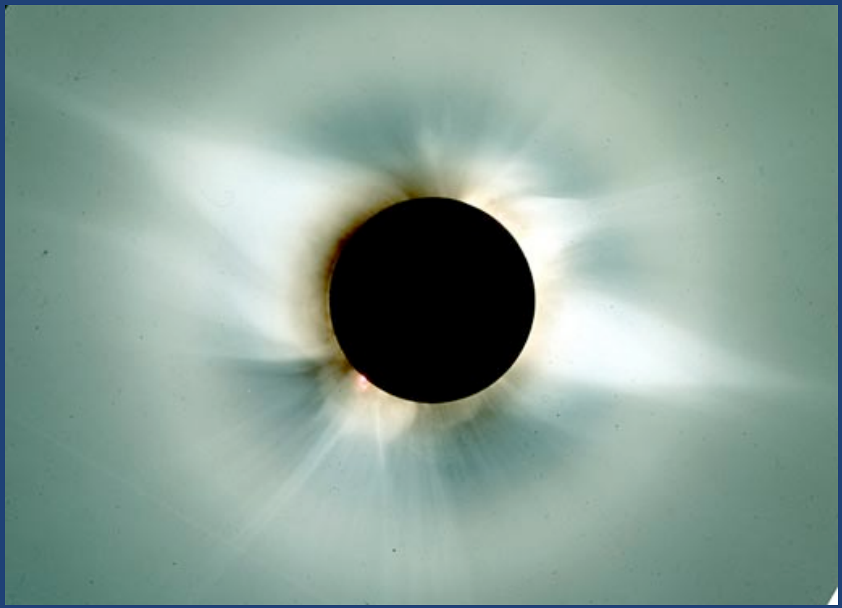
Extending Hall Reconnection to Large-scale Reconnection in the Corona



Paul Cassak, West Virginia University

Contributors -
James Drake[1], Michael Shay[2],
Bruno Eckhardt[3], Dermott Mullan[2]
Kittipat Malakit[2], and Lucas Shepherd[4]

[1]University of Maryland
[2]University of Delaware
[3]Phillipps-Universität Marburg
[4]West Virginia University

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Overview

- **Hall reconnection takes place at ion gyroscale $\delta_k = d_i, \rho_s$**
  - Magnetosphere: Many observations
  - Laboratory: Ren et al., 2005; Cothran et al., 2005; Frank et al., 2006
  - Corona: No direct observations, but reconnection electric fields are super-Dreicer, so Hall reconnection possible (probable?)

- **Separation of scales**
  - Magnetotail: $d_i \sim 0.1\ R_E$, system size $L \sim 100\ R_E \sim 1000\ d_i$
  - Corona: $d_i \sim 100\ cm$, system size $L \sim 10^9\ cm \sim 10^7\ d_i$

- **Sweet-Parker reconnection?**
  - Magnetotail: $\delta_{SP} \sim 320\ cm << d_i \Rightarrow$ should never occur (with Spitzer η)
  - Corona: $\delta_{SP} \sim 200\ cm \sim d_i \Rightarrow$ may occur
  - Secondary islands in Sweet-Parker arise for large $S > 10^4$

- **Issues of scaling to large systems (in the corona)**
  - What is reconnection dynamics in system with both Sweet-Parker and Hall reconnection available, and how does Hall reconnection onset? (Topic 1)
  - How do secondary islands in Sweet-Parker change the picture? (Topic 2)
  - Are there observable ramifications?

When Sweet-Parker? When Hall?

- Previous knowledge of onset of Hall reconnection
  - Reconnection gets faster when thickness of layer reaches kinetic scales (Aydemir, 1991; Wang and Bhattacharjee, 1993; Mandt et al., 1994; Ma and Bhattacharjee, 1996; …)
- Consider the generalized Ohm's Law (Vasyliunas, 1975)

$$\delta_{SP} \sim \sqrt{\frac{\eta c^2}{4\pi c_A} L_{SP}}$$

δ = thickness

L = length

$$\vec{E} + \frac{\vec{v}_i \times \vec{B}}{c} = \eta \vec{J} + \frac{1}{nec} \vec{J} \times \vec{B} - \frac{1}{ne} \vec{\nabla} \cdot \overleftrightarrow{p}_e - \frac{m_e}{e} \frac{d\vec{v}_e}{dt}$$

Convection | Resistivity | Hall Effect | Electron Pressure | Electron Inertia

Sweet-Parker is valid when
Convection ~ Resistivity » Hall

$$\delta_{SP} > \delta_k = \{c/\omega_{pi} \text{ or } c_s/\Omega_{ci}\}$$

$$\hat{\eta} > \frac{\delta_k}{L_{SP}}$$

Hall reconnection is valid when
Convection ~ Hall » Resistivity

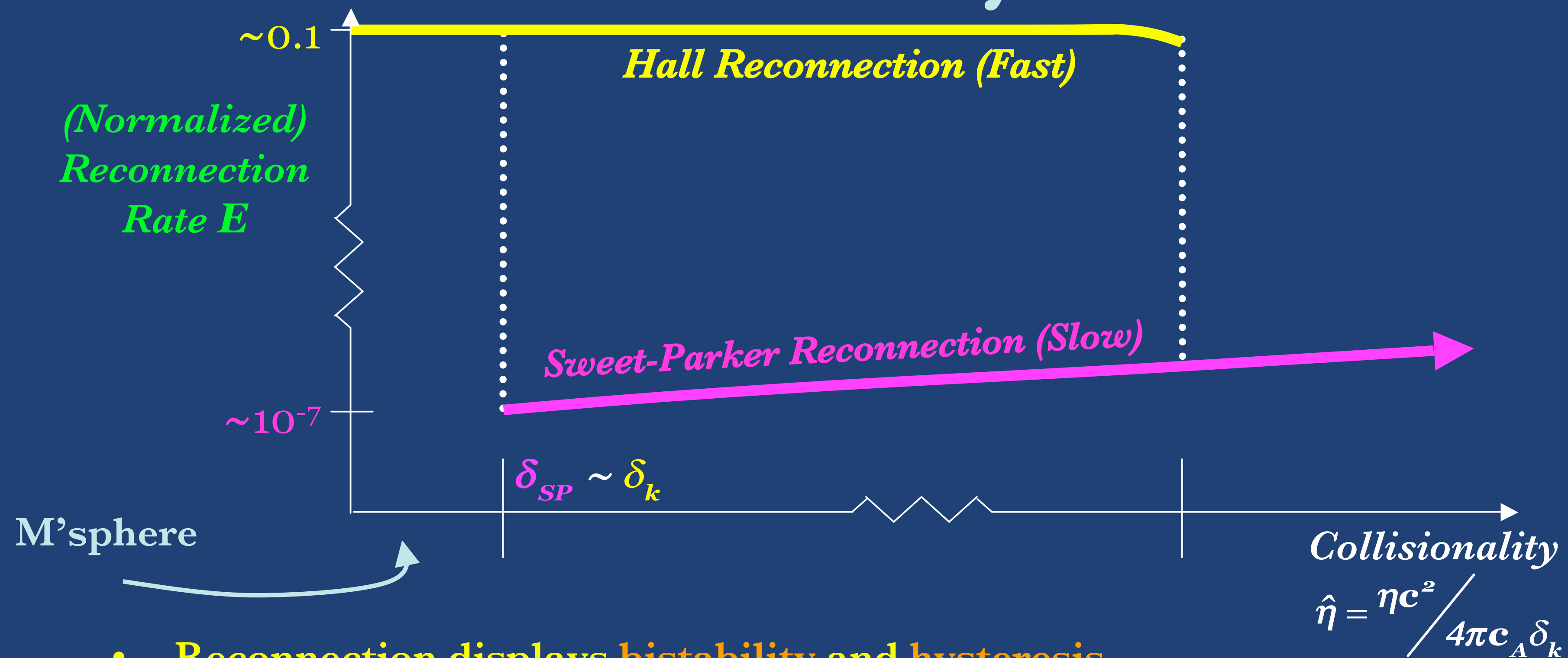
$$\left(\vec{v}_e \cdot \vec{\nabla}\right) B_x > \frac{\eta c^2}{4\pi} \nabla^2 B_x$$

$$\hat{\eta} < 0.1$$

- These are very different conditions! (Cassak et al., 2005)
  - This is because convection is much larger (10^6 times for solar flares!) during Hall reconnection than it is during Sweet-Parker reconnection.

$$\hat{\eta} = \frac{\eta c^2}{4\pi c_A \delta_k}$$

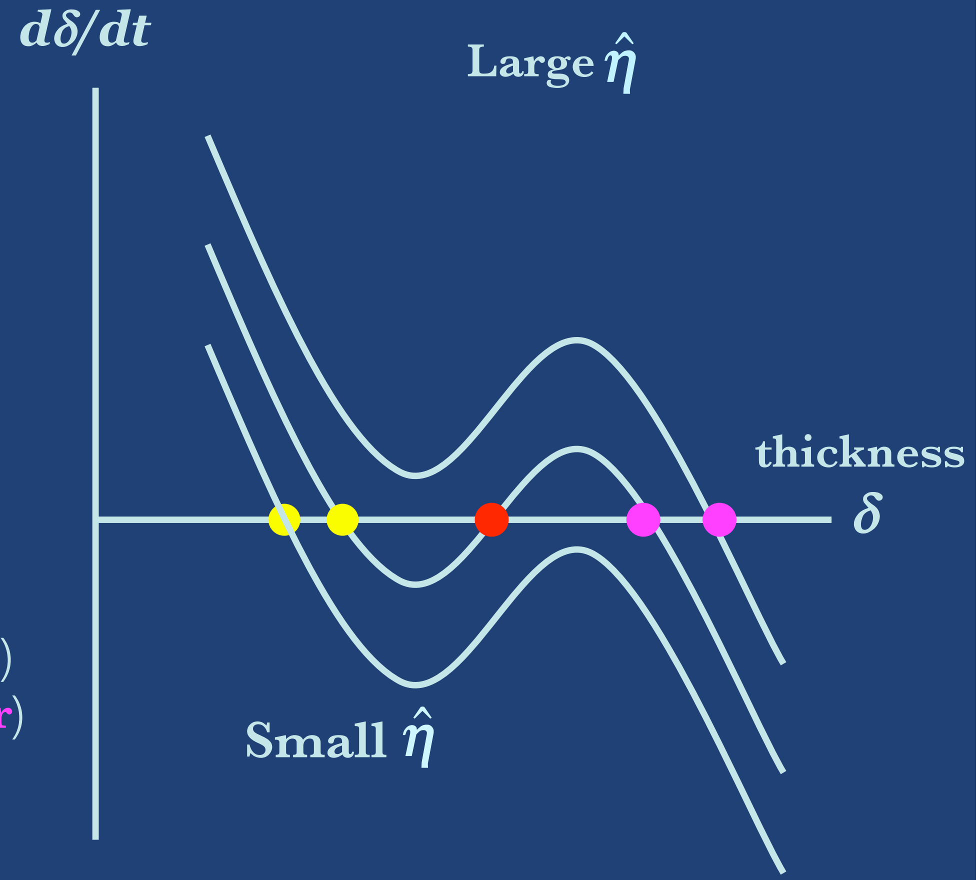
Reconnection Dynamics



- Reconnection displays bistability and hysteresis
  - Verified with (low *S*) simulations (Cassak et al., 2005; 2007)
- Hall reconnection onsets catastrophically
  - Occurs when thickness δ_{SP} of Sweet-Parker layer reaches kinetic scale δ_k
  - Observed in reconnection experiments (Ren et al., 2005; Egedal et al., 2007) and collisional particle-in-cell simulations (Daughton et al., 2009)

Interpretation with Bifurcation Theory

- **Bistability/hysteresis** is well known in nonlinear dynamics
  - "Saddle-node bifurcations" bring fixed points into/out of existence as a control parameter ($\hat{\eta}$) is varied (Cassak et al., submitted)



- (yellow dot) = Stable fixed point (**Hall**)
- (red dot) = Unstable fixed point (**Unknown!**)
- (magenta dot) = Stable fixed point (**Sweet-Parker**)

Predicts the existence of an unstable reconnection solution!

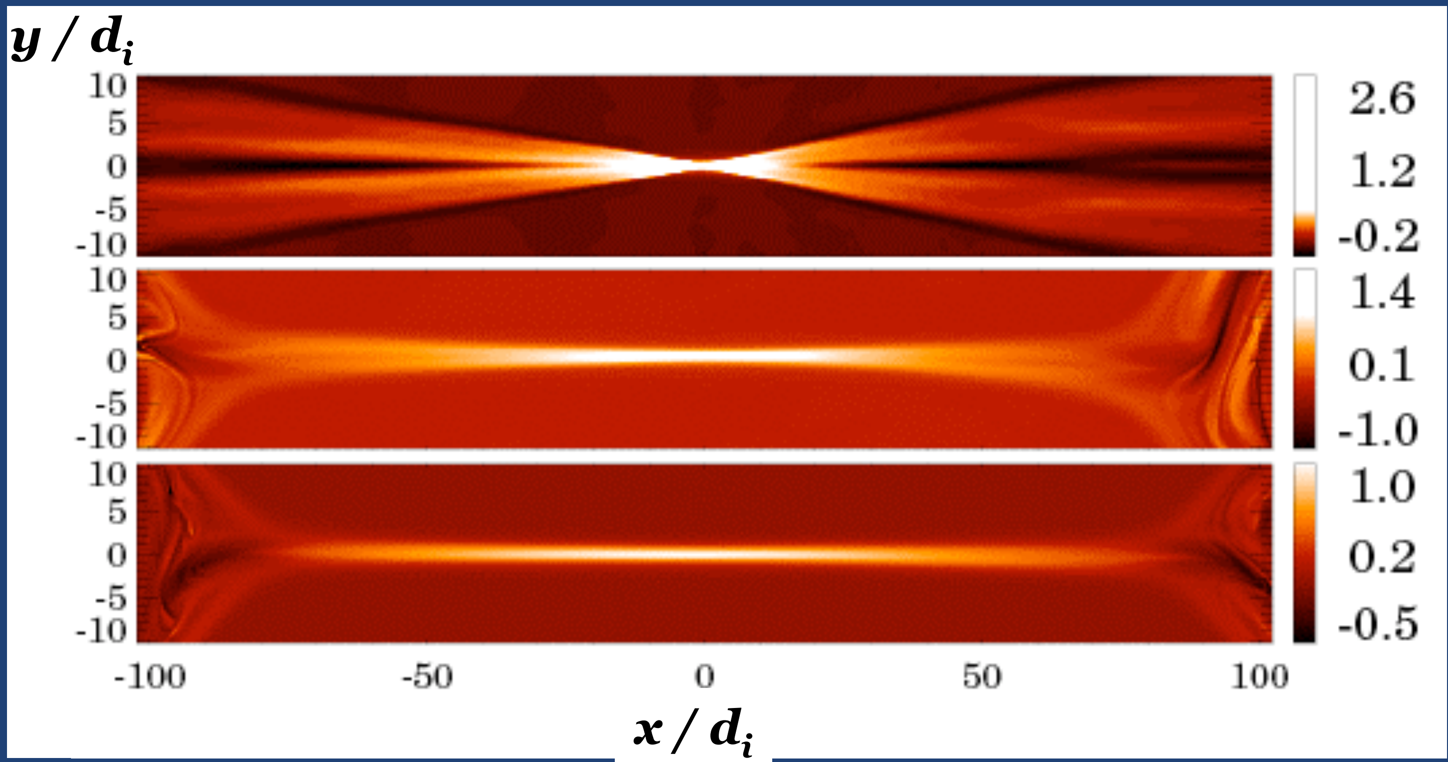
The Unstable Equilibrium

- We used a novel iterative technique (Skufca et al., 2006) to find the unstable solution (Cassak et al., 2007).
  - Out of plane current density J_z for the unstable solution for η = 0.015

Hall (Fast)

Unstable (Intermediate)

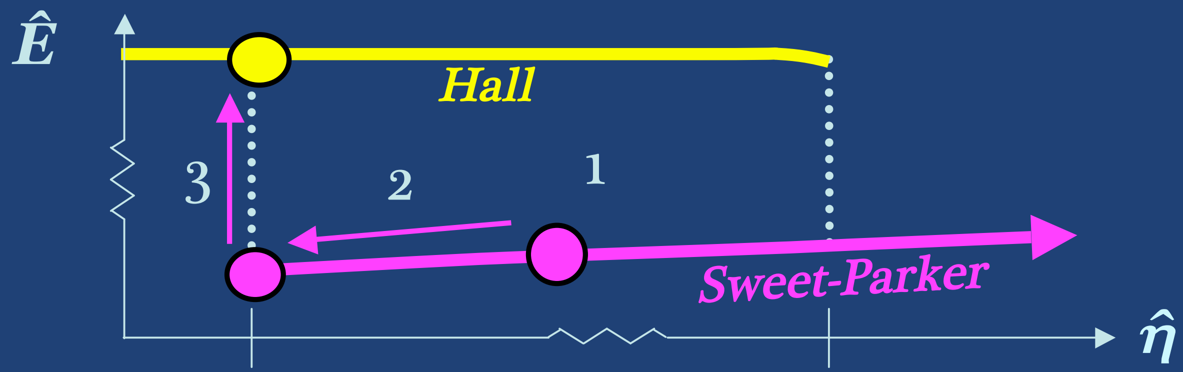
Sweet-Parker (Slow)



The unstable solution is a hybrid of the Sweet-Parker and Hall solutions
- Interesting implications about dynamics!

Onset Model

1) Before an eruption, reconnection in the corona must be collisional
   - If it wasn't, the stored energy would be released!
   - Reconnection is slow (Sweet-Parker), so magnetic energy accumulates
2) Something drives the corona to a state of lower collisionality
   - Hall reconnection does not begin because reconnection is bistable
3) When $\delta_{SP} \sim \delta_k$, system undergoes a bifurcation
   - Hall reconnection onsets catastrophically
   - The stored energy is rapidly released, manifested as an eruption
4) Reconnection in the post-eruption corona is again collisional, and the process repeats



Note - slow, then fast reconnection inferred in corona (Ron Moore's talk).
Other example - flux emergence reconnection (Longcope et al., 2005)

Effect of Secondary Islands

- **Secondary islands in Sweet-Parker reconnection spontaneously occur when $S > S_{crit} \sim 10^4$ (Biskamp, 1986)**
  - **Also occur in presence of externally imposed turbulence (Matthaeus and Lamkin, 1985 & 1986; Lazarian and Vishniac, 1999)**
    - **Classical Sweet-Parker *cannot* be relevant in the corona where $S \sim 10^{13\text{-}14}$**
    - ***To be distinguished from secondary islands in collisionless reconnection (Li-Jen Chen, Bill Daughton talks)***

- **Secondary islands make Sweet-Parker reconnection faster**

  (Matthaeus & Lamkin, 1985-6; Kliem, 1995; Lazarian & Vishniac, 1999; Shibata & Tanuma, 2001; Fan et al., 2004; Smith et al., 2004; Lapenta, 2008; Kowal et al., 2009; Daughton et al., 2009; Loureiro et al., 2009; Bhattacharjee et al., 2009; Cassak et al., 2009; …)

- **Open Questions:**
  - **How much faster than Sweet-Parker?**
  - **How many secondary islands appear for given *S*?**
    - **Linear theory (Loureiro et al., 2007) predicts $N \sim S^{3/8}$. Holds nonlinearly?**
  - **How do secondary islands impact Sweet-Parker reconnection?**
    - **If it remains *slow*,**
      - **how much do secondary islands hasten onset of Hall reconnection?**
      - **does *E* exceed Dreicer field E_D?**
    - **If it becomes *fast*,**
      - **how does magnetic free energy accumulate before an eruption?!?**

Scaling of Reconnection Rate

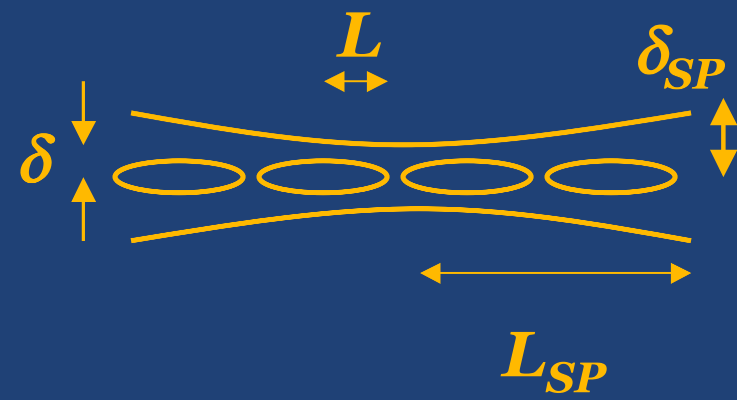
- **Recent Hypothesis**
  - Fragmented sheets described by Sweet-Parker model (Daughton et al., 2009)
  - Thickness of fragmented sheets scales as

$$\delta \sim \sqrt{\frac{\eta c^2}{4\pi c_A} L} \sim \frac{\delta_{SP}}{\sqrt{N}}$$

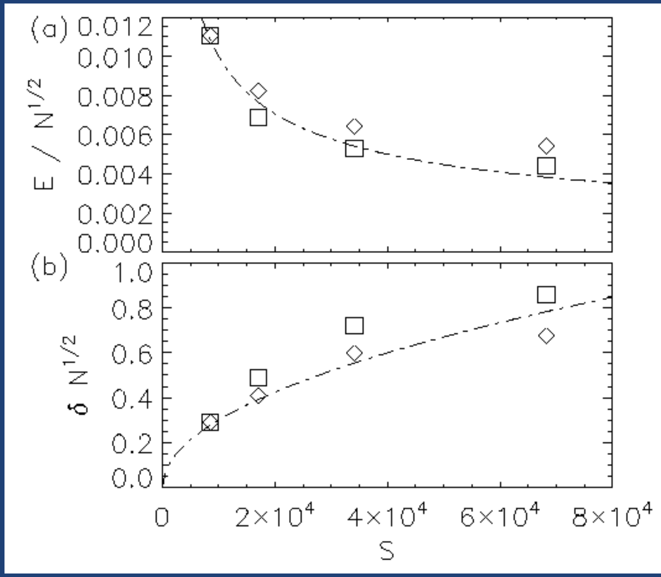
Reconnection rate scales as (Cassak et al., 2009)

$$E' \sim \frac{cE}{Bc_A} \sim \frac{\delta}{L} \sim E'_{SP}\sqrt{N}$$

    - Predicts thinner layers, faster reconnection (Shibata & Tanuma, 2001)



- **Numerical test (Cassak et al., 2009)**
  - Plot time-averaged values during sufficiently "quasi-steady" evolution
    - Simplistic prediction pretty good!



- **Caveats**
  - Only up to $S \sim 7 \times 10^4$
  - "Sufficiently quasi-steady"
    - Omitted times when island gets "stuck" (E plunges) and when island starts moving again (E spikes).
    - Ignores hierarchical island formation (Shibata and Tanuma, 2001; Daughton et al., 2009; Bhattacharjee et al., 2009)

Embedded Reconnection

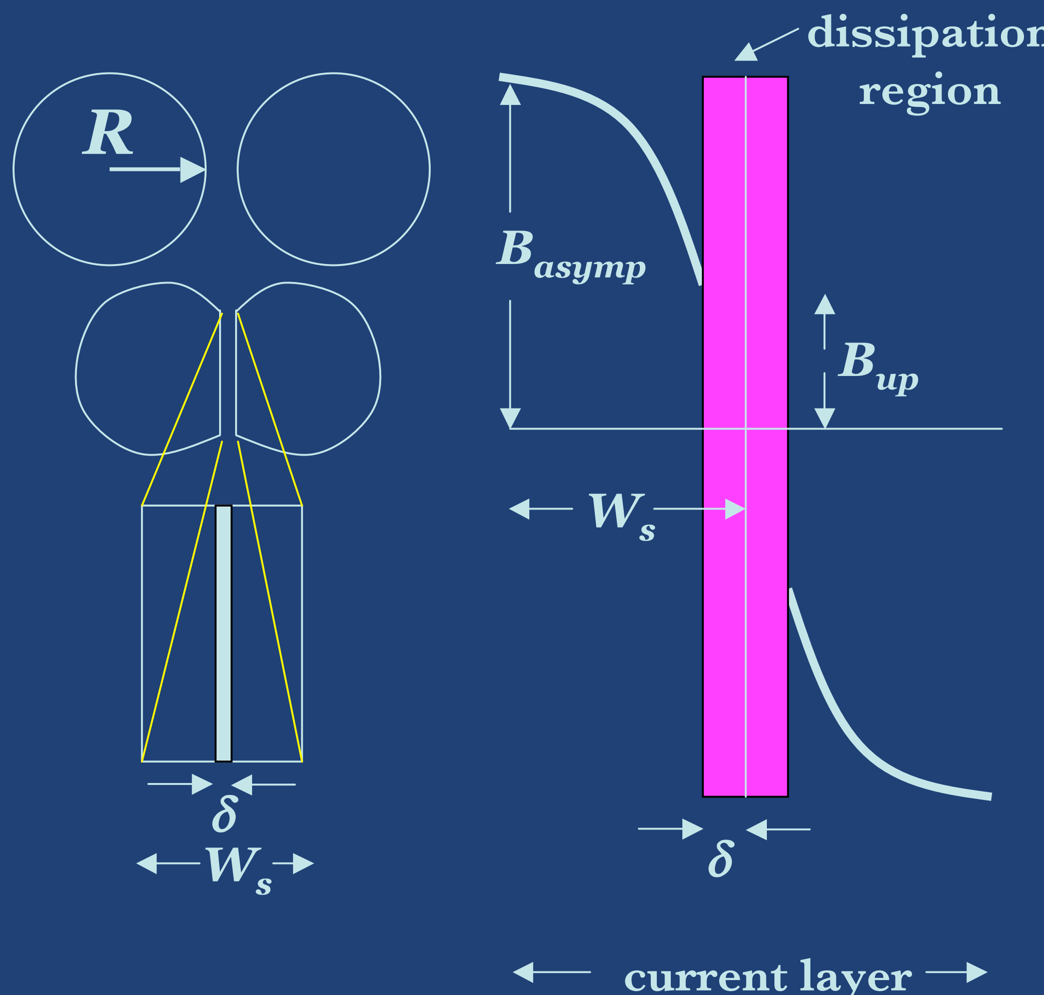
- **In corona:**
  - Flux tube radius $R \sim L_{SP} \sim 10^9$ cm
  - Thickness of current sheet $W_s \sim 10^8$ cm
  - Thickness of dissipation region $\delta \sim 10$ cm

    $\Rightarrow \delta \ll W_s$

  - B_{asymp} = global (asymptotic) field
  - B_{up} = upstream field

    $\Rightarrow B_{up} \ll B_{asymp}$

    $\Rightarrow$ embedded reconnection



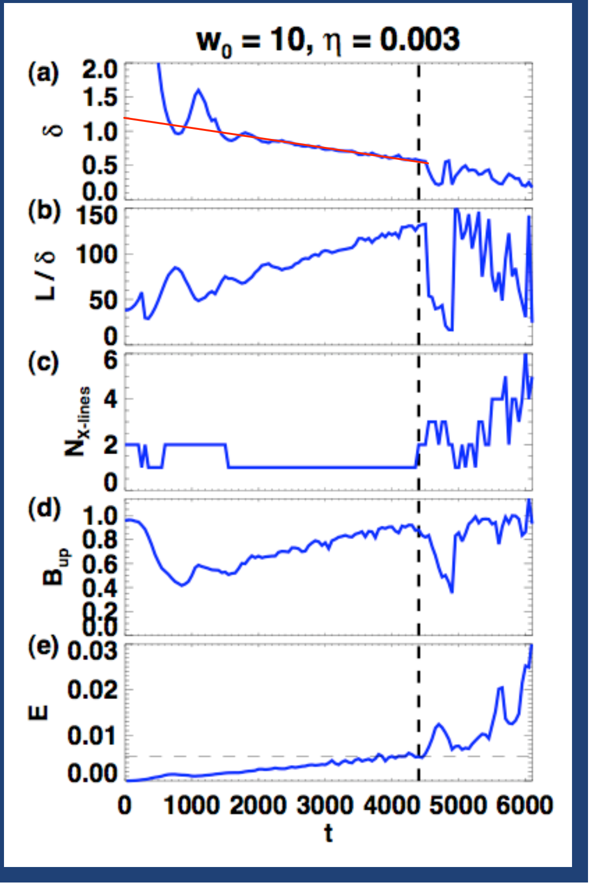
Cassak et al., 2006

Embedding and Secondary Islands

- **Secondary island condition is $S > S_{crit} \sim 10^4$ (Biskamp, 1986)**
  - Is S based on B_{up} or B_{asymp}?!? (Hypothesis - B_{up})

$$S \sim \frac{4\pi c_A L}{\eta c}$$

- **Simulations (MHD, 2D, …) (Cassak and Drake, 2009)**
  - Choose η, L such that $S_{asymp} > S_{crit} > S_{up}$. (Here, $S_{asymp} = 2.5 \times 10^4$)
  - Make $W_{s0} \gg \delta_{SP}$ (Here W_{s0} - 5, 10, 15)
    - None initially has secondary islands
    - Thickness δ decreases, B_{up} increases in time
    - Secondary islands occur when $L / \delta \sim 130$



- **Can estimate thickness δ**
  - Use SP theory and $B_{up} \sim B_{asymp}\, \delta / W_s$

$$\delta \sim \left(\frac{W_s L_{SP}^2}{S_{asymp}}\right)^{\frac{1}{3}} \sim \left(W_s \delta_{SP,asymp}^2\right)^{\frac{1}{3}}$$

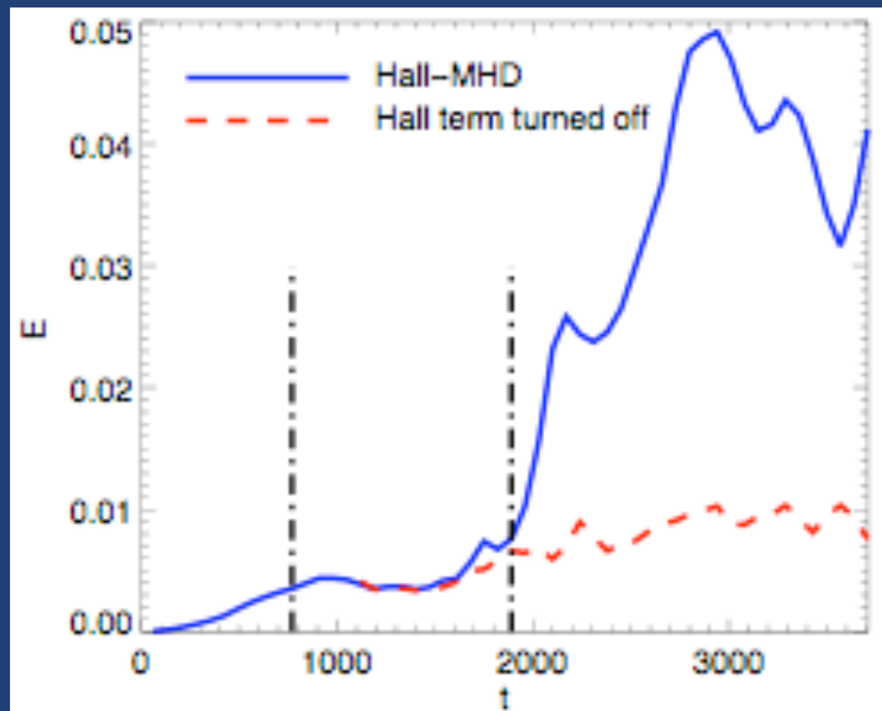
- **Effect of embedded reconnection**
  - Postpones onset of secondary islands relative to prediction based on asymptotic field
  - Makes diffusion region thicker than prediction based on asymptotic field - *can be substantial*!

Onset with Secondary Islands

- Question - How do secondary islands during Sweet-Parker reconnection influence onset of Hall reconnection?
  - Some argue secondary islands alone are sufficient to make reconnection fast (Lazarian and Vishniac, 1999; Lapenta, 2008)
  - Others argue secondary islands do not (necessarily) make reconnection fast, but hastens onset of collisionless effects due to thinner current sheets (Shibata and Tanuma, 2001)
    - Confirmed in PIC (Daughton et al., 2009) and MHD (Cassak et al., 2009) simulations
      - PIC simulations in regime where secondary island formation immediately leads to fast reconnection; MHD simulations did not contain Hall physics

Are secondary islands sufficient to give fast reconnection or is Hall effect necessary?

Simulation Results



← $E_{Hall} \sim 0.04$

← $E_{SI} \sim 0.009$

← $E_{SP} \sim 0.006$

Secondary island appears

Hall reconnection onset

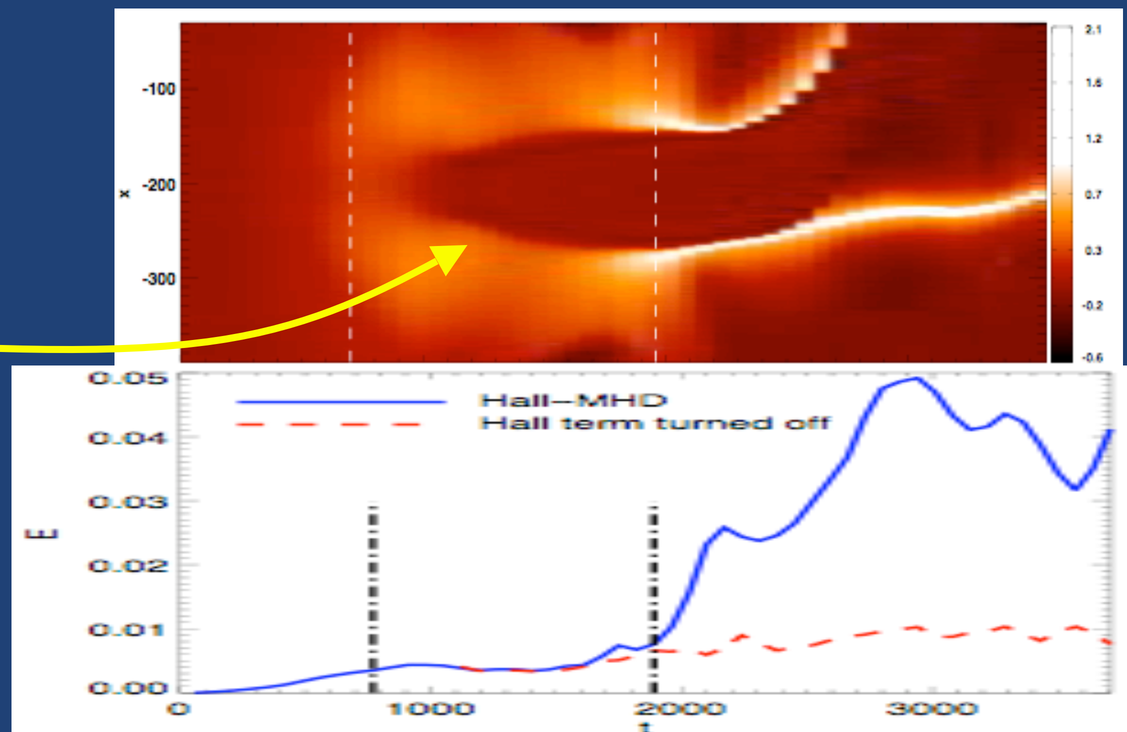
- Distinct period with secondary islands before Hall onset occurs
- For these parameters, $E_{SP} \sim E_{SI} < E_H$

Shepherd and Cassak, in prep.

Dynamics with Secondary Islands

- *y* axis - Cut of J_z in outflow direction
- *x* axis - time

secondary island



- *y* axis - cut of $E_{Hz} = J_y B_x / n$ in inflow direction

- Secondary islands appear long before transition to Hall
  - Supports notion (Shibata and Tanuma, 2001; Daughton et al., 2009) that they makes current thinner which reaches kinetic scales
  - Does not support notion that they make reconnection “fast” on their own

Summary/Conclusions

- **Reconnection at low *$S < 10^4$***
  - **Reconnection in this parameter regime is bistable**
    - Sweet-Parker or Hall reconnection dependent on time history
      - Potentially helps explain energy storage
    - Transition to Hall reconnection is catastrophic
      - Potentially helps explain abrupt onset
    - Corona evolves toward lower collisionalities
      - May explain regulation of coronal temperature

- **Secondary islands alter classical Sweet-Parker picture**
  - Make reconnection faster, dependent on number of islands
    - Scaling of number of islands unknown
  - Embedded effects are very important in corona
  - Secondary islands so far seem to hasten onset due to Hall effect
  - Cannot yet determine whether secondary islands make Sweet-Parker reconnection fast
    - Biggest simulations to date (Bhattacharjee et al., 2009)
      - $E_{SP} \sim 10^{-3}$, $E_{SI} \sim 10^{-2}$, $E_H \sim 10^{-1}$

Thank you!