What reconnection can do for you:
Reconsidering the role of current sheets and reconnection in solar flares

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OUTLINE

I. A 2d setting for reconnection

   A. Fast (dynamical) reconnection

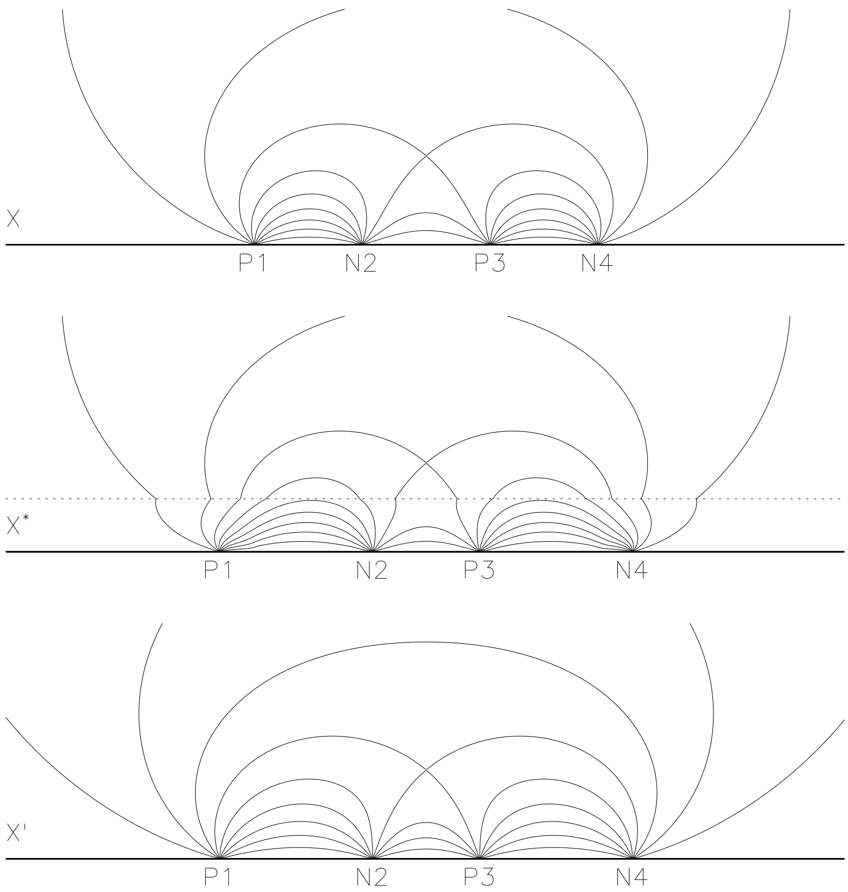
   B. Slow (no) reconnection

II. A hybrid alterntaive:
Current accumulation punctuated by fast reconenction

III. Implications for flares — 3d

A 2d setting for reconnection

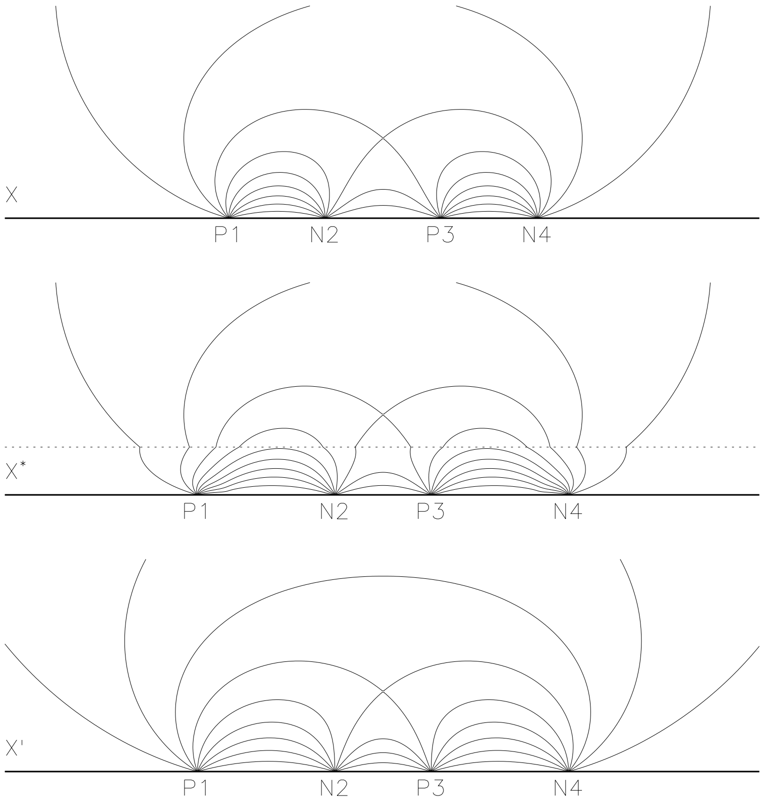
- X: Initial state with $\psi_{23} = \Psi_X$ between $P3$ & $N2$



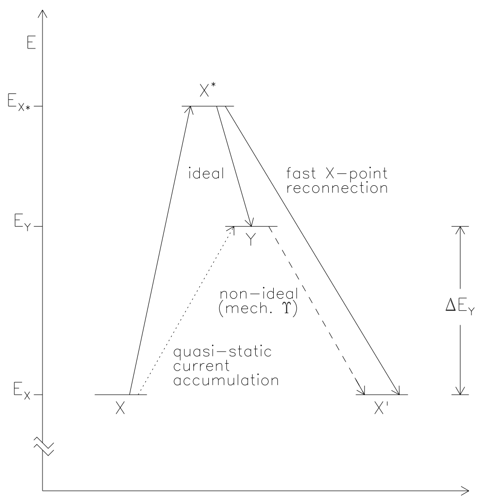
$$\underbrace{\frac{\partial \psi}{\partial t} + \mathbf{v} \cdot \nabla \psi}_{\dot{\psi}} = \underbrace{\eta \nabla^2 \psi}_{\text{diffusion}}$$

- Displace photospheric sources (boundary driving)
- Introduces energy into field X^*
- X': potential field w/ $\psi_{23} = \Psi_X + \Delta\psi$

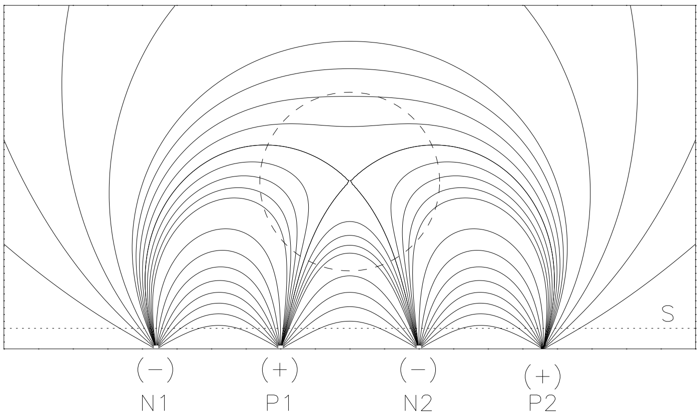
Scenario A: Fast reconnection



- $X^* \;\rightarrow\; X'$ on times $\sim \tau_{\mathrm{A}}$
- $\Delta\mathcal{E} = \mathcal{E}_{X^*} - \mathcal{E}_{X'}$ released radpidly.



Example: X-point collapse (Hassam 1992, Craig 1994)



linearized* MHD

$$\partial_t \mathbf{v} \;=\; -\frac{1}{4\pi\rho}\nabla^2\psi\,\nabla\psi_X$$

$$\partial_t\psi \;+\; \mathbf{v}\cdot\nabla\psi_X \;=\; \eta\nabla^2\psi$$

$$\Longrightarrow \quad \partial_t^2\psi \;=\; \frac{\overbrace{|\nabla\psi_X|^2}^{v_{\mathrm{A}}^2}}{4\pi\rho}\,\nabla^2\psi \;+\; \eta\partial_t\nabla^2\psi$$

- Ideal limit $\eta = 0 \quad (\eta\nabla^2 \ll \partial_t)$
- Yields wave equation (Alfvén waves)

$$\partial_t^2\psi \;=\; v_{\mathrm{A}}^2\nabla^2\psi \;=\; \gamma_{\mathrm{A}}^2 r^2\,\nabla^2\psi$$

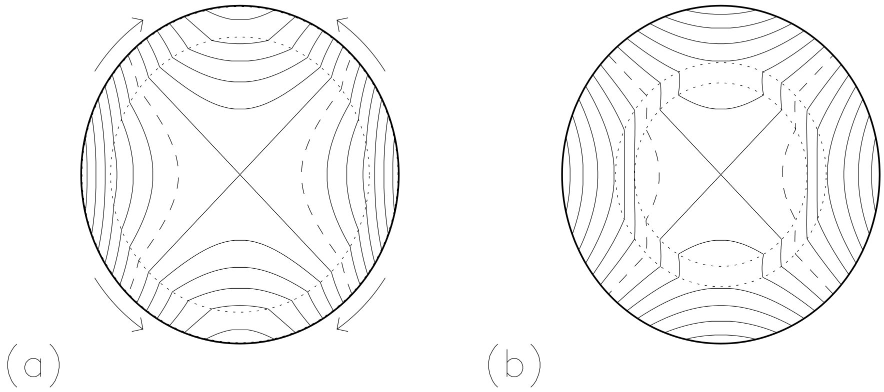
- characteristic time: $\gamma_{\mathrm{A}}^{-1} \equiv \sqrt{4\pi\rho}/B' \quad v_{\mathrm{A}}^2 \;=\; \gamma_{\mathrm{A}}^2 r^2$
- $\boxed{\text{Dynamical significance of X-point — } v_{\mathrm{A}} \to 0}$

∗ about $\psi(x,y) = \psi_X(x,y)$

Dynamical X-point collapse

- Wave eq. solution — cylindrical implosion

$$\psi(r,t) = \Delta\psi\, H\left[\gamma_{\mathrm{A}} t \;+\; \ln\left(\frac{r}{a}\right)\right]$$



- Ideal limit applies while $\eta/\gamma_{\mathrm{A}} r^2 \ll 1$

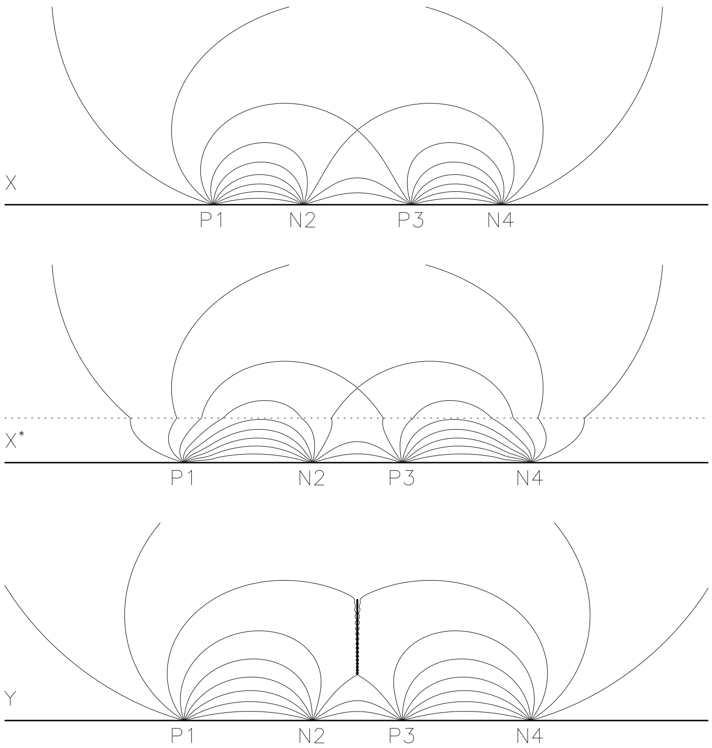
$$r \gg r_\eta \;=\; \sqrt{\frac{\eta}{\gamma_{\mathrm{A}}}} \;\simeq\; a\, S^{-1/2}$$

- Violated in time

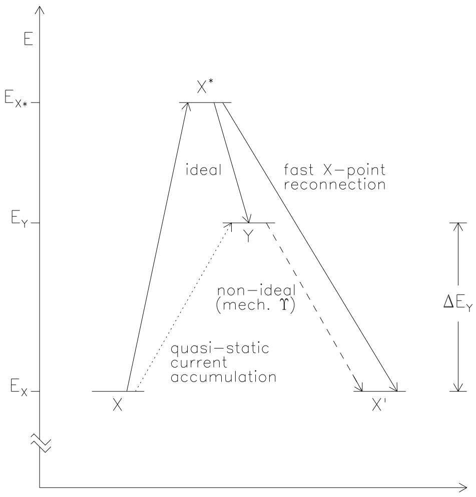
$$t \simeq \gamma_{\mathrm{A}}^{-1} \ln\left(\frac{a}{r_\eta}\right) \;=\; \tau_{\mathrm{A}} \ln S \qquad \text{FAST}$$

- Wave is absorbed — $\Delta\mathcal{E}$ dissipated
- *Bona fide* example of **Fast magnetic reconnection**
- Petschek scaling — no shocks
- Dissipates much energy in $t \sim \tau_{\mathrm{A}}$
- Flux transfer? — not relevant @ short times

Scenario B: Slow reconnection



- $X^* \;\rightarrow\; Y$ on times $\gg \tau_{\rm A}$
- ideal: $\psi_{23} = \Psi_X$ $(P3\text{–}N2)$ unchanged

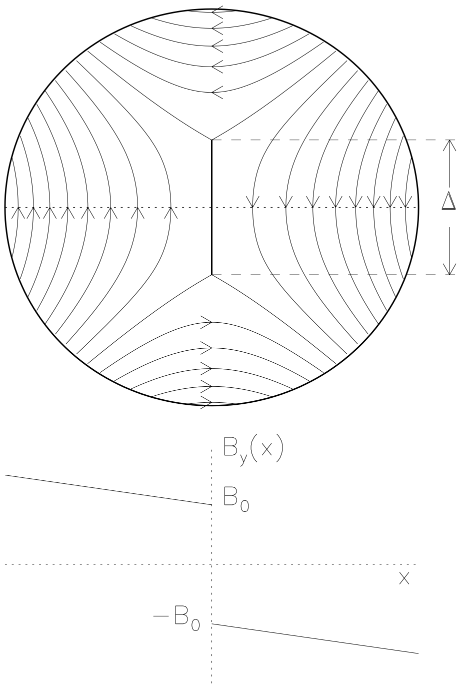


The singular equilibrium Y

- Minimize energy $\mathcal{E}\{\psi\} \quad \Longrightarrow \quad \nabla^2\psi = 0$

  solution: $\psi(x,y) \;=\; \frac{1}{2}B'(x^2 - y^2) \;+\; \text{const.}$

- Impose constraint on Ψ_X (ψ on sep'x) $\Longrightarrow \quad Y$



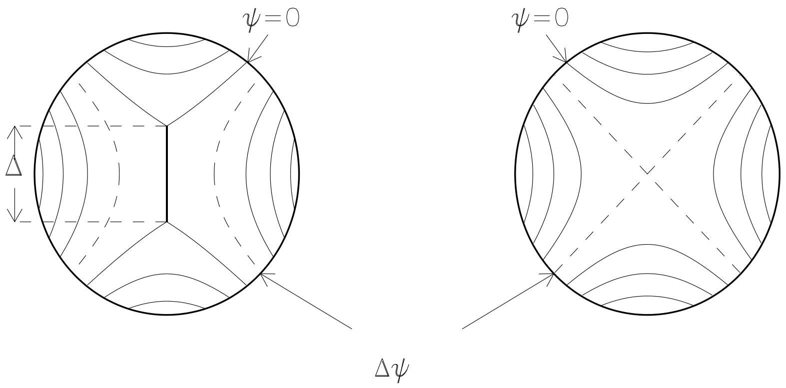
Current Sheet

- Discontinuity in $B_y(x)$
- $J_z(x) = \partial B_y/\partial x = -2B_0\delta(x)$
- Only when $\eta = 0$ (no diffusion of layer)
- Takes time to settle — approached in $t \gg \tau_\mathrm{A}$
- Forms @ interface between 4 domains

  $\boxed{\text{Topological signifance of X-point: separator}}$

Current Sheet properties ...

- ... depend on perturbation amplitude $\Delta\psi$
- ... and potential field shear: B'
- ... and *weakly* on global scale a



$$\Delta\psi \;\equiv\; \Psi_X \;-\; \Psi_X^{(\mathrm{vac})}$$

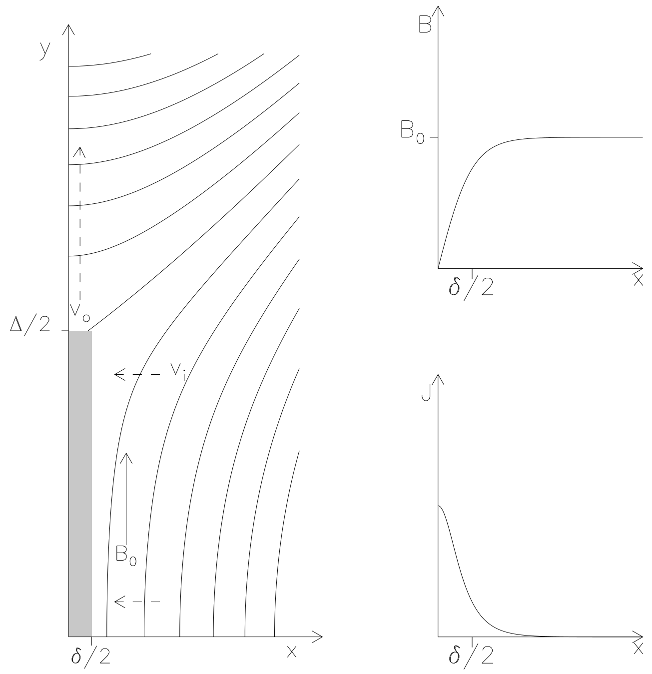
$$\Delta(\Delta\psi) \;\simeq\; \sqrt{\frac{\Delta\psi}{B'}}\,[\,\ln(a^2B'/\Delta\psi)\,]^{-1/2} \;\sim\; \sqrt{\Delta\psi/B'}$$

$$B_0(\Delta\psi) \;\simeq\; \sqrt{\Delta\psi B'}\,[\,\ln(a^2B'/\Delta\psi)\,]^{-1/2} \;\sim\; \sqrt{B'\Delta\psi}$$

$$I_Y(\Delta\psi) \;\simeq\; \pi\,\Delta\psi\,[\,\ln(a^2B'/\Delta\psi)\,]^{-1} \;\sim\; \Delta\psi$$

$$\Delta\mathcal{E}_Y(\Delta\psi) \;\equiv\; \mathcal{E}_Y \;-\; \mathcal{E}_{X'} \;\simeq\; (\Delta\psi)^2\,[\,\ln(a^2B'/\Delta\psi)\,]^{-1} \;\sim\; \Delta\psi^2$$

Effect of η on Current Sheet



<u>Sweet-Parker scaling:</u>
Mass conservation:

$$v_i\,\delta \sim v_o\,\Delta \sim v_{\mathrm{A}}\,\Delta \quad \text{(i)}$$

Flux transfer rate:

$$v_i\,B_0 \sim \eta J \sim \eta\,\frac{B_0}{\delta} \quad \text{(ii)}$$

$$\text{(i)/(ii)} \Rightarrow \;\; \delta \sim \Delta\left(\frac{v_{\mathrm{A}}\Delta}{\eta}\right)^{-1/2}$$

- Related to total current

$$I_Y \;=\; \frac{1}{4\pi}\oint \mathbf{B}\cdot d\mathbf{l} \;=\; \frac{1}{2\pi}\,B_{\mathrm{cs}}\Delta \qquad \text{cgs-emu}$$

- CS Lundquist number via $I_S = \eta\sqrt{\rho/\pi} = 10^{-2}$ A

$$S_{\mathrm{cs}} \;=\; \frac{v_{\mathrm{A}}\Delta}{\eta} \;=\; \frac{B_{\mathrm{cs}}\,\Delta}{\eta\sqrt{4\pi\rho}} \;=\; \frac{I_Y(\Delta\psi)}{I_S}$$

- Sweet-Parker scaling:

$$\delta \;\sim\; \Delta\left(\frac{v_{\mathrm{A}}\Delta}{\eta}\right)^{-1/2} \;\sim\; \Delta S_{\mathrm{cs}}^{-1/2} \;\sim\; \sqrt{\frac{I_S}{B'}} \quad \text{narrow sheet}$$

- $B' \sim 10^{-9}\,\mathrm{G/cm}$, $I_S \sim 10^{-3}\,\mathrm{G\,cm} \;\Longrightarrow\; \delta \sim 1000$ cm

The curses of of a narrow sheet…

- Flux transfer rate:

$$\dot{\psi} \;\sim\; \eta J \;\sim\; \frac{\eta I_Y}{\delta\Delta} \;\sim\; \gamma_{\mathrm{A}}\,\Delta\psi\,\left(\frac{\delta}{\Delta}\right)^{1/2}$$

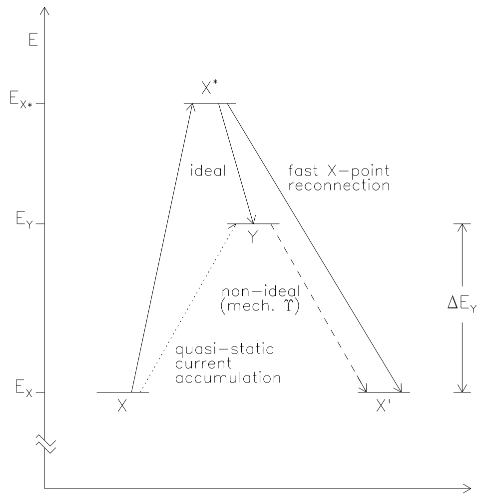
- Reconnection time:

$$\tau_{\mathrm{rx}} \;=\; \frac{\Delta\psi}{\dot{\psi}} \;\sim\; \gamma_{\mathrm{A}}^{-1}\left(\frac{\Delta}{\delta}\right)^{1/2} \;=\; \tau_{\mathrm{A}}\,S_{\mathrm{cs}}^{1/2} \;\gg\; \tau_{\mathrm{A}}$$

$$\begin{Bmatrix}\text{Slow reconn.}\\ (\tau_{\mathrm{rx}} \gg \tau_{\mathrm{A}})\end{Bmatrix} \Leftrightarrow \begin{Bmatrix}\text{narrow sheet}\\ (\delta \ll \Delta)\end{Bmatrix} \Leftrightarrow \begin{Bmatrix}\text{large perturb.}\\ (\Delta\psi \gg I_S)\end{Bmatrix}$$

- Sweet-Parker reconnection

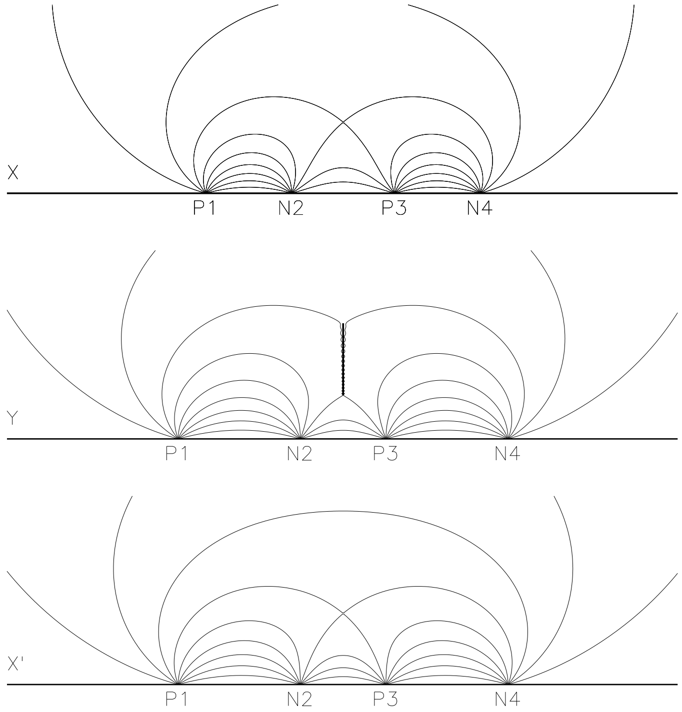
- Slow increase in $\Delta\psi$
  $\Longrightarrow$ Quasi-static current accumulation (QSCA)

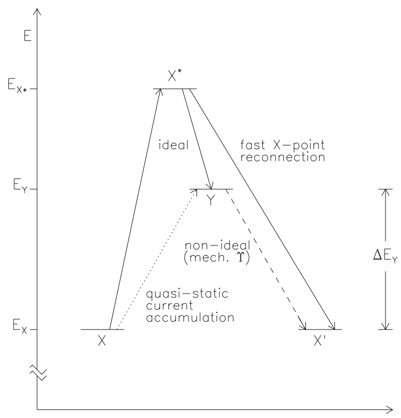


- Current sheet — energy storage

- Sweet-Parker reconnection is **Non-reconnection**

II. A Hybrid Alternative





QSCA punctuated by fast reconnection

- CS accumulates energy
- Forever? – No.
- Releasing energy $\Delta\mathcal{E}_Y \Longleftarrow$ transfering flux: $\psi_{23} \rightarrow \Psi_X^{(\mathrm{vac})}$
- Must transfer $\Delta\psi$ across sheet
- Energy stored globaly — release by localized means
- Hypothetical fast non-ideal process in CS
  — **mechanism-**Υ

Requirements for mechanism-Υ —

- Inactive during storage
- Transfer flux rapidly (i.e. large $E_{\|}$)
- Localized to current sheet
- Energy release rate

$$P_Y \;=\; -\frac{d\Delta\mathcal{E}_Y}{dt} \;=\; \frac{\partial\Delta\mathcal{E}_Y}{\partial\Delta\psi}\,\frac{d\Delta\psi}{dt} \;=\; I_Y\,\dot{\psi}$$

- Must exceed dissipation (by e.g. resisitivity)

$$\frac{P_\eta}{P_Y} \;=\; \frac{P_\eta}{I_Y\dot{\psi}} \;\lessapprox\; 1$$

- Must be as good if not better at flux transfer

$$\underbrace{P_\eta}_{\text{dissipation}} \quad \lessapprox \quad \underbrace{\dot{\psi}\,\Delta\psi}_{\text{transfer}}$$

- Sweet-Parker slow, but checks out $P_\eta \sim S_{\rm cs}^{-1/2} \sim \dot{\psi}$
- Flux pile-up (fast) does not: $P_\eta \sim S_{\rm cs}^{-1/3} \gg \dot{\psi} \sim S_{\rm cs}^{0}$

III. Extension to Corona — 3 dimensions

Set-up

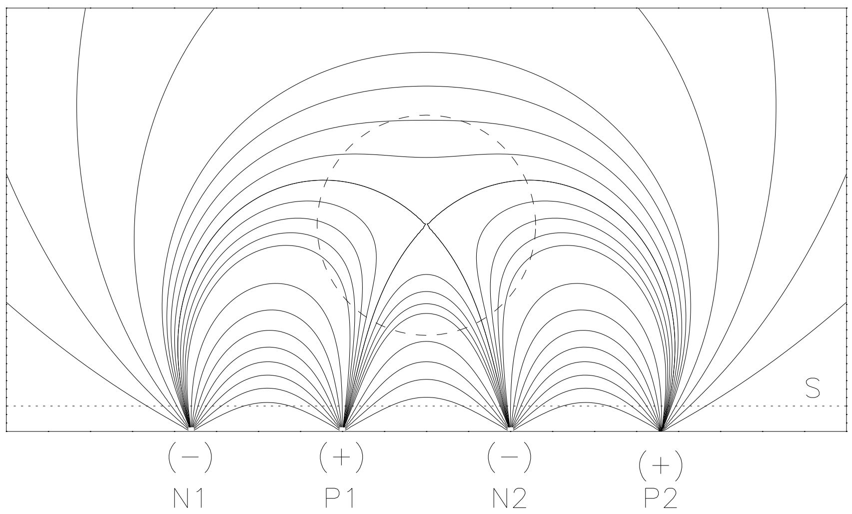
- Medium AR — two bipoles
  - $\Phi \sim 10^{22}$ Mx
  - $L \sim 10^{10}$ cm
- Medium compact flare — $\Delta\mathcal{E} \sim 10^{30}$ erg
- typical impulsive phase — $\Delta t_{\rm imp} \sim 300$ sec

Task — explain event as reconnection

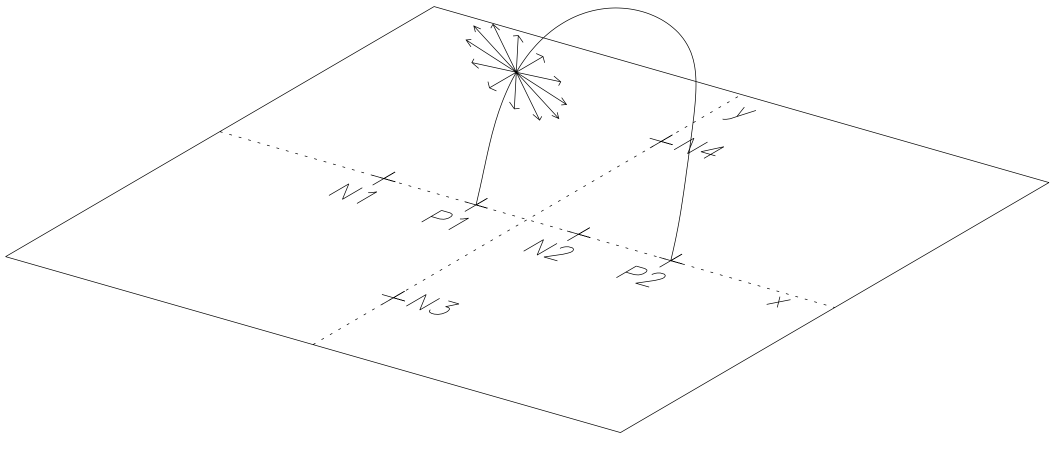
- Energy release rate $P \sim 3 \times 10^{27}$ ergs/sec
- Transfer flux $\Delta\Phi = f\Phi$ —
  transfer rate $\dot{\Phi} \sim 3 \times 10^{18} f$ Mx/sec

Dynamical Reconnection (null-point collapse)

- ∘ disturbance implodes
- ∘ asymptote of characteristics — magnetic null: $\mathbf{B} = 0$

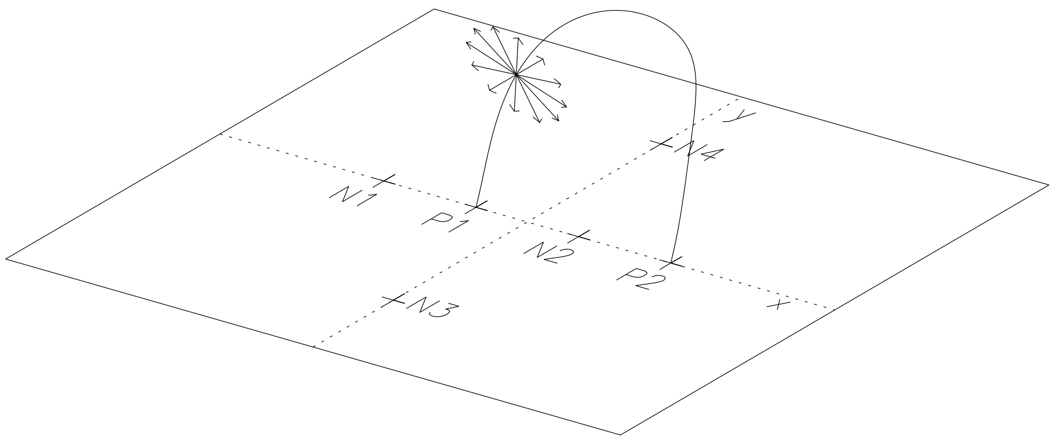


- ∘ 3d — break symmetry



- ∘ Null in corona
- ∘ “Spines” connect to like-sign footpoints

Dynamical (fast) reconnection in a flare...



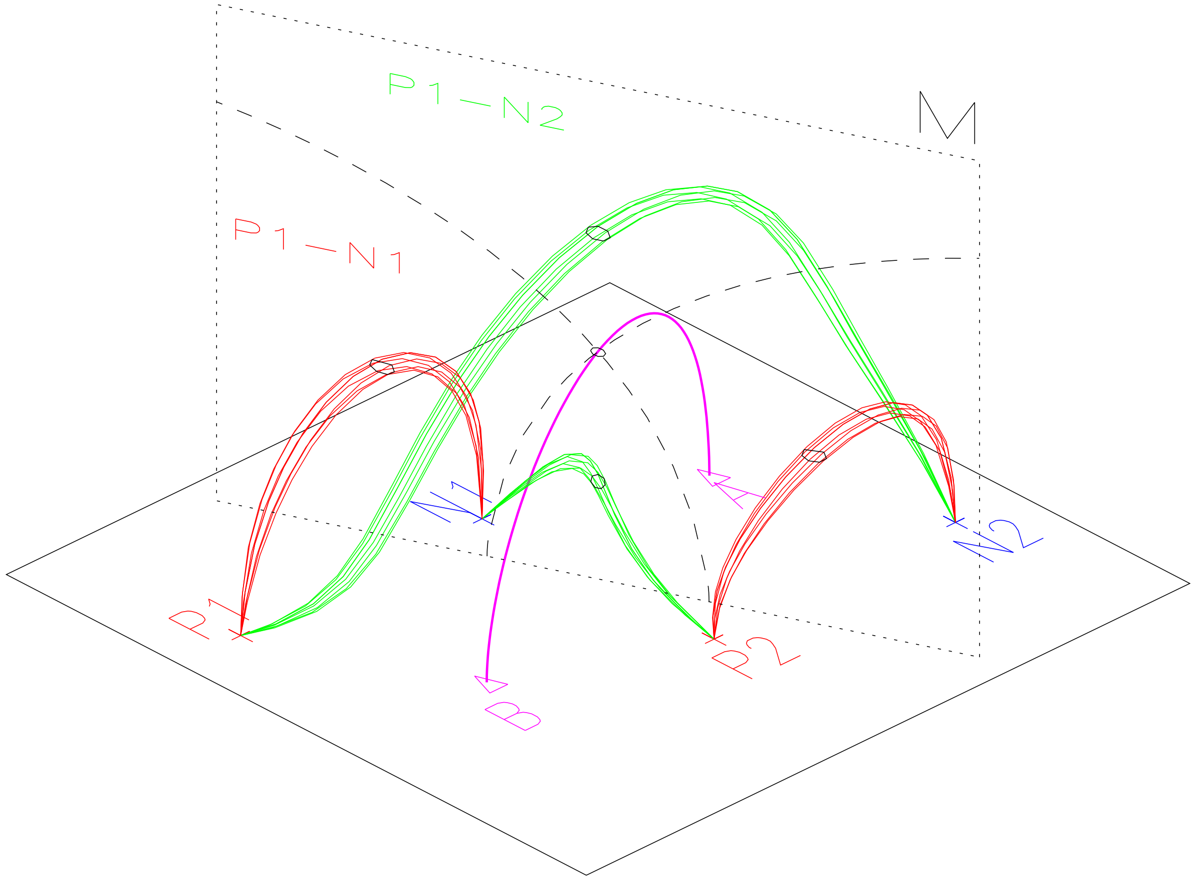
- Disturbance energy — wave

$$F_{\mathrm{wave}} \;\sim\; \sqrt{\rho}\,\Phi\,\langle v^2\rangle \;\sim\; 10^{25}\,\Phi_{22}\,\langle v_5^2\rangle \text{ erg/sec}$$

- requires $v \;\sim\; 10$ km/sec
- disturbance life $\;\sim\;$ impulsive phase
- Homologous flare $\Longleftrightarrow$ repeating disturbances
- Current enhanced along spines (Craig & Fabling 1996)
  $\Longrightarrow$ SXR loop w/ like-sign footpoints?
- Only some AR have coronal null (non-generic)
  $\Longrightarrow$ fraction of non-flaring ARs

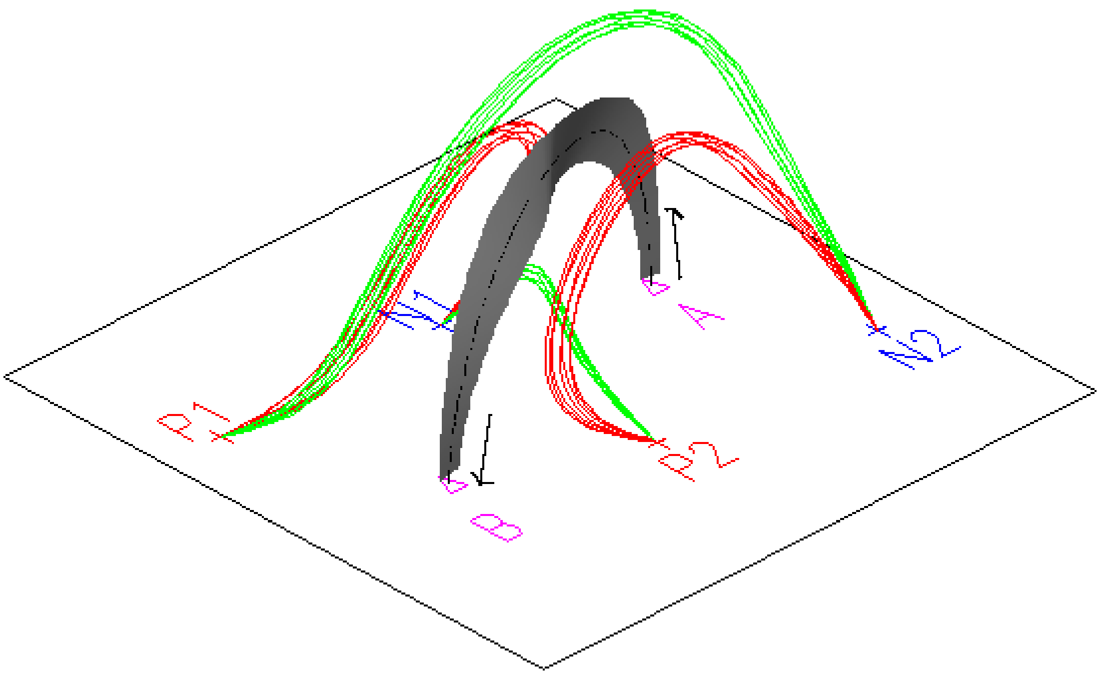
Topological (slow-punctuated) reconnection

- 2 bipoles $\Longrightarrow$ 4 flux domains
- Interface between all 4: **separator** (top'l analog of X-point)



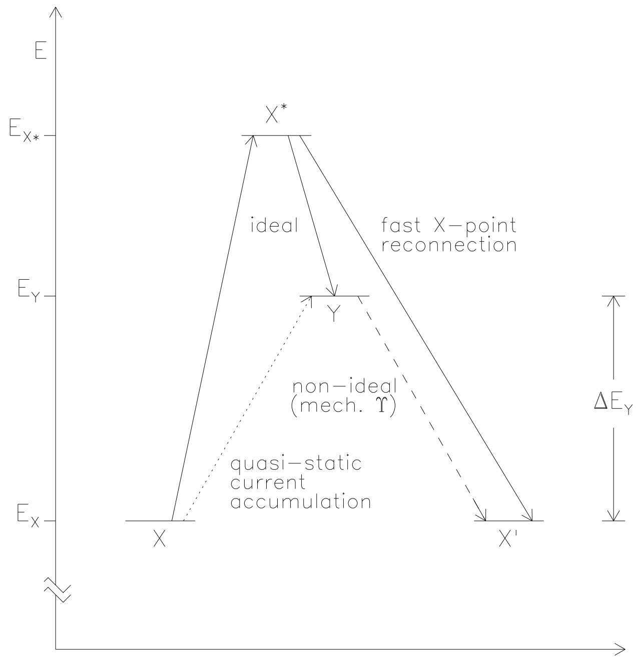
- No coronal nulls — $B \neq 0$ on separator

- ∘ Move poles slowly — $\dot{\Phi} = 0$
- ∘ Current ribbon forms at separator



- ∘ Current from circuit theory (taking $f = 3\%$)

$$I_Y(\Delta\Phi) \;\simeq\; \frac{\Delta\Phi}{L}\,[\,\ln(\Phi/\Delta\Phi)\,]^{-1}$$
$$\simeq\; \frac{f}{\ln(1/f)}\,10^{12}\,\mathrm{G\,cm} \;\sim\; 10^{11}\,\mathrm{Amp}$$



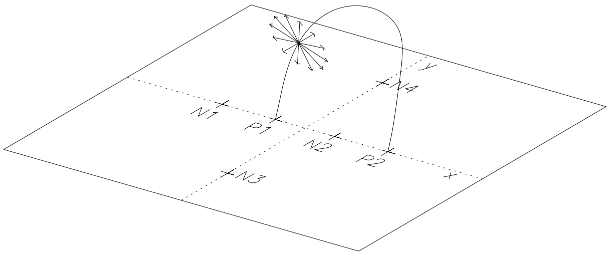
- Poles moving @ 0.1 km/sec
- Displacing to $\Delta\Phi = 0.03\Phi$ takes 8 hours $\gg \ \tau_{\rm A}$
- Stores energy in current sheet

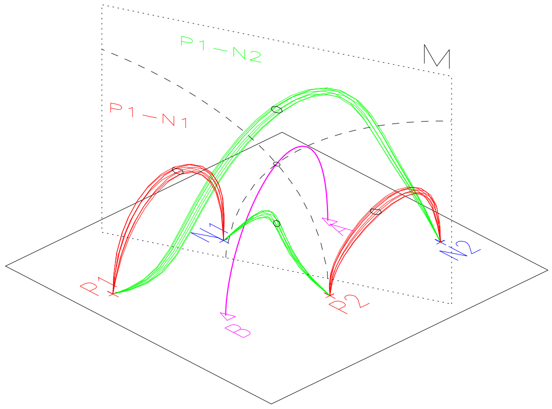
$$\Delta\mathcal{E}_Y \ \simeq \ 10^{34}\,\frac{f^2}{\ln(1/f)}\,\text{ergs} \ \sim \ 3\times 10^{30}\,\text{ergs}$$

- Work done by p-sphere against 10^{22} dyne force
- Flux storage: 10^{16} Mx/sec $\ = \ 10^8$ Volts
- Sweet-Parker undoes: 10^{11} Mx/sec $\ = \ 1000$ Volts
- Mechanism-ϒ transfers 10^{18} Mx/sec $\ = \ 10^{10}$ Volts
- Energy release

$$I\,V \ = \ 10^{11}\,\text{A}\times 10^{10}\,\text{V} \ = \ 10^{21}\,\text{W} \ = \ 10^{28}\,\text{erg/sec}$$

Comparison: Fast vs. Slow-puncutated





	FAST	**PUNCTUATED**
Location (3d)	Coronal magnetic null point (rare)	Separator line (ubiquitous)
Significance	Dynamical: focus of wave characteristics	Topological: interface between domains
Energy	Waves transmitted over time $\sim$ flare duration	Global field energy stored slowly
Role of current sheet	Dissipate energy in short times	Energy storage & localized trigger site
Non-ideal mechanism	Energy dissipation	Mechanism-Υ: $E_{\parallel}$ transfers flux between domains

Conclusions

- Dynamical (fast) reconnection
  - 2d — @ X-point ($\mathbf{B}_\perp = 0$)
  - 3d — @ null point ($\mathbf{B} = 0$) — 0d
  - Energy dissipation $\Longrightarrow$ no time for storage
  - 2d models suggest only small disturbances work

$$\Delta\psi \lessapprox I_S \sim 0.01\,\mathrm{Amps}$$

- Topological (slow-punctuated) reconnection
  - 2d — @ X-point ($\mathbf{B}_\perp = 0$)
  - 3d — @ separator field line — 1d
  - Energy stored by current sheet
  - 2d models suggest only large disturbances work

$$\Delta\psi \gtrapprox I_S \sim 0.01\,\mathrm{Amps}$$

  - Requires hypothetical mechanism-Υ
    - Inactive over long times
    - Initiated (triggered) quickly
    - Transfers flux rapidly
    - Energy dissipation? not necessary
    - Works in adverse geometry ($\delta \ll \Delta$)