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**Magnetic Reconnection, from Slow to Fast:
CURRENT UNDERSTANDING,
ASTROPHYSICAL APPLICATIONS,
AND OPEN ISSUES**

Dmitri A. Uzdensky

Princeton University/CMSO

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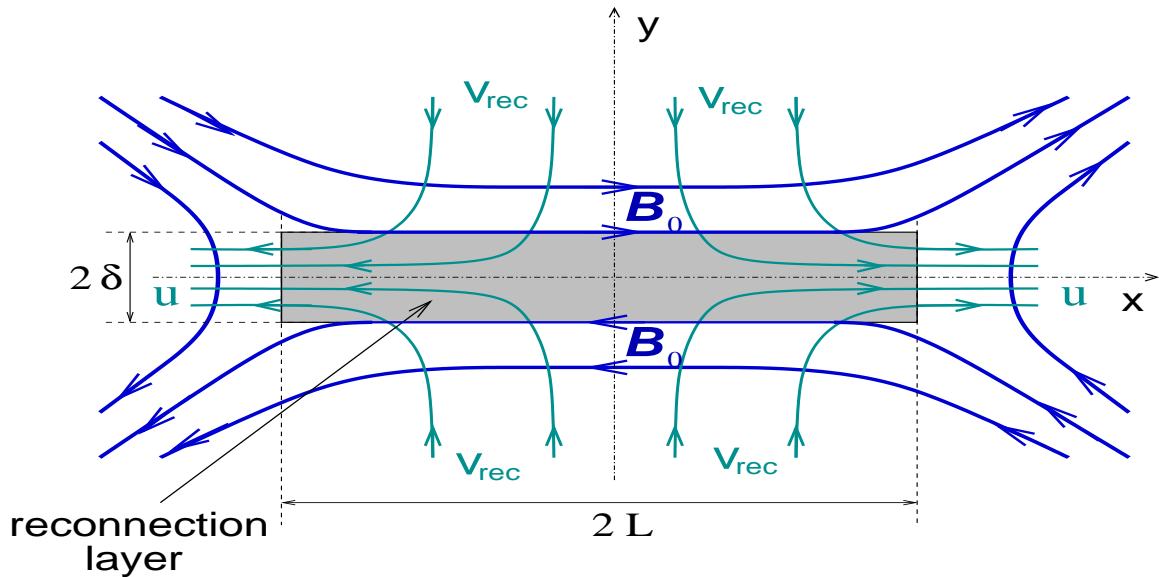
OUTLINE

- Condition for Fast Collisionless Reconnection
- Self-Regulation of Coronal Heating:
Marginally Collisionless Astrophysical
Coronae
- Open Issues in Magnetic Reconnection

**CONDITIONS
FOR FAST
MAGNETIC RECONNECTION**

SWEET-PARKER MODEL

(Sweet 1958; Parker 1957, 1963)



- Ohm's Law: $\eta = v_{rec}\delta$
- Equation of motion: $u = V_A \equiv B_0/\sqrt{4\pi\rho}$
- Mass Conservation: $v_{rec} L = u \delta$

- Sweet-Parker Scaling:

$$\frac{v_{rec}}{V_A} = \frac{\delta_{SP}}{L} = \frac{1}{\sqrt{S}} \ll 1$$

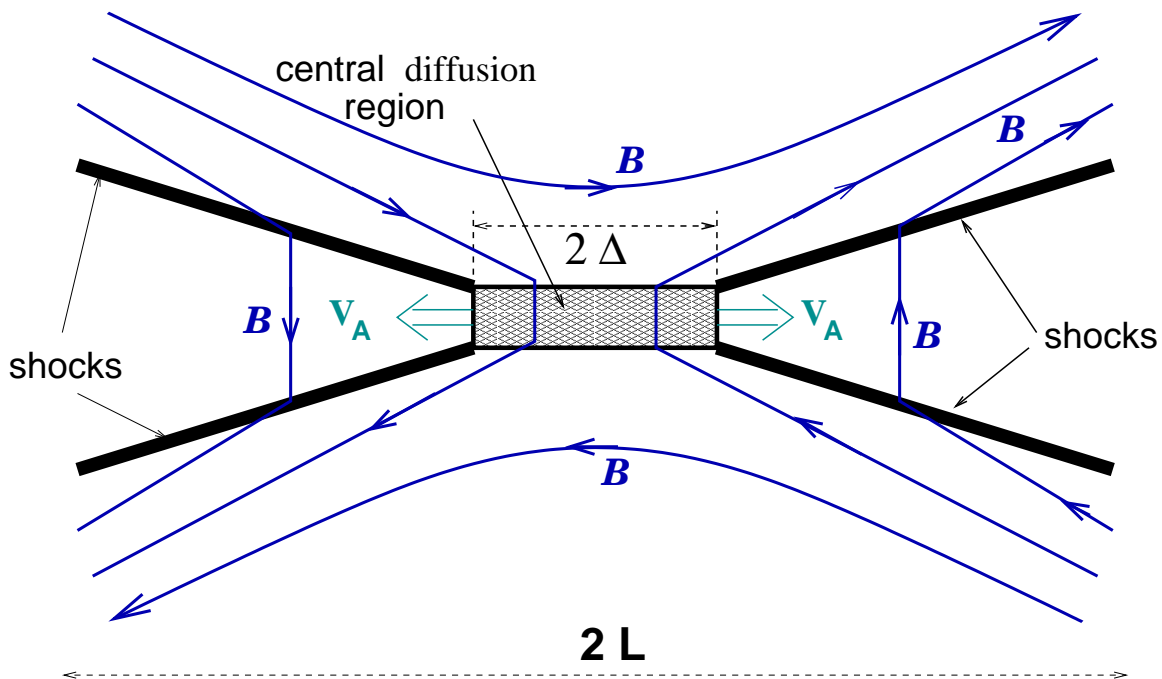
$$S \equiv \frac{LV_A}{\eta} \gg 1 \quad \Rightarrow \quad \tau_{rec} \sim \tau_A \sqrt{S} \quad - \text{slow}$$

Solar Flares: $S \sim 10^{12} \Rightarrow \tau_{rec} \sim \text{months} \gg \tau_{flare} \sim 10^3 \text{ sec}$

PETSCHEK'S FAST RECONNECTION MODEL

(*Petschek 1964*):

Sweet–Parker reconnection is slow because plasma has to flow out through a narrow current channel.



A family of models with

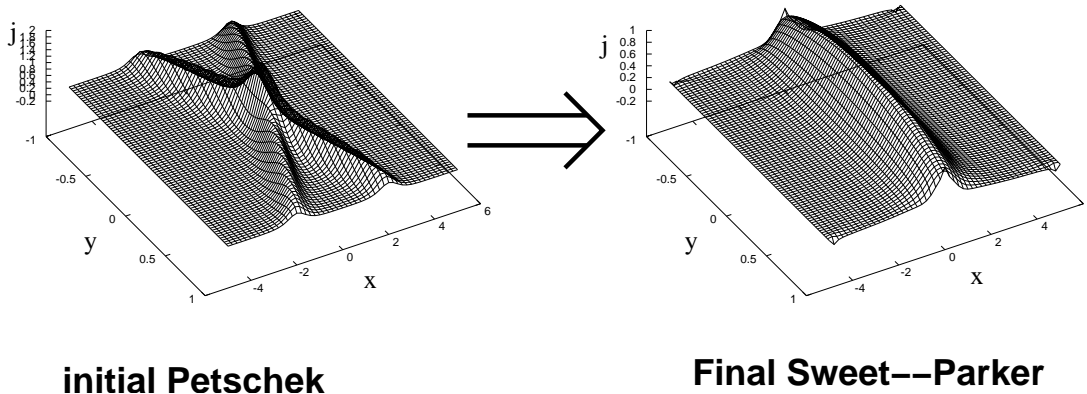
$$S^{-1/2} < \frac{v_{\text{rec}}}{V_A} < \frac{1}{\log S}$$

- fast enough to explain solar flares!

NO FAST RECONNECTION IN COLLISIONAL PLASMAS

- Numerical Simulations (*e.g.*, Biskamp 1986; Ma & Bhattacharjee 1996; Uzdensky & Kulsrud 1998, 2000; Breslau & Jardin 2003; Malyshkin et al. 2005; Loureiro et al. 2005)
- Analytical Work (*Kulsrud 2001; Malyshkin et al. 2005*)
- Laboratory Experiments (MRX) (*Ji et al. 1998*)

show: Reconnection in collisional plasmas is **SLOW!**



(Uzdensky & Kulsrud 2000)

Large-scale fast reconnection requires
collisionless plasma.

FAST RECONNECTION: means COLLISIONLESS RECONNECTION

Q: Is Fast Reconnection Possible in Collisionless Plasmas ?

YES !!

Two mechanisms for fast (Petschek-like) collisionless reconnection:

- Spatially-localized **anomalous resistivity** due to plasma micro-instabilities (*e.g.*, Ugai & Tsuda 1977; Sato & Hayashi 1979; Scholer 1989; Erkaev et al. 2001; Kulsrud 2001; Biskamp & Schwarz 2001; Malyshkin et al. 2005) → [Malyshkin's talk!](#)
- **Hall-MHD reconnection** involving two-fluid laminar configuration (*e.g.*, Mandt et al. 1994; Ma & Bhattacharjee 1996; Shay et al. 1998; Birn et al. 2001; Bhattacharjee et al. 2001; Breslau & Jardin 2003; Cassak et al. 2005, 2006) → [Cassak's talk!](#)

Signatures of both mechanisms observed in MRX!

Fast Reconnection = Collisionless Reconnection

Condition for Collisionless Reconnection: Weak Guide Field Case and MRX results

- Collisional (resistive) reconnection scale — Sweet–Parker reconnection layer thickness:

$$\delta_{\text{SP}} = \sqrt{L\eta/V_A}$$

- Collisionless reconnection scale — ion skin depth:

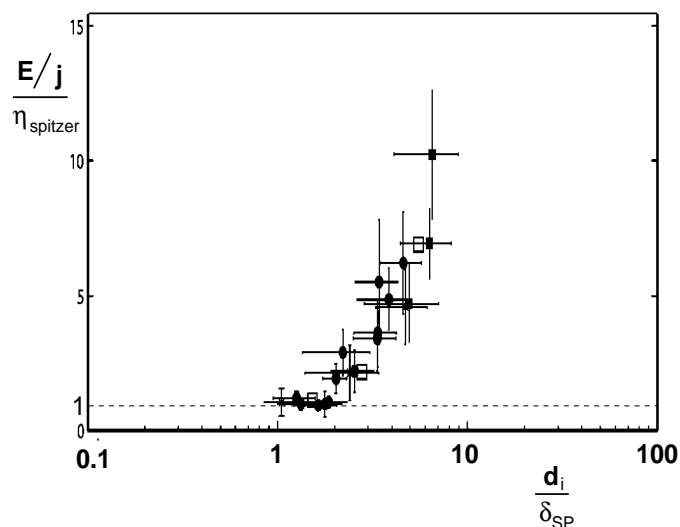
$$d_i \equiv \frac{c}{\omega_{pi}} = c \sqrt{\frac{m_i}{4\pi n_e e^2}}$$

- **Collisionless Reconnection Condition:**

$$\delta_{\text{SP}} < d_i$$

(Ma & Bhattacharjee 1996; Kulsrud 2001, '05; Uzdensky 2003, '06, '07; Cassak et al. 2005, '06; Yamada et al. 2006)

- **Experimental evidence (MRX) for this transition:**



Condition for Collisionless Reconnection: Weak Guide Field Case

Collisionless vs. collisional: in what sense?

- Using collisional resistivity (*Yamada et al. 2006*):

$$\frac{\delta_{\text{SP}}}{d_i} \sim \left(\frac{L}{\lambda_{e,\text{mfp}}}\right)^{1/2} \left[\frac{m_e}{m_i}\right]^{1/4}$$

- Then, fast reconnection requires

$$L < \lambda_{e,\text{mfp}} \sqrt{m_i/m_e} \sim 40 \lambda_{e,\text{mfp}}$$

Moving Forward: (*Uzdensky 2006, 2007*)

- Collisional mean-free path: $\lambda_{e,\text{mfp}} \simeq 7 \cdot 10^7 \text{ cm } n_{10}^{-1} T_7^2$
- Central Electron Temperature:

$$T_e = \frac{B_0^2/8\pi}{2k_B n_e} \simeq 1.4 \cdot 10^7 \text{ K } B_{1.5}^2 n_{10}^{-1}$$

Here, $B_{1.5} \equiv B_0/(30 \text{ G})$, etc.

- Final **fast collisionless reconnection condition:**

$$L < L_c(n, B_0) \simeq 6 \cdot 10^9 \text{ cm } n_{10}^{-3} B_{1.5}^4$$

– in terms of **macroscopic** quantities!

Condition for Collisionless Reconnection: Strong Guide Field Case

- Collisional (resistive) reconnection scale — Sweet–Parker reconnection layer thickness:

$$\delta_{\text{SP}} = \sqrt{L\eta/V_A}$$

- Collisionless reconnection scale in the strong guide field case, $B_z \gg B_0$, — ion-sound Larmor radius:

$$\rho_s = c_s \Omega_i^{-1} \sim d_i \beta_e^{1/2} \frac{B_0}{B_z}$$

- **Collisionless Reconnection Condition:**

$$\delta_{\text{SP}} < \rho_s$$

Experimental evidence from VTF (*Egedal et al. 2007*)

- **Final form:**

$$L < L_c = \lambda_{e,\text{mfp}} \sqrt{\frac{m_i}{m_e}} \left(\frac{B_0}{B_z}\right)^2 \sim 6 \cdot 10^9 \text{ cm } n_{10}^{-3} B_{1.5}^4 \left(\frac{B_0}{B_z}\right)^2$$

SUMMARY I:

Fast Reconnection Condition

- Fast Reconnection \Rightarrow Petschek-like Reconnection
 \Rightarrow Collisionless Reconnection.

- Collisionless Reconnection Condition:

- weak/moderate guide field: $\delta_{\text{SP}} < d_i$
- strong guide field: $\delta_{\text{SP}} < \rho_s$

- Collisional Sweet–Parker regime:

electron thermal conduction is not effective

$\Rightarrow 2k_B n_e T_e \simeq B_0^2 / 8\pi$ is a good approximation

- Weak guide-field case:

$$L < L_c(n, B_0) \equiv \sqrt{\frac{m_p}{m_e}} \lambda_{e,\text{mfp}} \simeq 6 \cdot 10^9 \text{ cm } n_{10}^{-3} B_{1.5}^4.$$

- Strong guide-field case:

$$L < 6 \cdot 10^9 \text{ cm } n_{10}^{-3} B_{1.5}^4 \left(\frac{B_0}{B_z}\right)^2.$$

Astrophysical Applications:

Self-Regulating Marginally-Collisionless Astrophysical Coronae

Examples:

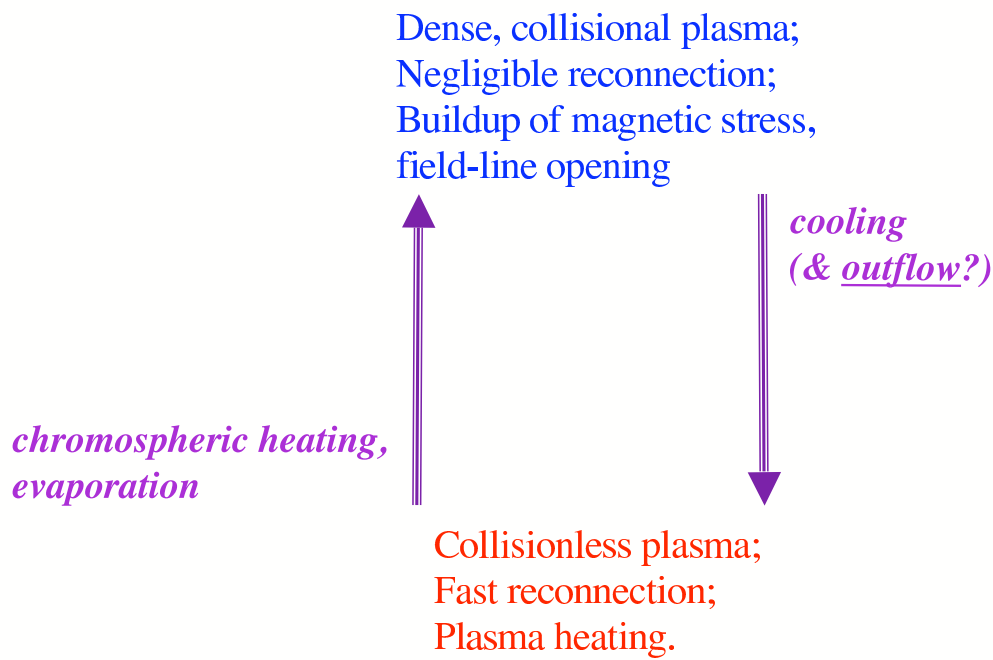
- The Sun (*Cassak 2006; Uzdensky 2006, 2007*)
- Other Stars (*Cassak et al. 2008*)
- Accreting Black Holes (*Goodman & Uzdensky 2008*)
- GRB Central Engines?? (*Uzdensky & MacFadyen 2006*)

Self-Regulation of Coronal Heating

(Uzdensky 2006, 2007)

MAIN IDEA: coronal heating is a self-regulating process keeping plasma roughly **marginally collisionless!**

Coronal Collisionality Cycle



Uzdensky 2007

(schematic by J. Goodman)

- **Quasi-periodic behavior:**
slow field-line twisting + gradual radiative cooling \Rightarrow
transition to fast collisionless reconnection, energy release \Rightarrow
surface evaporation, n_e rises \Rightarrow reconnection suppressed.
- **Applications:** solar/stellar coronae, BH accretion disk coronae.

Requirements for Solar Corona Models

Numerical simulations of solar corona should include ALL of the following:

- flux emergence and photospheric footpoint motions;
- physically-motivated prescription for transition from slow to fast reconnection (a subgrid model for a large-scale MHD simulation);
- mass exchange between corona and solar surface (chromospheric evaporation and plasma precipitation);
- radiative cooling and anisotropic thermal conduction (including non-thermal electrons).

OPEN QUESTIONS I:

Collisional (resistive-MHD) regime

Is it really slow? How slow?

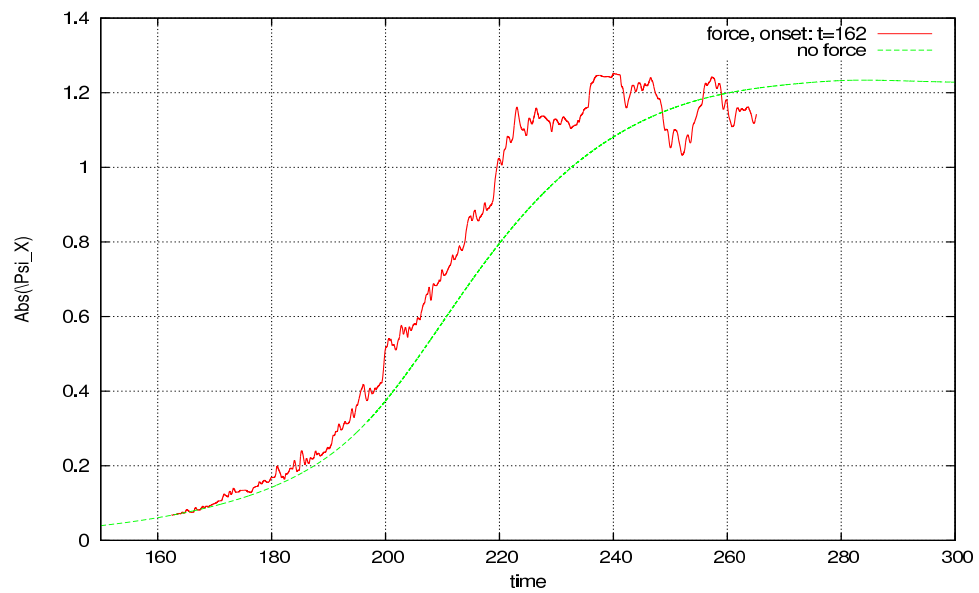
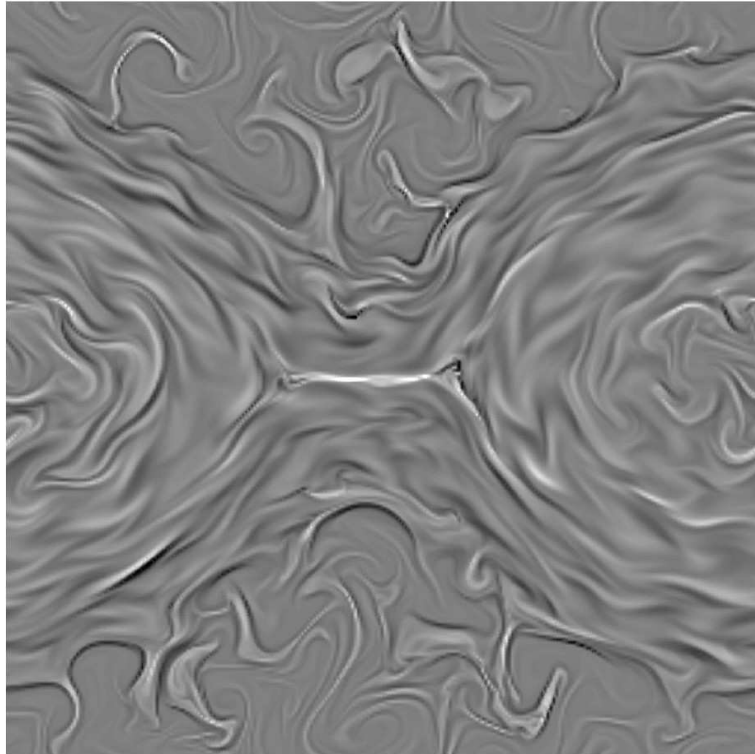
What are the effects of:

1. Actual Spitzer resistivity instead of constant uniform resistivity?
2. Ohmic heating and realistic e -thermal conduction?
3. Compressibility: small β_{upstream} ?
4. Viscosity (anisotropic)?
5. Hall term (when $\delta_{\text{SP}} > d_i, \rho_s$)? (*Cassak et al. 2005, 2006*)
6. MHD turbulence? (*e.g., Lazarian & Vishniac 1999*)
7. Secondary tearing instability of the current layer (for $S > 10^4$)?
(*e.g., Bulanov et al. 1978; Loureiro et al. 2007*)
8. The secondary instability? (*Dahlburg et al. 2003, 2005*)
9. Additional (astro-)physical effects:
 - weakly-ionized plasma (ISM, molecular clouds) (*Zweibel 1989*);
 - radiative (e.g., Compton) cooling (black-hole coronae);
 - Compton resistivity (radiation drag; black-hole coronae and jets);
 - pair creation (black holes and magnetars)

More lab studies, especially in large- S limit!

Turbulent Reconnection

2D Simulations by *Loureiro et al. 2008*



OPEN QUESTIONS I:

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OPEN QUESTIONS II:

Fast collisionless reconnection

1. Physical nature of η_{anom} ? (*e.g.*, *Kulsrud et al. 2005; Ji et al. 2005?*)
2. Petschek-like structure for given functional shape of η_{anom} ?
Reconnection rate in terms of basic plasma parameters?
Where is η_{anom} excited: central diffusion region/separatrices?
(*Malyshkin et al. 2005*)
3. How do two-fluid effects and anomalous resistivity interact?
4. What are the effects of B_z and β_{upstream} on triggering η_{anom} ?
on Hall reconnection?
5. What system parameters affect reconnection rate in two-fluid regime?
6. Is collisionless reconnection impulsive, bursty?
What is time-averaged reconnection rate?
(*Bhattacharjee 2004; Daughton et al. 2006; Karimabadi et al. 2007*)
7. How is the released energy partitioned between:
 E_{kin} , $E_{e,\text{th}}$, $E_{i,\text{th}}$, and $E_{\text{non-therm}}$?