Magnetic Reconnection in Solar, Space, and Laboratory Plasmas

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With thanks to a few $\times 10^2$ people

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Outline

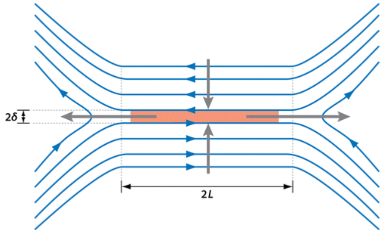
- Recent important advances in magnetic reconnection
- Observational signatures of reconnection in the solar atmosphere
- Constrasting studies of reconnection in solar, space, and laboratory plasmas
- A review of important results on reconnection from the laboratory

Introduction

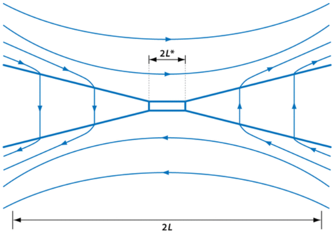
- Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma
- Reconnection occurs in:
  - Solar flares/coronal mass ejections
  - Loss of confinement in tokamaks and other devices
  - Magnetospheric and solar wind plasmas
- Each strategy for studying reconnection has advantages and disadvantages
- A complete understanding of reconnection will require multi-disciplinary research

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

Sweet-Parker



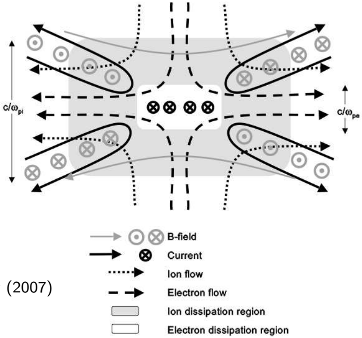
Petschek



Zweibel & Yamada (2009)

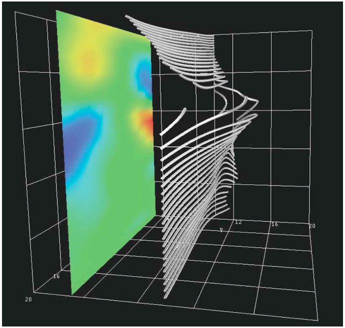
- Petschek reconnection not observed in the laboratory
- The Sweet-Parker vs. Petschek dichotomy ignores important advances in our understanding of high Lundquist number and collisionless reconnection

Fundamentals of collisionless reconnection



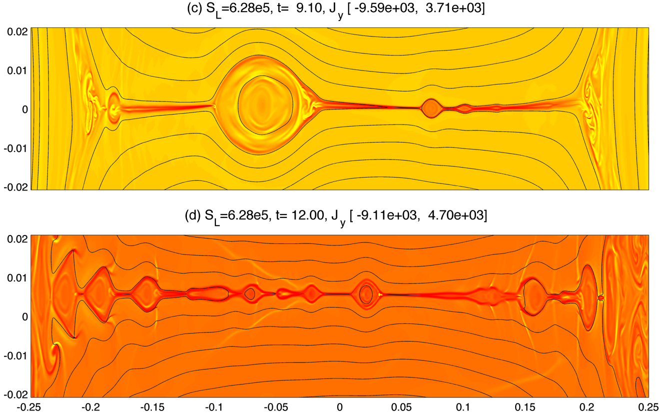
Drake & Shay (2007)

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

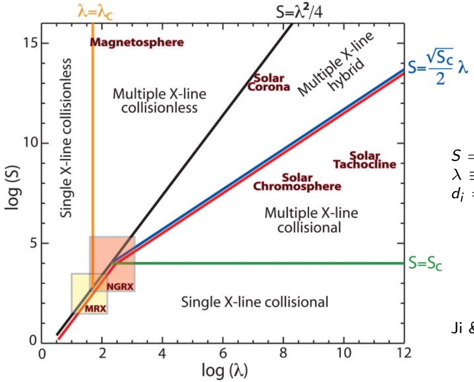
Elongated current sheets are susceptible to the plasmoid instability (Loureiro et al. 2007)



Bhattacharjee et al. (2009)

- The reconnection rate levels off at ~ 0.01 for $S \gtrsim 4 \times 10^4$
- Shepherd & Cassak (2010) argue that this instability leads to small enough scales for collisionless reconnection, which then gives very fast reconnection

Emerging phase diagram for collisionless vs. plasmoid dominated reconnection

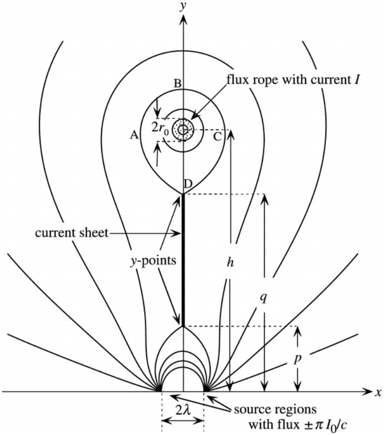


$S = \mu_0 L V_A / \eta$
$\lambda \equiv L/d_i$
d_i = ion inertial length

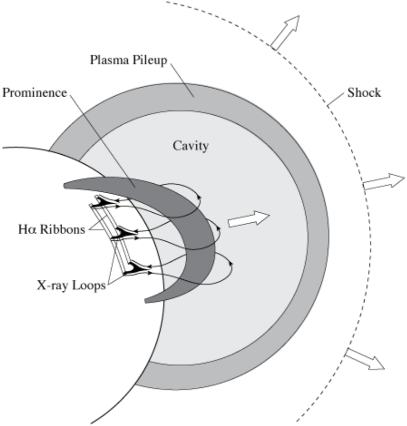
Ji & Daughton (2011)

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

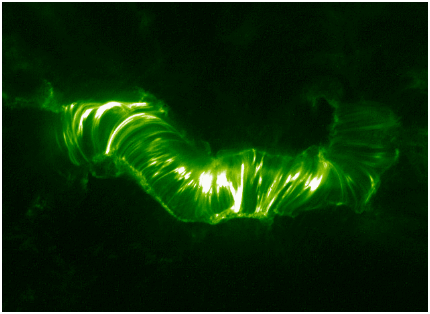
Flux rope models of CMEs predict a current sheet behind the rising flux rope

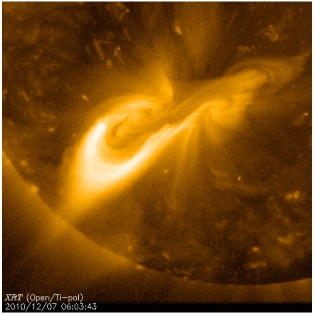


Lin & Forbes (2000)



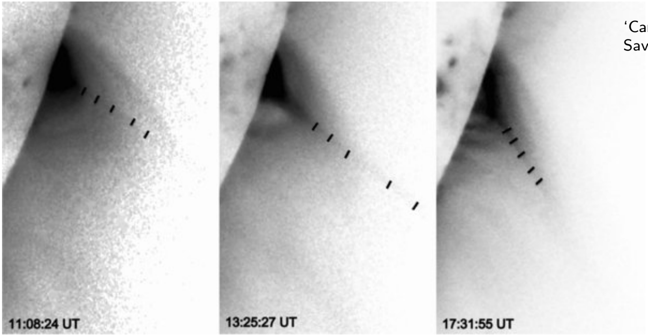
Signatures of reconnection: cuspy post-flare loops





- Shrinkage of loops after reconnection
- Footpoints of most recently reconnected loops show apparent motion away from the neutral line
- These observations provide information on the energetics, thermodynamics, reconnection rate, and magnetic topology

Signatures of reconnection: ‘current sheet’ structures

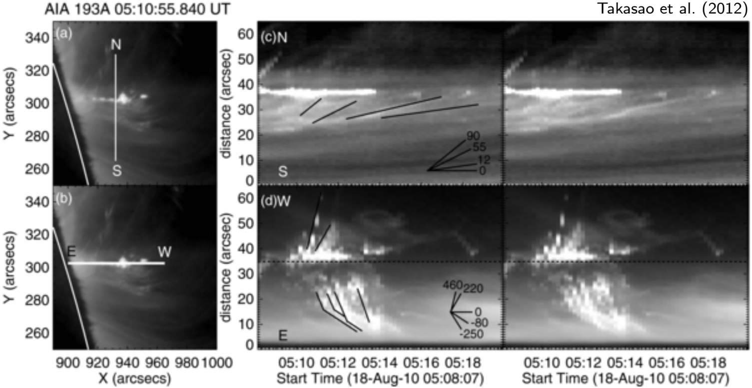


‘Cartwheel CME’
Savage et al. (2012)

- 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

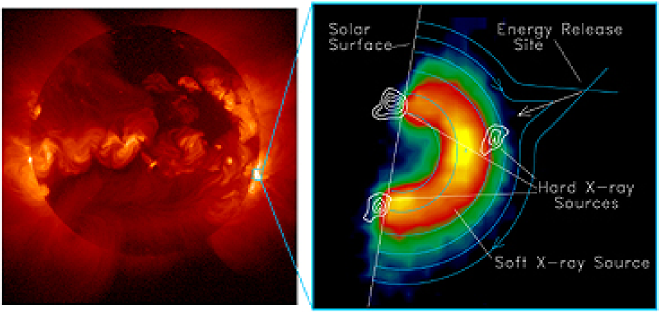
Signatures of reconnection: inflows, upflows, downflows

Takasao et al. (2012)



- High cadence observations show reconnection inflows and sunward/anti-sunward exhaust
- Supra-arcade downflows (SADs) re-interpreted as wakes behind contracting loops (Savage et al. 2012)
- Downflows often sub-Alfvénic: due to asymmetry? (Reeves et al. 2010; Murphy 2010; Murphy et al. 2012)

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



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

- Evidence that particle acceleration occurs at or above the apex of the post-flare loop

Open questions in solar/astrophysical reconnection

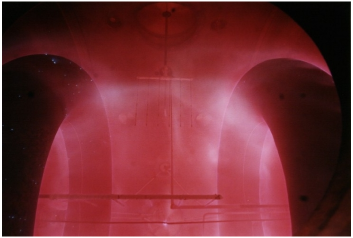
- What sets the reconnection rate?
- What are the small-scale physics of reconnection?
- What is the interplay between small-scale physics and global dynamics?
- Why is there a sudden onset to fast magnetic reconnection?
- How are particles accelerated and heated?
- What sets the observed thickness of current sheets?
- How does 3D reconnection occur?
- What are the roles of turbulence, instabilities, and asymmetry?
- How does magnetic reconnection occur in partially ionized plasmas such as the chromosphere?

All of these questions are being addressed by laboratory experiments on magnetic reconnection.

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
  - Uncertainties from atomic data
- 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

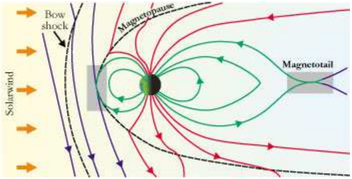
Learning about reconnection from laboratory experiments



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:
  - MRX, VTF, TS-3/4, SSX, RSX, CS-3D
  - Tokamaks, spheromaks, reversed field pinches

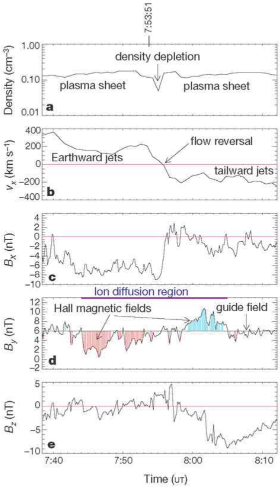
Learning about reconnection in space plasmas

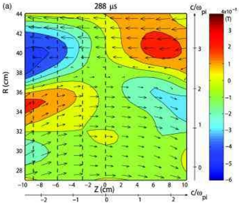


- Advantages:
  - Extremely detailed data at a small number of points
  - Parameter regimes inaccessible to experiment
  - Excellent for studying collisionless physics
- Disadvantages:
  - Difficult to connect observations to global dynamics
    - Use global MHD simulations
  - Difficult to disentangle cause and effect
  - No experimental control
- Missions:
  - Cluster, THEMIS, Geotail, ACE, Wind, Ulysses, STEREO, Voyagers 1 & 2
  - Future: Magnetospheric Multiscale Mission, Solar Probe Plus

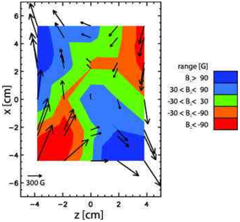
In situ measurements in space and laboratory plasmas show the signatures of collisionless reconnection

Wind
Øieroset et al. (2001)





MRX
Ren et al. (2005)
Yamada et al. (2006)

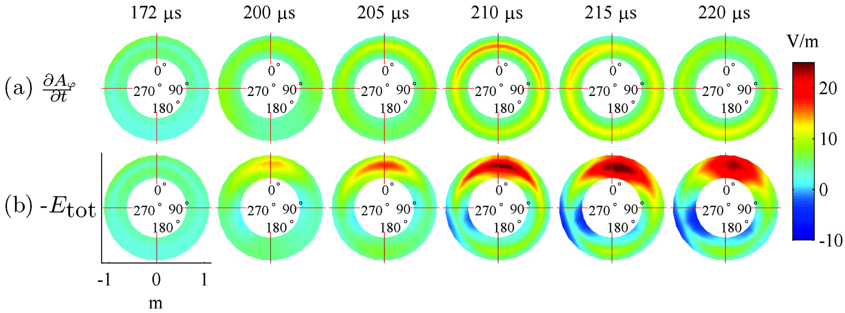


SSX
Matthaeus et al. (2005)
Brown et al. (2006)

- Quadrupole magnetic field
- Electron diffusion region

VTF experiments show the 3D onset and propagation of reconnection with a guide field

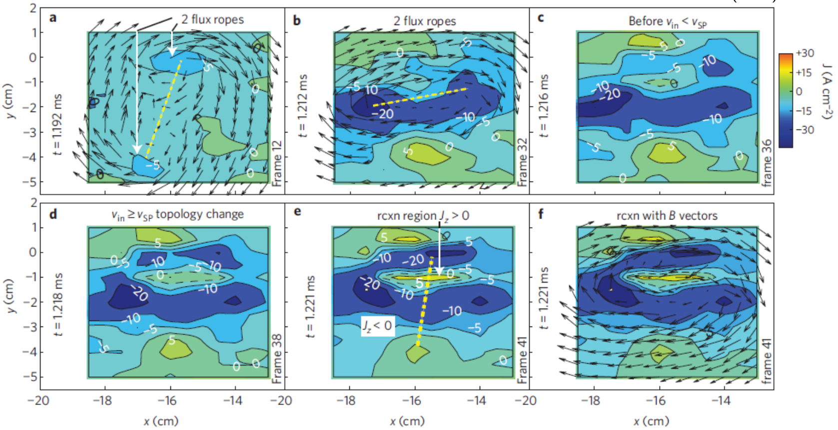
Katz et al. (2011)



- Reconnection starts at $\phi \sim 0^\circ$ and propagates around the torus at the Alfvén velocity
- Implications for Bastille Day flare

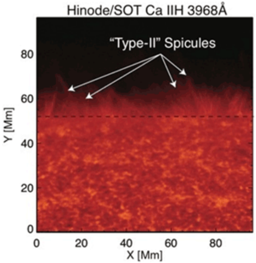
RSX experiments show 3D effects of flux rope merging

Intrator et al. (2009)



- Flux ropes sometimes bounce rather than merge
- Implications for merging of 3D flux ropes during plasmoid instability

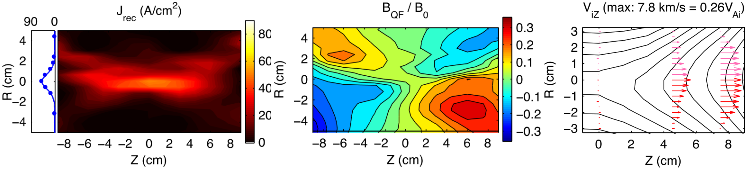
Magnetic reconnnection is ubiquitous in the partially ionized solar chromosphere



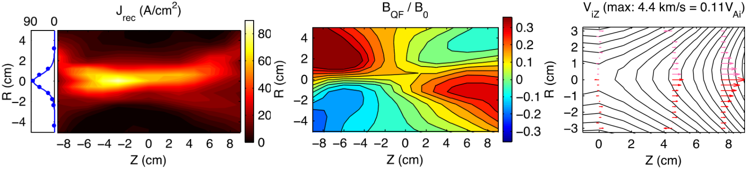
- Ionization fraction: $\lesssim 0.01$ to ~ 0.5
- Chromospheric jets and Type II spicules may be manifestations of reconnection in partially ionized plasmas
  - Sources of mass and energy for corona and solar wind?
- Interpretation limited due to confusion and difficulty in inferring the chromospheric magnetic field

MRX is investigating the physics of partially ionized reconnection (Lawrence et al., submitted to PRL)

High ionization fraction ($n_i = 2 \times 10^{13}$ cm^{-3}, $\frac{n_i}{n_n} \sim 0.12$, $\frac{L}{\lambda_{in}} \sim 0.5$)



Low ionization fraction: ($n_i = 2 \times 10^{13}$ cm^{-3}, $\frac{n_i}{n_n} \sim 0.009$, $\frac{L}{\lambda_{in}} \sim 50$)



- Ion outflow is Alfvén speed based on total mass density
- Reconnection rate is reduced due to lower ion flux, and is independent of resistivity: ions control reconnection rate

Conclusions

- 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 the magnetic field and small-scale dynamics
  - *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
- Important results from the laboratory include:
  - Transition from slow/collisional to fast/collisionless reconnection
  - The structure of the inner diffusion region
  - Roles of instabilities and turbulence
  - Dynamics of flux ropes
  - Effects of partial ionization