension of identity
  - Most often: either gender, race, or LGBTIQ+ identity
  - People with more than one of these identities often left behind
- *Intersectionality* is the sociological framework describing the intersections between different forms of oppression, domination, or discrimination (Crenshaw 1989)
- The Inclusive Astronomy meeting will focus on intersectionality and is being organized by members of the Committee on the Status of Minorities in Astronomy, the Committee on the Status of Women in Astronomy, and the Working Group on LGBTIQ Equality
- Tentative dates: June 17-19, 2015 at Vanderbilt University in Nashville, Tennessee (to be confirmed soon!)