Magnetic Reconnection

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Astronomy 253: Plasma Astrophysics

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These lecture notes are based off of Priest & Forbes (2000), Birn & Priest (2007), Zweibel & Yamada (2009), and numerous other sources.

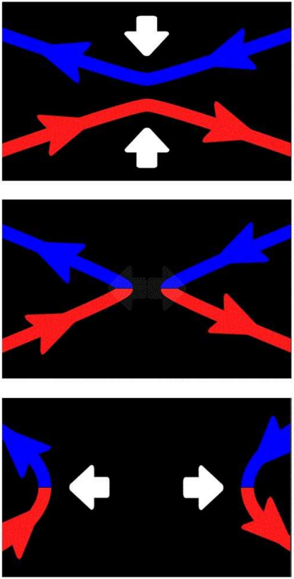
Outline for magnetic reconnection

- Basic physics of reconnection
  - Usual ingredients and open questions
  - Sweet-Parker vs. Petschek reconnection
  - Collisionless vs. plasmoid-unstable reconnection
  - Turbulence, 3D effects, asymmetry
- Reconnection across the universe
  - Solar eruptions
  - Earth's magnetosphere
  - Laboratory plasmas
  - Interstellar medium

Introduction

- Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma
- Reconnection converts magnetic energy into kinetic energy, thermal energy, and particle acceleration energy
- Reconnection was proposed to explain fast energy release in solar flares (Giovanelli 1946), and was later applied to Earth's magnetosphere (Dungey 1961)
- Physical processes often associated with reconnection include
  - Resistivity, viscosity, and thermal conduction
  - Hall effect
  - Particle drifts
  - Kinetic effects (including electron scale physics)
  - Particle acceleration
  - Waves, shocks, and instabilities
  - Turbulence
  - Relativity, radiative losses, or partial ionization (sometimes)

Picturing 2D magnetic reconnection



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

This is missing essential 3D effects!

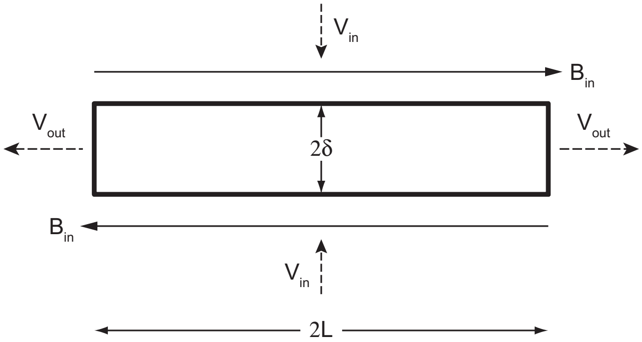
Usual ingredients of magnetic reconnection

- Occurs in regions of strong magnetic shear
  - Direction of **B** changes significantly over a short distance
- Release of magnetic energy into kinetic and thermal energy
  - Often explosive
  - Energy released on small scales but with global consequences
- Changes in magnetic topology
- Alfvénic outflow jets
- 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
- How does reconnection behave in partially ionized plasmas?
  - Stellar chromospheres, protoplanetary disks, some laboratory experiments

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



- Elongated current sheet of half-length L and half-width δ
- Characteristic inflow velocity V_{in} and magnetic field B_{in}
- Characteristic outflow velocity V_{out}
- Uniform density ρ and resistivity η

Assumptions of Sweet-Parker model

- Steady-state
  - Uniform out-of-plane electric field
  - Balance stuff going into sheet with stuff leaving it
- Elongated current sheet
  - Neglect kinetic energy of inflow
  - Neglect magnetic energy of outflow
- Ignore resistivity outside of current sheet
- Ignore 3D effects
- Don't worry about factors of order unity to find scaling relationships

Deriving the Sweet-Parker model

- Conservation of mass: mass flux in equals mass flux out

$$LV_{in} \sim \delta V_{out} \tag{1}$$

- Conservation of energy: magnetic energy flux in equals kinetic energy flux out

$$LV_{in} \left(\frac{B_{in}^2}{8\pi} \right) \sim \delta V_{out} \left(\frac{\rho V_{out}^2}{2} \right) \tag{2}$$

- Combining these two equations shows that the outflow scales with the upstream Alfvén speed

$$V_{out} \sim V_A \equiv \frac{B_{in}}{\sqrt{4\pi\rho}} \tag{3}$$

Finding the current density and inflow velocity

- The ideal electric field outside the layer balances the resistive electric field inside the layer

$$\frac{V_{in} B_{in}}{c} \sim \eta J \tag{4}$$

- We find the current from Ampere's law: $\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$

$$J \sim \frac{c}{4\pi} \frac{B_{in}}{\delta} \tag{5}$$

- Inflow occurs at a rate which is balanced by resistive diffusion

$$V_{in} \sim \frac{D_\eta}{\delta} \tag{6}$$

where $D_\eta \equiv \frac{\eta c^2}{4\pi}$ is in units of length^2 time^{-1}

How does the Sweet-Parker reconnection rate scale with Lundquist number?

- The dimensionless reconnection rate scales as

$$\frac{V_{in}}{V_A} \sim \frac{1}{S^{1/2}} \tag{7}$$

- The Lundquist number S is the ratio of the resistive diffusion time scale to the Alfvén wave crossing time scale:

$$S \equiv \frac{LV_A}{D_\eta} = \frac{\tau_{res}}{\tau_{Alf}} \tag{8}$$

  Typically S is somewhere between 10^9 and 10^{20} in astrophysics

- The Sweet-Parker model predicts **slow** reconnection

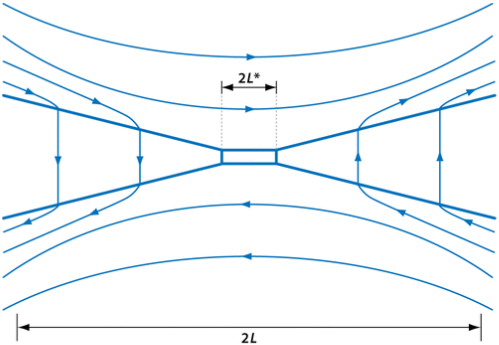
The Sweet-Parker model predicts reconnection rates much slower than observed in solar flares and space/lab plasmas

- Solar flares occur on time scales of minutes, but the Sweet-Parker model predicts time scales of months
- Many of the Sweet-Parker approximations are not well justified
- Highly elongated current sheets are unstable to the plasmoid instability above a critical Lundquist number of $S_c \sim 10^4$
- **The Sweet-Parker model does not describe astrophysical reconnection!**
- How do we explain reconnection that is fast in the limit of weak resistivity ($S \to \infty$)?

Fast reconnection through anomalous resistivity?

- Thus far, we've calculated S based on Spitzer resistivity
- What if there are other mechanisms that generate a higher effective resistivity?
  - Kinetic instabilities, wave-particle interactions, microturbulence
- Anomalous resistivity is often represented by an ad hoc function of position or current density
  - But what would cause this enhancement?
- Laboratory experiments have not identified the mechanism(s)

The Petschek Model predicts fast reconnection for large Lundquist number plasmas

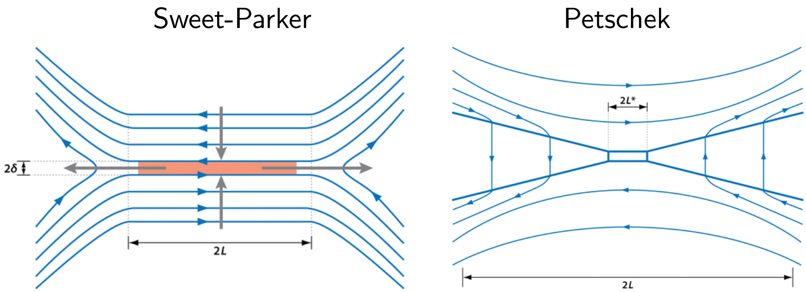


- Petschek (1964) proposed an X-point geometry
  - No bottleneck from conservation of mass
- Inflow and outflow separated by slow mode shocks
  - Where most of the magnetic energy is dissipated
- Reconnection rate $\propto \frac{1}{\ln S} \Rightarrow$ **fast** reconnection!

Problems with the Petschek Model

- Not much evidence for Petschek reconnection in laboratory and space plasmas
  - Slow shocks occasionally observed in space plasmas
- Need localized dissipation (e.g., anomalous resistivity) to get Petschek reconnection in resistive MHD simulations
- Anomalous resistivity requires collisionless effects
- However, these effects occur only on short length scales where MHD breaks down
  - Leads to collisionless reconnection, not Petschek
- Therefore, the original Petschek model is not a viable mechanism for fast reconnection
- The key insight is that reconnection is 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

The resistive MHD Ohm's law

- Thus far we have the resistive MHD Ohm's law

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = \eta \mathbf{J} \tag{9}$$

  where resistivity is what breaks the frozen-in condition

- The induction equation is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \tag{10}$$

  $\Rightarrow$ resistive diffusion of **B**

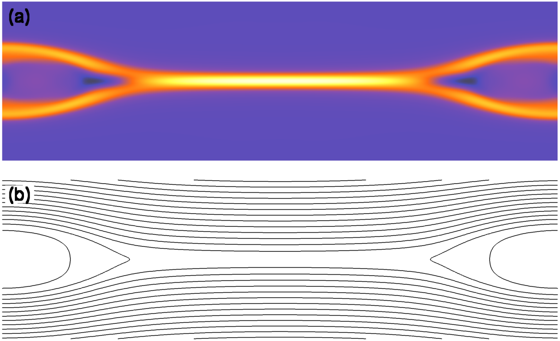
Return of the generalized Ohm's law

- The generalized Ohm's law is given by

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = \eta \mathbf{J} + \underbrace{\frac{\mathbf{J} \times \mathbf{B}}{e n_e c}}_{\text{Hall}} - \underbrace{\frac{\nabla \cdot \mathbf{P_e}}{n_e e c}}_{\text{elec. pressure}} + \underbrace{\frac{m_e}{n_e e^2} \frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t}}_{\text{elec. inertia}} \tag{11}$$

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

Simulation with the Hall term off (resistive MHD)



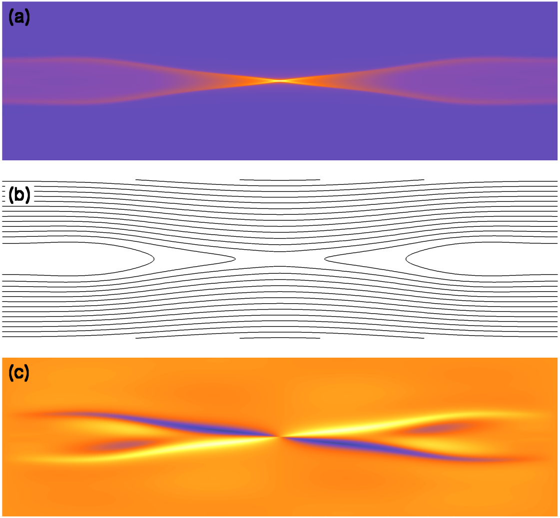
Current density

Magnetic flux

Murphy (2009)

- Elongated current sheet $\Rightarrow$ slow reconnection

Simulation with the Hall term on (Hall MHD)



Current density

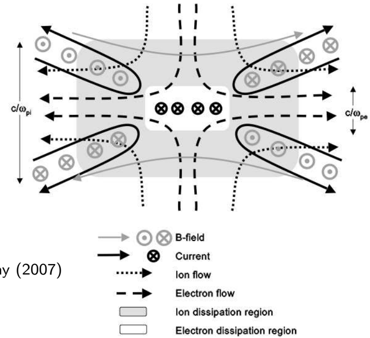
Magnetic flux

Out-of-plane
magnetic field

Murphy (2009)

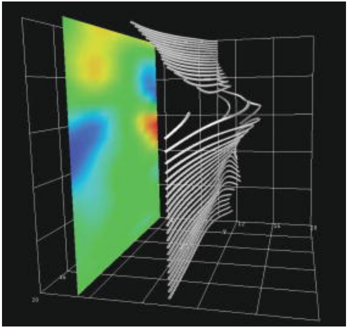
- X-point structure in diffusion region! Fast reconnection! Quadrupole out-of-plane magnetic field!

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

The Hall effect is not the whole story

- In resistive Hall MHD, elongated current sheets become more like X-points
- The $\frac{\nabla\cdot\mathbf{P}_e}{n_e e c}$ term is best studied using particle-in-cell (PIC) simulations
- PIC simulations of reconnection in a positron-electron plasma still show fast reconnection!
  - Hall term is absent because $m_{e^+} = m_{e^-}$

2D PIC simulations with a large domain show an elongated current sheet with occasional island formation

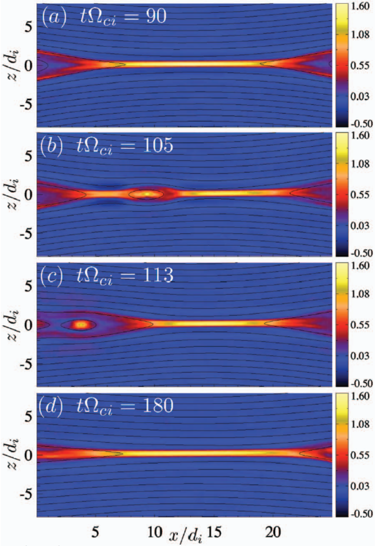
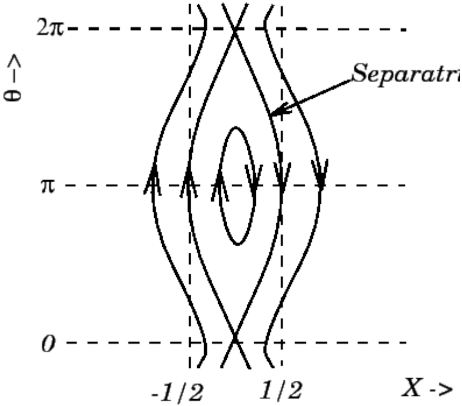


FIG. 9. (Color) Out-of-plane electron velocity U_{ey} at four different simulation times showing the stretching of the electron diffusion region and production of a secondary island. These results are for the $25d_i \times 25d_i$ open boundary case.

Daughton et al. (2006)

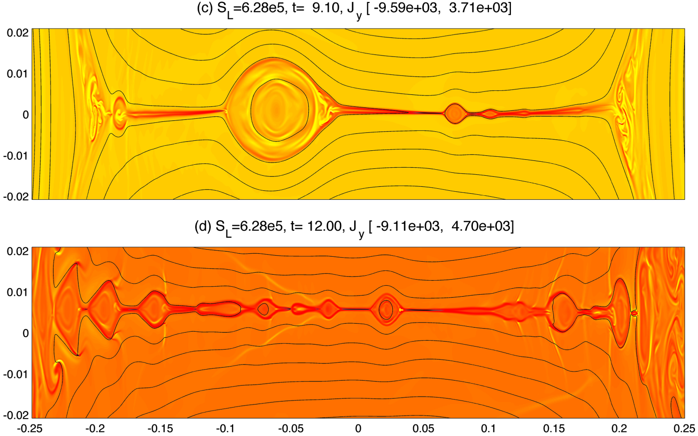
The tearing mode is a resistive instability



Furth, Killeen, & Rosenbluth (1964)

- The tearing instability breaks up a current sheet into a chain of X-points and magnetic islands
- Use asymptotic matching between inner and outer solutions to calculate exponential growth rate
- Degrades confinement in magnetically confined fusion plasmas

Elongated current sheets are susceptible to the tearing-like **plasmoid instability** (Loureiro et al. 2007)

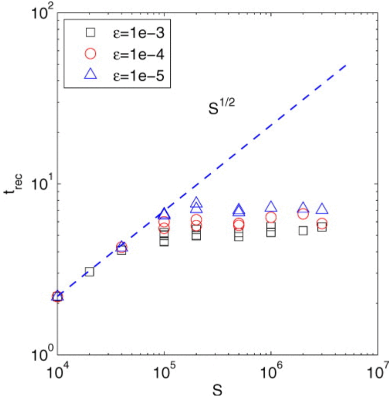


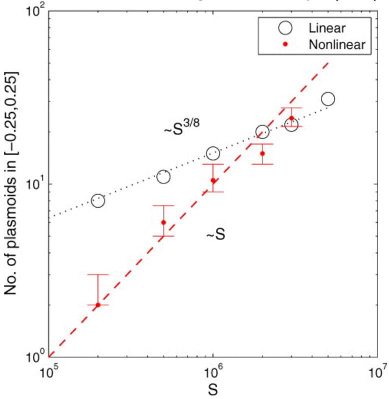
Bhattacharjee et al. (2009); simulations by Y.-M. Huang

- The linear growth rate increases as S increases
- The reconnection rate levels off at $\frac{V_{in}}{V_A} \sim 0.01$ for $S \gtrsim 10^4$
- The Sweet-Parker model is not applicable to astrophysical reconnection!

The scaling of the plasmoid instability can be investigated using large-scale 2D resistive MHD simulations

Huang & Bhattacharjee (2010)



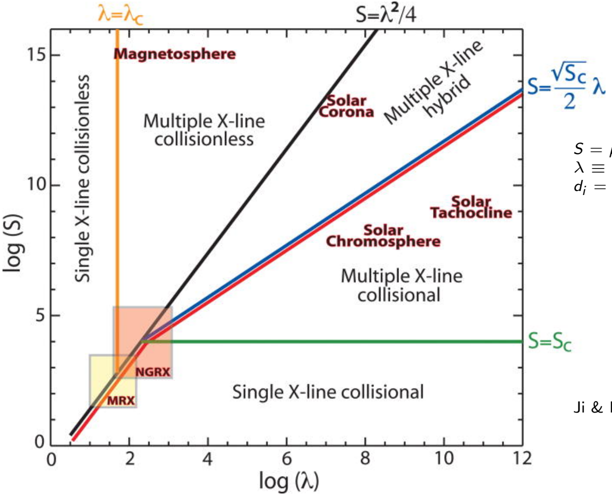


- The reconnection time scale asymptotes to a roughly constant value above a critical Lundquist number! (left)
  - Fast reconnection occurs even in resistive MHD!

But does the plasmoid instability lead to fast enough reconnection?

- The plasmoid instability predicts $\frac{V_{in}}{V_A} \sim 0.01$
- Reconnection rates of 0.1 are needed to describe flare reconnection
- 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
- What happens in 3D?

Emerging phase diagram for collisionless vs. plasmoid dominated reconnection

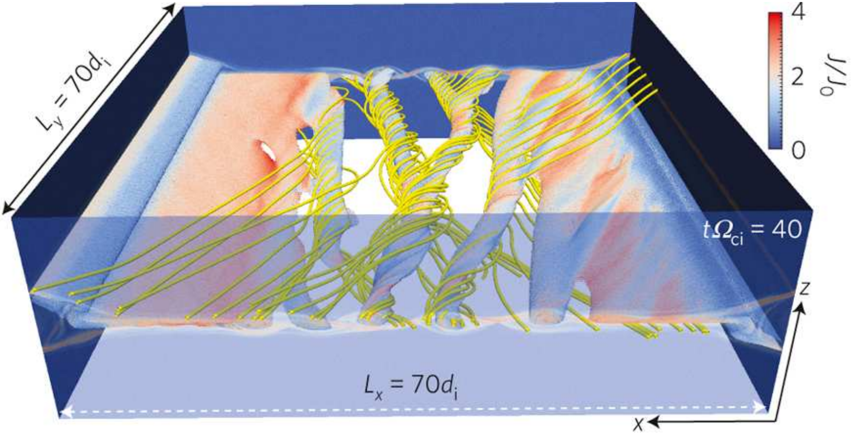


$S = \mu_0 L V_A / \eta$
$\lambda \equiv L/d_i$
d_i = ion inertial length

Ji & Daughton (2011)

- Next-generation reconnection experiments could test this parameter space diagram (e.g., FLARE)

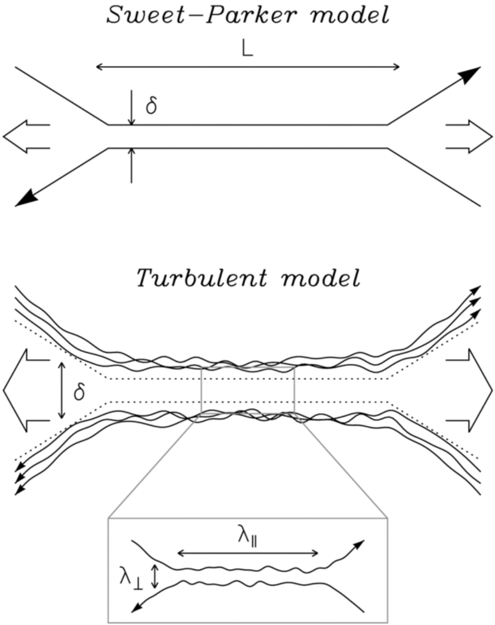
3D effects in fully kinetic simulations of reconnection



Daughton et al. (2011)

- 2D: Coherent magnetic island structures
- 3D: Highly twisted interconnected flux rope structures

Turbulent reconnection (Lazarian & Vishniac 1999)



Turbulent reconnection (Lazarian & Vishniac 1999)

- Many simultaneous reconnection events
- Field line wandering determines reconnection rate
- Predicts fast reconnection even for very low resistivity
- Numerical tests by Lazarian group agree with model
- Not supported by laboratory or in situ measurements
  - Magnetospheric Multiscale Mission: reconnection events tend to be more laminar than turbulent
- How do small-scale reconnection sites interact?
- What is the filling factor of these reconnection sites?
- Reconnection plays an important role in the dissipation of magnetized turbulence

Properties of 2D reconnection (Priest et al. 2003)

- Reconnection occurs only at X-points
- A flux tube velocity exists everywhere except at null points
- While in the diffusion region, field lines preserve their connections except at X-points
- Reconnecting flux tubes rejoin perfectly after reconnecting

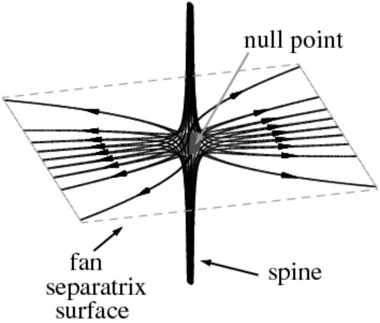
Properties of 3D reconnection (Priest et al. 2003)

- Reconnection occurs continually throughout the diffusion region
  - While in the diffusion region, field lines continually change their connections
- A flux tube velocity does not generally exist
- The mapping of field lines is continuous
- Reconnecting flux tubes split into multiple parts that do not rejoin perfectly after reconnecting

2D vs. 3D reconnection

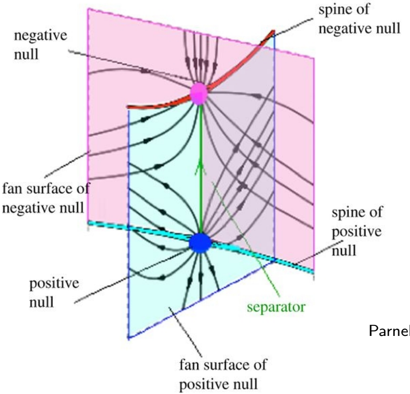
- So, is everything we've learned about 2D reconnection wrong?
- Sort of!
- 2D studies allow us to investigate which terms in the Ohm's law are important and which instabilities are likely to develop
- 2D simulations allow us to probe more extreme parts of parameter space than we can in 3D
- Many reconnection events are quasi-2D
  - Standard model of flares
  - Dedicated reconnection experiments
- However, we must keep in mind that reconnection is **fundamentally 3D**

Null point reconnection



- Null points are locations where $\mathbf{B} = 0$ (Parnell et al. 1996)
    - Called linear if the Jacobian matrix of $\mathbf{B}$ is invertible
    - Appear and disappear through bifurcations
- In 2D, linear nulls are either X-points or O-points
- In 3D, the magnetic field surrounding linear nulls contains:
    - Two spine field lines that approach or recede from the null
    - A separatrix surface (or fan) with infinitely many field lines that recede from or approach the null

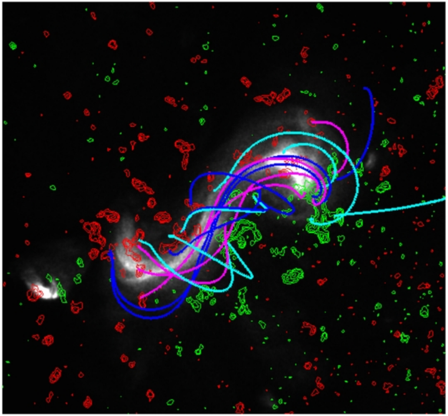
A magnetic skeleton includes the topological boundaries that demarcate a plasma into different magnetic domains



Parnell et al. (2015)

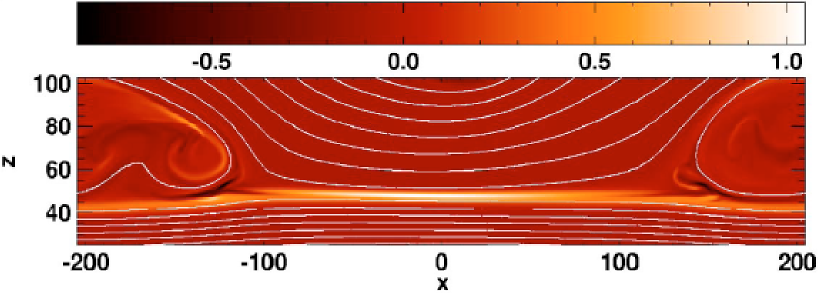
- Separators are field lines that connect two null points
  - Given by the intersection of two separatrix surfaces
- Magnetic skeletons consist of null points, spine field lines, separatrix surfaces, and separators
  - Each of these features is a preferred location of reconnection

Non-null reconnection



- Reconnection may occur in the absence of null points
  - Example: Parker's problem
- Reconnection preferentially occurs in regions where the magnetic connectivity is changing rapidly
  - Quasi-separatrix layers (QSLs, see above sigmoid)

Asymmetric reconnection



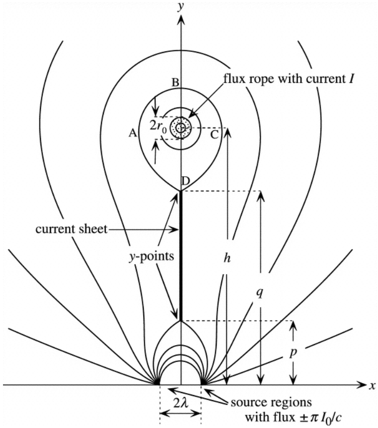
Cassak & Shay (2007)

- Most reconnection models assume symmetric inflow
- In general, no reason to expect symmetry!
- Prototypical example: Earth's dayside magnetopause
  - Solar wind plasma reconnecting with magnetospheric plasma

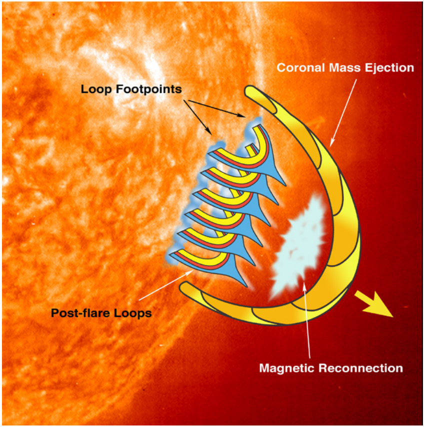
Key properties of asymmetric reconnection

- Outflow velocity scales as a hybrid Alfvén speed based on plasma properties in both upstream (inflow) regions
- Non-ideal plasma flow across null point (Murphy et al. 2015)
- Can also have asymmetric outflow reconnection
  - Flare reconnection jet toward Sun is impeded by flare loop structures
  - Earthward jet from magnetotail reconnection impeded by Earth's magnetic field (Oka et al. 2008, 2011)

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



Lin & Forbes (2000)

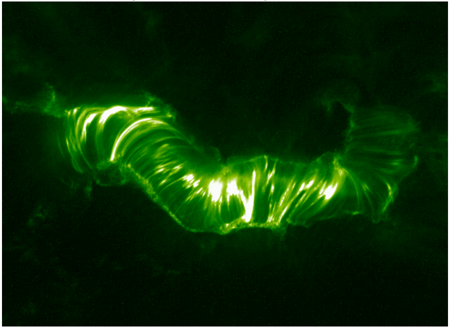


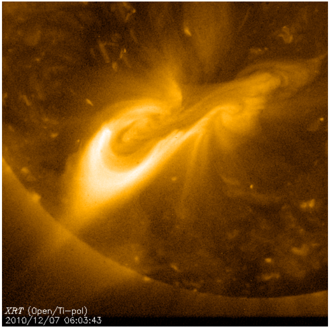
Reconnection is an essential ingredient in solar flares and coronal mass ejections (CMEs)

- 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 the loop top

Signatures of reconnection: cuspy post-flare loops

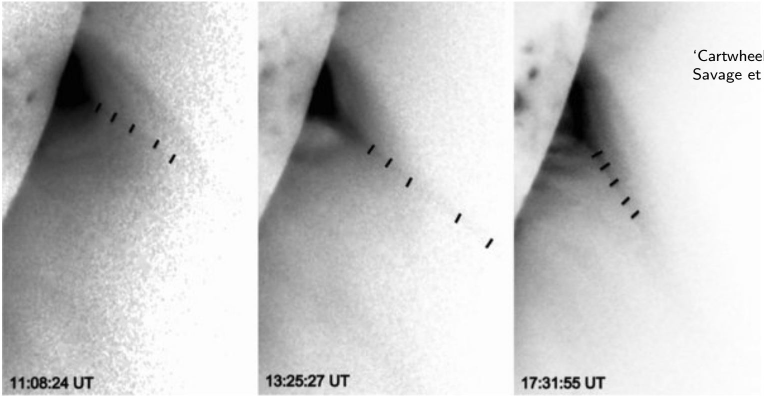
Bastille day event observed by TRACE at 195 Å





- Shrinkage 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

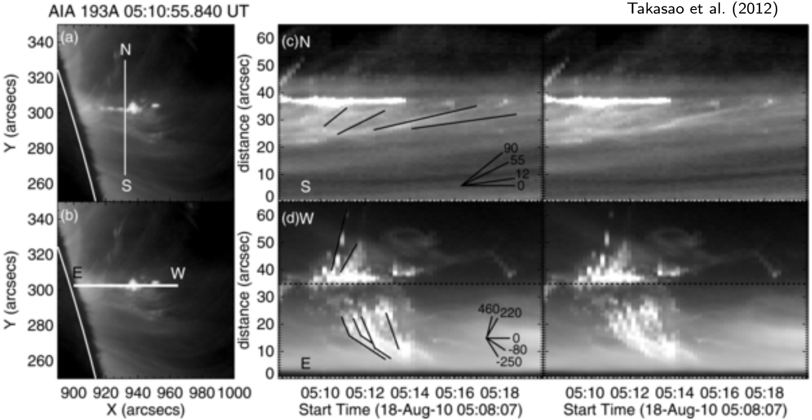


'Cartwheel CME'
Savage et al. (2012)

- White light, X-ray, and EUV observations show elongated structures between the flare loops and rising flux rope
- Much thicker than predicted; the current sheets may be embedded in a larger-scale plasma sheet

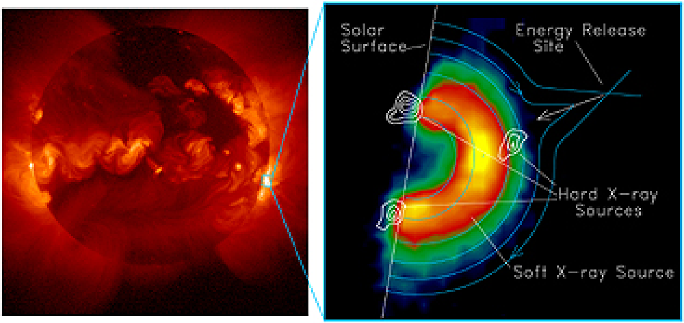
Signatures of reconnection: inflows, upflows, downflows

Takasao et al. (2012)



- High cadence EUV observations show reconnection:
  - Inflows (top panels)
  - Outflows (upflows/downflows; bottom panels)

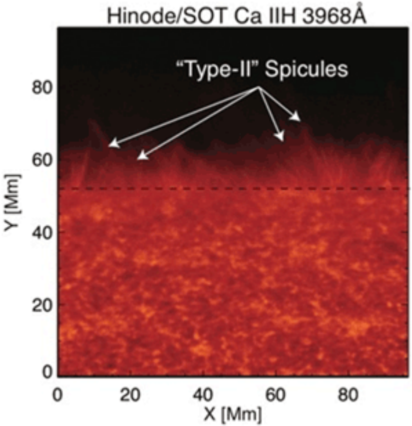
Signatures of reconnection: Above-the-loop-top hard X-ray (HXR) sources (Masuda et al. 1994)



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

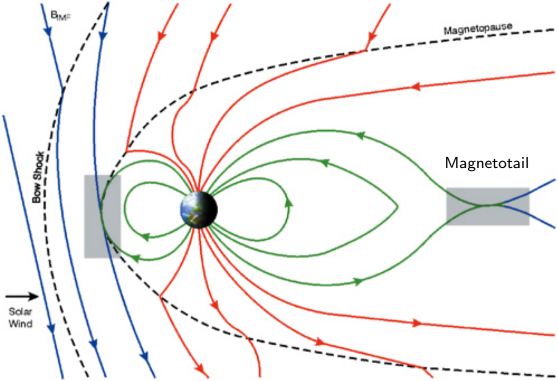
Magnetic reconnnection is ubiquitous in the partially ionized solar chromosphere



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

Magnetic reconnection in Earth's magnetosphere

Southward interplanetary magnetic field (IMF)

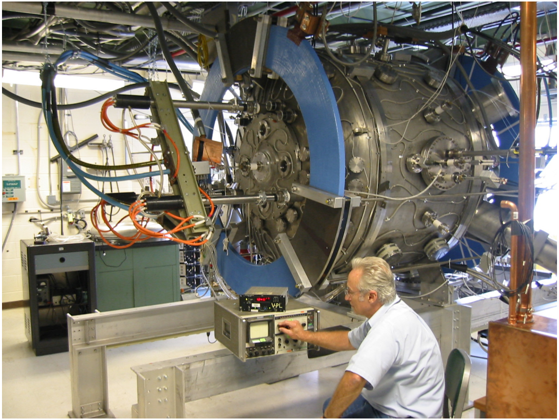


- Magnetic reconnection occurs in two primary locations in Earth's magnetosphere in response to driving from solar wind
  - Dayside magnetopause: solar wind plasma reconnecting with magnetospheric plasma
  - Magnetotail: in response to magnetic energy building up in lobes due to solar wind driving

Magnetic reconnection in Earth's magnetosphere

- MHD not valid; need collisionless physics
  - Kinetic theory; particle-in-cell (PIC) simulations
- 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; MMS)
- Reconnection is an important part of space weather (geomagnetic storms & substorms)
  - Depends on the orientation of interplanetary magnetic field (IMF)
  - Key goal of space weather forecasting: predicting B_z
  - Southward IMF more geoeffective than northward IMF
    - Reconnection is more antiparallel
- Analogous physical processes in solar flares and magnetotail

Magnetic reconnection in laboratory plasmas (e.g., MRX)



- 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

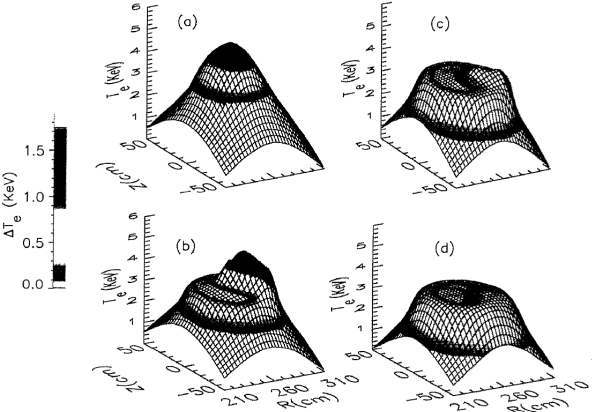


FIG. 1. The $T_e(r,\theta)$ profiles in three dimensions during the crash period of a sawtooth. Heat transfer ΔT_e is superposed with coded color contours. The time intervalbetween each figure is $\sim 120\ \mu s$.

- Reconnection degrades confinement in magnetically confined fusion plasmas when field lines become stochastic
- Above: peaked temperature profile reduces to flat profile (Yamada et al. 1994)

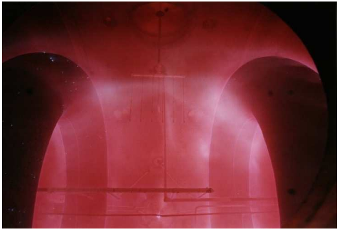
Magnetic reconnection in the ISM

- Occurs on scales too small to observe directly
- Indirect observations: dissipation range of ISM turbulence?
- No reconnection would imply that the number of field reversals $\approx$ the number of past galactic rotations
- There are $\sim$5–10 reversals
  - Suggests that reconnection in ISM does occur
  - Linked to problem of forming large-scale field in dynamo theory
- Best bet: understand reconnection locally and then apply results to ISM
- Or, if you have a few gigadollars and decades to spare, an interstellar probe!
  - Voyagers 1 & 2, but not New Horizons since it lacks magnetometers

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

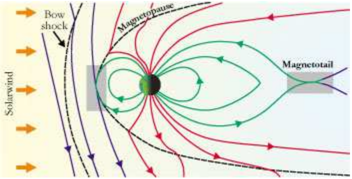
Learning about reconnection from laboratory experiments



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, and soon FLARE

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

Summary – Part 1

- **Magnetic reconnection** is a fundamental process in astrophysical, heliospheric, and laboratory plasmas
- The **Sweet-Parker** model describes the scaling of steady-state resistive reconnection at modest Lundquist numbers
- The **Petschek** model predicts fast X-point reconnection with slow shocks at the boundary between the inflow and outflow
- The **plasmoid instability** facilitates fast reconnection even in resistive MHD for high Lundquist numbers
    - But is it fast enough?
- **Collisionless** reconnection occurs when current sheets develop structures comparable to the ion inertial length or ion sound gyroradius

Summary – Part 2

- Understanding magnetic reconnection requires complementary, cross-discipline efforts
  - Solar observations show large-scale dynamics in parameter regimes inaccessible in the laboratory, but with limited information on **B** and small-scale dynamics
  - Astrophysical reconnection provides information about extreme regions of parameter space
  - *In situ* measurements in space plasmas provide extremely detailed information, but only at a few spatial locations
  - Laboratory experiments allow controlled studies with detailed measurements at both small and large scales, but at relatively modest plasma parameters
- Active research topics include
  - Collisionless/3D effects
  - Connection of reconnection to turbulence
  - Interplay between small and large scales
  - Onset of reconnection