Magnetic Reconnection in Laboratory, Astrophysical, and Space Plasmas

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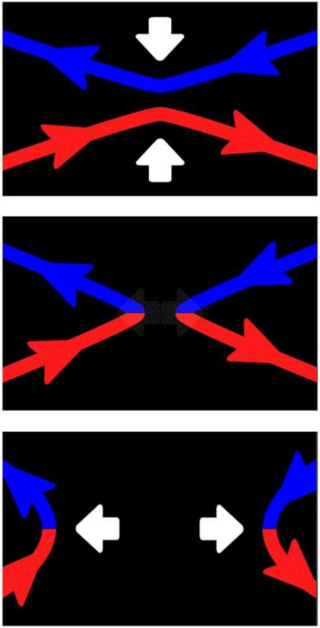
Goals for this talk

- 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!

Introduction

- 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

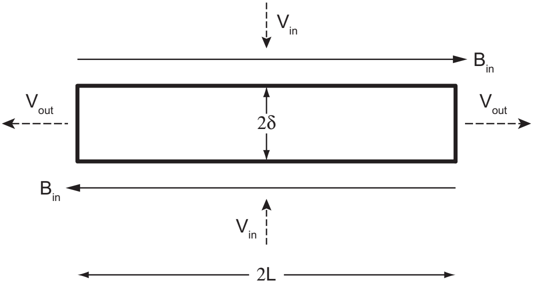
Defining magnetic reconnection



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

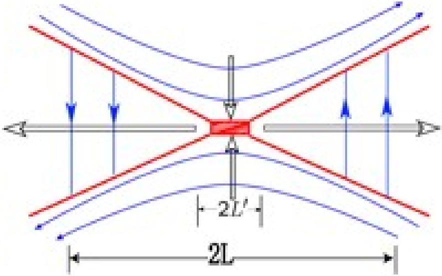


- Alfvénic outflow: $V_{out} \sim V_A \equiv \frac{B_{in}}{\sqrt{\mu_0 \rho}}$
- The reconnection rate scales as

$$\frac{V_{in}}{V_A} \sim \frac{1}{S^{1/2}}$$

  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

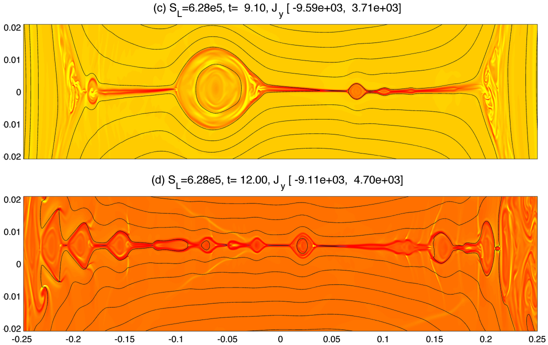


- Petschek (1964) proposed an X-line geometry
- The inflow and outflow are separated by slow mode shocks
- No bottleneck from conservation of mass
- Reconnection rate $\propto \frac{1}{\ln S}$

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
  - $\Rightarrow$ collisionless reconnection, not Petschek
- Therefore, the original Petschek model is not a viable mechanism for fast reconnection

The plasmoid instability



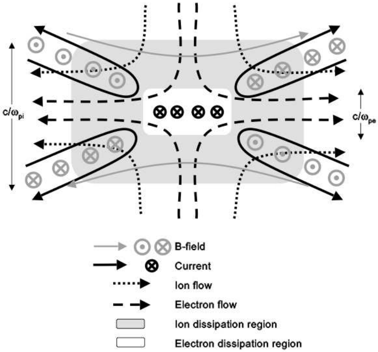
- Extremely high Lundquist number current sheets are susceptible to the newly discovered plasmoid instability (Loureiro *et al.* 2007; Huang *et al.* 2010; Ni *et al.* 2010)
- Current sheet breaks up into a chain of X-lines and islands
- Reconnection rate becomes much less sensitive to resistivity
- 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

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{J} \times \mathbf{B}}{ne} - \frac{\nabla \cdot \mathbf{P}_e}{ne} + \frac{m_e}{ne^2} \frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t}$$

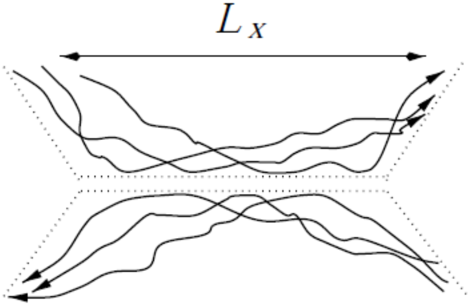
- $\mathbf{V} \times \mathbf{B}$ represents the ideal electric field
- $\eta \mathbf{J}$ represents resistive diffusion (with $\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$)
- The Hall term $\frac{\mathbf{J} \times \mathbf{B}}{ne}$ freezes $\mathbf{B}$ into the electron fluid
- $\frac{\nabla \cdot \mathbf{P}_e}{ne}$ is the divergence of the electron pressure tensor
- $\frac{m_e}{ne^2} \frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t}$ 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

Turbulence is an alternate explanation for fast reconnection

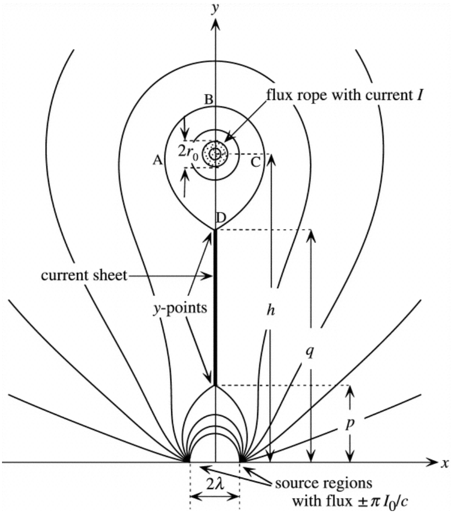


- Lazarian & Vishniac (1999) argue that a 3-D large-scale reconnection layer will be broken up into many small reconnection sites to allow fast reconnection
- Numerical tests by Kowal show this scaling but artificially drive turbulence within the current sheet

Open questions in turbulent reconnection

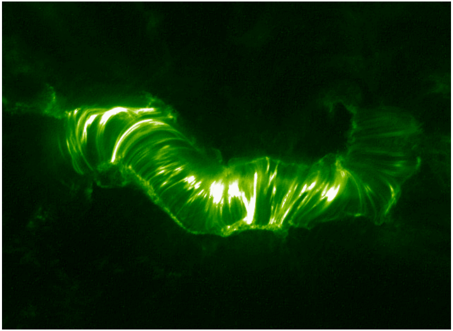
- How does turbulence affect the reconnection rate?
- Does reconnection feed back on the turbulent cascade?
- How do small-scale reconnection sites interact with each other in 3-D?
- Is the Lazarian & Vishniac scaling accurate when turbulence is not artificially driven?

Flare/CME current sheets



- 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

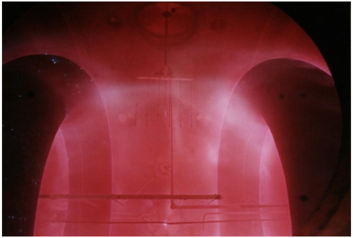


- Newly reconnected post-flare loops
  - Loop footpoints move as more flux is reconnected
- Reconnection inflows from apparent motions of coronal plasma
- Downflows and upflows
  - Downflows often sub-Alfvénic, but probably because reconnection is asymmetric
- Above-the-loop-top hard X-ray sources
 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

Learning about reconnection from astrophysics

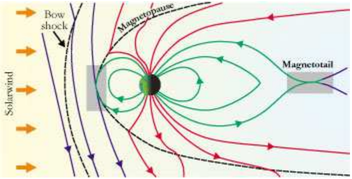
- Advantages
  - Parameter regimes inaccessible by experiment
  - Observations possible for a variety of emission mechanisms
- Disadvantages
  - No experimental control
  - Small-scale physics impossible to observe directly
- Examples
  - Solar and stellar flares
  - Chromospheric jets
  - Interstellar medium and star formation regions
  - Accretion disks
  - Neutron star magnetospheres

Learning about reconnection from laboratory experiments



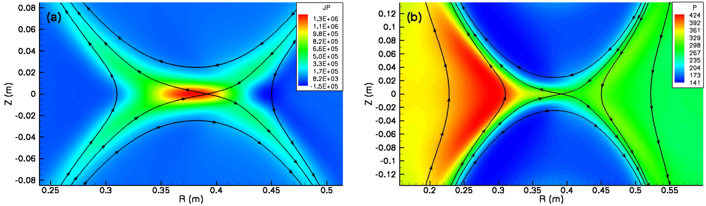
- Advantages
  - Can insert probes directly
  - Study small-scale physics and global dynamics simultaneously
  - Control over experiment
- Disadvantages
  - Limited parameter regimes
  - Results influenced by boundary conditions/experimental method
- Examples
  - MRX, VTF, TS-3, SSX, RSX
  - Tokamaks, 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

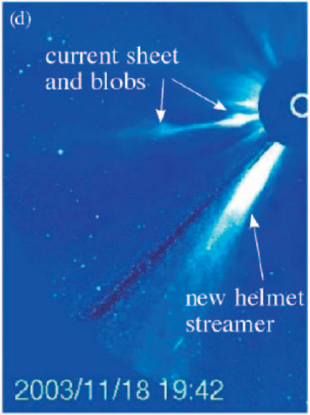
Learning about reconnection from analytic theory

- 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

Results from the laboratory and magnetosphere

- 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

Observations of CME current sheets

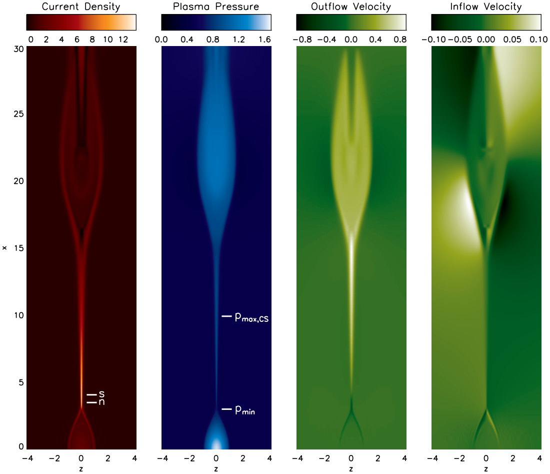


- Current sheets behind CMEs are observed in many events
- Outward moving blobs could be 'monster plasmoids' formed by repeated merging of smaller plasmoids

Open questions in CME current sheets

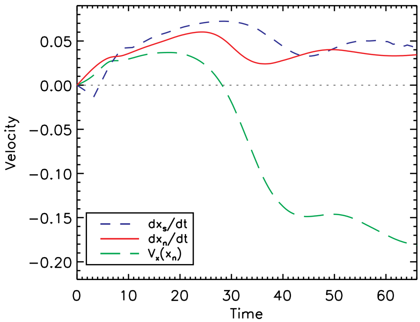
- Are CME current sheets energetically important to CMEs?
  - Compare upflow energy to CME kinetic energy
  - Do the current sheets heat CME plasma? (Murphy *et al.* 2011)
- Are post-flare current sheets actively reconnecting?
- What is the role of the plasmoid instability?
  - Very recent work by Shen *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)

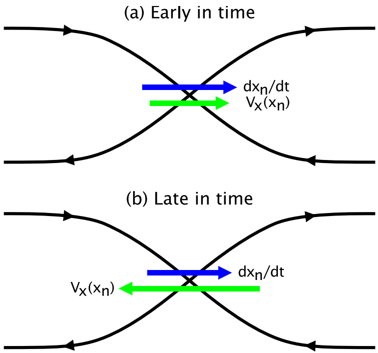
CME current sheets have asymmetric outflow



- 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

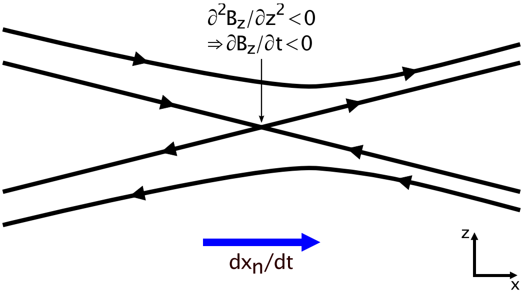




- Any difference between $\frac{\mathrm{d}x_n}{\mathrm{d}t}$ and $V_x(x_n)$ must be due to diffusion
- The velocity *at* the X-line is not the velocity *of* the X-line:

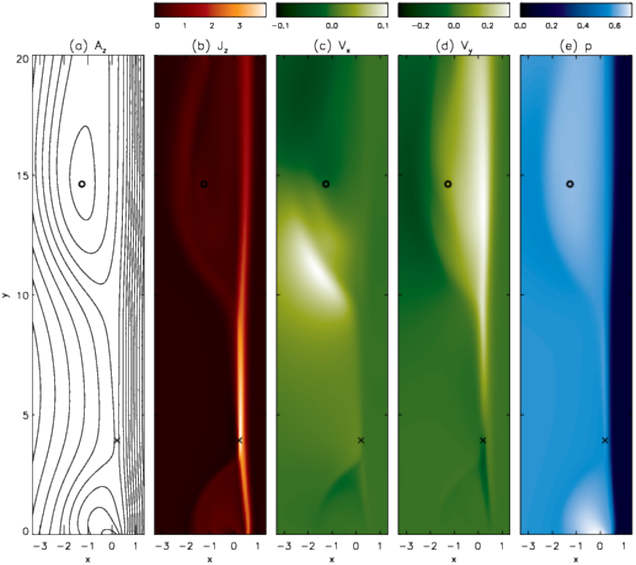
$$V_x(x_n) \neq \frac{\mathrm{d}x_n}{\mathrm{d}t}$$

The X-line retreats in response to derivatives in the out-of-plane electric field (Murphy 2010)



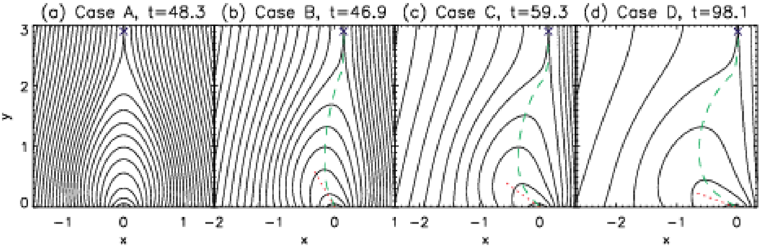
- X-line retreat occurs through a combination of:
  - Advection by the bulk plasma flow
  - Diffusion of the normal component of the magnetic field
- $B_z < 0$ above and below the X-line
- This negative B_z diffuses towards the X-line
- $\Rightarrow$ The X-line retreats to the right

Simulations of line-tied asymmetric reconnection



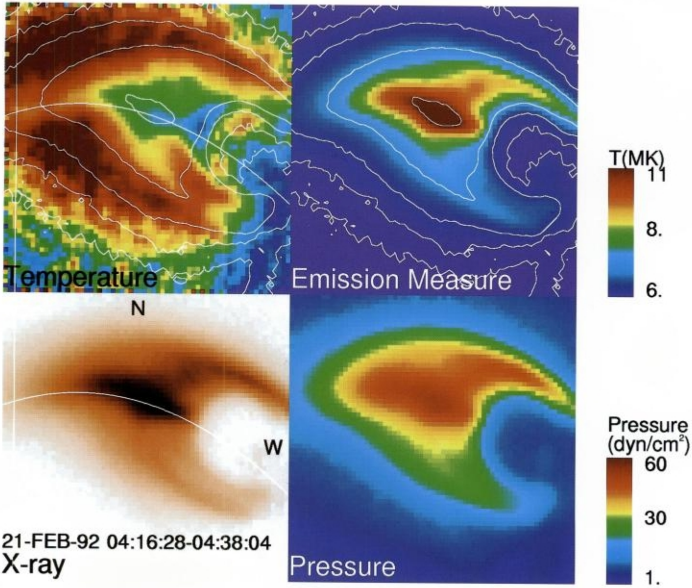
- Lower boundary is conducting wall
- Reconnecting magnetic fields are asymmetric

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 ionizaion, 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