Magnetic Reconnection in Laboratory, Astrophysical, and Space Plasmas

Nick Murphy

Harvard-Smithsonian Center for Astrophysics
namurphy@cfa.harvard.edu
http://www.cfa.harvard.edu/~namurphy/

November 18, 2011
Goals for this talk

- Introduce important reconnection models
- Review reconnection signatures in solar flares
- Show that astronomers must work with laboratory and near-Earth space plasma physicists
- Present recent work on asymmetric reconnection in line-tied coronal mass ejection current sheets
- Motivate future work on partially ionized chromospheric reconnection
- Finish before lunch!
In ideal magnetohydrodynamics (MHD), the magnetic field is “frozen-in” to the plasma.

- If two parcels of plasma are connected by a field line at one time, they will be connected by a field line at all future times.

Real plasmas allow some magnetic field slippage.

*Magnetic reconnection* occurs when magnetic field lines are broken and rejoined in a highly conducting plasma.

This process occurs in:
- Solar flares and CMEs
- Solar wind, planetary magnetospheres, and cometary magnetotails
- Interstellar medium (ISM) and star formation regions
- Neutron star magnetospheres
- Laboratory plasmas
Defining magnetic reconnection
Open questions in magnetic reconnection

- What causes fast magnetic reconnection?
- How does reconnection start?
- How are particles accelerated?
- What is the interplay between small-scale physics and global dynamics?
- How does 3-D reconnection occur?
- How does reconnection occur in extreme astrophysical environments?
- What can astrophysicists learn about reconnection from laboratory experiments and near-Earth space plasmas?
The Sweet-Parker model describes steady, resistive reconnection in long and thin current sheets

$B_{in} \parallel B_{in} \parallel 2\delta \parallel L \parallel V_{in} \parallel V_{in} \parallel V_{out} \parallel V_{out}$

- Alfvénic outflow: $V_{out} \sim V_{A} \equiv \frac{B_{in}}{\sqrt{\mu_0 \rho}}$
- The reconnection rate scales as
  \[ \frac{V_{in}}{V_{A}} \sim \frac{1}{S^{1/2}} \]

where the Lundquist number is $S \equiv \frac{\mu_0 L V_A}{\eta} = \frac{t_{\text{diffusion}}}{t_{\text{Alfven}}}$

- The predicted rates are much slower than observations
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 $\propto \frac{1}{\ln S}$
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 magnetosphere
- Anomalous resistivity requires collisionless effects
- However, these effects occur only on short length scales where MHD breaks down
  - ⇒ collisionless reconnection, not Petschek
- Therefore, the original Petschek model is not a viable mechanism for fast reconnection
Extremely high Lundquist number current sheets are susceptible to the newly discovered plasmoid instability (Loureiro et al. 2007; Huang et al. 2010; Ni et al. 2010). Current sheet breaks up into a chain of X-lines and islands. Reconnection rate becomes much less sensitive to resistivity. Shepherd & Cassak (2010) argue that:

- The plasmoid instability leads to small-scale structure
- Collisionless reconnection then leads to very fast reconnection
The generalized Ohm’s law contains terms that facilitate fast reconnection:

\[
E + V \times B = \eta J + \frac{J \times B}{ne} - \frac{\nabla \cdot P_e}{ne} + \frac{m_e}{ne^2} \frac{dJ}{dt}
\]

- \(V \times B\) represents the ideal electric field
- \(\eta J\) represents resistive diffusion (with \(\mu_0 J = \nabla \times B\))
- The Hall term \(\frac{J \times B}{ne}\) freezes \(B\) into the electron fluid
- \(\frac{\nabla \cdot P_e}{ne}\) is the divergence of the electron pressure tensor
- \(\frac{m_e}{ne^2} \frac{dJ}{dt}\) represents electron inertia
- Magnetic topology can be changed by:
  - Resistivity
  - Non-scalar electron pressure
  - Electron inertia
Two-fluid effects allow fast reconnection

- On scales shorter than the ion inertial length, electrons and ions decouple. The magnetic field freezes into electron fluid.
- 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
Lazarian & Vishniac (1999) argue that a 3-D large-scale reconnection layer will be broken up into many small reconnection sites to allow fast reconnection.

Numerical tests by Kowal show this scaling but artificially drive turbulence within the current sheet.
Open questions in turbulent reconnection

- How does turbulence affect the reconnection rate?
- Does reconnection feed back on the turbulent cascade?
- How do small-scale reconnection sites interact with each other in 3-D?
- Is the Lazarian & Vishniac scaling accurate when turbulence is not artificially driven?
Flux rope models of coronal mass ejections predict a current sheet behind the rising flux rope (e.g., Lin & Forbes 2000)
Signatures of reconnection in solar corona

- Newly reconnected post-flare loops
  - Loop footpoints move as more flux is reconnected
- Reconnection inflows from apparent motions of coronal plasma
- Downflows and upflows
  - Downflows often sub-Alfvénic, but probably because reconnection is asymmetric
- Above-the-loop-top hard X-ray sources
  - Evidence for particle acceleration
Learning about reconnection from astrophysics

- **Advantages**
  - Parameter regimes inaccessible by experiment
  - Observations possible for a variety of emission mechanisms

- **Disadvantages**
  - No experimental control
  - Small-scale physics impossible to observe directly

- **Examples**
  - Solar and stellar flares
  - Chromospheric jets
  - Interstellar medium and star formation regions
  - Accretion disks
  - Neutron star magnetospheres
Learning about reconnection from laboratory experiments

Advantages
- Can insert probes directly
- Study small-scale physics and global dynamics simultaneously
- Control over experiment

Disadvantages
- Limited parameter regimes
- Results influenced by boundary conditions/experimental method

Examples
- MRX, VTF, TS-3, SSX, RSX
- Tokamaks, spheromaks, reversed field pinches
Learning about reconnection in the Earth’s magnetosphere

- **Advantages**
  - Extremely detailed data at a small number of points
  - Parameter regimes inaccessible to experiment
  - Excellent for studying collisionless physics
- **Disadvantages**
  - Difficult to connect to large-scale evolution
    - Use global MHD simulations
  - Difficult to know which is cause and which is effect
  - No experimental control
- **Satellites**
  - Cluster, THEMIS, Geotail, ACE, Wind
  - Magnetospheric Multiscale Mission (MMS) in future
Learning about reconnection from numerical simulations

▸ Advantages
   ▶ Have data everywhere for all time
   ▶ Can isolate physical effects by turning terms on and off
   ▶ Can study simplified systems in great detail
   ▶ Less expensive than space missions or laboratory experiments

▸ Disadvantages
   ▶ Limited parameter regimes
   ▶ Must make many assumptions (such as 2-D)
   ▶ Initial and boundary conditions affect results
   ▶ Not yet predictive

▸ Need to:
   ▶ Verify that a code solves equations correctly
   ▶ Validate that the results represent reality
Learning about reconnection from analytic theory

- **Advantages**
  - Extreme parameter regimes are often accessible
  - Can determine characteristic properties
  - Exact solutions
  - Able to explain instability thresholds

- **Disadvantages**
  - Must make many assumptions
  - Idealized geometries
  - Difficult for non-theorists to understand
Collisionless physics advances
  - Detection of out-of-plane quadrupole field
  - Measurements of inner electron diffusion region
Detection and study of magnetic islands and plasmoids
Role of asymmetry
Energetic particles/ion heating
Experimental verification of (generalized) Sweet-Parker model and collisional Spitzer resistivity
Experimental correlations between certain fluctuations and effective resistivity enhancements
Current sheets behind CMEs are observed in many events.

Outward moving blobs could be ‘monster plasmoids’ formed by repeated merging of smaller plasmoids.
Open questions in CME current sheets

- Are CME current sheets energetically important to CMEs?
  - Compare upflow energy to CME kinetic energy
  - Do the current sheets heat CME plasma? (Murphy et al. 2011)
- Are post-flare current sheets actively reconnecting?
- What is the role of the plasmoid instability?
  - Very recent work by Shen et al.; Ni et al.; Mei et al.
- What is the role of energetic particles?
- What is the role of asymmetry? (e.g., Murphy et al. 2010)
- Why are reconnection downflows sub-Alfvénic? (e.g., Warren et al. 2011)
CME current sheets have asymmetric outflow

Simulations of asymmetric outflow reconnection show most of the outflow energy going away from the obstruction (Murphy 2010)
Late in time, the X-line diffuses against strong plasma flow.

- Any difference between $\frac{dx_n}{dt}$ and $V_x(x_n)$ must be due to diffusion.
- The velocity at the X-line is not the velocity of the X-line:

\[ V_x(x_n) \neq \frac{dx_n}{dt} \]
The X-line retreats in response to derivatives in the out-of-plane electric field (Murphy 2010)

- $\frac{\partial^2 B_z}{\partial z^2} < 0$
- $\Rightarrow \frac{\partial B_z}{\partial t} < 0$

- Advection by the bulk plasma flow
- Diffusion of the normal component of the magnetic field
- $B_z < 0$ above and below the X-line
- This negative $B_z$ diffuses towards the X-line
- $\Rightarrow$ The X-line retreats to the right
Simulations of line-tied asymmetric reconnection

- Lower boundary is conducting wall
- Reconnecting magnetic fields are asymmetric
The post-flare loops develop a characteristic candle flame structure.

- Above: magnetic flux contours for four different asymmetries ($B_L/B_R = 1, 0.5, 0.25, 0.125$)
- The loop-top positions (dashed green line) are a function of height
- Analytic theory predicts the asymptotic slope near the field reversal reasonably well (dotted red line)
The Tsuneta flare is a famous candidate event.
Partially Ionized Reconnection

- Newly discovered Type II spicules are generated by reconnection in the chromosphere.
- De Pontieu et al. hypothesize that these spicules power the solar wind.
- MHD assumes full ionization, but chromospheric plasmas are partially ionized (0.001–0.5).
- We will be developing a code to model partially ionized chromospheric reconnection.
  - Is chromospheric reconnection responsible for the coronal abundance enhancement of elements with low first ionization potentials? (the FIP effect)
  - Can enhancement of the Hall effect in partially ionized plasmas lead to fast reconnection?
Conclusions

- Models for fast reconnection include collisionless reconnection, turbulent reconnection, and the plasmoid instability.
- Astronomers must work with space and laboratory plasma physicists to understand astrophysical reconnection.
- Reconnection in CME current sheets is asymmetric:
  - Most of the outflow energy will go upward when the principal X-line is located at low heights.
  - Asymmetry in the upstream magnetic fields leads to candle flame shaped post-flare loops.
- In future work we will model partially ionized reconnection in the solar chromosphere.