Magnetic Reconnection: A Universal Process

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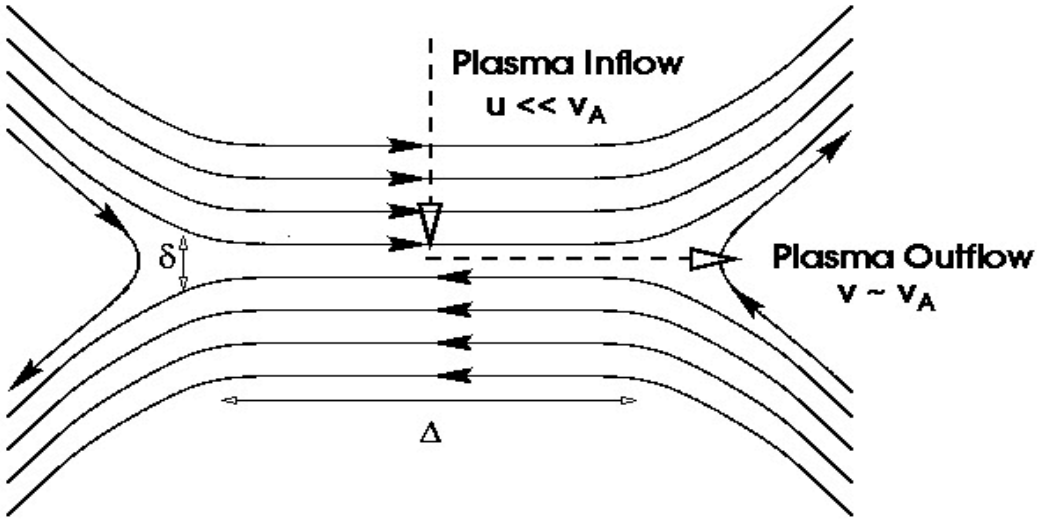
Why Do We Study Reconnection?

- It's an essential component of dynamos *(irreversible topological change, elimination of small scale field).*
- Magnetic connectivity affects transport, diffusion, plasma mixing.
- As a mechanism for plasma relaxation & self-organization.
- For its role in conversion of magnetic to plasma energy *(outflows, heating, particle acceleration)*.

The Quest for Fast Reconnection

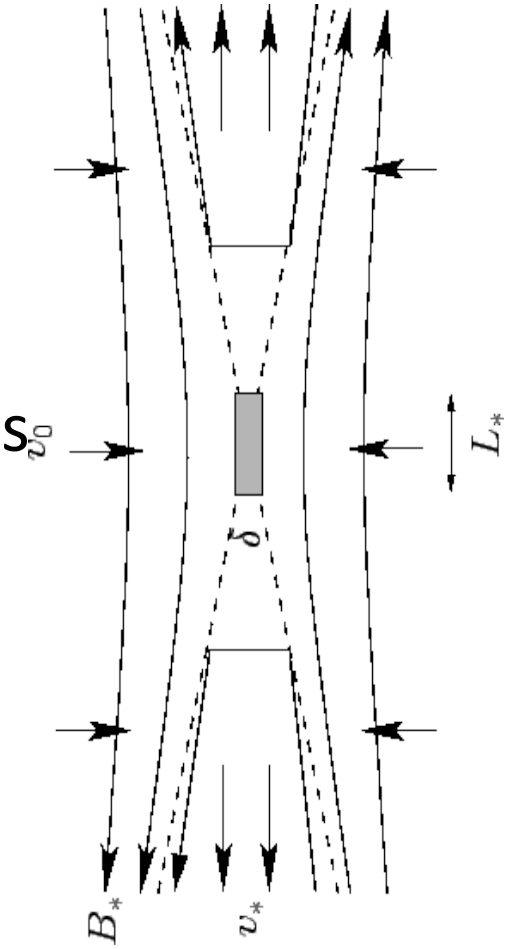


Sweet-Parker bottleneck:
At high *S,* outflow layer
Is thin, so to conserve
mass inflow speed is slow.

Note that length of layer, Λ is not adjustable in this theory.

Ways to Avoid the Bottleneck

- Petschek reconnection
  - Now known to require η enhancement at X point
- Strong cooling or recombination
  - Only works without guide field
- Wandering fieldlines to broaden outflows
  - Must wander at diffusion layer scale
- Broaden the current sheet
  - Anomalous resistivity
- Shorten the current sheet
  - Hall effect, instabilities



What's the status of this quest?

At This Meeting

- Continuing numerical studies of reconnection with driven 2D & 3D turbulence.
- Theory & simulation of instabilities that break up or shorten the current layer.
- Both steady and bursty/patchy examples in space & solar plasmas.

Can these current sheet instabilities be studied in lab experiments?

``The Plasma is Smarter than You"[1]

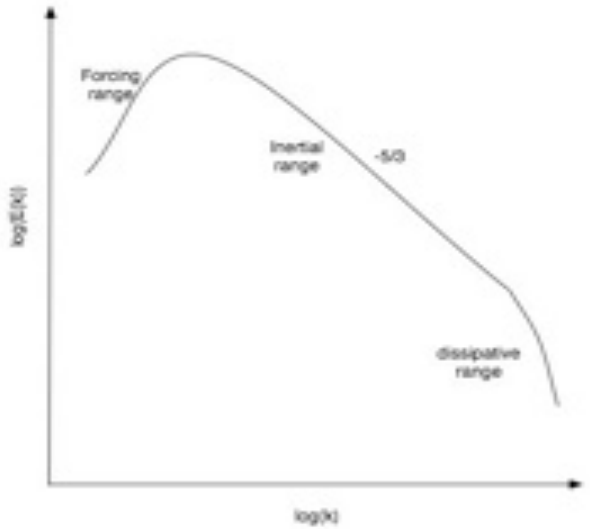
Magnetic flux will find a way to reconnect at whatever rate it's driven[2], up to v_A. If driving is initially superalfvenic, B builds up till $v_A = v_{in}$ and then reconnects at that rate.

1. Anonymous, but not imaginary

2. Driven here means brought in through boundaries.

Example: A Turbulent Cascade

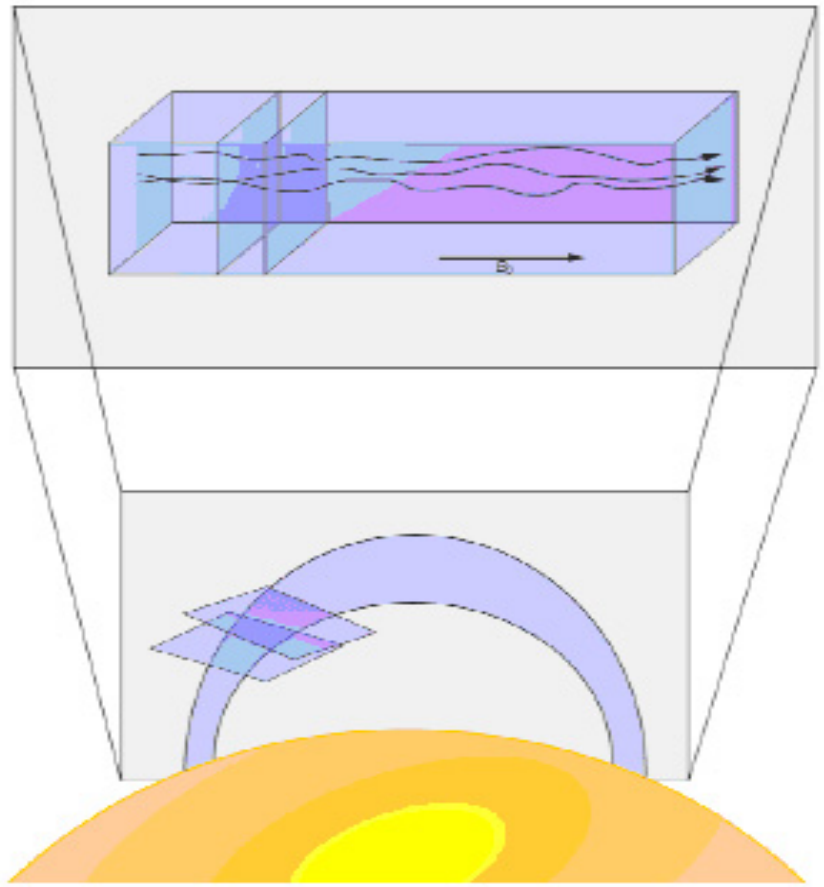
- If energy is steadily supplied at an outer scale *L*, a turbulent cascade will develop down to the scale $l \sim (\nu^3/\varepsilon)^{1/4}$ at which the supply rate = the dissipation rate.



If a flux is introduced at scale L and velocity v_{in}, will the system reconnect at that rate by adjusting the scale L and possibly v_A ?

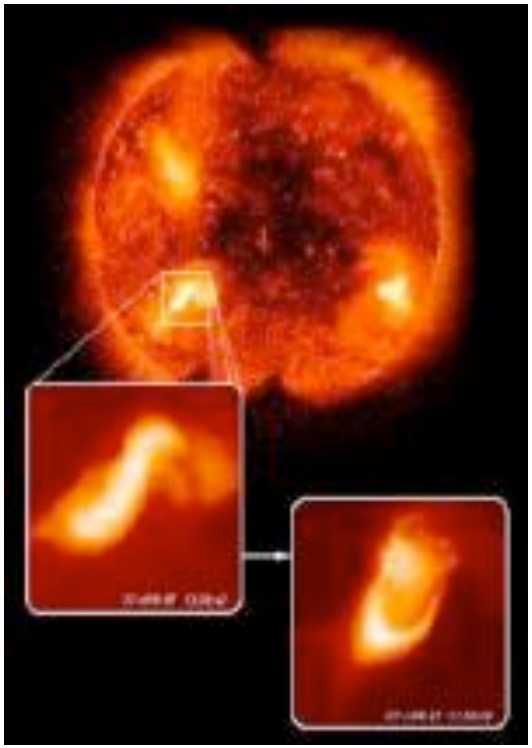
We saw 2fluid & e-p simulations of this, also alternatives: bouncing flux tubes & Statistics showing infrequent reconnection.

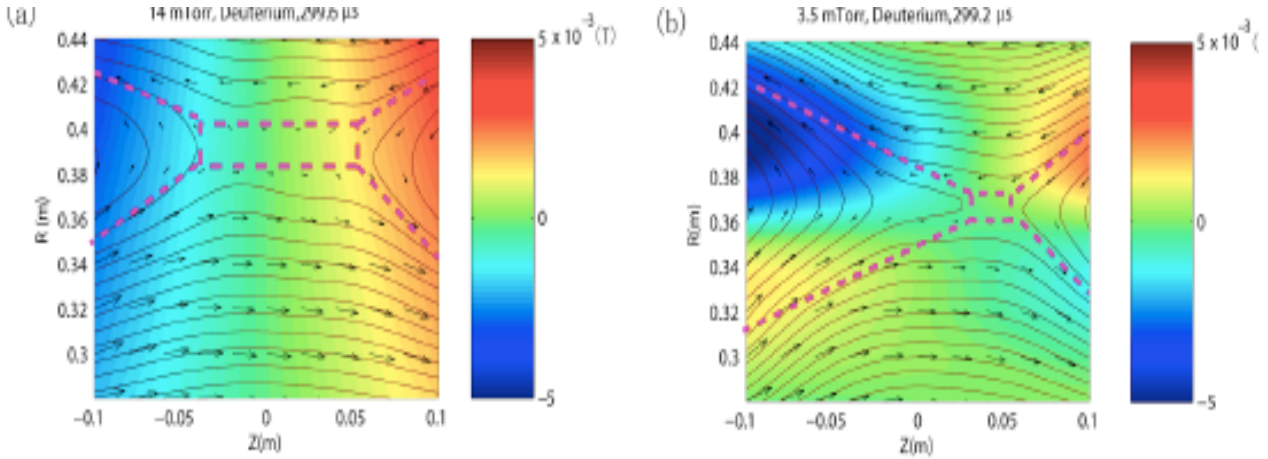
Not all Reconnection Problems Involve Flux Introduction

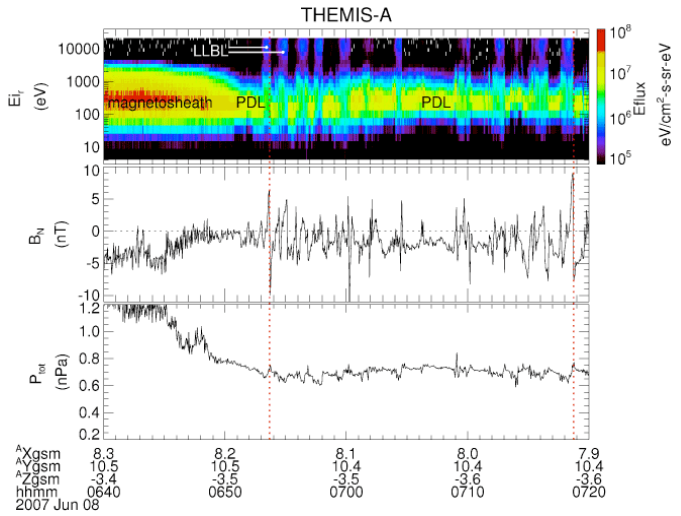


Poynting flux into corona ~ $B_v B_h v$, but horizontal field B_h is determined in part by relaxation rate.

We Study Reconnection Through its Plasma & Magnetic Signatures *(sometimes ambiguous)*







Opportunities to compare theory, experiment, observation, & simulations in lab, magnetosphere, & heliosphere.

Progress in Probing the Diffusion Region

- Identified in lab & space plasmas *(broader than expected).*
- Models of broadening by linear waves, nonlinear structures.
- Models based on pressure anisotropy.
- Models of energetic particle signatures.
- *What will MMS contribute? What is the next step for experiment?*

Progress in Probing Reconnection Outflows

- Measured ion distribution functions in space plasmas.
- Discovered solar wind reconnection on large scales.
- Theory & simulation of relativistic outflows.
- Theoretical, numerical, experimental, & observational identification of instabilities.
- Particle acceleration mechanisms developed through theory & simulation.

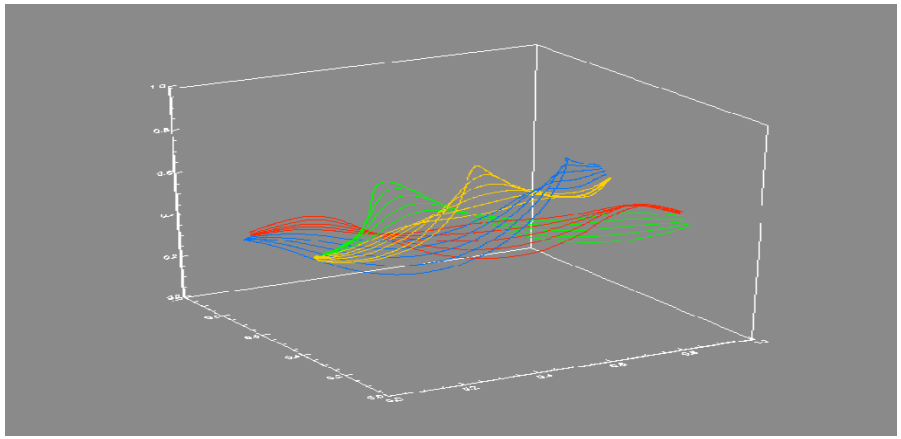
Progress on Local/Global Coupling

- Driven reconnection studied in lab plasmas.
- Effects of boundary conditions studied through theory, simulation, experiment.
- Effects of asymmetries assessed in lab, space, theory, simulation.
- Detailed simulation of driving by flux emergence & shearing in solar atmosphere.

Unresolved Issues: I

How does reconnection occur when there are no rational surfaces? (*Intrinsically 3D situations, e.g. line tied or stochastic magnetic fields).*

– Separatrix concept is powerful, does it carry over to very high *S*?



Unresolved Issues: II

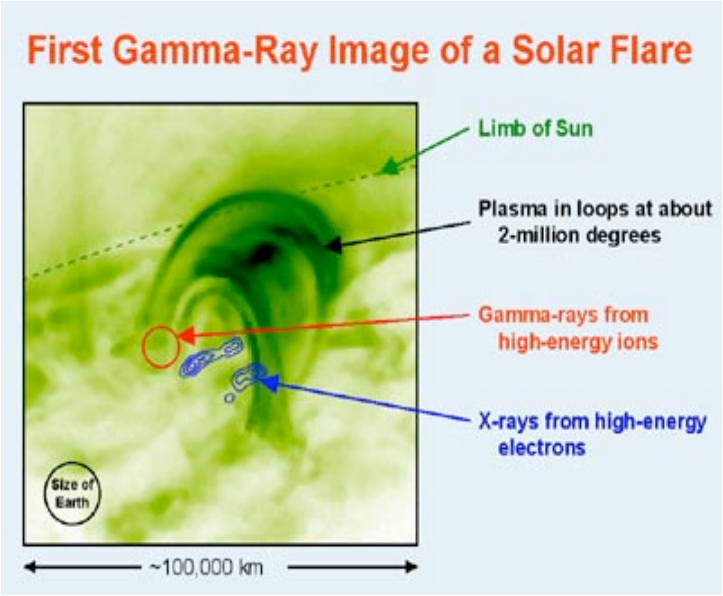
- What determines the structure of the diffusion region?
  - Competing models, each may be valid in some situations.
  - Intrinsically or extrinsically determined?
  - Does the structure of the diffusion region affect the outflow and/or the reconnection rate?

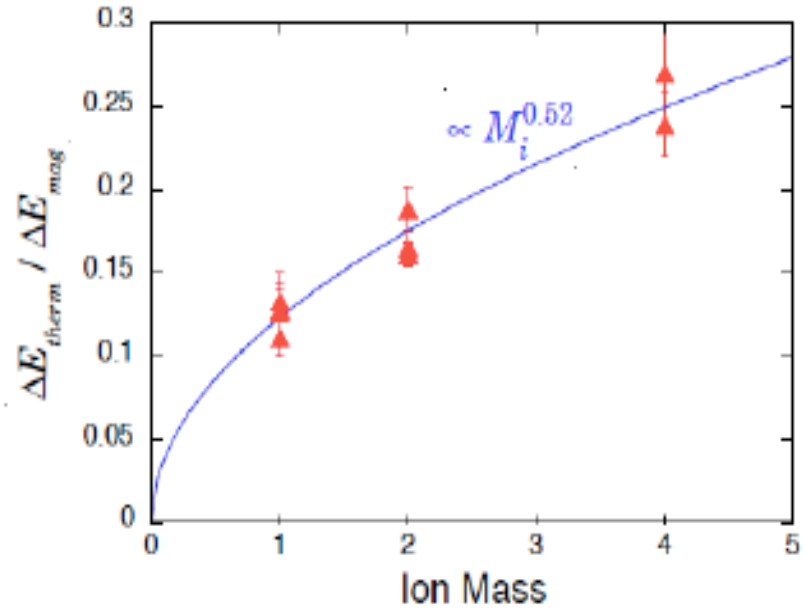
Unresolved Issues: III

- What is the long time evolution of large systems with high *S*?
  - Instabilities: plasmoid, ballooning, Weibel…
  - Is there a steady state and if so what is the average reconnection rate?
  - Are 3D effects important?
  - What is the effect of a guide field?

Unresolved Issues: IV

- How are electrons & ions heated (thermal distribution) and accelerated (nonthermal distribution) as a result of reconnection?
  - High efficiency -> spatially distributed mechanism.





Applying What We've Learned

Reconnection in Astrophysics,
Including Solar Physics.

Solar Flares Large & Small

- What is the correspondence between footpoint motion/ flux emergence and energy release in the corona?
- How can acceleration of electrons to 10s of keV & beyond be as efficient as observed?
- How are ions accelerated?
- Is reconnection collisionless or collisional?
- Is partial ionization in the lower atmosphere important?

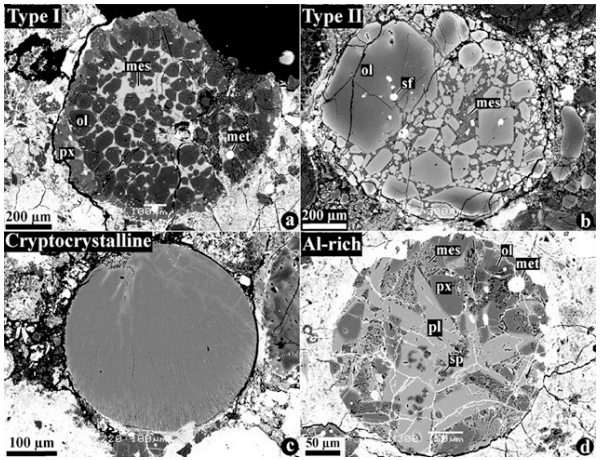
Reconnection in the Interstellar Medium

- Magnetic field lines are undoubtedly chaotic, lack good magnetic surfaces.
- M_A and β are ~ 1.
- Large Pm ($\nu >> \eta$)
- Most of the mass is weakly ionized.
- $(d_i/L)(\omega\tau) << 1$ -> MHD reconnection at huge *S*.
- Are there observable signatures of reconnection (although we infer that it occurs).

Reconnection in Accretion Disks

- Variety of conditions, from cold & collisional to hot & collisionless.
- Affects angular momentum transport, particle heating, disk dynamo.
- Could observed disk flares be driven by reconnection?

Chondrule meteorites have been rapidly heated.



Opportunities for Progress

- Observational opportunities are very rich & inspire new theory & simulations.

Solar Dynamics Observatory launched 02/11/10

New Experimental Opportunities?

Theorists: Have no Regrets

We'll eventually get it right!

Thank You!