Magnetic Reconnection in Heliospheric, Laboratory, and Astrophysical Plasmas

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ITC Lunch Talk
March 3, 2015

The second talk will be "Magnetic Reconnection in Relativistic Astrophysical Jets" by Lorenzo Sironi

Astronomy 253: Plasma Astrophysics[1]

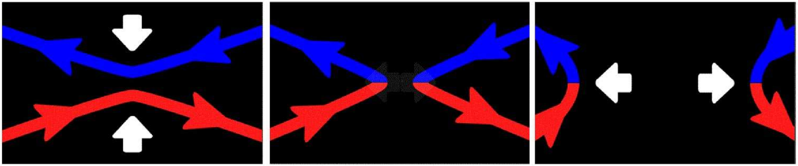
- Co-taught by Steve Cranmer and Nick Murphy in spring 2014
- Likely to be offered again in spring 2016
- Topics:
  - Magnetohydrodynamics
  - Kinetic theory
  - Waves, shocks, instabilities
  - Dynamos
  - Turbulence
  - Cosmic rays/particle acceleration
  - Magnetic reconnection
  - Partially ionized plasmas
  - Puns about computational magnetohydrodynamics

[1] Lecture slides are available on the course website at: `https://www.cfa.harvard.edu/~scranmer/Ay253/`

Outline

- Overview of magnetic reconnection
- Reconnection in different environments
  - Solar atmosphere
  - Earth's magnetosphere
  - Laboratory plasmas
- A dichotomy of dichotomies, and an emerging phase diagram
  - Sweet-Parker vs. Petschek reconnection
  - Plasmoid-dominated vs. collisionless reconnection
- Simulations of the plasmoid instability during asymmetric reconnection (Murphy et al. 2013; Murphy & Lukin, in prep)
  - Resistive MHD
  - Partially ionized chromospheric plasmas
- Announcement of Inclusive Astronomy meeting at Vanderbilt from June 17–19!

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

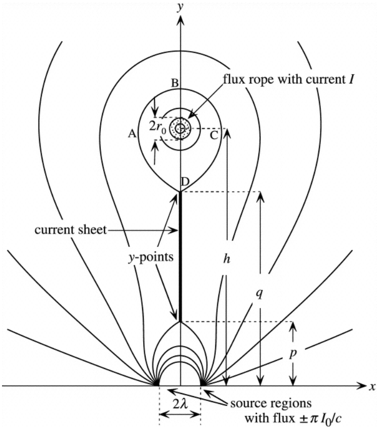


- Occurs in regions of strong magnetic shear
- Changes the magnetic topology
- Releases magnetic energy into kinetic and thermal energy
- Often efficiently accelerates particles
- Typically produces bidirectional Alfvénic outflow jets
- Often *fast* after a slow buildup phase

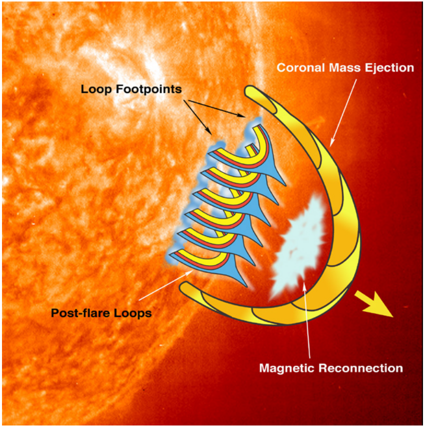
Open questions in magnetic reconnection

- 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, shocks, and instabilities?
- How does reconnection occur in 3D?
- How does reconnection behave in typical and extreme astrophysical environments?

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

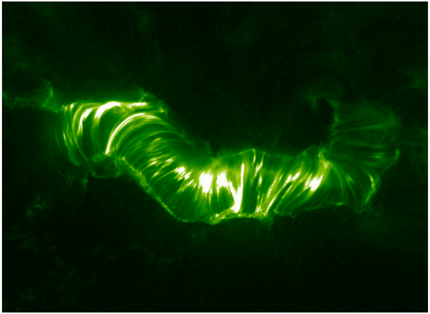


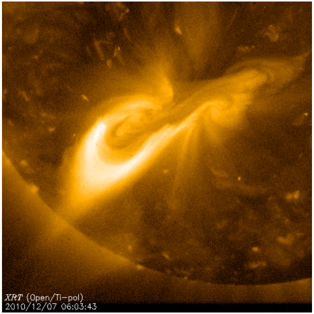
Lin & Forbes (2000); edge-on view



- Observational signatures of reconnection include flare loops, ‘current sheet’ structures, inflows/outflows, and loop-top hard X-ray sources

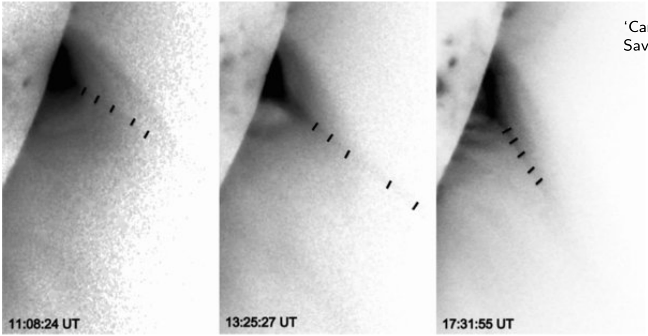
Signatures of reconnection: cuspy post-flare loops





- Shrinkage (contraction) of flare loops after reconnection
- Footpoints of newly reconnected loops show apparent motion away from the neutral line (field reversal)

Signatures of reconnection: 'current sheet' structures

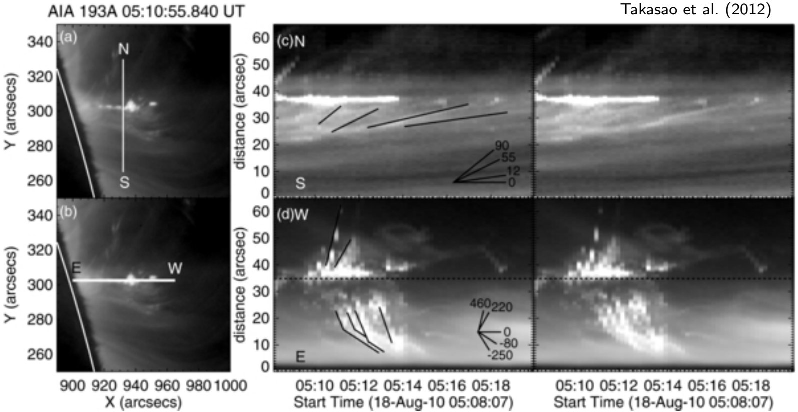


'Cartwheel CME'
Savage et al. (2012)

- 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

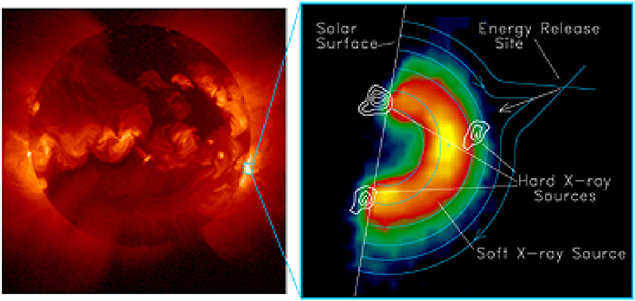
Signatures of reconnection: inflows, upflows, downflows

Takasao et al. (2012)



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

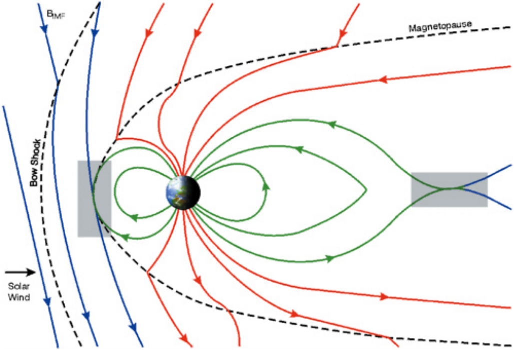
Signatures of reconnection: Above-the-loop-top hard X-ray (HXR) sources (Masuda et al. 1994)



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

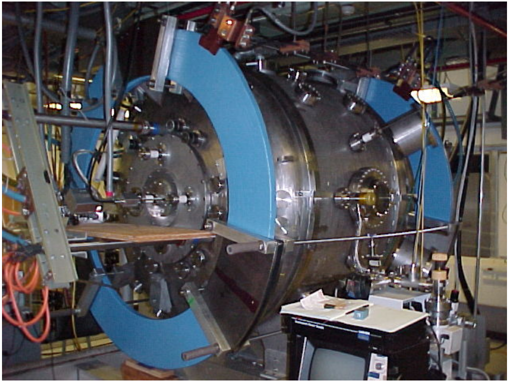
- Evidence for particle acceleration occuring at or above the apex of the post-flare loop
- Lower HXR sources due to energetic particles or a thermal conduction front impacting the chromosphere

Magnetic 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

Magnetic reconnection in laboratory plasmas



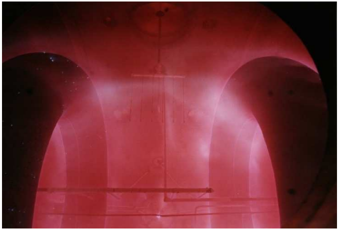
MRX

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

Learning about reconnection 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

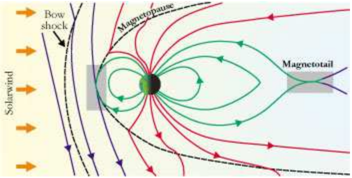
Learning about reconnection from laboratory experiments



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

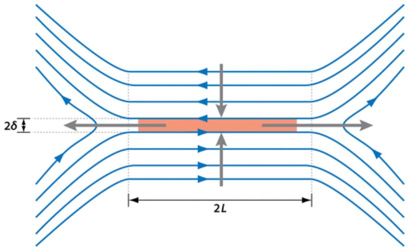
Learning about reconnection in space plasmas



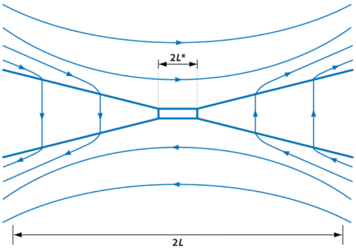
- Advantages:
  - Extremely detailed data at a small number of points
  - Parameter regimes inaccessible to experiment
  - Excellent for studying collisionless physics
- Disadvantages:
  - Difficult to connect observations to global dynamics
  - Difficult to disentangle cause and effect
  - No experimental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

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

Sweet-Parker

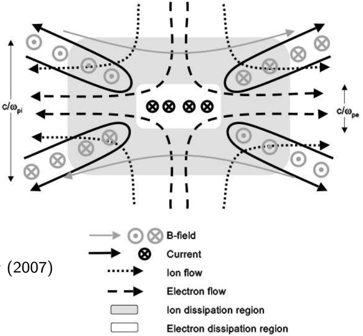


Petschek



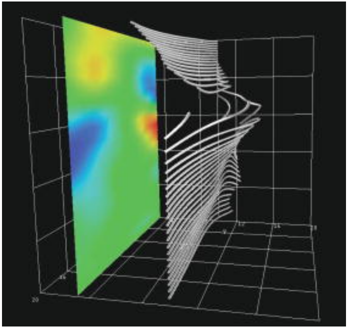
- The Sweet-Parker vs. Petschek dichotomy ignores important advances in our understanding of high Lundquist number and collisionless reconnection (Zweibel & Yamada 2009)

Fundamentals of collisionless reconnection



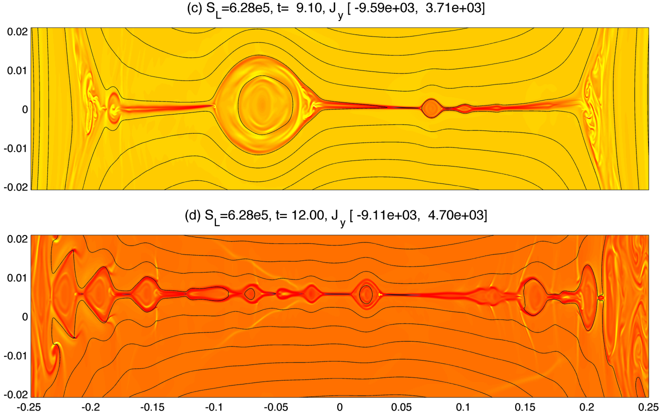
Drake & Shay (2007)

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)

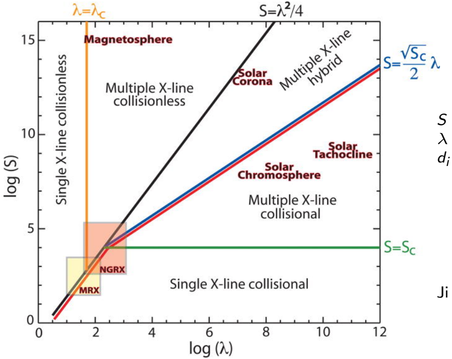


Bhattacharjee et al. (2009)

$S = \mu_0 L V_A / \eta$ 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



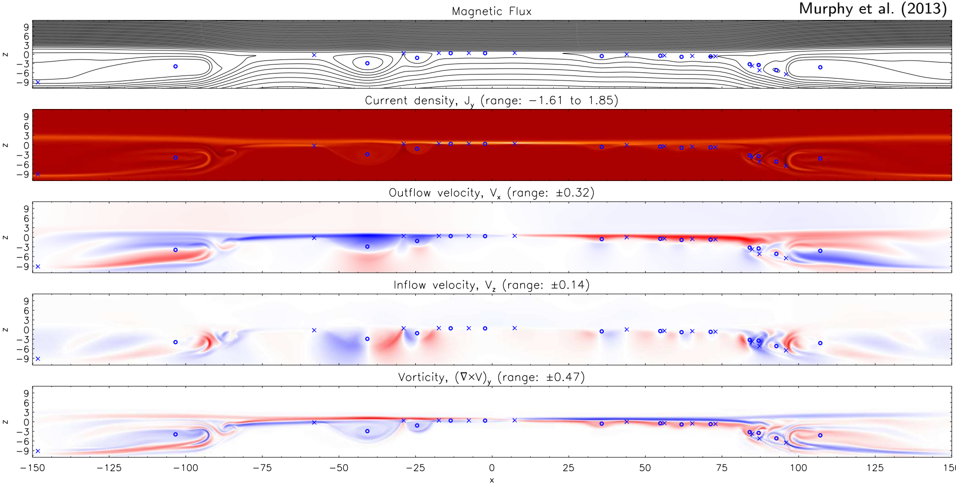
$S = \mu_0 L V_A / \eta$
$\lambda \equiv L/d_i$
d_i = ion inertial length

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

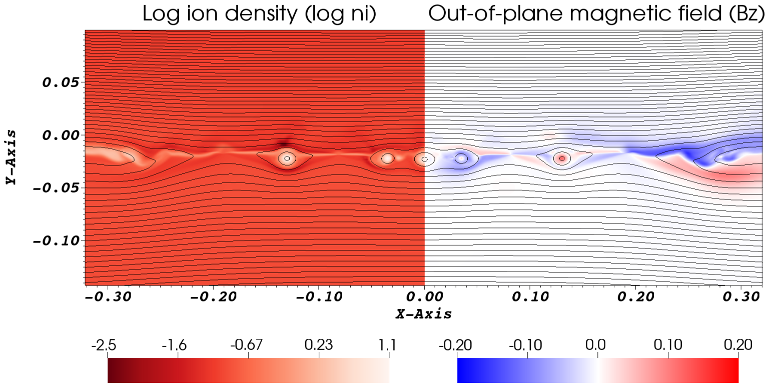
Plasmoid instability as modified by magnetic asymmetry

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

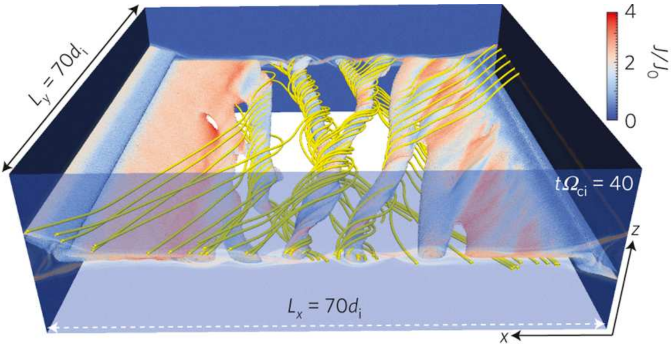
Plasmoid instability in the weakly ionized chromosphere



- Two-fluid (plasma-neutral) simulations with HiFi
  - Leake et al. (2012, 2013); Murphy & Lukin (submitted)
- 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 (!?)

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
- How is the plasmoid instability affected?

Summary

- Magnetic reconnection is a fundamental process in magnetized plasmas in astrophysical, heliospheric, and laboratory plasmas
- Understanding magnetic reconnection requires complementary, cross-discipline efforts
- The classical dichotomy of Sweet-Parker vs. Petschek reconnection ignores advances in our understanding of high Lundquist number and collisionless reconnection
- Emerging phase diagram:
  - Collisionless reconnection (fast)
  - Plasmoid-dominated reconnection (also kind of fast)
- Magnetic asymmetry changes the dynamics of the plasmoid instability in both resistive MHD and partially ionized plasmas

- Most work on diversity 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
  - Often missing is work on inclusion of disabled astronomers
- This meeting will take a multi-dimensional (intersectional) approach to diversity, equity, and inclusion.
- Registration now open at `http://vu.edu/ia2015`