ApJ, 671, 2139 (2007); ApJ, 688, 555 (2008)

Astrophysical Magnetic Reconnection: a Status Report

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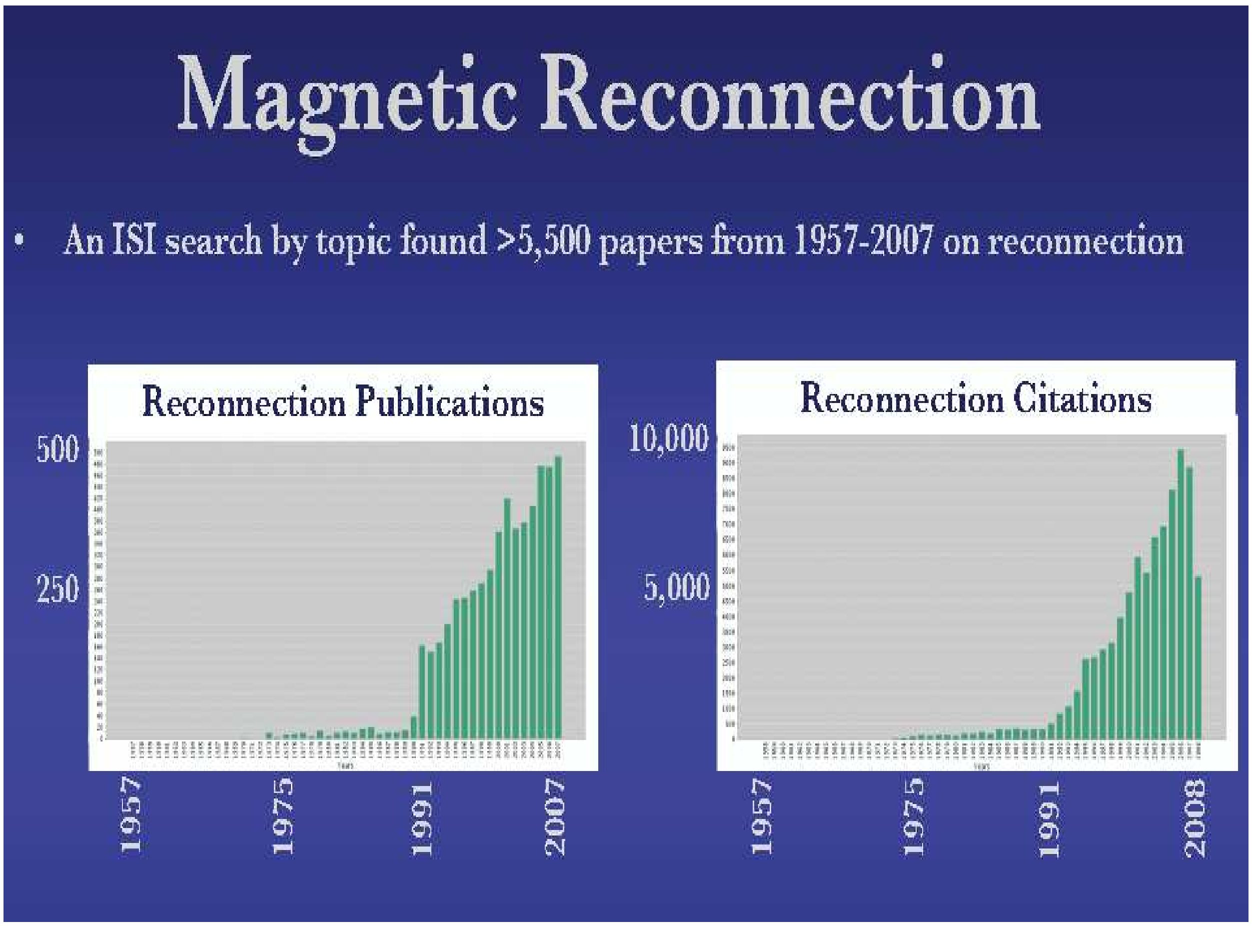
OUTLINE

- Magnetic Reconnection from Heavens to Earth
- Reconnection Theory: an Overview
- Condition for transition to **Fast Collisionless Reconnection**
- Astrophysical Applications:
  - Solar/Stellar Coronal Heating
  - Black-hole Accretion Disk Coronae
- Summary

Magnetic Reconnection on the Rise!

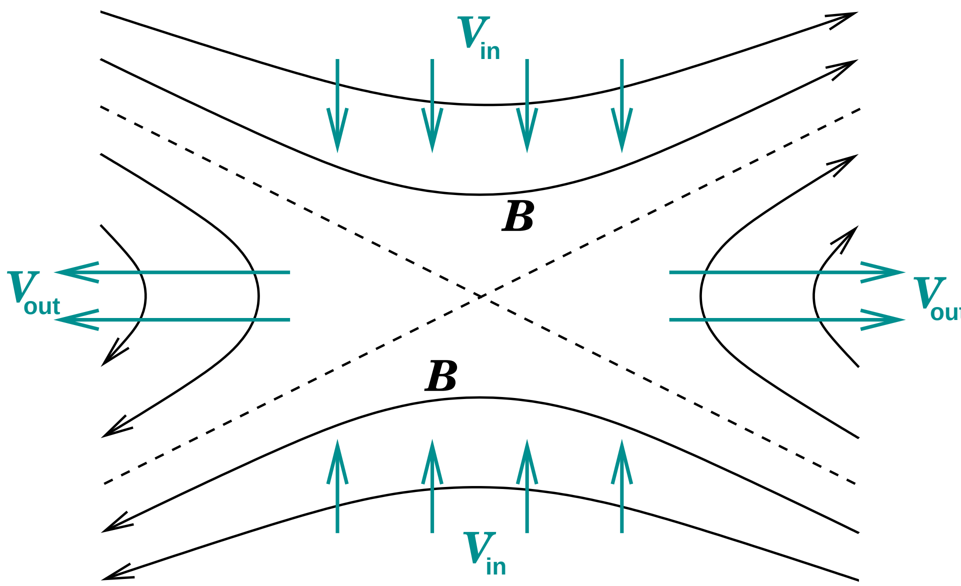


P. Cassak 2008

RECONNECTION: INTRODUCTION

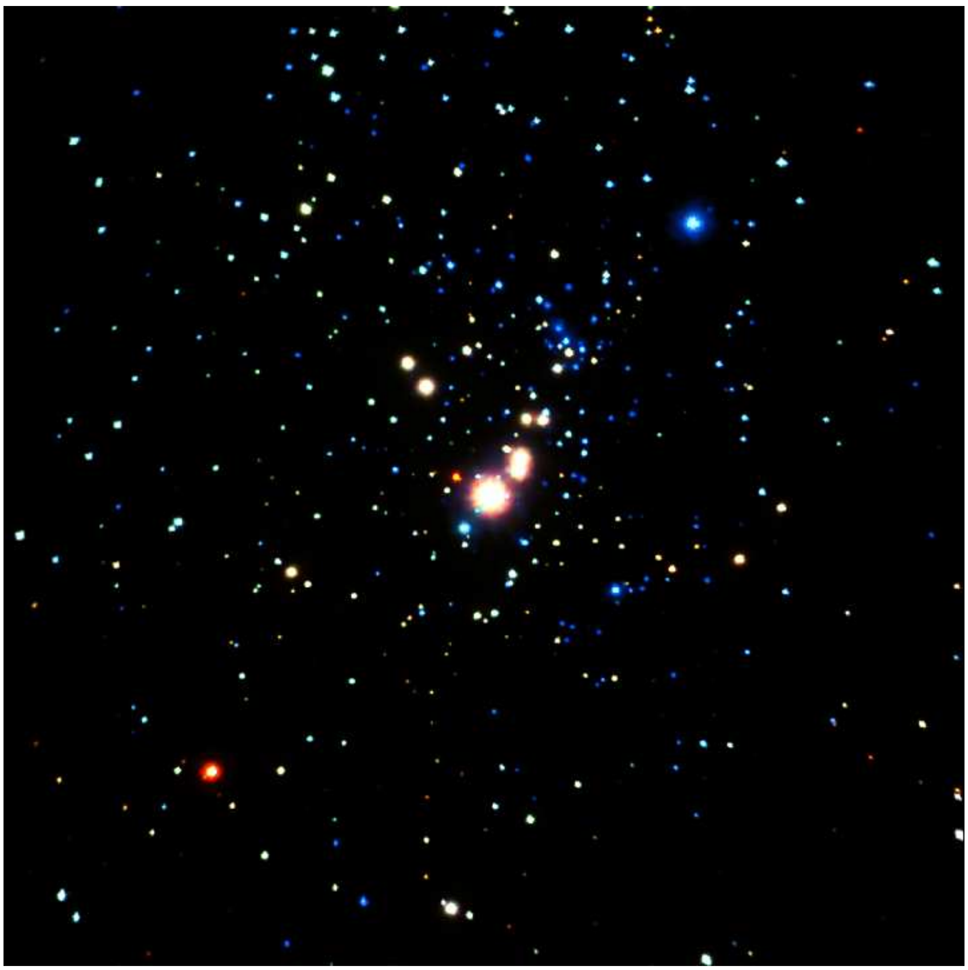
Q: What is **magnetic reconnection**?

Magnetic reconnection is a rapid rearrangement of the magnetic field **topology**.



- Reconnection leads to a rapid, violent release of magnetically-stored energy and its transformation into:
  - heat — plasma thermal energy
  - bulk-motion — kinetic energy
  - nonthermal particle acceleration — cosmic rays

RECONNECTION IN ASTROPHYSICS:
Flaring Young Stars



Chandra X-ray Image of Orion Nebula
(COUP – Chandra Orion Ultradeep Project)

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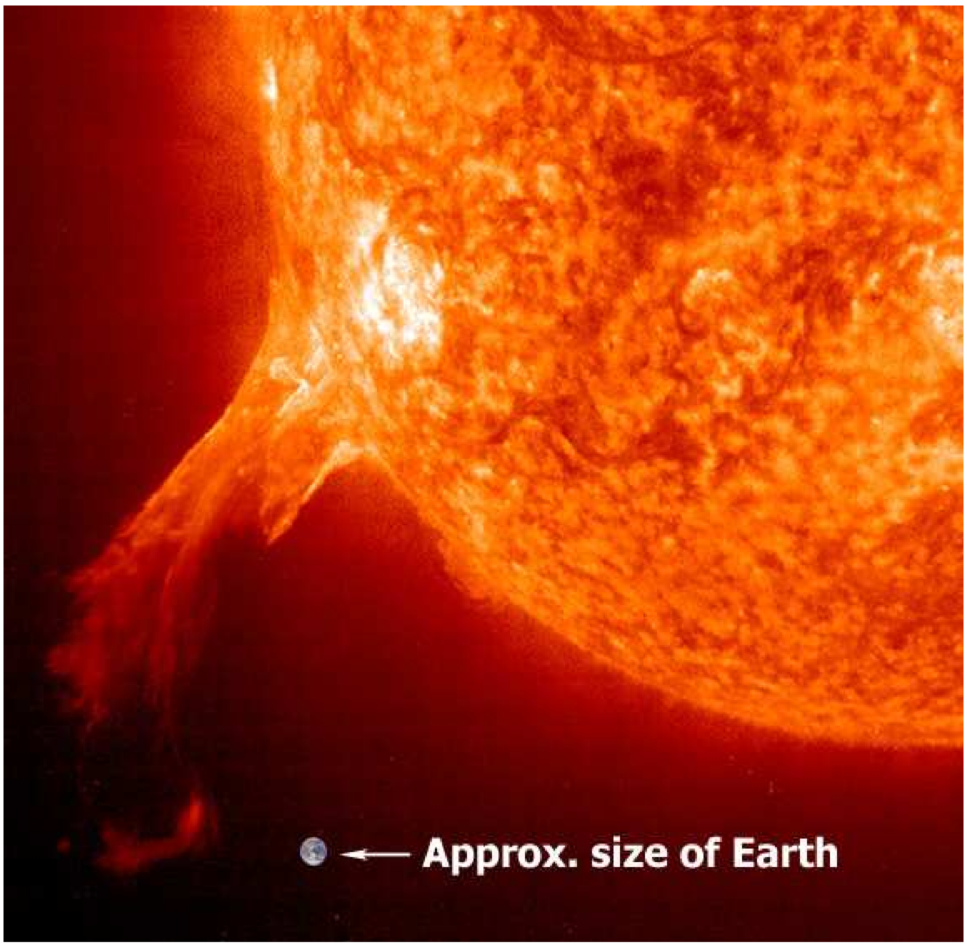
RECONNECTION IN ASTROPHYSICS:
Regular Solar/Stellar Flares

Smaller Flares: $L \leq R_*$ — usual stellar (e.g., solar) flares.

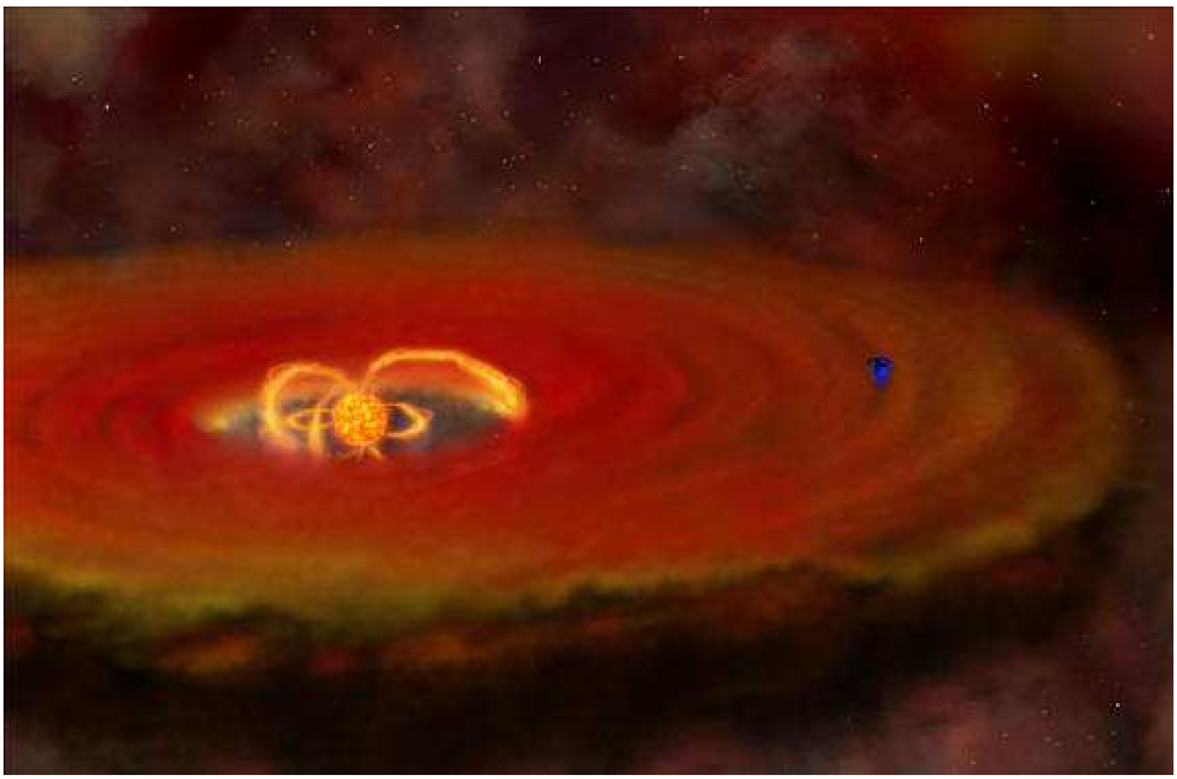


SOHO UV (He)

Solar flares are the most energetic events in Solar System.

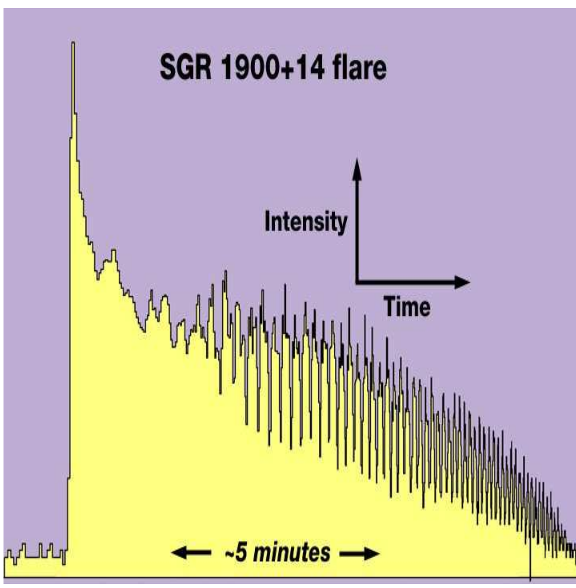
RECONNECTION IN ASTROPHYSICS:
Star–Disk Interaction

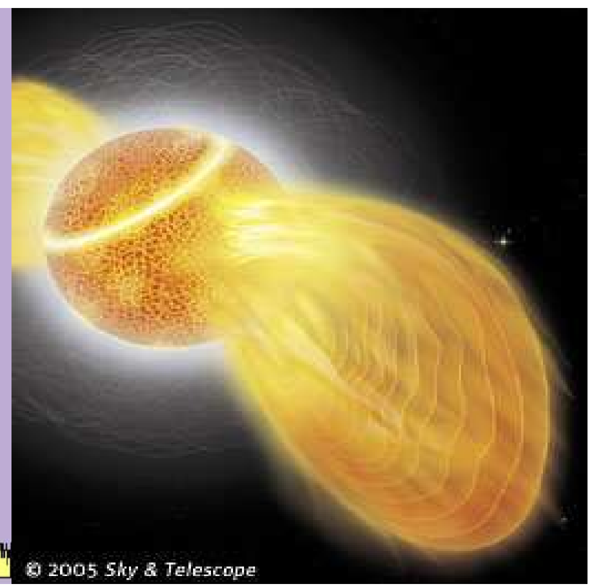
Largest Flares: $L \sim 20 R_* \Rightarrow$ Star–Disk Magnetic Loops ?

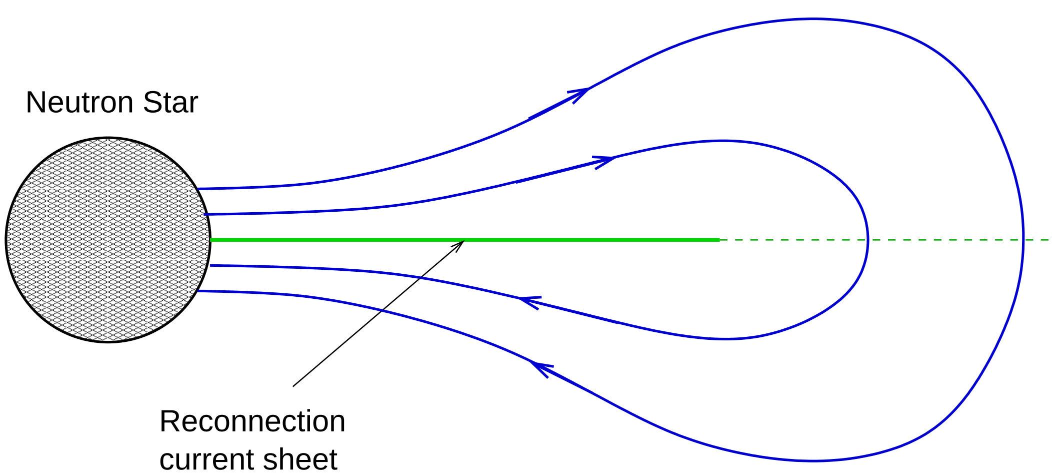


RECONNECTION IN ASTROPHYSICS: Magnetar (SGR) Flares

- **Magnetars:** neutron stars with 10^{15} G fields.
- Soft Gamma Repeaters (SGRs): magnetars exhibiting powerful (up to $10^{44} - 10^{46}$ ergs in ~ 0.3 sec) γ-ray flares.







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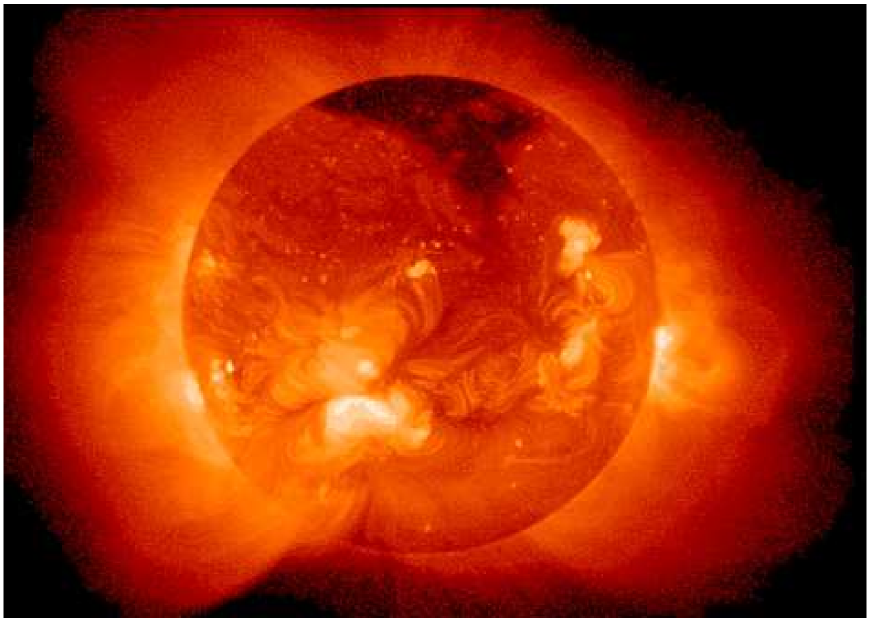
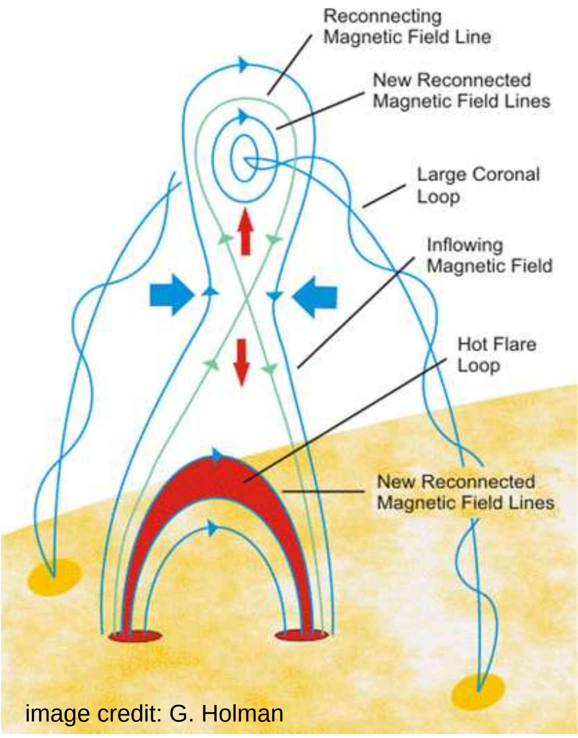
RECONNECTION IN SOLAR CORONA:
Solar Flares





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SUN–EARTH CONNECTION

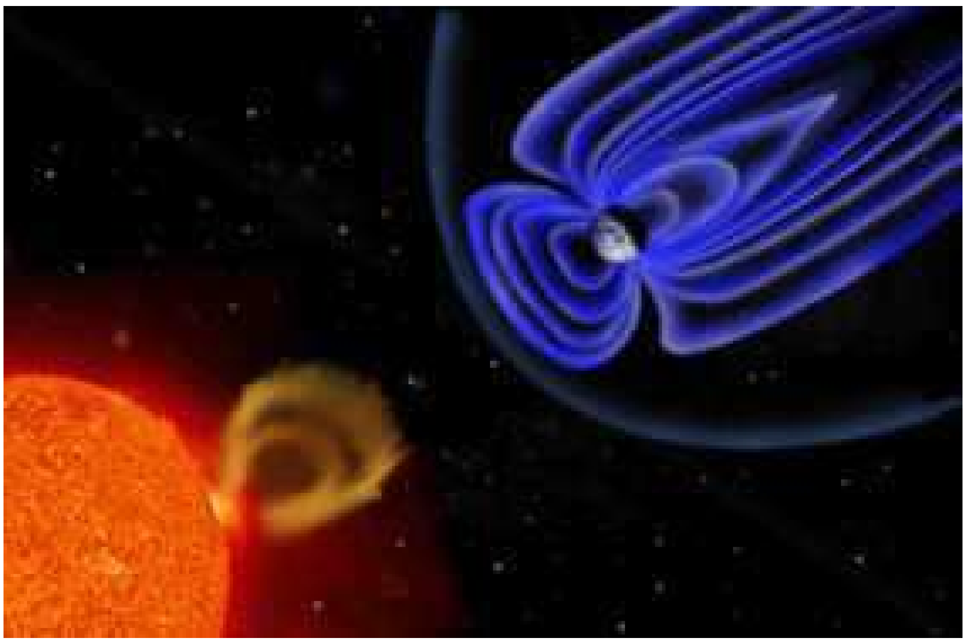

Illustration by Steele Hill

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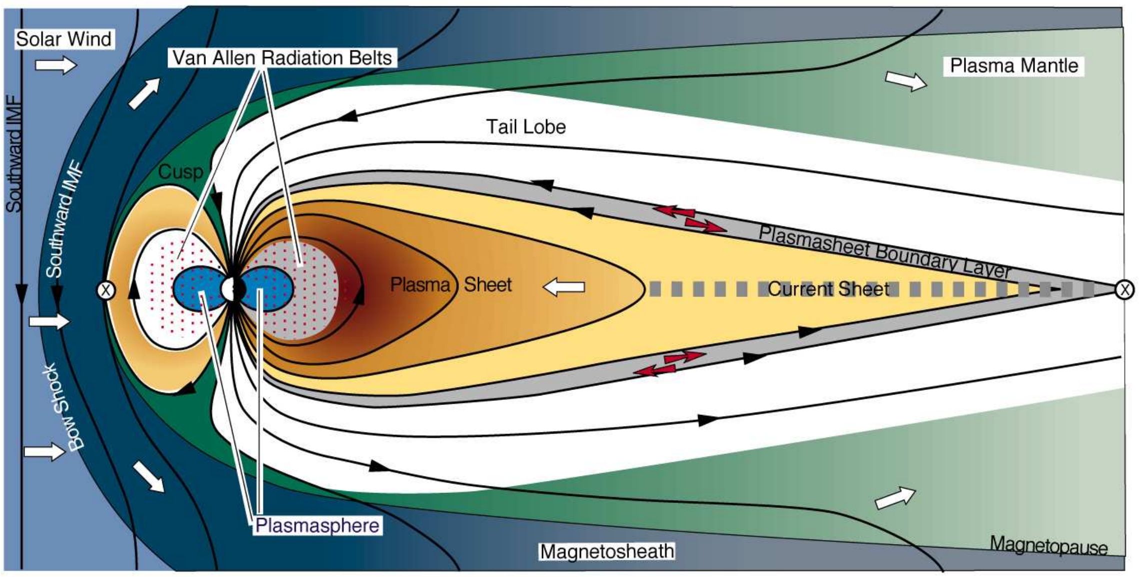
Reconnection in Earth's Magnetosphere



credit: Patricia Reiff

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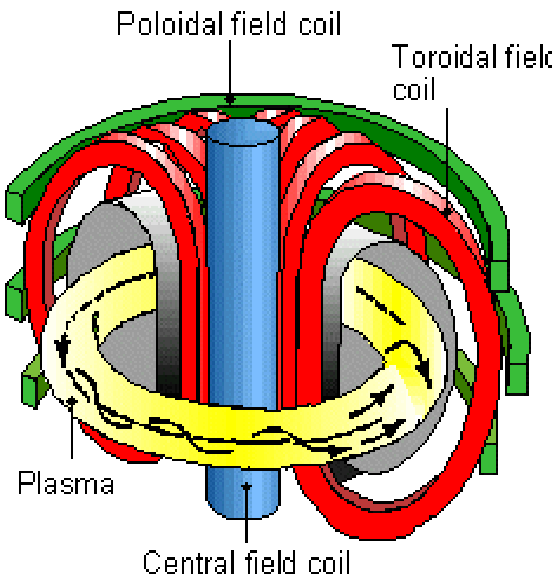
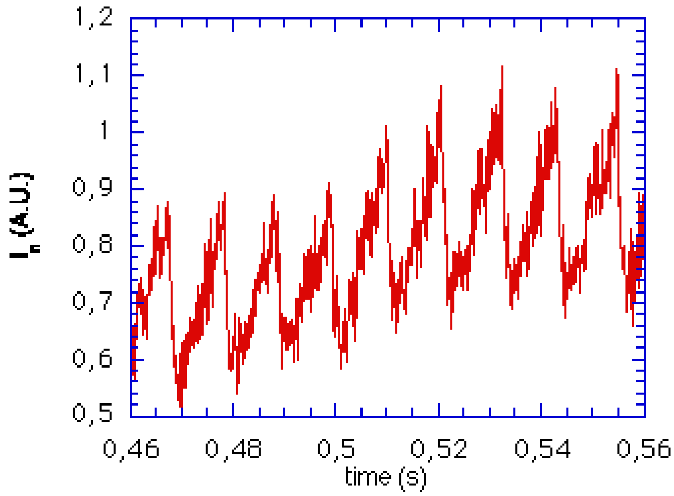
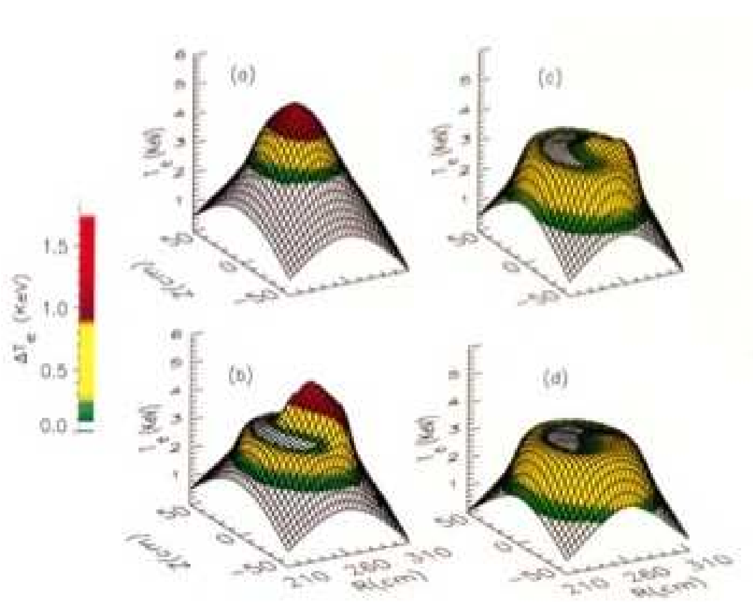
RECONNECTION IN THE LAB:

Sawtooth Crashes in Tokamaks







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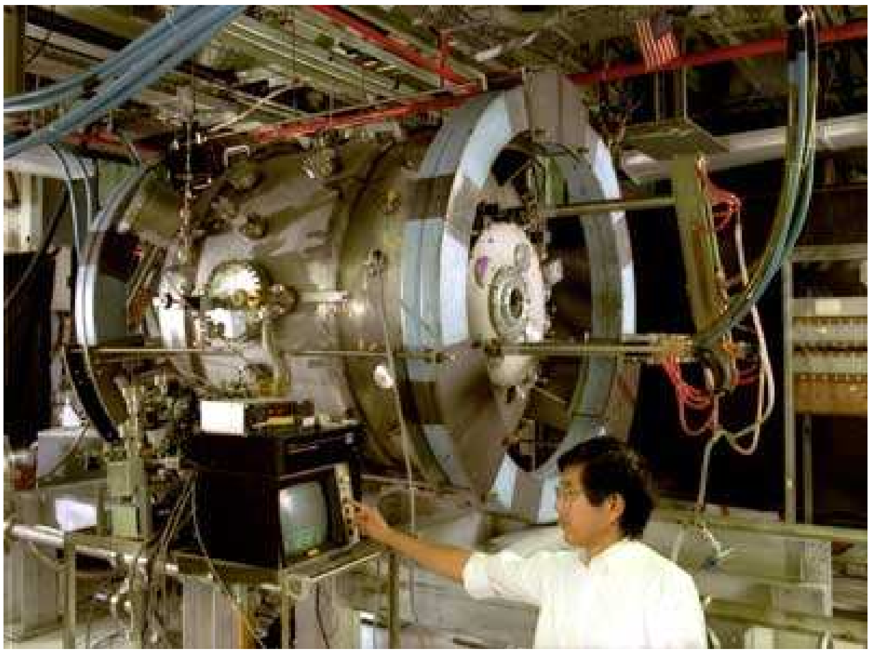
RECONNECTION IN THE LAB:
Magnetic Reconnection Experiment (MRX)

MRX at Princeton Plasma Physics Laboratory (M. Yamada)



Other reconnection experiments throughout the world:

- LAPD (UCLA, Stenzel & Gekelman)
- Lebedev Physics Inst. (A. Frank)
- Univ. of Tokyo (TS-3, TS-4, Y. Ono)
- Swarthmore (SSX, M. Brown)
- MIT (VTF, J. Egedal)

MAGNETIC RECONNECTION:

WHAT WE KNOW

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RECONNECTION: MAIN QUESTIONS

- Where and when reconnection takes place ? (**reconnection onset problem**)
- How rapid is it? (**reconnection rate problem**)
- Where does the energy go?
  - heat (thermal energy) vs. bulk motion (kinetic energy) ?
  - electrons vs. ions ?
  - thermal (heat) vs. non-thermal (particle acceleration) ?

FAST RECONNECTION:

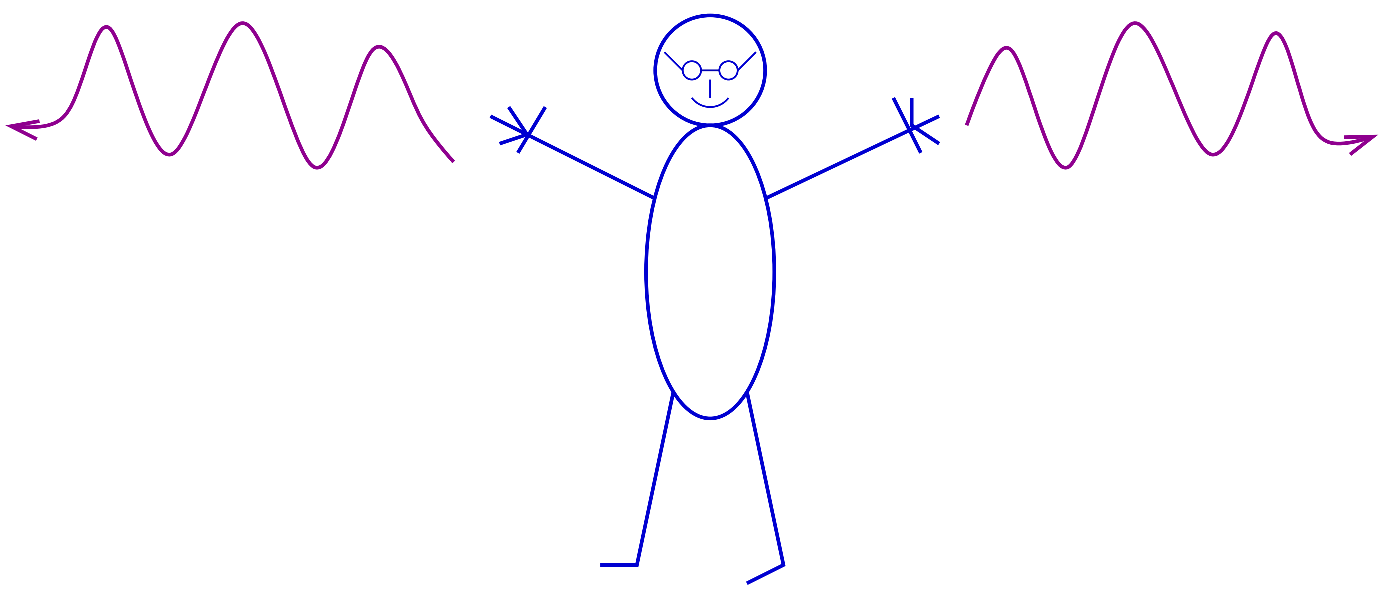
The Magic of Fast Reconnection

Often in Astrophysics, **"Reconnection"** is a magic word invoked whenever needed.

FAST RECONNECTION:
The Magic of Fast Reconnection

Often in Astrophysics, **"Reconnection"** is a magic word invoked whenever needed.

Most Popular Reconnection Mechanism:



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FAST MAGNETIC RECONNECTION: UNDER WHAT CONDITIONS?

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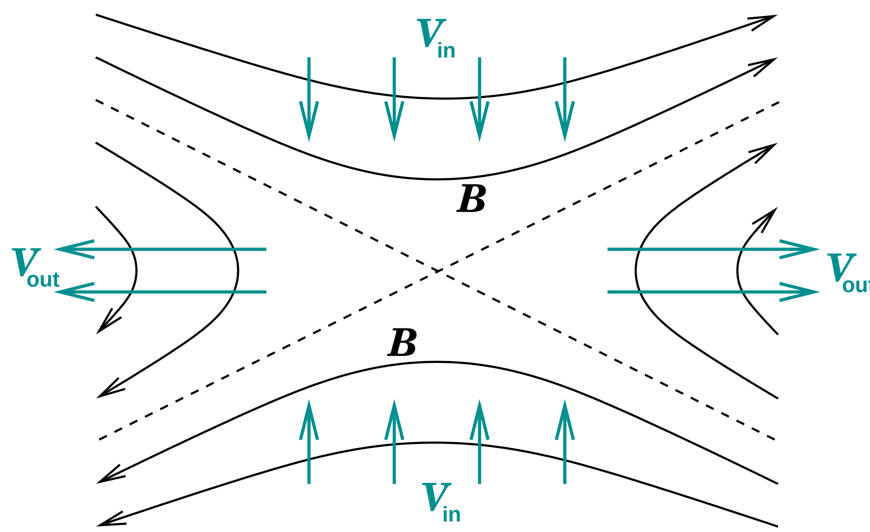
WHY IS RECONNECTION DIFFICULT: NO RECONNECTION IN IDEAL MHD

Q: What makes reconnection special, non-trivial?

Reconnection is a change in magnetic field topology.

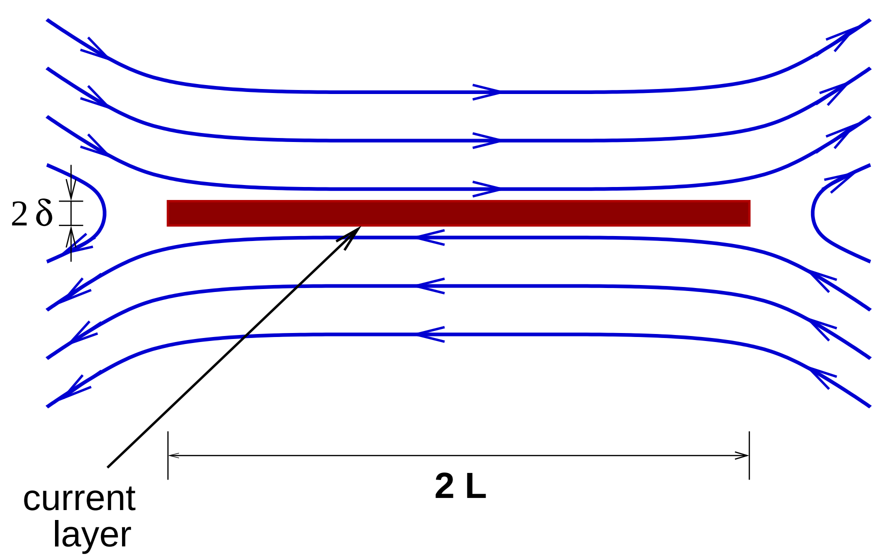


But ideal MHD preserves the identity of field lines, does not allow magnetic field topology to change.

⇒ Reconnection requires a (local) violation of ideal MHD.

Reconnection Needs Thin Current Layers

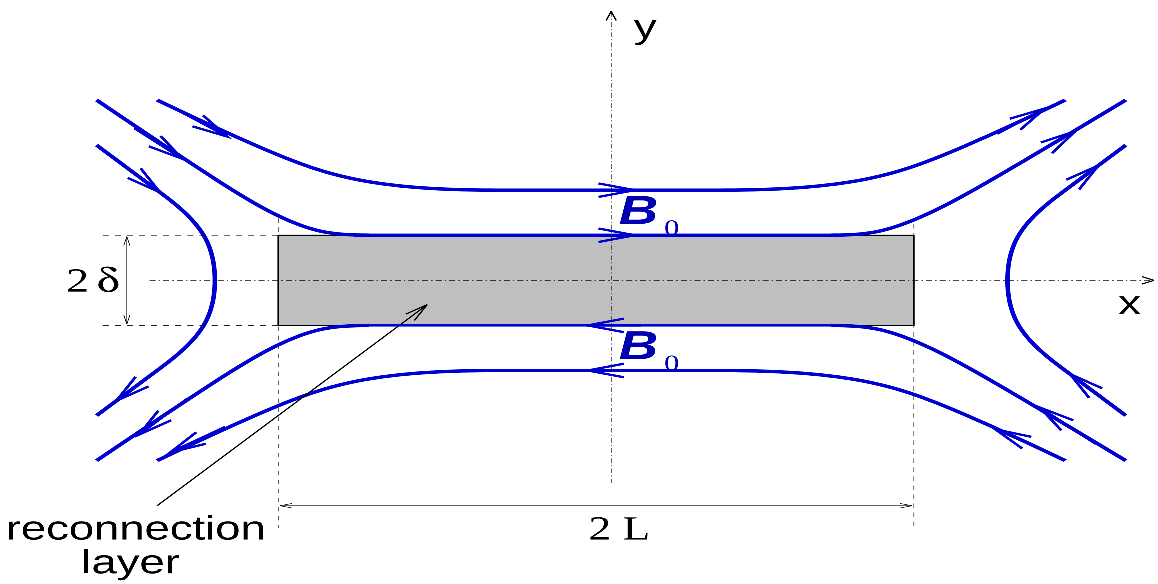
- Often in Space and Astrophysics, the **Lundquist number $S = LV_A/\eta \gg 1$** $\Rightarrow$ ideal MHD is fine on large scales L.
- But notice:
  - resistive diffusion term $\sim \nabla^2\mathbf{B}$
  - advection term $\sim \nabla\mathbf{B}$
- Hence, ideal MHD breaks down on small enough scales. Reconnection occurs in thin **current sheets.**



- Current sheets form naturally in complex magnetic systems *(Syrovatskii 1971, 1978).*

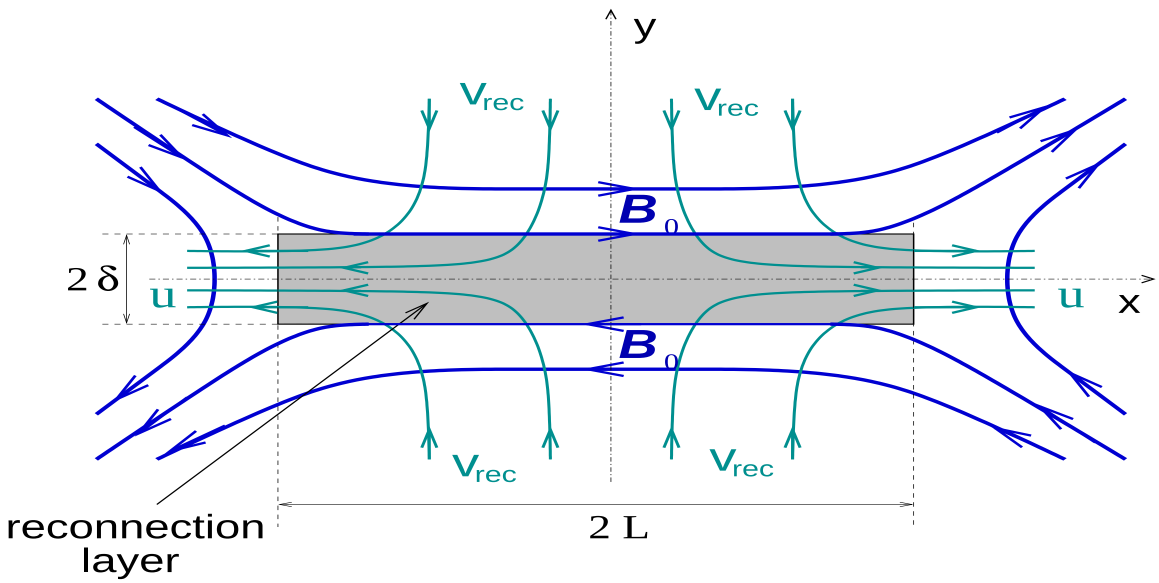
SWEET–PARKER MODEL

(Sweet 1958; Parker 1957, 1963)



SWEET–PARKER MODEL

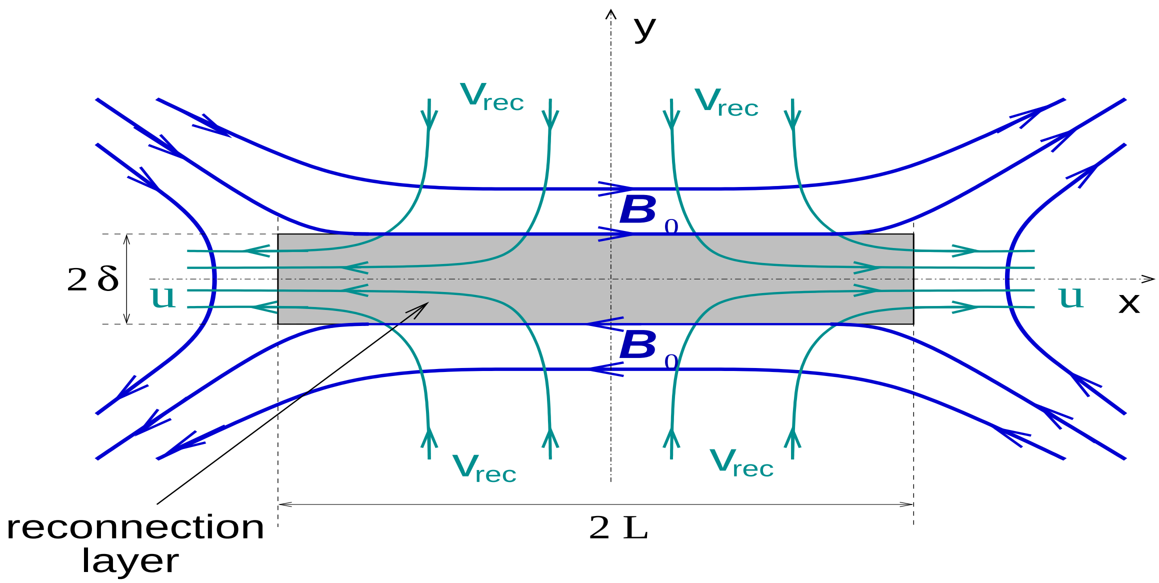
(Sweet 1958; Parker 1957, 1963)



- 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 MODEL

(Sweet 1958; Parker 1957, 1963)



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

- **Sweet-Parker Scaling:**

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

$S \equiv \frac{LV_A}{\eta} \gg 1$

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Sweet–Parker Reconnection: Too Slow for Solar Flares!

- Typical Solar Corona parameters:

$$L \sim 10^9 - 10^{10}\,\text{cm} \qquad B \sim 100\,\text{G}$$
$$n_e \sim 10^9 - 10^{10}\,\text{cm}^{-3} \qquad T \sim 2 \cdot 10^6\,\text{K}$$
$$V_A \sim 10^8\,\text{cm/sec} \qquad \tau_A \sim 10 - 100\,\text{sec}$$

- Lundquist number:

$$S = \frac{L V_A}{\eta} \sim 10^{12}$$

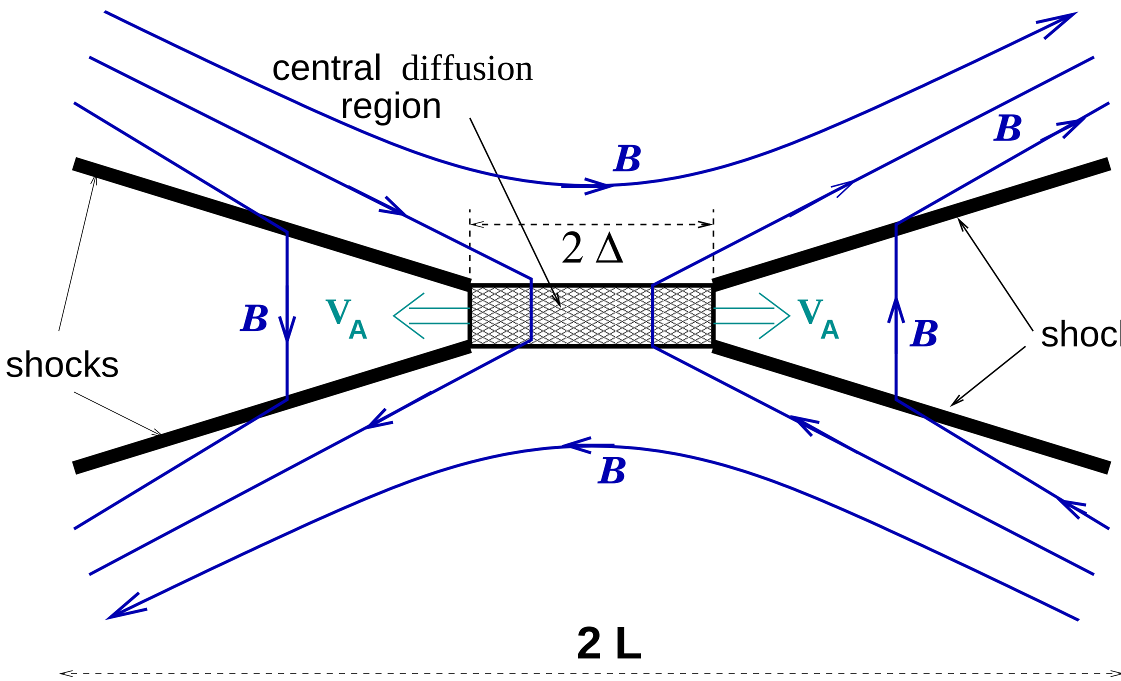
- Sweet–Parker timescale:

$$\tau_{\text{rec}} \sim \tau_A \sqrt{S} \sim \text{months} \gg \tau_{\text{flare}} \sim 15\,\text{min}$$

Thus, Sweet–Parker reconnection is too slow!

PETSCHEK'S (1964) FAST RECONNECTION MODEL

(Petschek 1964):
Sweet–Parker reconnection is slow because plasma has to flow out through a narrow current channel.

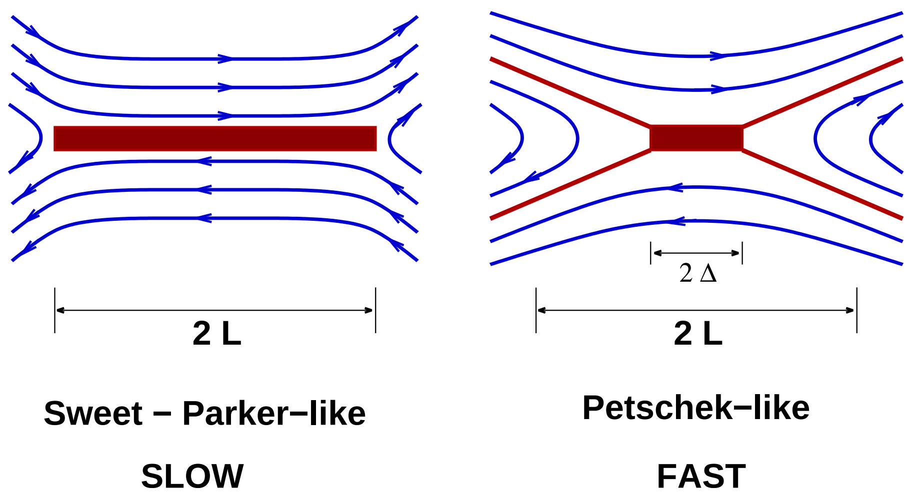


A family of models with

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

- fast enough to explain solar flares!

Two Basic Reconnection Configurations: Sweet–Parker and Petschek



- Astronomical systems are **astronomically large:**

$$L \gg \rho_i, d_i, \delta_{\mathrm{SP}}$$

(e.g., solar flares: $L \sim 10^9$ cm $\gg$ $d_i \sim \delta_{\mathrm{SP}} \sim 10^2 - 10^3$ cm)

- $\Rightarrow \quad \delta > \delta_{\mathrm{SP}}$ is not enough for rapid reconnection !
- *Petschek's (1964)* idea is especially important in Space- and Astrophysics.

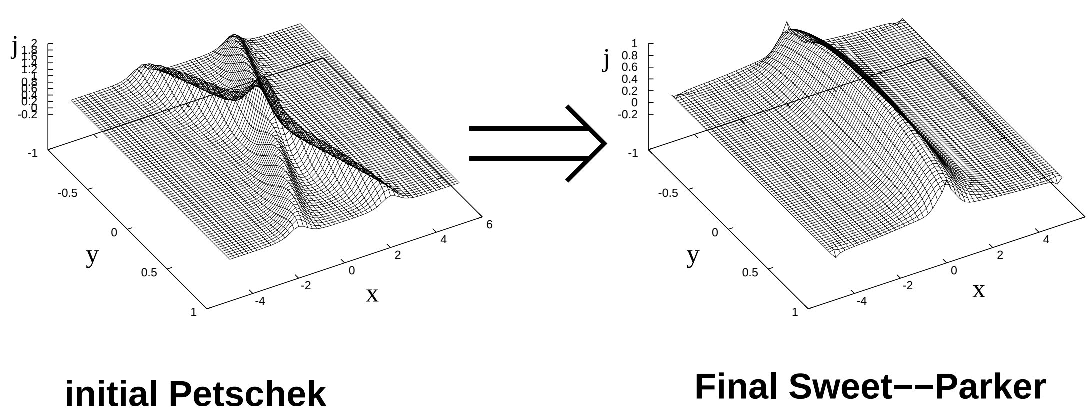
Fast Reconnection $\Leftrightarrow$ Petschek Reconnection

NO FAST RECONNECTION
IN COLLISIONAL PLASMAS

However,

- Numerical Simulations *(e.g., Biskamp 1986; Uzdensky & Kulsrud 1998, 2000; Erkaev et al. 2001; Malyshkin et al. 2005)*
- Analytical Work *(Kulsrud 2001; Malyshkin et al. 2005)*
- Laboratory Experiments *(Ji et al. 1998)*

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



(Uzdensky & Kulsrud 2000)

No Fast Reconnection in Collisional Plasma

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A Digression:

Break-up of SP Layer into a Chain of Plasmoids

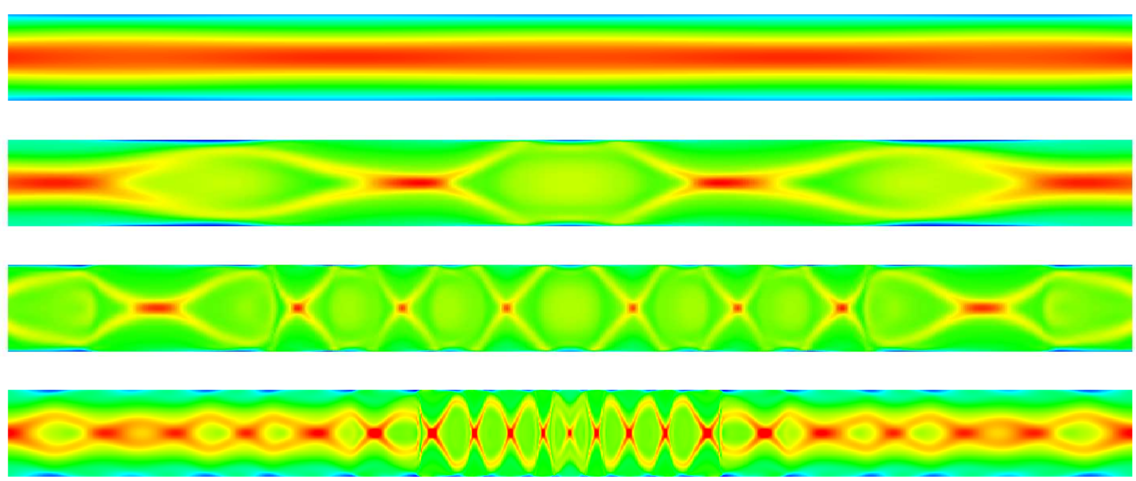
- Long Sweet–Parker current layers are tearing unstable for $S > 10^4$ *(Bulanov, Syrovatskii, & Sakai; Loureiro et al. 2007, 2009)* $\Rightarrow$ bursty reconnection.
- 2D Resistive-MHD Simulations
  (Samtaney, Loureiro, Uzdensky, Schekochihin, & Cowley 2009)

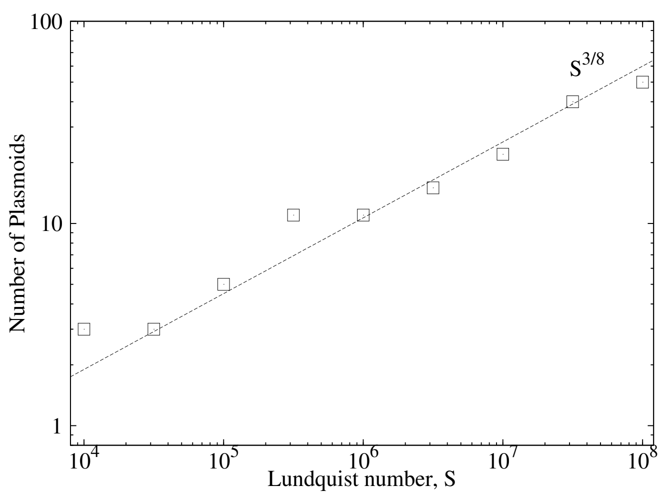
$S = 10^4$

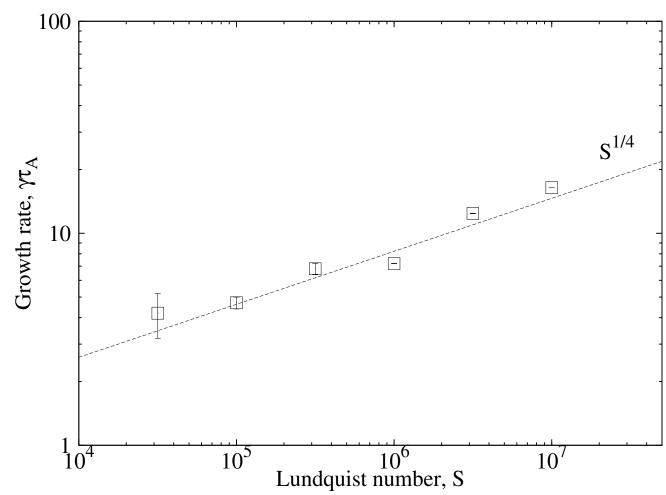
$S = 10^5$

$S = 10^6$

$S = 10^7$







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FAST RECONNECTION
means COLLISIONLESS RECONNECTION

Q: Is Fast Reconnection Possible in Collisionless Plasmas ?

FAST RECONNECTION
means COLLISIONLESS RECONNECTION

<u>**Q:**</u> Is Fast Reconnection Possible in Collisionless Plasmas ?

YES !!!

FAST RECONNECTION
means COLLISIONLESS RECONNECTION

Q: Is Fast Reconnection Possible in Collisionless Plasmas ?

YES !!!

Two candidates for fast Petschek-like collisionless reconnection:

- **Hall-MHD reconnection** involving two-fluid laminar configuration *(e.g., Mandt et al. 1994; Shay et al. 1998; Birn et al. 2001; Bhattacharjee et al. 2001; Breslau & Jardin 2003; Cassak et al. 2005)*
- 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)*

Signatures of both mechanisms observed in MRX.

Fast Reconnection = Collisionless Reconnection

Condition for Collisionless Reconnection

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

$$\delta_{\mathsf{SP}} = L S^{-1/2} = \sqrt{L\eta/V_A}$$

- Collisionless reconnection scale — ion skin depth:

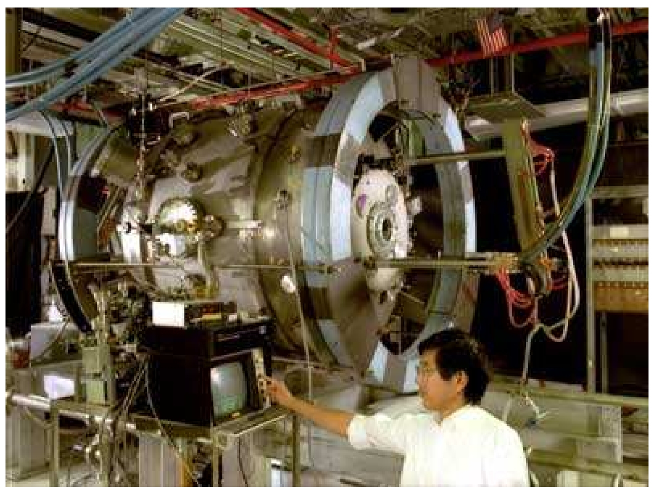
$$d_i \equiv \frac{c}{\omega_{pi}} = c\sqrt{\frac{m_i}{4\pi n_e e^2}}$$

- **Collisionless Reconnection Condition:**

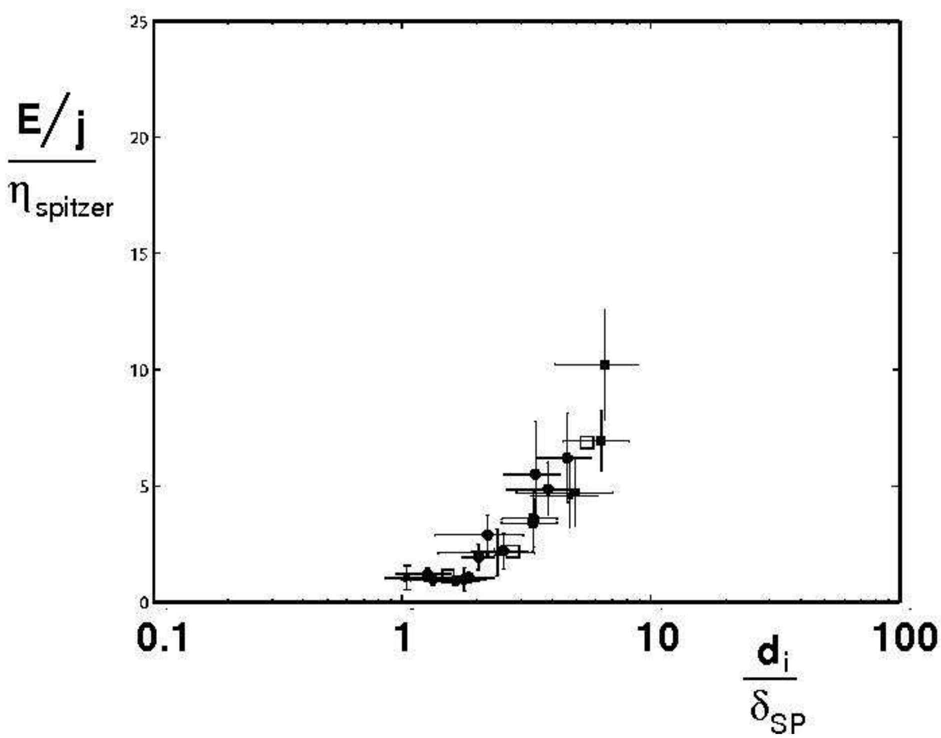
$$\delta_{\mathsf{SP}} < d_i$$

Reconnection in the Lab:
Magnetic Reconnection Experiment (MRX)

MRX at Princeton Plasma Physics Laboratory:

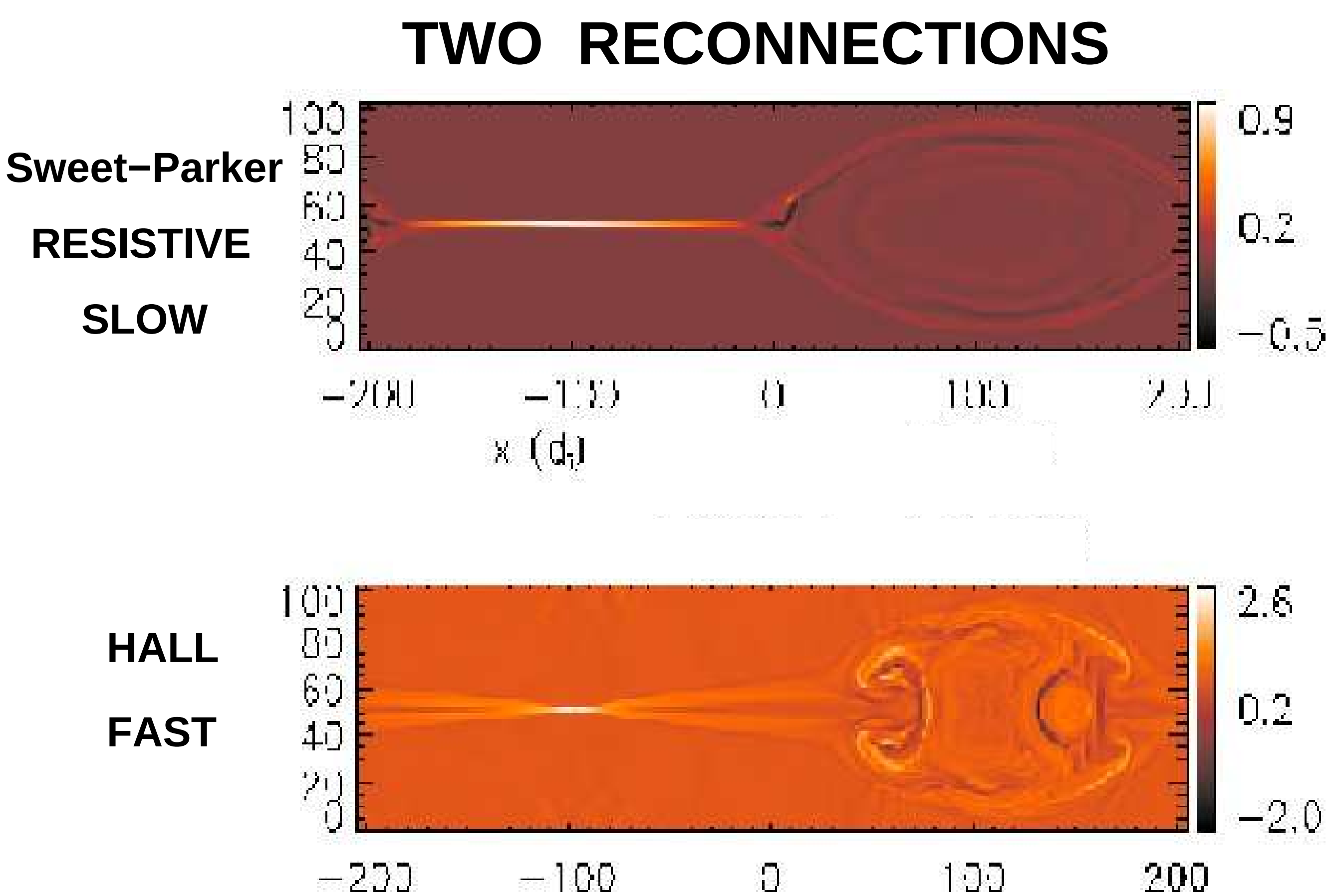


Experimental evidence for transition to fast collisionless reconnection:



FAST COLLISIONLESS RECONNECTION: HALL EFFECT

- Numerical simulations:
  Hall effect enables Petschek-like structure
  with $v_{\rm rec} \leq 0.1\, V_A$ *(e.g., Shay et al. 1998).*



(Cassak, Shay, & Drake 2005)

Condition for Collisionless Reconnection

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

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

- 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:**

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

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

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

- Then, fast reconnection requires

$$L < \lambda_{e,\mathsf{mfp}}\sqrt{m_i/m_e} \simeq 40\,\lambda_{e,\mathsf{mfp}}$$

MOVING FORWARD....

(Uzdensky 2006, 2007)

Next Crucial Step: Taking It All Seriously !!

- Classical collisional electron mean-free path:

$$\lambda_{e,\mathrm{mfp}} \simeq 7 \cdot 10^7 \mathrm{cm}\; n_{10}^{-1}\, T_7^2$$

(here $n_{10} \equiv n_e/10^{10}\,\mathrm{cm}^{-3}$ and $T_7 \equiv T_e/10^7\,\mathrm{K}$)

- Criterion for Collisionless Reconnection:

$$L < L_c(n,T) \equiv 40\,\lambda_{e,\mathrm{mfp}} \simeq 3 \cdot 10^9 \mathrm{cm}\; n_{10}^{-1}\, T_7^2$$

MOVING FORWARD....

(Uzdensky 2006, 2007)

Next Crucial Step: Taking It All Seriously !!

- Classical collisional electron mean-free path:

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- Criterion for Collisionless Reconnection:

$$L < L_c(n,T) \equiv 40\,\lambda_{e,\mathrm{mfp}} \simeq 3 \cdot 10^9 \mathrm{cm}\; n_{10}^{-1}\, T_7^2$$

- Central Electron Temperature:

$$T_e = \frac{B_0^2/8\pi}{2k_B n_e} \simeq 1.3 \cdot 10^8\,\mathrm{K}\; B_2^2\, n_{10}^{-1}$$

(here $B_2 \equiv B_0/100\,\mathrm{G}$)

- Collisionless reconnection condition: final form:

$$L < L_c(n, B_0) \simeq 5 \cdot 10^{11}\,\mathrm{cm}\; n_{10}^{-3}\, B_2^4$$

Astrophysical applications:

SELF-REGULATED MARGINALLY COLLISIONLESS ASTROPHYSICAL CORONAE

- The Sun
- Accreting Black Holes

I. SOLAR CORONA

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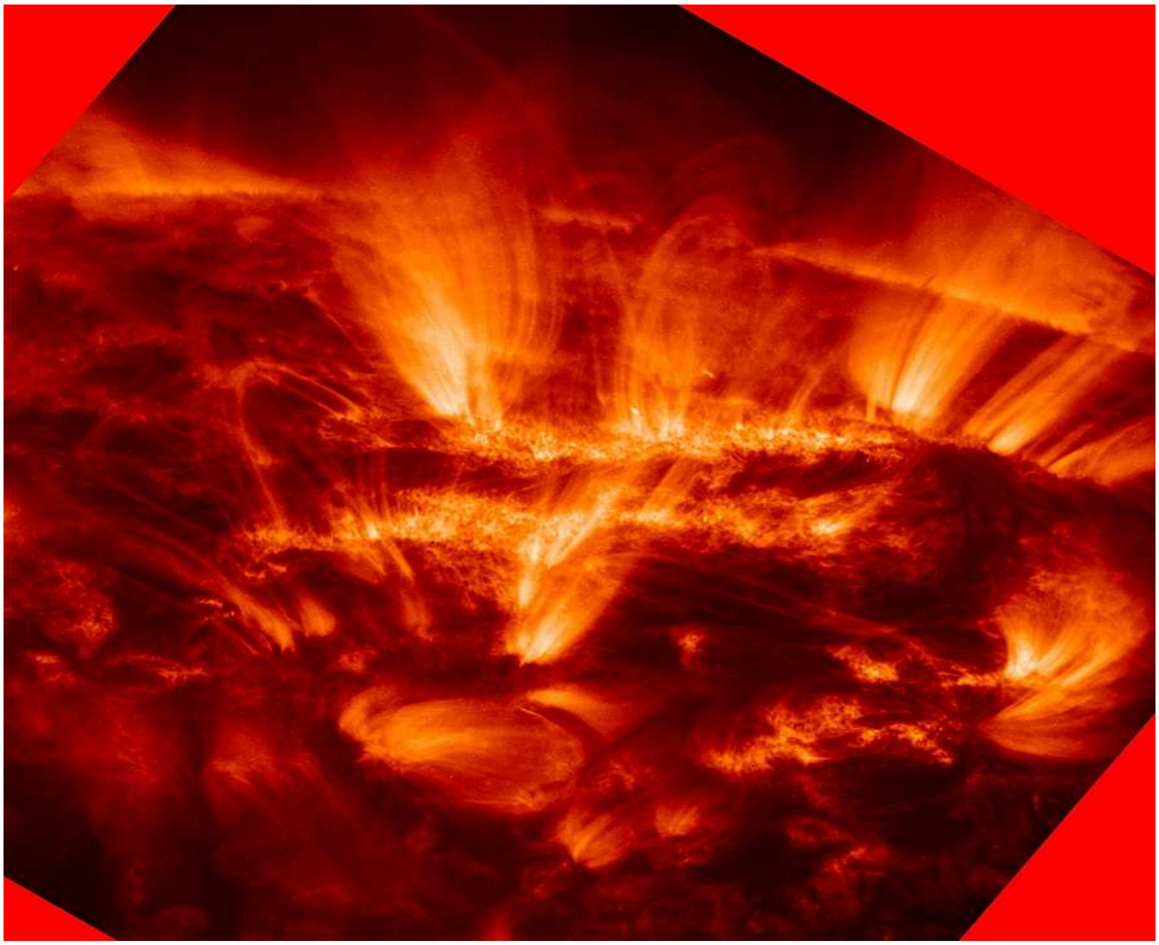
SOLAR CORONA



TRACE –171 Å

- Typical Solar Corona parameters:

$$L \sim 10^9 - 10^{10}\,\mathrm{cm} \qquad B \sim 100\,\mathrm{G}$$
$$n_e \sim 10^9 - 10^{10}\,\mathrm{cm}^{-3} \qquad T \sim 2\cdot 10^6\,\mathrm{K}$$

Critical Density for Collisionless Reconnection

(Uzdensky 2006, 2007)

MAIN IDEA: coronal heating is a self-regulating process keeping plasma marginally collisionless.

EXAMPLE:

- Consider a reconnecting structure set up by loop dynamics: L and B_0 are fixed.

- **Critical density** for fast collisionless reconnection:

$$n < n_c \sim 2 \cdot 10^{10}\,\mathrm{cm}^{-3}\, B_{1.5}^{4/3}\, L_9^{-1/3}$$

- Plasma density acts as a reconnection switch:
  - $n_e > n_c$: no reconnection ⇒ no heating: plasma gradually cools via radiation/thermal conduction, density scale-height decreases, n_e drops.
  - $n_e < n_c$: rapid collisionless reconnection commences, energy is released.

Self-Regulation of Coronal Heating

(Uzdensky 2006, 2007)

- Key feedback:
  coronal energy release $\Rightarrow$ chromospheric evaporation $\Rightarrow$ coronal density rises.
- $n > n_c$ in post-flare loops $\Rightarrow$ subsequent magnetic dissipation is suppressed.

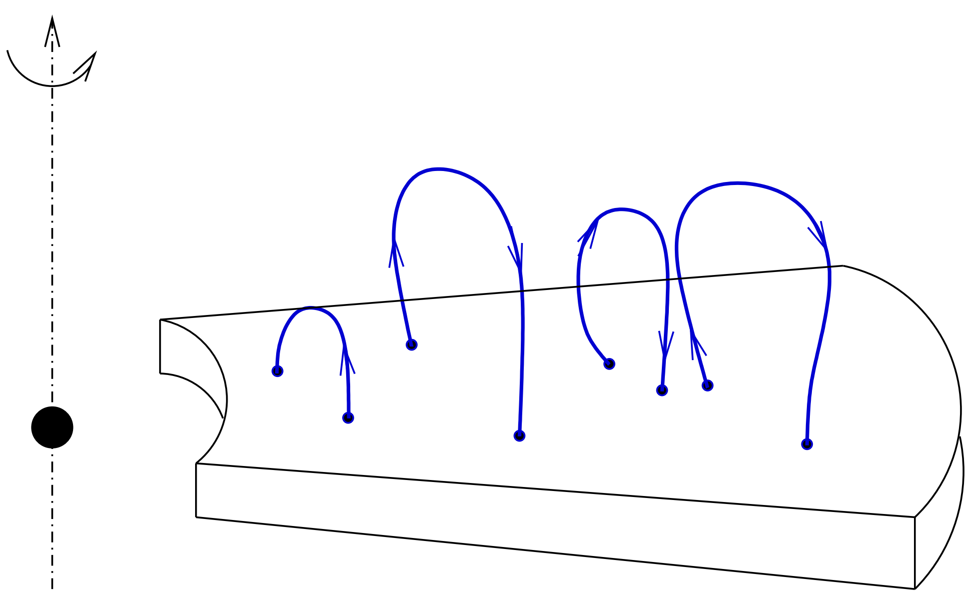
Thus, although highly intermittent and inhomogeneous, corona is working to keep itself roughly at the critical density $n_c(L, B_0)$.

$\Rightarrow$ **Self-Regulation of Coronal Heating !**

Q:

Similar processes be at work in coronae of other stars *(Cassak et al. 2008)* and accretion disks *(Goodman & Uzdensky 2008).*

ACCRETION DISK CORONA



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Marginally Collisionless Coronae
of Black-Hole Accretion Disks

(Goodman & Uzdensky 2008)

- Observational Evidence:
  - Moderate optical depth: $\tau = n_e \sigma_T H \sim 1.$
  - Quasi-relativistic $\bar{e}$-s: $\theta_e = T_e/m_e c^2 \sim 0.1 - 0.5$
- Spitzer resistivity: $\eta_{\text{Spitzer}} \simeq c r_e \theta_e^{-3/2} \log \Lambda$
- Lundquist number:

$$S = \frac{H V_A}{\eta} \simeq \left(\frac{R_{\text{BH}}}{r_e \log \Lambda} \right) f^{1/2} \dot{m}^{1/2} \tau^{-1/2} \theta_e^{3/2} \, h \, r^{1/4} \sim 10^{17}$$

- Sweet–Parker reconnection layer thickness: $\delta_{\text{SP}} \sim H S^{-1/2}$
- Ion collisionless skin-depth: $d_i = c/\omega_{pi} \sim [(m_p/m_e) \, r_e \, H/\tau]^{1/2}$
- Coronal collisionality parameter:

$$\frac{\delta_{\text{SP}}}{d_i} \sim [\frac{m_e \log \Lambda}{m_p}]^{1/2} (f \dot{m})^{-1/4} \tau^{3/4} \theta_e^{-3/4} r^{3/8}$$

BH ADCe are **marginally collisionless: $\delta_{\text{SP}} \sim d_i$.**

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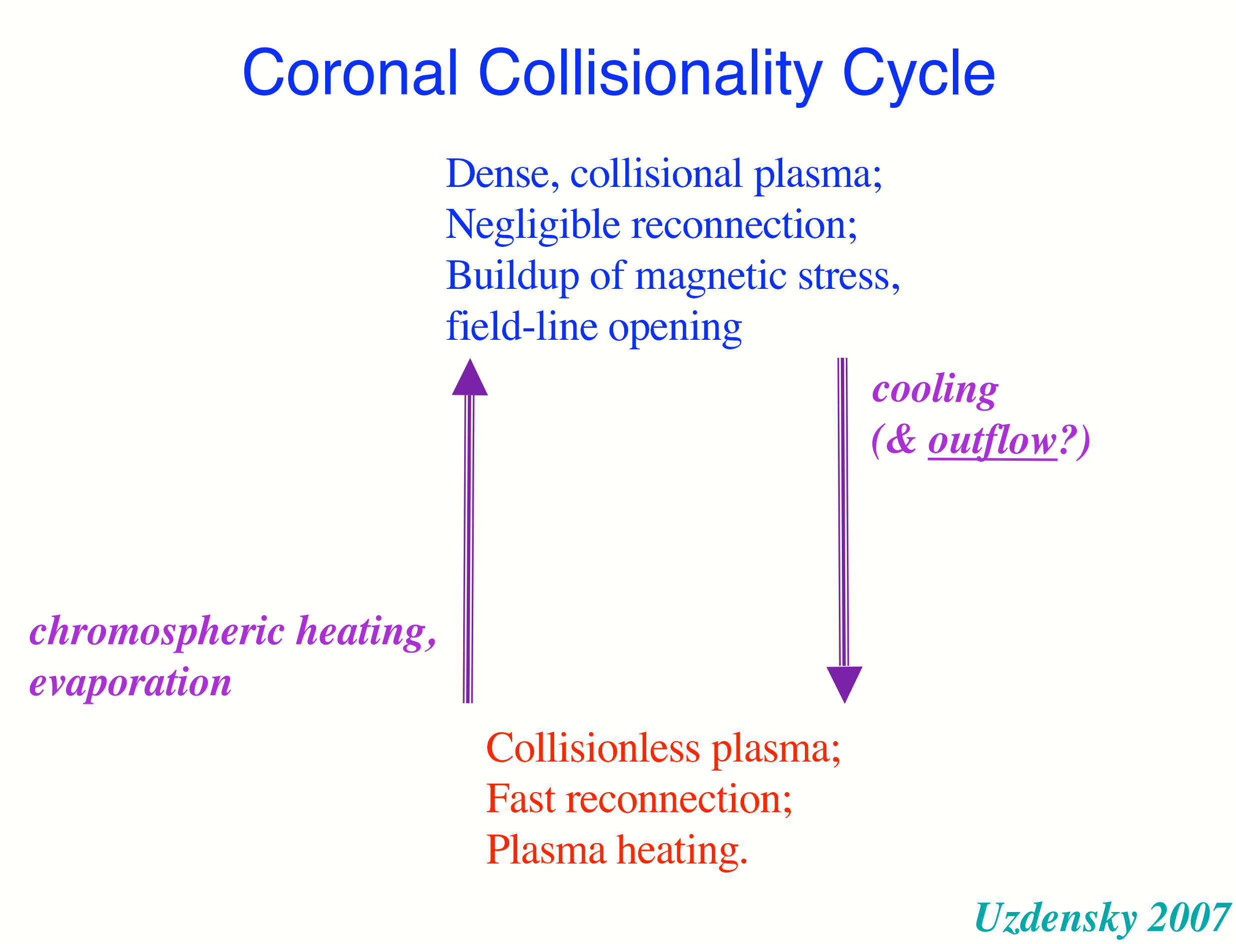
Self-Regulation of Coronal Heating

Two Reconnection Regimes:

- $\underline{\delta_{\mathsf{SP}} > d_i}$: slow collisional Sweet–Parker reconnection
- $\underline{\delta_{\mathsf{SP}} < d_i}$: fast collisionless reconnection



applications: solar/stellar coronae, accretion disk coronae

FUTURE DIRECTIONS

OF MAGNETIC RECONNECTION RESEARCH

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FUTURE DIRECTIONS I

- Time-dependent, non-stationary reconnection in very large systems susceptable to secondary tearing instability (both collisional and collisionless):
  - resistive-MHD reconnection in long current layers ($S > 10^4$) *(e.g., Bulanov et al. 1978; Loureiro et al. 2007, 2009; Lapenta 2008; Bhattacharjee et al. 2009; Samtaney et al. 2009)*
  - collisionless reconnection
  - what is the effect of secondary plasmoids on the time-averaged reconnection rate?
  - what is the effect of secondary plasmoids on non-thermal particle acceleration
  - now accessible to numerical simulations!
- Interaction between two fundamental plasma processes: **reconnection and turbulence**, e.g., externally-driven resistive-MHD turbulence

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. Secondary tearing instability in very long current layers (for $S > 10^4$) ? *(e.g., Bulanov et al. 1978; Loureiro et al. 2007; Samtaney et al. 2009)*
6. MHD turbulence ? *(e.g., Lazarian & Vishniac 1999)*
7. 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 !

OPEN QUESTIONS II:
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 $\beta_{\mathrm{upstream}}$ on triggering η_{anom} ?
   on Hall reconnection ?

5. What system parameters affect reconnection rate in two-fluid regime ?

6. Is collisionless reconnection laminar or 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}, $E_{e,\mathrm{th}}$, $E_{i,\mathrm{th}}$, and $E_{\mathrm{non-therm}}$?

SUMMARY

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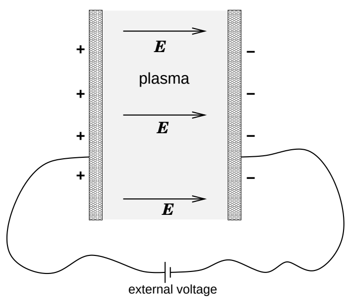
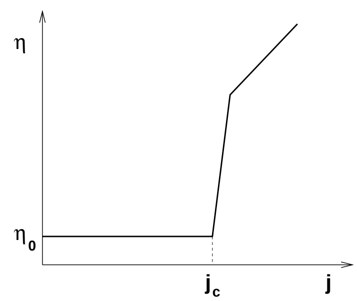
Fast Collisionless Reconnection
ANOMALOUS RESISTIVITY

- What is the physically-relevant resistivity η?





- Physical Mechanism:
  when
  $$v_d = \frac{j}{en_e} > v_c \sim v_{\rm thermal}\,,$$
  plasma instabilities are excited $\Rightarrow$ developed microturbulence. Scattering of electrons by waves enhances resistivity.
- As the layer's thickness δ decreases down to critical thickness
  $$\delta_c \equiv \frac{cB_0}{4\pi j_c}, \qquad \text{where } j_c \equiv en_e v_c,$$
  anomalous resistivity $\eta = \eta(j)$ turns on.
- Anomalous resistivity $\eta = \eta(j)$ is localized near the center.
- Simulations: strongly-localized resistivity $\Rightarrow$ Petschek-like configuration (also theory by *Kulsrud 2001; Malyshkin et al. 2005).*
- Dual role of anomalous resistivity:
  - *direct:* $\eta_{\rm anom} \gg \eta_{\rm coll}$
  - *indirect:* enables Petschek mechanism
- Resulting rate plausible for solar flares *(e.g., Uzdensky 2003).*

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FAST COLLISIONLESS RECONNECTION: HALL EFFECT

- Electron equation of motion $\Rightarrow$ Generalized Ohm's law:

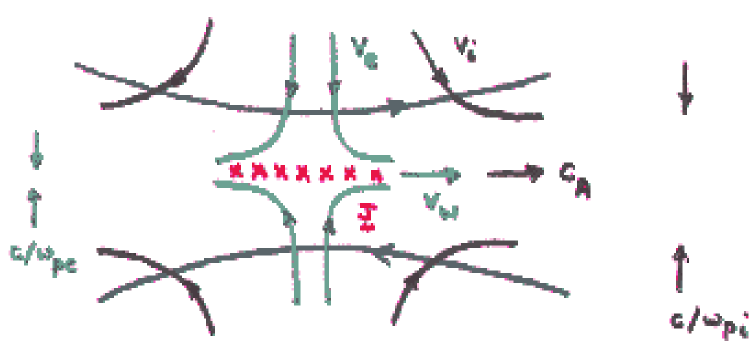
$$\mathbf{E} = -\frac{1}{c}\left[\mathbf{v}_e \times \mathbf{B}\right] + \eta \mathbf{j} = \underbrace{-\frac{1}{c}\left[\mathbf{v} \times \mathbf{B}\right] + \eta \mathbf{j}}_{resistive\ MHD} + \underbrace{\frac{\mathbf{j} \times \mathbf{B}}{n_e e c}}_{Hall\ term}$$

$[\mathbf{j} = n_e e\,(\mathbf{v_i} - \mathbf{v_e})]$

- Hall-term spatial scale:

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

- Two-fluid effects: on scales $< d_i$, ions are no longer tied to field lines but electrons still are $\Rightarrow$ ions and electrons move separately:



- Reconnection layer thickness $\delta \simeq d_i$ $(\gg \delta_{\mathrm{SP}})$.
  But this is not sufficient since still $d_i \ll L$!

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Central Electron Temperture

Role of Central Temperature *(Uzdensky 2007)*

- $\lambda_{\mathrm{mfp}} \sim T_e^2 \quad \Rightarrow \quad$ important to determine T_e.
- Two temperatures: ambient ($T_{\mathrm{cor}} \sim 2 \cdot 10^6\ K$) and central layer $T_e \gg T_{\mathrm{cor}}$
- T_e is not measured directly in solar corona.
  How to estimate it?
- Pressure balance by itself is not enough:
  degeneracy between T_e and n_e.
- T_e is determined by balance btw heating and cooling
- Ohmic heating + advective cooling: $T_e = T_e^{\mathrm{equipartition}}$
- Radiative heat losses: small for the solar corona
- Heat losses by electron thermal conduction:
  $\tau_{\mathrm{cond}} \geq \tau_A$ for the collisional regime.
- Thus, Joule heat is deposited but does not have enough time to escape if the collisionality requirement is met.
- Density will not increase by more than a factor of a few above the ambient level, but T_e may become much higher, reaching the equipartition level.

Requirements for Solar Corona Models

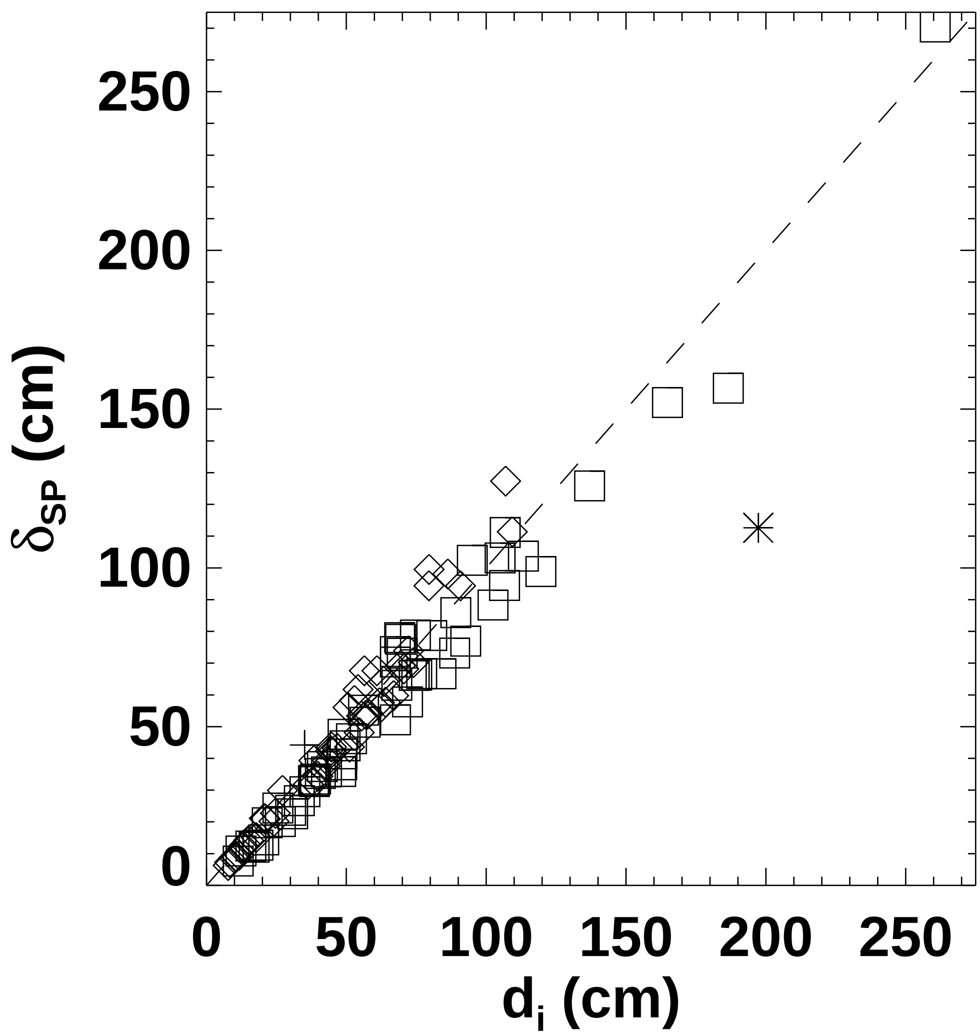
Numerical simulations of solar corona should include ALL of the following:

- 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 (e.g., chromospheric evaporation and plasma precipitation);
- optically-thin radiative cooling and thermal conduction (including by nonthermal e-s) along $\mathbf{B}$.

II. OTHER STARS

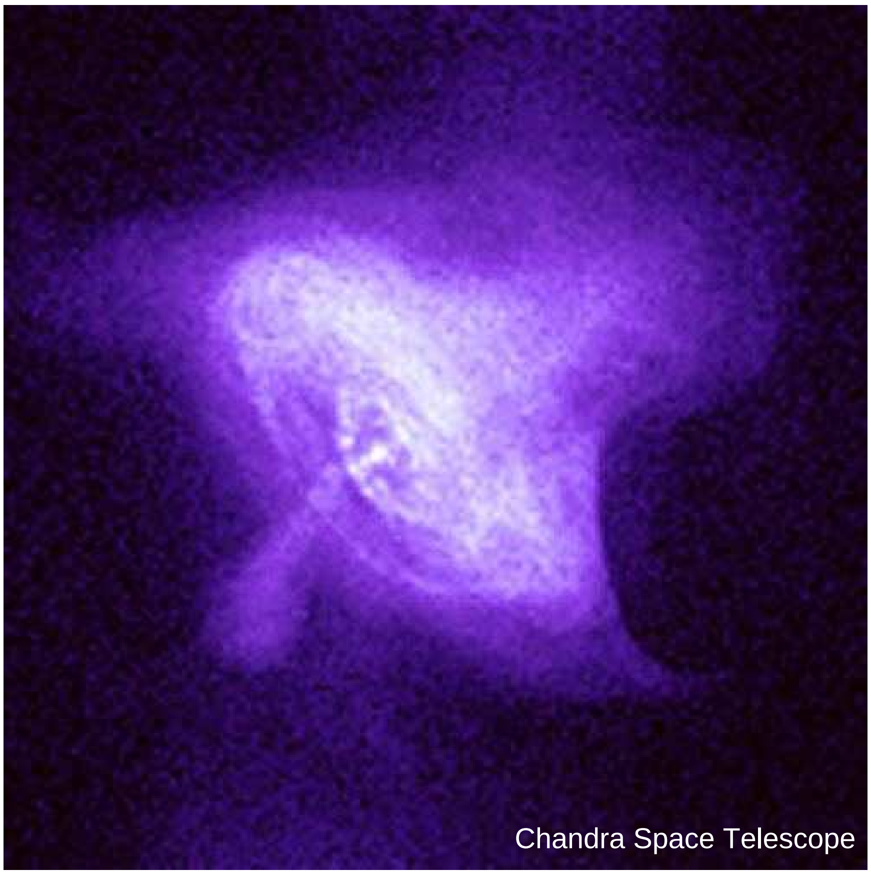
CORONAE OF OTHER STARS

EUVE observations of 107 flares in 37 sun-like (F,G,K) and M-type stars:



(Cassak, Mullan, & Shay 2008)

RECONNECTION IN ASTROPHYSICS: Pulsar Wind



Close to pulsar (light cylinder): $L_{\rm magn} \gg L_{\rm particles}$
Far from pulsar (termination shock): $L_{\rm magn} \ll L_{\rm particles}$

Q: How is magnetic energy transferred to particles?

Reconnection in pulsar wind.

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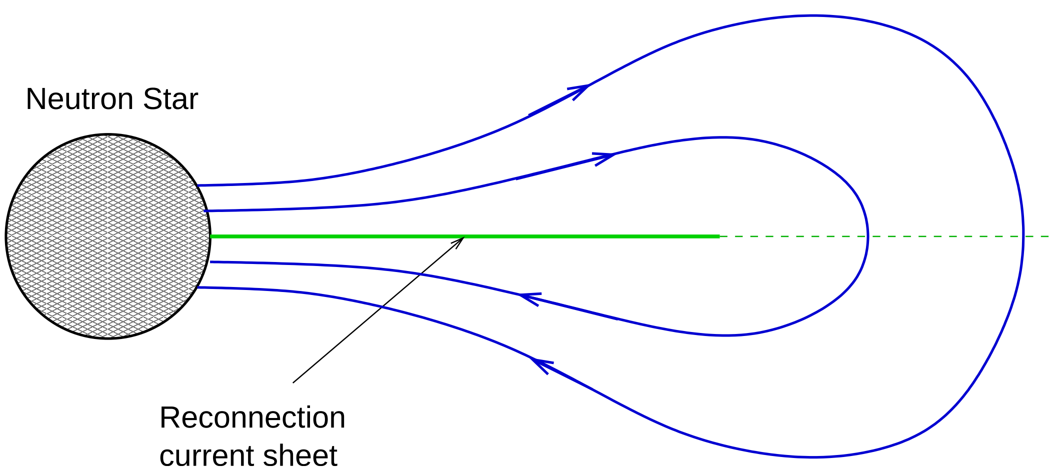
RECONNECTION IN ASTROPHYSICS: GIANT SGR FLARES

Reconnection in **Magnetar Magnetospheres**
as a model for giant flares in Soft Gamma Repeaters

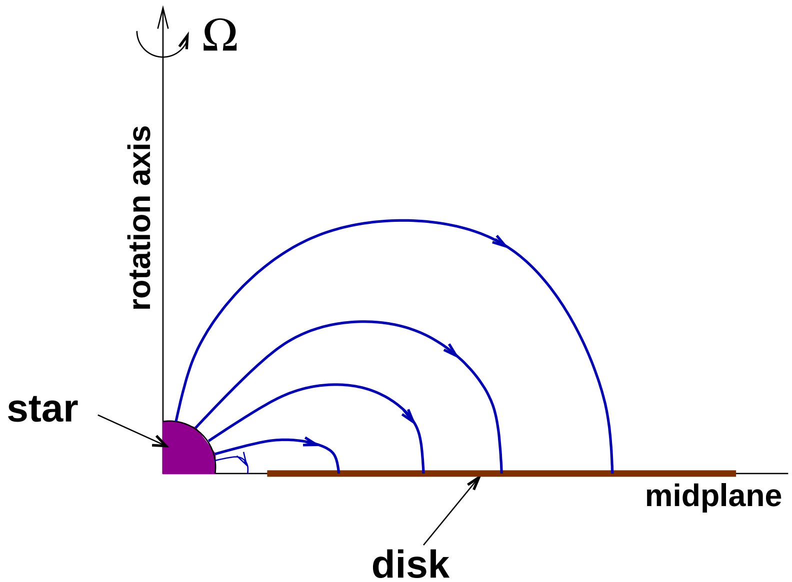
(Thompson, Lyutikov & Kulkarni 2002; Lyutikov 2003, 2006):

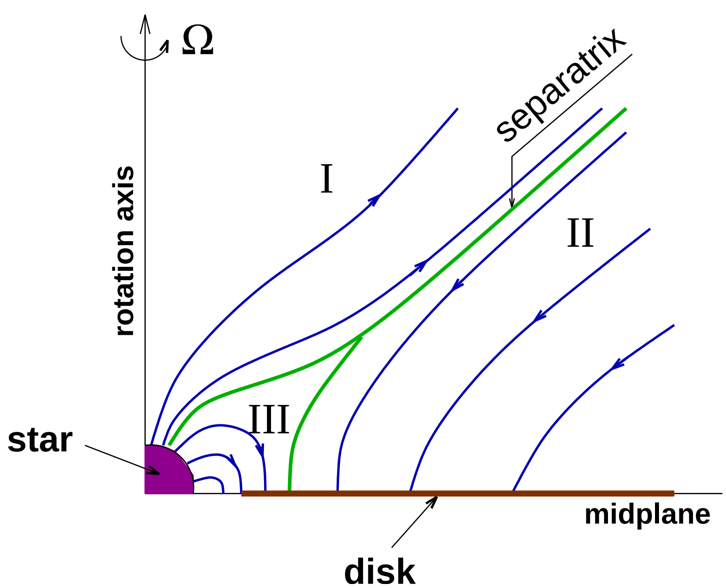


- twisted internal magnetic field breaks the NS crust
- sheared crust motion twists up the external magnetosphere
- subsequent reconnection in the magnetosphere leads to a flare

CURRENT SHEETS IN ASTROPHYSICS: STAR–DISK MAGNETIC INTERACTION

(van Ballegooijen 1994; Lynden-Bell & Boily 1994; Lovelace, Romanova, & Bisnovatyi-Kogan 1995; Hayashi, Shibata, & Matsumoto 1996; Goodson, Winglee, & Bohm 1999; Uzdensky, Königl & Litwin 2002; Uzdensky 2002, 2004)





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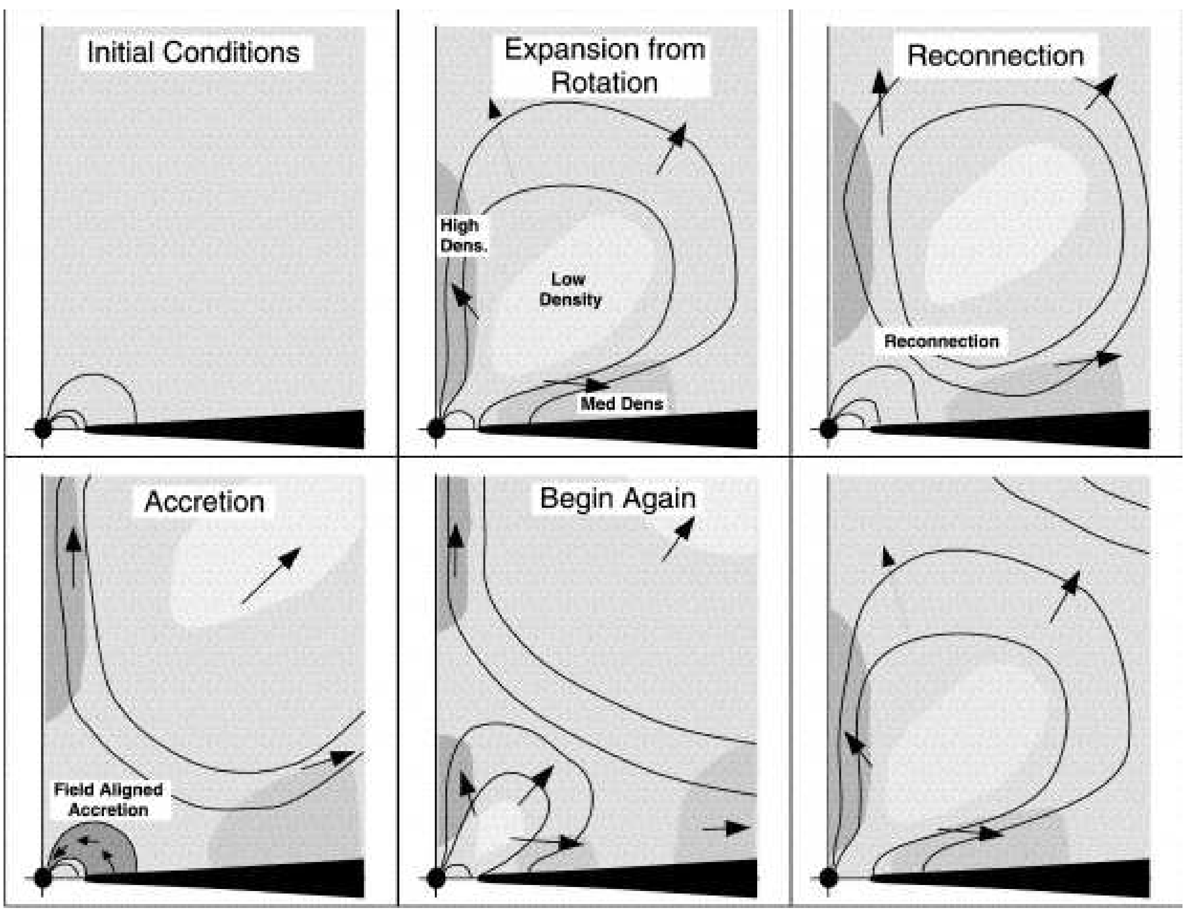
STAR–DISK MAGNETIC INTERACTION
RECONNECTION CYCLES

Cycles of Opening and Reconnection:



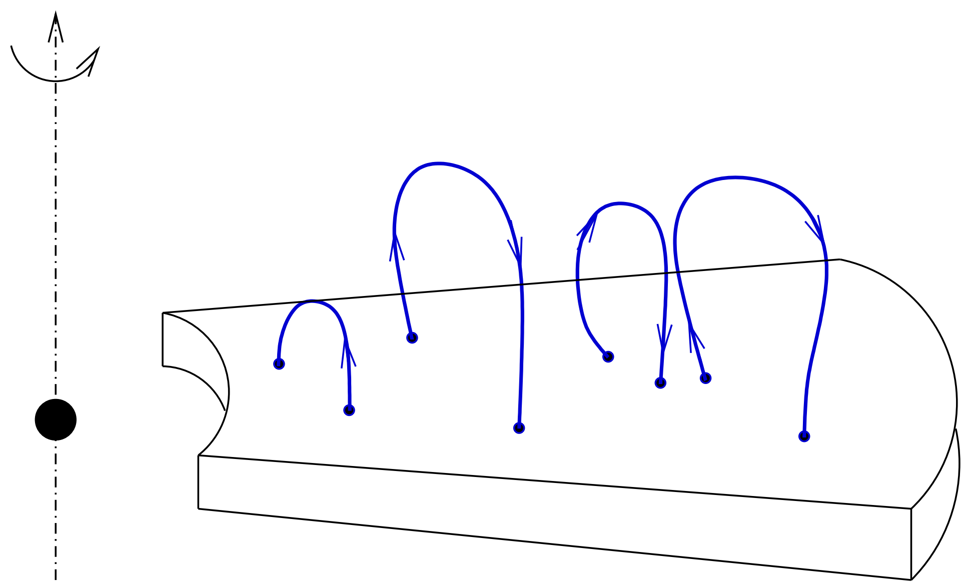
Goodson et al. (1999)

RECONNECTION in ASTROPHYSICS:
ACCRETION-DISK CORONA

(Uzdensky & Goodman 2008)

Magnetized Corona above a thin turbulent accretion disk:

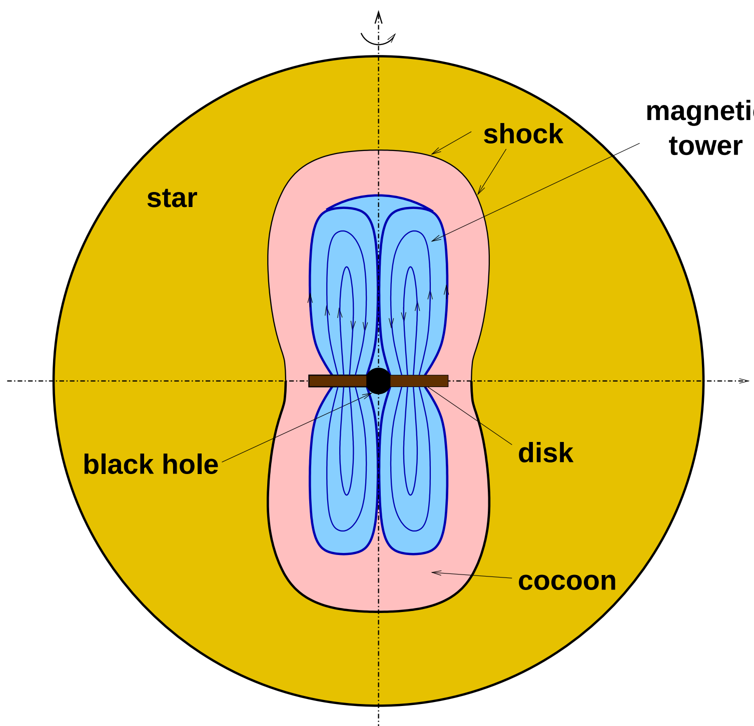
numerous magnetic loops subject to shear due to Keplerian rotation.



Role of reconnection:
controls magnetic scale height and energy dissipation.

A Teaser: No Reconnection in Collapsars ?

Magnetic Tower in a Star *(Uzdensky & MacFadyen 2006)*: magnetic version of collapsar model for long GRBs.



- **Q:** Can fast reconnection happen near central engine?
- Fiducial parameters: $B \sim 10^{14}$ G, $n_e \sim 10^{30}$ cm^{-3}, $T \sim 3 \cdot 10^9$ K, $L \sim 10^7$ cm.
- Reconnection parameters: $S \sim 10^{18}$, $\delta_{\rm SP} \sim 10^{-2}$ cm, $\lambda_{e,\rm mfp} \sim 10^{-6}$ cm, $\rho_e \sim 10^{-11}$ cm, $d_e \sim 10^{-9}$ cm.
- Implication: $L \gg \delta_{\rm SP} \gg \delta_{\rm collisionless}$
  $\Rightarrow$ no fast reconnection $\Rightarrow$ Magnetic outflow survives propagation through the inner part of the star!

FAST RECONNECTION:
CAVEATS AND ALTERNATIVES

- **3D-MHD Turbulent Reconnection:**
  (Lazarian & Vishniac 1999; Bhattacharjee & Hameiri 1986; Strauss 1988; Kim & Diamond 2001)

- **Bursty, Impulsive Reconnection:**
  (e.g., Bhattacharjee 2004)

- **Additional Physics:** e.g., partially-ionized plasmas in molecular clouds *(Zweibel 1989).*

FAST COLLISIONLESS RECONNECTION: HALL EFFECT

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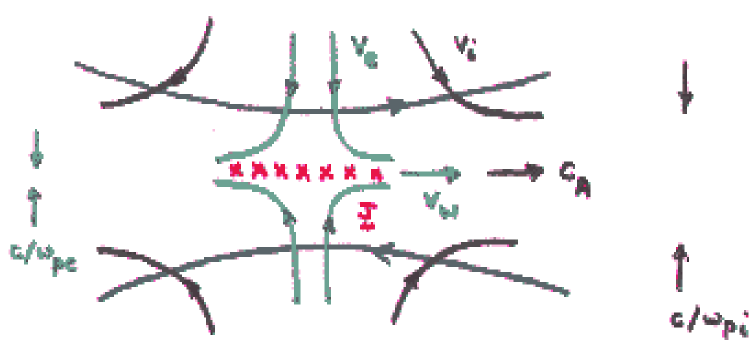

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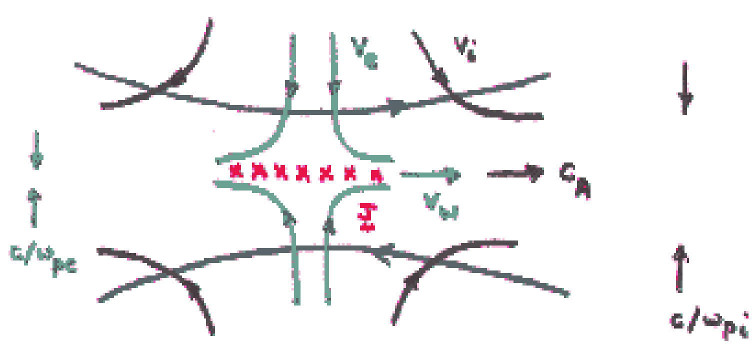

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  But this is not sufficient since still $d_i \ll L$!

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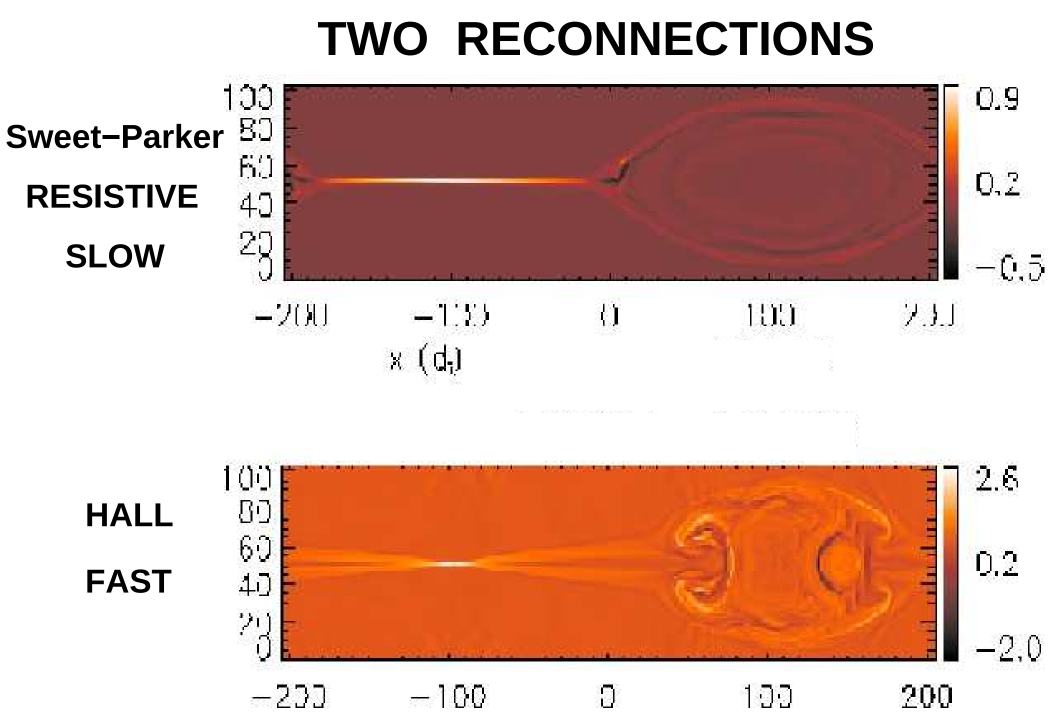
FAST COLLISIONLESS RECONNECTION: HALL EFFECT

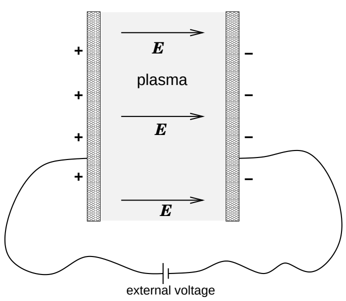
- Good news (numerical simuations):
  Hall effect enables Petschek-like structure
  with $v_{\rm rec} \le 0.1\, V_A$ *(e.g., Shay et al. 1998).*

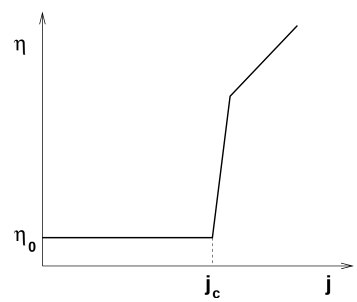


Cassak, Shay, & Drake 2005

Fast Collisionless Reconnection
ANOMALOUS RESISTIVITY

- What is the physically-relevant resistivity η?





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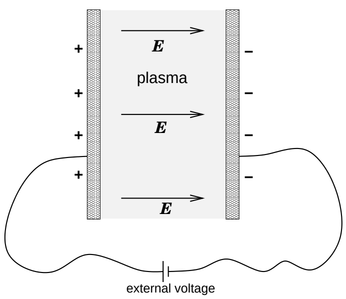

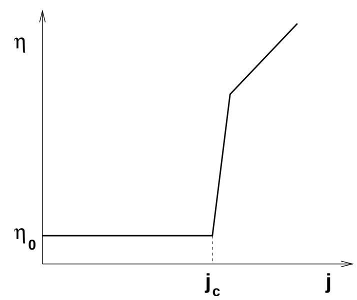

- Physical Mechanism:
when
$$v_d = \frac{j}{en_e} > v_c \sim v_{\rm thermal} \,,$$
plasma instabilities are excited $\Rightarrow$ developed microturbulence. Scattering of electrons by waves enhances resistivity.

- As the layer's thickness δ decreases down to critical thickness
$$\delta_c \equiv \frac{cB_0}{4\pi j_c}, \qquad \text{where } j_c \equiv e n_e v_c,$$
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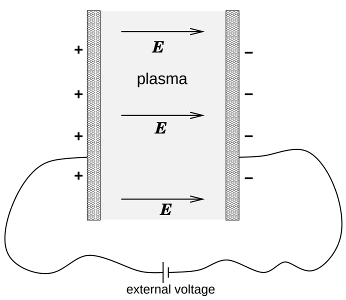

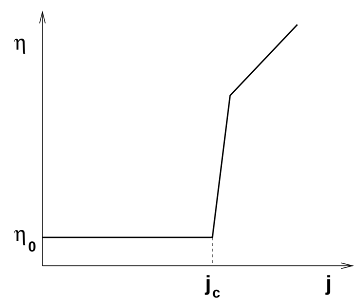

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- Simulations: strongly-localized resistivity $\Rightarrow$ Petschek-like configuration (also theory by *Kulsrud 2001; Malyshkin et al. 2005).*

- Dual role of anomalous resistivity:
  - *direct:* $\eta_{\rm anom} \gg \eta_{\rm coll}$
  - *indirect:* enables Petschek mechanism

- Resulting rate plausible for solar flares *(e.g., Uzdensky 2003).*

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Condition for Collisionless Reconnection: Strong Guide Field Case: $B_z \gg B_0$

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

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

- Collisionless reconnection scale for strong guide field case, — 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:**

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

- Final form:

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

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What is the Status of our Knowledge about Magnetic Reconnection ?

Common Perception:

"We don't know anything about reconnection. So we are free to assume anything we want."

NOT TRUE !!

INSTEAD:

We don't know everything about reconnection.

But there are **some things** we do know.

(or we think we know)

Sweet–Parker Reconnection: Too Slow for Solar Flares!

- Typical Solar Corona parameters:

$$L \sim 10^9 - 10^{10}\,\text{cm} \qquad B \sim 100\,\text{G}$$

$$n_e \sim 10^9 - 10^{10}\,\text{cm}^{-3} \qquad T \sim 2 \cdot 10^6\,\text{K}$$

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- Lundquist number:

$$S = \frac{LV_A}{\eta} \sim 10^{12}$$

- Sweet–Parker timescale:

$$\tau_{\mathsf{rec}} \sim \tau_A\sqrt{S} \sim \text{months} \gg \tau_{\mathsf{flare}} \sim 15\,\mathsf{min}$$

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OPEN QUESTIONS

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Most previous numerical studies were incompressible, with $\eta = \text{const}$, and in a limited range of Lundquist numbers ($S \sim 10^3 - 10^4$).

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7. Additional (astro-)physical effects:
- weakly-ionized and dusty plasma (ISM, molecular clouds) *(Zweibel 1989)*;
- Compton resistivity (radiation drag; black-hole coronae and jets);
- radiative (e.g., Compton) cooling (black-hole coronae);
- pair creation (black holes, magnetars) *(Uzdensky 2009, in preparation)*

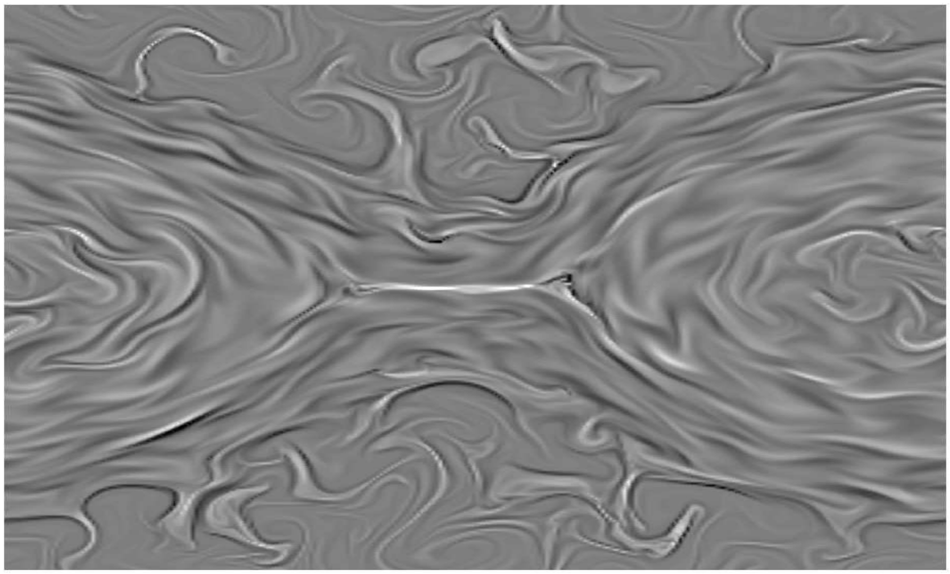
FUTURE DIRECTIONS I

- Non-stationary, bursty reconnection in very large systems susceptable to secondary tearing instability:
  - resistive-MHD reconnection in long current sheets ($S > 10^4$) *(e.g., Bulanov et al. 1978; Loureiro et al. 2007, 2009; Lapenta 2008; Bhattacharjee et al. 2009; Samtaney et al. 2009)*
  - collisionless reconnection *(Daughton et al. 2008);*
  - How does time-averaged reconnection rate scale with $S = LV_A/\eta$ for $S > 10^4$?
  - Role of secondary plasmoids in non-thermal particle acceleration *(Drake et al. 2006)*.
  - Radio-signatures: a direct probe into reconnection layer?
  - now accessible to numerical simulations!

- Interaction between two fundamental plasma processes:
  reconnection and turbulence,
  e.g., externally-driven resistive-MHD turbulence *(e.g., Lazarian & Vishniac 1999; Kowal et al. 2008; Loureiro et al. 2009, in preparation)*

MHD-Turbulent Reconnection

2D incompressible resistive-MHD simulations
(Loureiro, Uzdensky, Schekochikhin, Yousef, & Cowley 2009)



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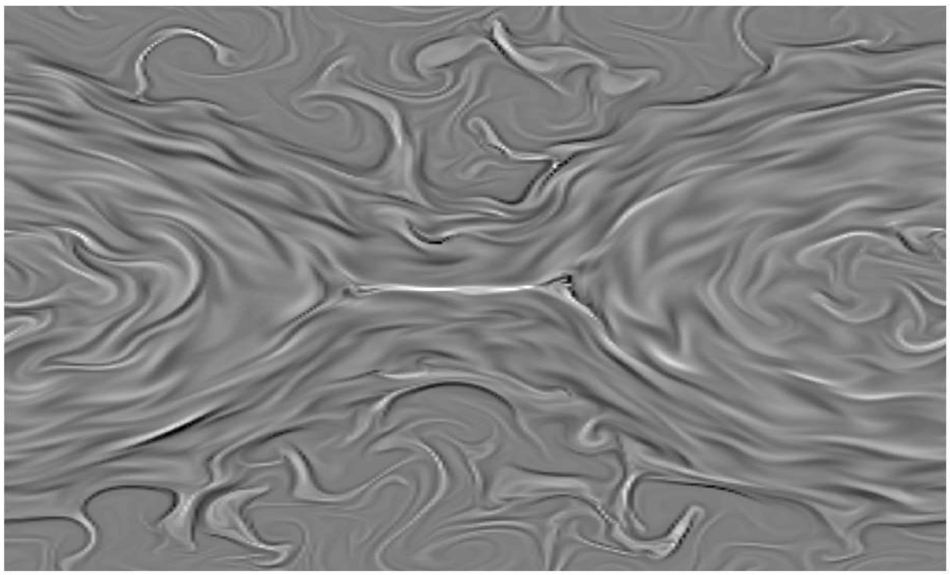
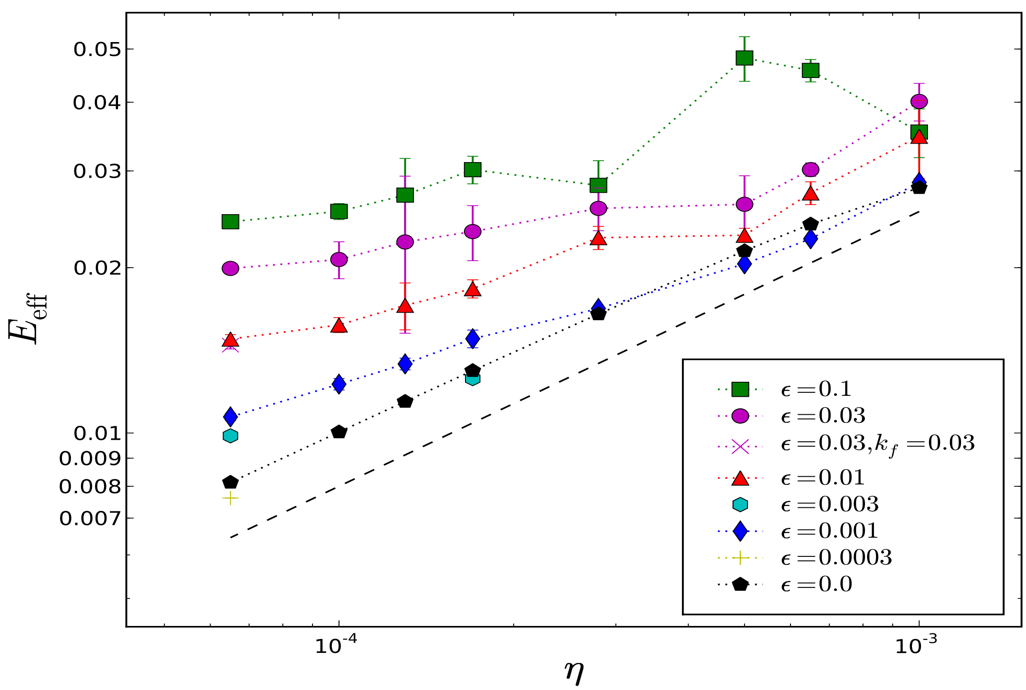




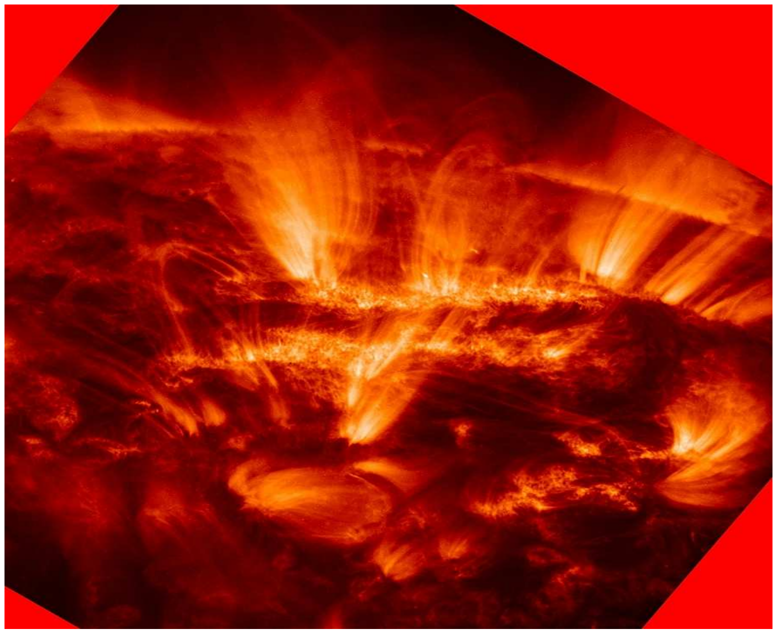
D. Uzdensky

FUTURE DIRECTIONS II

Astrophysically motivated questions:

- How is the released magnetic energy partitioned between: E_{kin}, $E_{e,\text{th}}$, $E_{i,\text{th}}$, and $E_{\text{non-therm}}$?
- A new frontier in astrophysical reconnection: High-energy-density (HED), radiative environements *(Uzdensky 2008, 2009 in prep.)*:
  - radiative cooling (e.g., Compton) of the reconnection layer (black-hole coronae; magnetar flares);
  - Compton resistivity (radiation drag; black-hole coronae/jets)
  - radiation pressure (collapsars and magnetar flares)
  - pair creation (BH coronae; collapsars and magnetar flares)
- **Prospects for experimental research:**
  - Next generation (medium-scale) reconnection expt: larger ($S > 10^4$), better separation of scales; better diagnostics (incl. energetic particles)
  - HED reconnection with radiation cooling/pressure effects: laser-plasma facilities

SOLAR CORONAL HEATING



TRACE –171 Å

Solar corona: $n_e \sim 10^{10}$ cm^{-3}, $T \sim 2 \cdot 10^6$ K.

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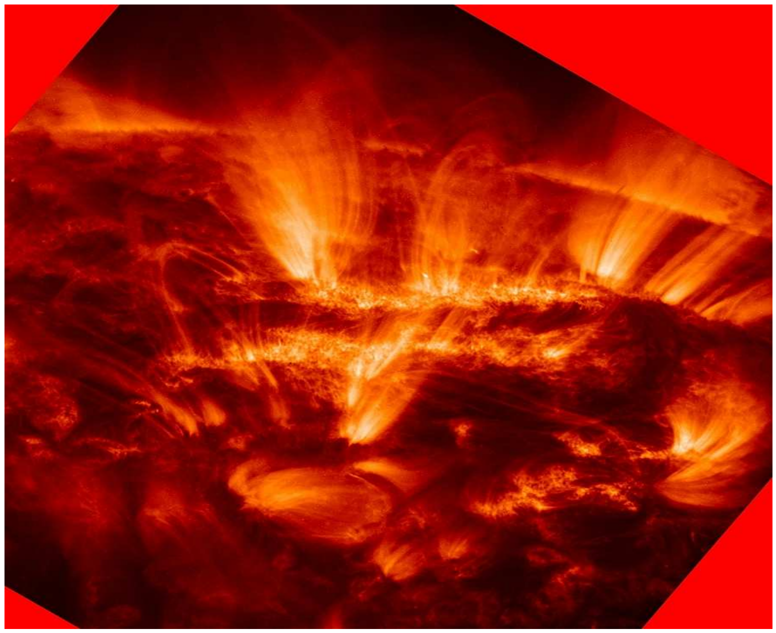

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Nanoflare model of coronal heating *(Parker 1988):*

- Footpoint motions pump magnetic energy into corona.
- Energy dissipates in the corona via reconnection.
- Characteristic scale (L) and field strength (B_0) of coronal magnetic structures are determined by photospheric motions, flux emergence, etc.
- But what determines coronal density ?

A DIGRESSION:

Secondary Tearing Instability in Current Sheets

- Very long Sweet–Parker resistive current sheets themselves becoming tearing unstable for $S > 10^4$ *(Bulanov et al. 1978; Loureiro et al. 2007, 2009)* leading to non-stationary, bursty reconnection.
- How does time-averaged reconnection rate scale with $S = LV_A/\eta$ for $S > 10^4$?
- Now accessible to numerical simulations! *(Lapenta 2008; Bhattacharjee et al. 2009; Samtaney et al. 2009)*

RESISTIVE MHD

- Resistive magnetohydrodynamics (MHD)

  Magnetic Induction Equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{-\left[\nabla \times [\mathbf{v} \times \mathbf{B}]\right]}_{advection} + \underbrace{\eta\,\nabla^2 \mathbf{B}}_{diffusion}$$

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- Characteristic velocity in MHD — Alfvén velocity:

$$V_A \equiv \frac{B}{\sqrt{4\pi\rho}}$$

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- Characteristic *resistive diffusion time:*

$$\tau_{\text{res}} = \frac{L^2}{\eta}$$

- Measure of flux-freezing — Lundquist number:

$$S \equiv \frac{\tau_{\text{res}}}{\tau_A} = \frac{L V_A}{\eta} \quad (\gg 1)$$

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- Usually in Space and Astrophysics $S = LV_A/\eta \gg 1$

  $\Rightarrow$ ideal MHD works well on large scales L.

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  $\Rightarrow$ ideal MHD works well on large scales L.

- But notice:
  - resistive diffusion term $\sim \nabla^2 \mathbf{B}$
  - advection term $\sim \nabla \mathbf{B}$