Magnetic Reconnection in Heliospheric, Laboratory, and Astrophysical Plasmas

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ITC Lunch Talk
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The second talk will be “Magnetic Reconnection in Relativistic Astrophysical Jets” by Lorenzo Sironi
Astronomy 253: Plasma Astrophysics

- 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

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1Lecture 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.

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

Lin & Forbes (2000); edge-on view
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

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

▶ 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)

- Evidence for particle acceleration occurring 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 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
Dedicated experiments on reconnection allow direct observations of reconnection under controlled conditions.

Complements observations of solar/space/astrophysical reconnection!
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

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

- The in-plane magnetic field is pulled by electrons in the out-of-plane direction ⇒ quadrupole magnetic field
Elongated current sheets are susceptible to the tearing-like plasmoid instability (Loureiro et al. 2007)

- 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!

\[ S = \frac{\mu_0 L V_A}{\eta} \] is the Lundquist number.

Bhattacharjee et al. (2009)
Emerging phase diagram for collisionless vs. plasmoid dominated reconnection

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

\[ S = \mu_0 L V_A / \eta \]
\[ \lambda \equiv L / d_i \]
\[ d_i = \text{ion inertial length} \]

\[ S = \frac{\sqrt{S_{\text{c}}}}{2} \lambda \]

Ji & Daughton (2011)
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 $\Rightarrow$ 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

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

Daughton et al. (2011)
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