Magnetic Reconnection

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

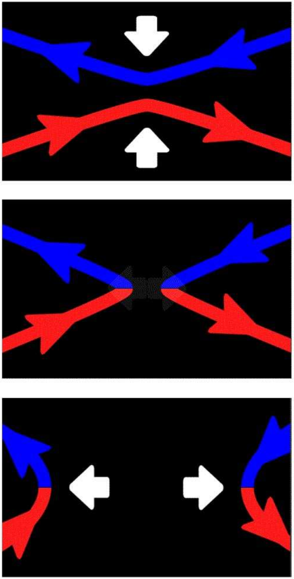
Outline

- Magnetic reconnection in laboratory, solar, space, and astrophysical plasmas
- Sweet-Parker model
- Petschek reconnection
- Collisionless reconnection
- Plasmoid-dominated reconnection
- Turbulent reconnection
- Three-dimensional reconnection
- Asymmetric reconnection

Introduction

- Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma
- Reconnection occurs in:
  - Solar atmosphere (flare, coronal mass ejections, jets)
  - Laboratory plasmas (fusion devices, dedicated reconnection experiments)
  - Earth's magnetosphere (in response to driving by solar wind)
  - Astrophysical plasmas (star formation regions, accretion disks, jets, ISM/galactic dynamos, stellar chromospheres/coronae)
- A complete understanding of reconnection will require a multi-disciplinary approach

Picturing 2D magnetic reconnection



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

This is missing essential 3D effects!

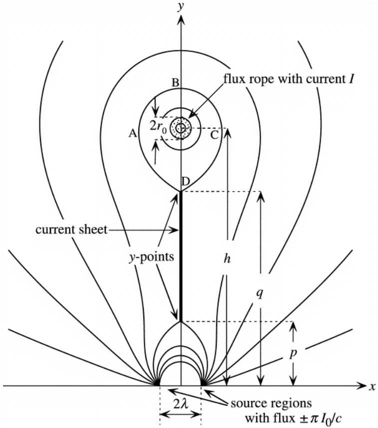
Usual ingredients of magnetic reconnection

- Occurs in regions of strong magnetic shear
- 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

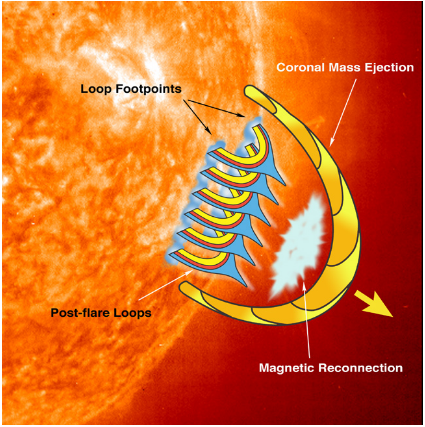
Open questions in magnetic reconnection

- 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
  - Weakly ionized plasmas such as the solar chromosphere and protoplanetary disks

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



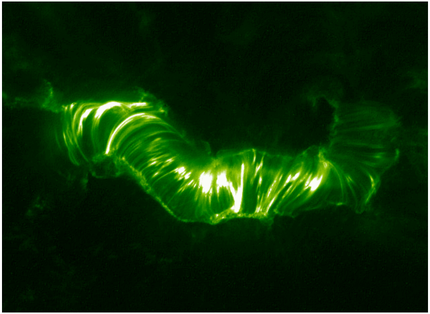
Lin & Forbes (2000)

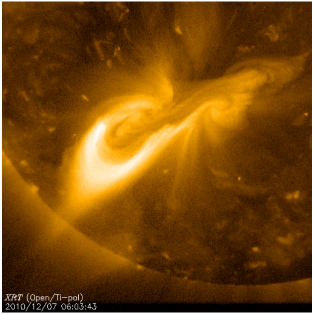


Reconnection is an essential ingredient in solar flares and coronal mass ejections (CMEs)

- 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

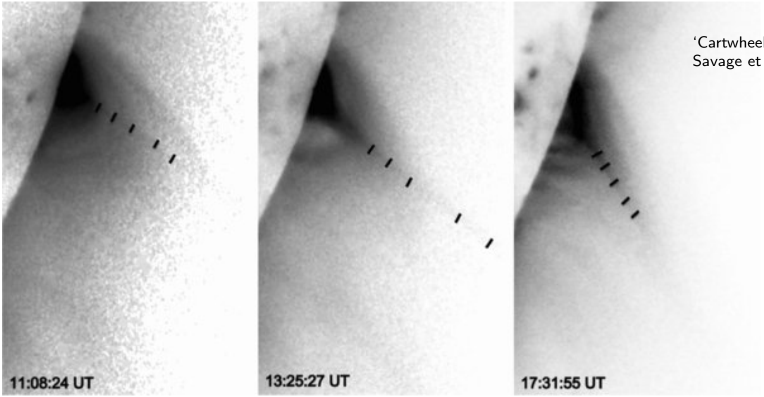
Signatures of reconnection: cuspy post-flare loops





- Shrinkage (contraction) 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

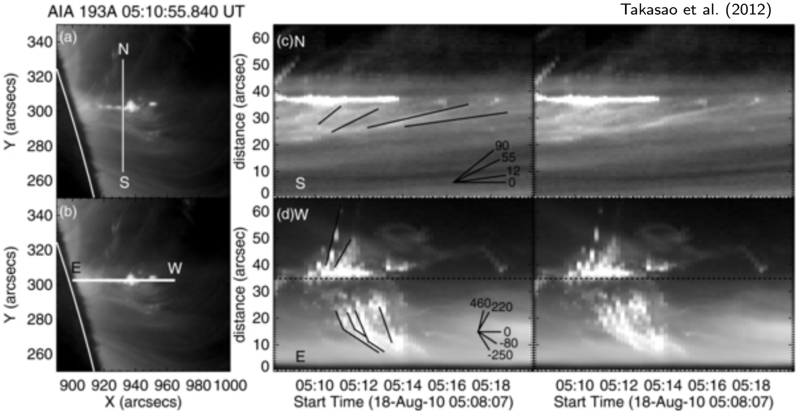


'Cartwheel CME'
Savage et al. (2012)

- White light, X-ray, and EUV observations show 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

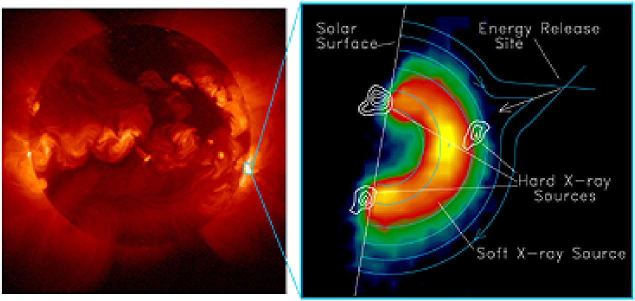
Signatures of reconnection: inflows, upflows, downflows

Takasao et al. (2012)



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

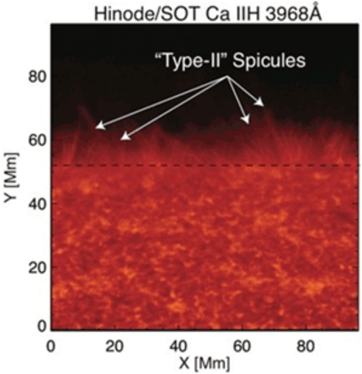
Signatures of reconnection: Above-the-loop-top hard X-ray (HXR) sources (Masuda et al. 1994)



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

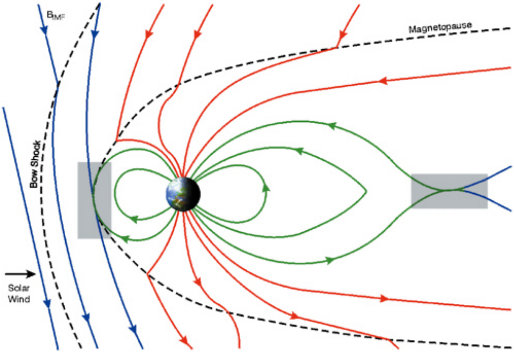
- Evidence for particle acceleration occuring at or above the apex of the post-flare loop
- Lower HXR sources due to energetic particles or a thermal conduction front impacting the chromosphere

Magnetic reconnnection is ubiquitous in the partially ionized solar chromosphere



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

Magnetic reconnection in Earth's magnetosphere

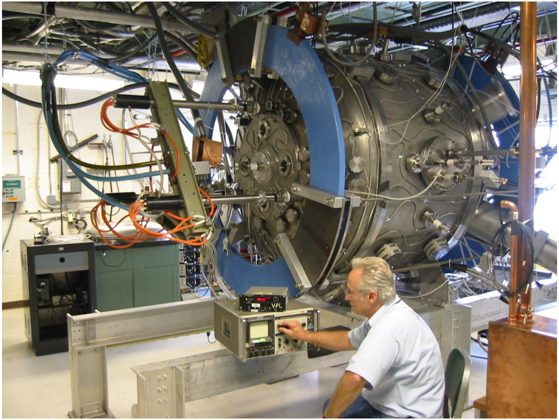


- Magnetic reconnection occurs in two primary locations in Earth's magnetosphere in response to driving from solar wind
  - Dayside magnetopause: solar wind plasma reconnecting with magnetospheric plasma
  - Magnetotail: in response to magnetic energy building up in lobes due to solar wind driving

Magnetic reconnection in Earth's magnetosphere

- MHD not valid; need collisionless physics
- 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*)
- 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



- 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

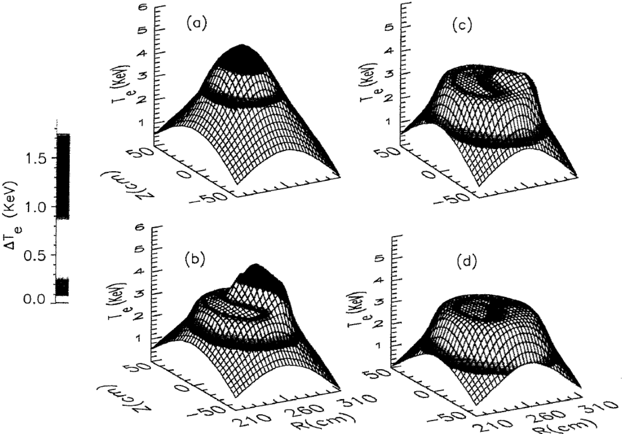


FIG. 1. The $T_e(r,\theta)$ profiles in three dimensions during the crash period of a sawtooth. Heat transfer ΔT_e is superposed with coded color contours. The time intervalbetween each figure is ~120 μs.

- Reconnection degrades confinement in magnetically confined fusion plasmas (peaked temperature profile → flat profile)

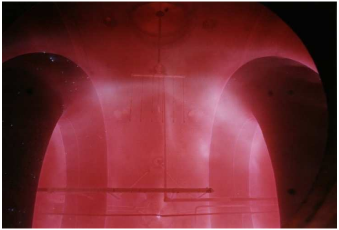
Magnetic reconnection in the ISM

- Occurs on scales too small to observe directly
- Indirect observations: dissipation range of ISM turbulence?
- In absence of reconnection, the number of magnetic field reversals in the Milky Way should $\approx$ the number of 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 in space plasmas using in situ measurements and apply results to ISM
- Or, if you have a few gigadollars and decades to spare, an interstellar probe!
  - *Voyagers 1 & 2, New Horizons*

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

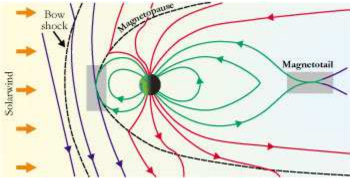
Learning about reconnection from laboratory experiments



MRX

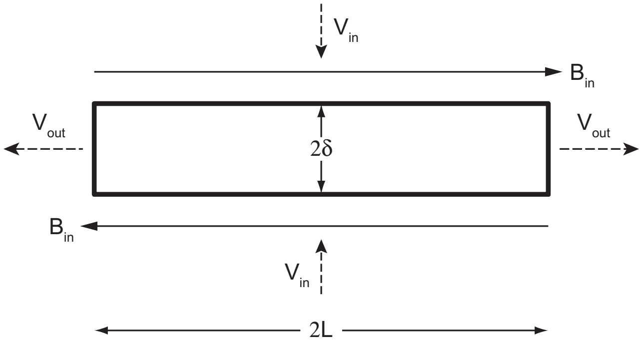
- Advantages:
  - Can insert probes directly (especially for $T \lesssim 20$ eV)
  - Study small-scale physics and global dynamics simultaneously
  - Controlled experiments
- Disadvantages:
  - Relatively modest parameter regimes
  - Modest separation of scales
  - Results influenced by BCs/experimental 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
  - Future: Magnetospheric Multiscale Mission, Solar Probe Plus

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
- Resistive electric field important only inside current sheet
- For scaling, ignore pressure effects/thermal energy
- Ignore 3D effects
- Don't worry about factors of order unity (e.g., $2 \approx 1$)

Deriving the Sweet-Parker model

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

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

- Conservation of energy (magnetic energy flux in equals kinetic energy flux out)

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

- 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

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

  where the Lundquist number is the ratio of a resistive diffusion time scale to an Alfvén wave crossing time scale

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

- In astrophysics, the Lundquist number is huge
  - S is typically somewhere between 10^9 and 10^{20}

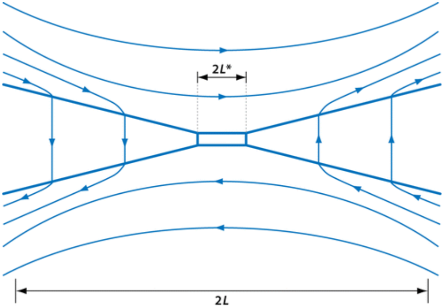
The Sweet-Parker model predicts reconnection rates much slow than observed in solar flares and space/lab plasmas

- Solar flares occur on timescales of tens of seconds to tens of minutes whereas the Sweet-Parker model predicts times of months
- Many of the Sweet-Parker approximations are not well justified
- Sweet-Parker-like 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 low resistivity?

Fast reconnection through anomalous resistivity?

- Thus far, we've calculated the Lundquist number based on Spitzer resistivity
- What if there are other mechanisms that generate a higher effective resistivity?
  - Kinetic instabilities, wave-particle interactions, microturbulence
- Often an *ad hoc* function of current density or position in theory and simulations
  - But what would cause an anomalous resistivity enhancement?
- Laboratory experiments provide support against several mechanisms

The Petschek Model predicts fast reconnection for large Lundquist number plasmas



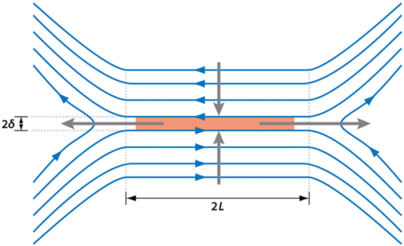
- Petschek (1964) proposed an X-line geometry
- The inflow and outflow are separated by slow mode shocks
- No bottleneck from conservation of mass
- Reconnection rate $\propto \frac{1}{\ln S} \Rightarrow$ fast reconnection!

Problems with the Petschek Model

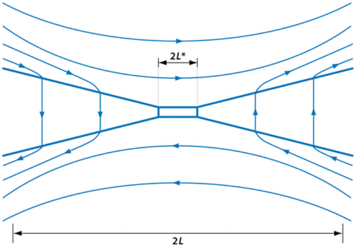
- Need localized anomalous resistivity to get Petschek reconnection in resistive MHD simulations
- Petschek reconnection not observed in the laboratory or space plasmas
- Anomalous resistivity requires collisionless effects
- However, these effects occur only on short length scales where MHD breaks down
  - $\Rightarrow$ collisionless reconnection, not Petschek
- Therefore, the original Petschek model is not a viable mechanism for fast reconnection
- The key insight from Petschek is that reconnection could be sped up when δ/L is of order unity

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

Sweet-Parker



Petschek



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 the mechanism that 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**

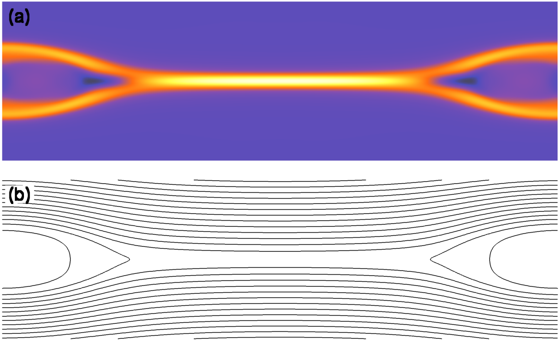
Return of the generalized Ohm's law

- The generalized Ohm's law is given by

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

- 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)

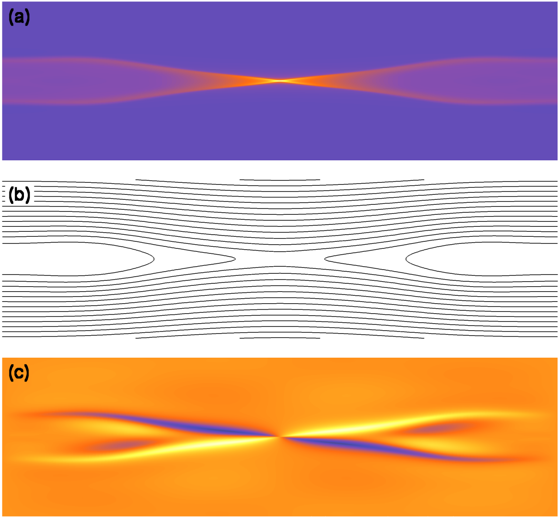


Current density

Magnetic flux

- Elongated current sheet $\Rightarrow$ slow reconnection

Simulation with the Hall term on (Hall MHD)



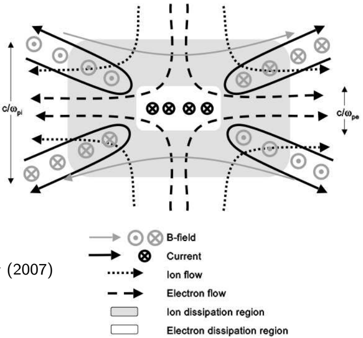
Current density

Magnetic flux

Out-of-plane magnetic field

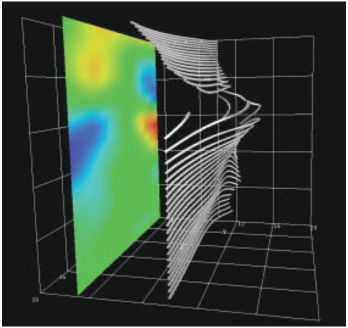
- X-point structure in diffusion region! Fast reconnection! Quadrupole out-of-plane magnetic field!

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 $\frac{\nabla\cdot\mathbf{P_e}}{n_e ec}$ term is best studied using fully kinetic particle-in-cell (PIC) simulations
  - Important area of current research
- 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

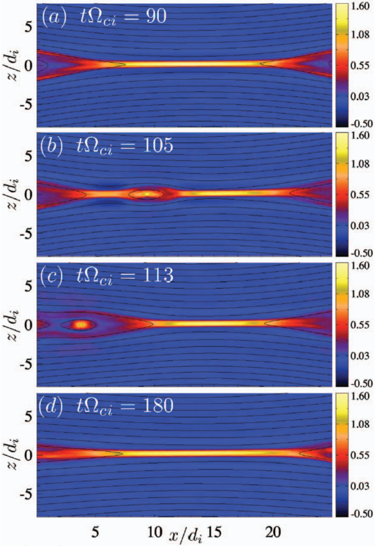
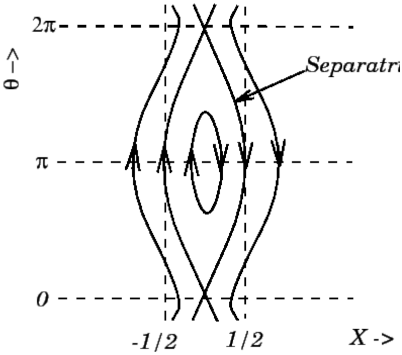


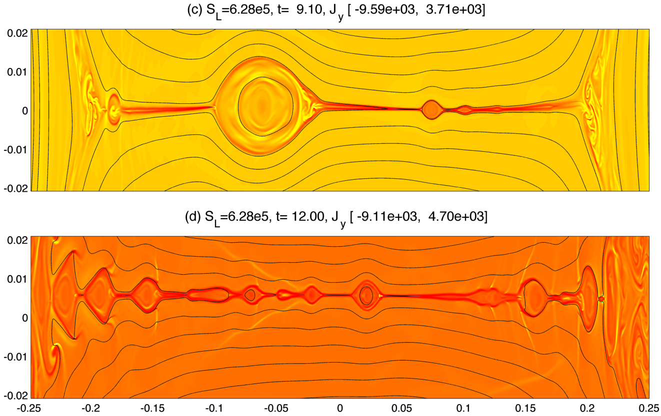
FIG. 9. (Color) Out-of-plane electron velocity U_{ey} at four different simulation times showing the stretching of the electron diffusion region and production of a secondary island. These results are for the $25d_i \times 25d_i$ open boundary case.

The tearing mode is a resistive instability



- 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)



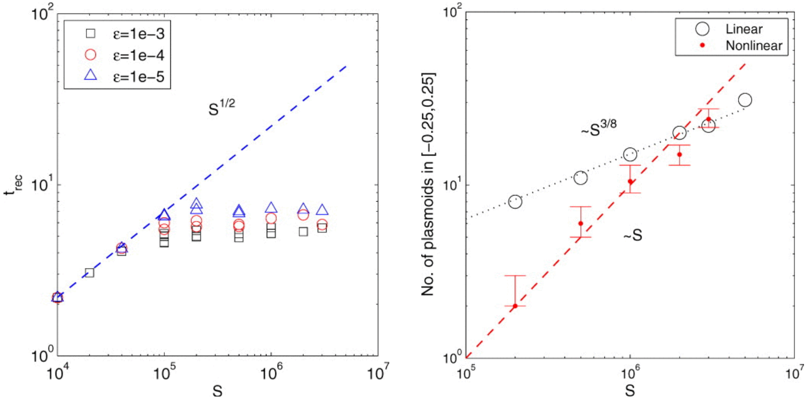
Bhattacharjee et al. (2009)

- 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!

Properties of the plasmoid instability

- The linear growth rate scales as $\sim S^{1/4} V_A/L$
  - Instability gets worse with increasing Lundquist number!
  - Number of islands scales as $S^{3/8}$ in linear regime
- The tearing mode scales as $S^{-3/5}$ or $S^{-1/3}$ depending on the regime
  - Growth rate decreases with increasing Lundquist number
- The difference in scaling occurs because the thickness of Sweet-Parker current sheets scales as $\delta \sim S^{-1/2}$

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

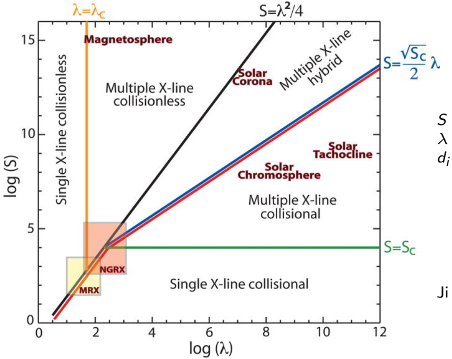


- The reconnection time scale asymptotoes to a roughly constant value above a critical Lundquist number! (left)
  - Fast reconnection occurs even in resistive MHD!

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

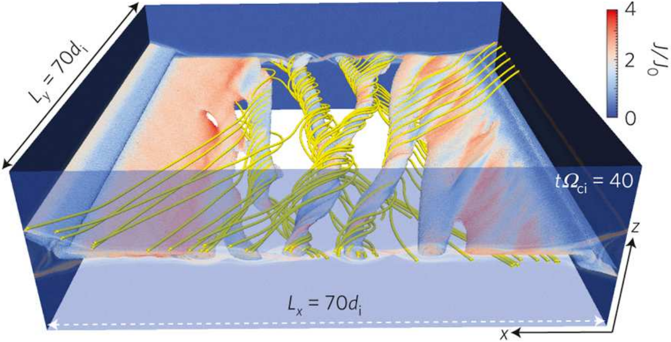


$S = \mu_0 L V_A / \eta$
$\lambda \equiv L/d_i$
d_i = ion inertial length

Ji & Daughton (2011)

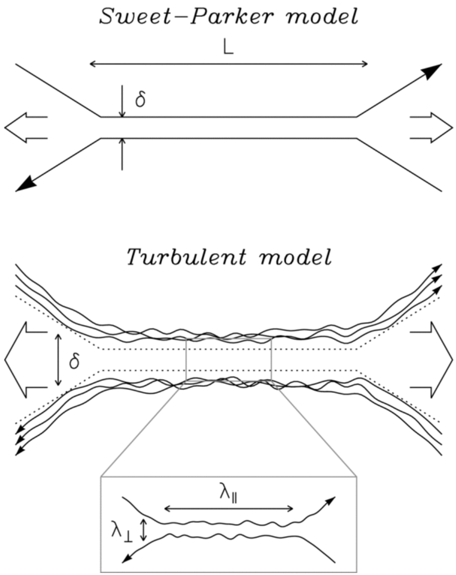
- Caveats:
  - Extrapolation for $S \gtrsim 10^6$
  - 3D effects/scaling not well understood
- Next-generation reconnection experiments could test this parameter space diagram

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?

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 in agreement with picture
- Not supported by laboratory or in situ measurements
  - Wrong regime?
- How do small-scale reconnection sites interact with each other?
- 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 null points
- While in the diffusion region, field lines preserve their connections except at X-points
- Reconnecting flux tubes rejoin perfectly after reconnecting

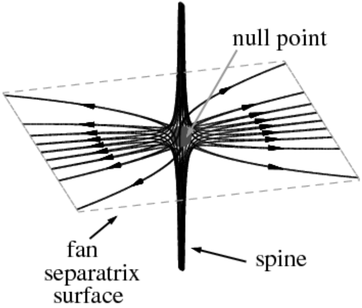
Properties of 3D reconnection (Priest et al. 2003)

- Reconnection occurs continually throughout 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?
- The good news and bad news is: 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 three-dimensional*

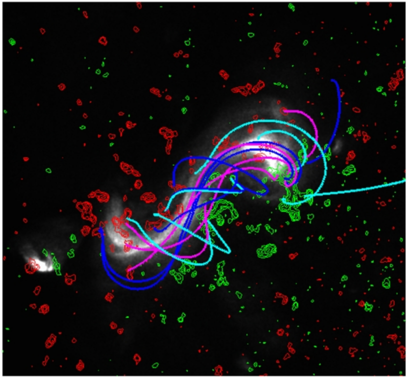
Null point reconnection



- Null points are preferred locations for reconnection
  - Often occur in regions with strong magnetic shear
- Linear null points[1] are structurally stable
  - Null lines and null planes are structurally unstable
- Null points emerge and disappear in pairs

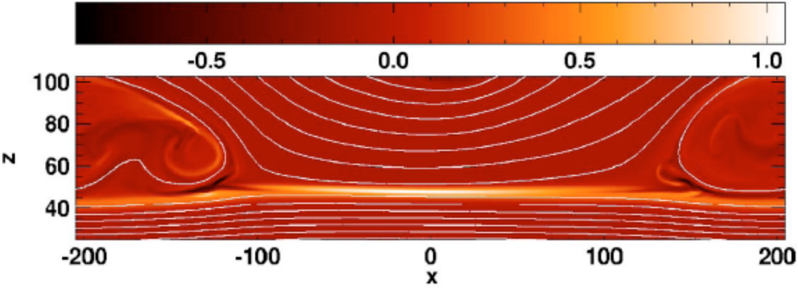
[1] Where the Jacobian of **B** is non-singular

Non-null reconnection



- Reconnection in 3D does not need null points or X-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



- Most reconnection research assume symmetric inflow
- In many situations, no reason to expect symmetry!
- Prototypical example: Earth's dayside magnetopause
  - Solar wind plasma reconnecting with magnetospheric plasma
- Homework problem: derive the outflow velocity for Sweet-Parker-like asymmetric reconnection

Key properties of asymmetric reconnection

- Outflow velocity scales as a hybrid Alfvén speed based on plasma properties in both upstream (inflow) regions
- There will be net plasma flow across the null point
- 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

Summary – Part I

- Magnetic reconnection is a fundamental process in magnetized plasmas in astrophysical, heliospheric, and laboratory plasmas
- The Sweet-Parker model describes the scaling of steady-state resistive reconnection at low to moderate Lundquist numbers
- The Petschek model is not supported by in situ observations of reconnection
- 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 II

- 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