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Scaling of magnetic reconnection with a limited x-line extent

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Motivation

- Previous studies of magnetic reconnection, x-line is infinitely long:

1. 2D
2. 3D with periodic boundary condition in the x-line direction

- Question:
- How does reconnection work with a finite x-line extent?

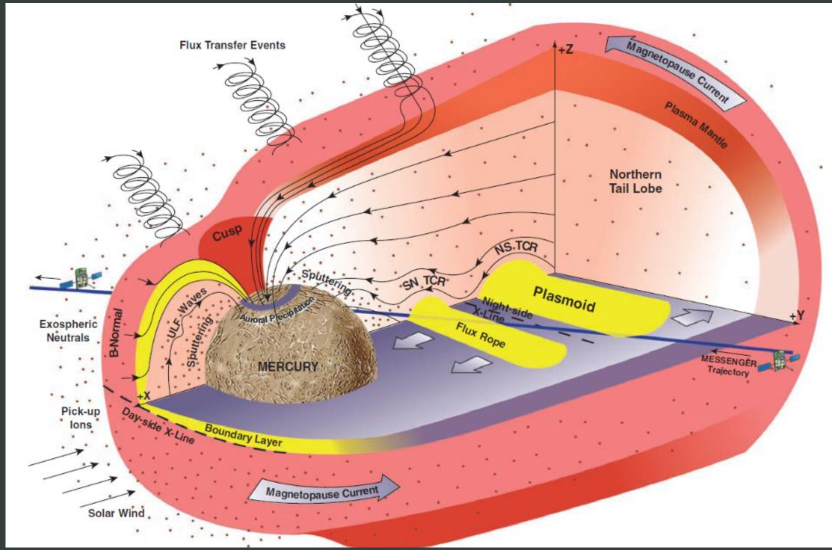
- In this work:
- Study magnetic reconnection with a limited x-line extent, model the reconnection rate and outflow speed as a function of the x-line extent.

Motivation

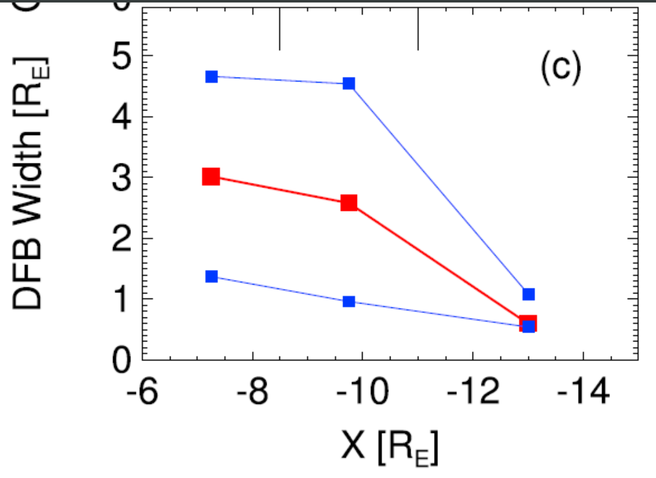
- Observations indicate that reconnection with a finite x-line extent is a universal phenomenon:

1. Planets/moons with small magnetotail, like Mercury, Ganymede…Spatial scale of Mercury magnetotail in Dawn-dusk direction: 20-50d_i

2. Dipolarizing flux bundles(DFBs), Bursty bulk flows(BBFs) in Earth magnetotail. The minimum extent of DFBs in dawn-dusk direction: $0.5R_E$~$10d_i$



Slavin et al. 2009



Liu et al. 2015

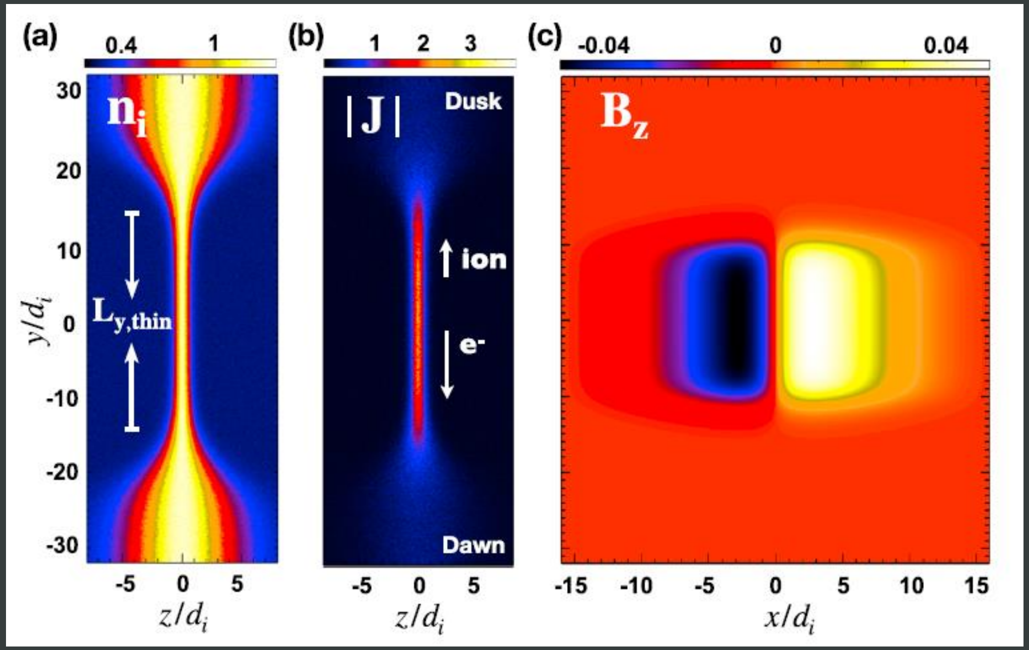
Simulation setup

- GSM coordinate
- Initial condition: Harris sheet with varies thickness along the y direction

$$\mathbf{B}(y,z) = B_0 \tanh\left[z/L(y)\right]\mathbf{e}_x$$
$$n(y,z) = n_0 \operatorname{sech}^2\left[z/L(y)\right] + n_b$$
$$L(y) = L_{\min} + \left(L_{\max} - L_{\min}\right)\left[1 - f(y)\right]$$

- Length of the x-line $L_{y,thin}$

$$n_b = 0.3n_0, \quad L_{\min} = 0.5d_i, \quad L_{\max} = 4d_i$$
$$m_i = 25m_e, \quad c = 20V_A$$
$$L_x \times L_y \times L_z = 32d_i \times 64d_i \times 32d_i$$



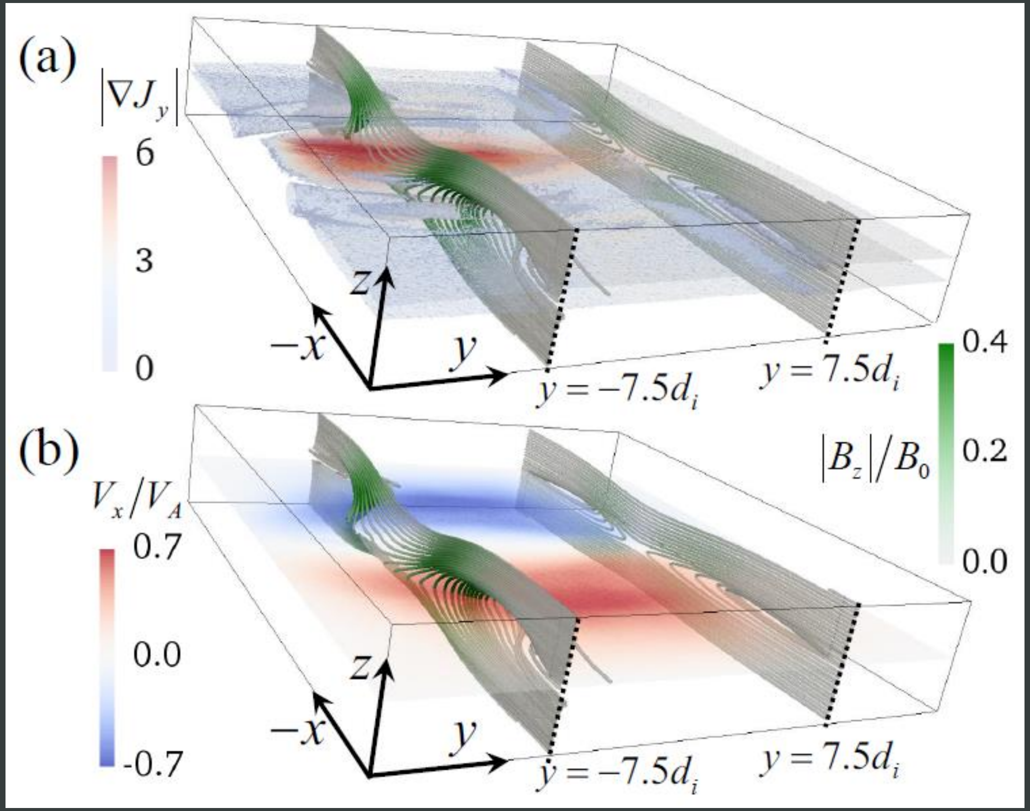
Liu et al. 2019

Internal x-line asymmetry

$\boxed{L_{y,thin} = 30d_i}$

Electron drift

Ion drift



Dawn side(active region)
Thinner current sheet
Larger outflow speed
Stronger outflow Bz

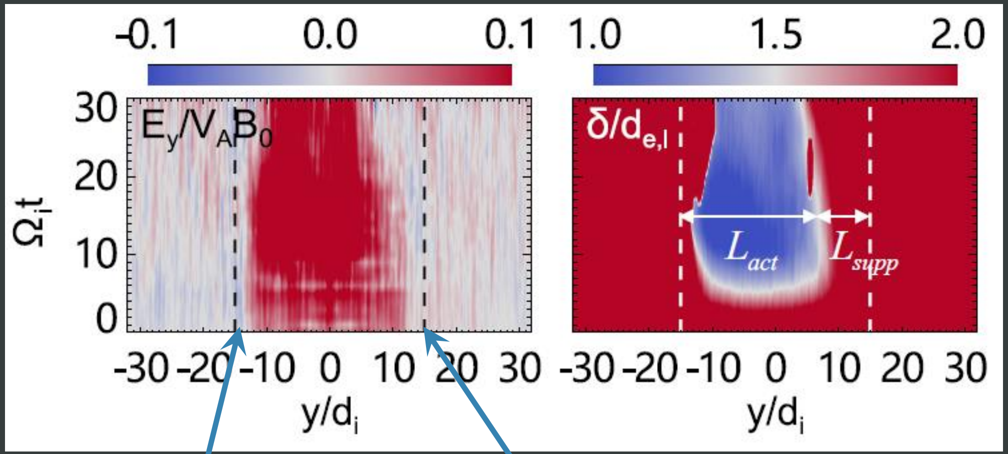
Dusk side(suppression region)
Thicker current sheet
Smaller outflow speed
Weaker outflow Bz

Huang et al. 2020

- Reason: dawnward transport of magnetic flux B_z by electron.(Liu et al. 2019)

Define the active region

- Define the active region: $\delta < 2d_{e,l}$
- Active region coincide with the region with large E_y (reach 0.1).
- Length of the active region: L_{act}
- Length of the suppression region: L_{supp}
- $L_{y,thin} = L_{act} + L_{supp}$
- $L_{supp} \sim 10 d_i$ (Liu et al. 2019)



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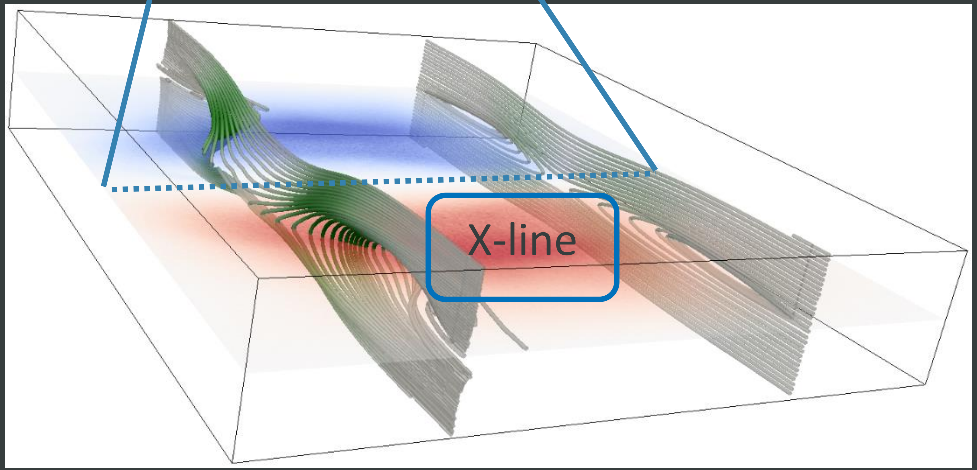


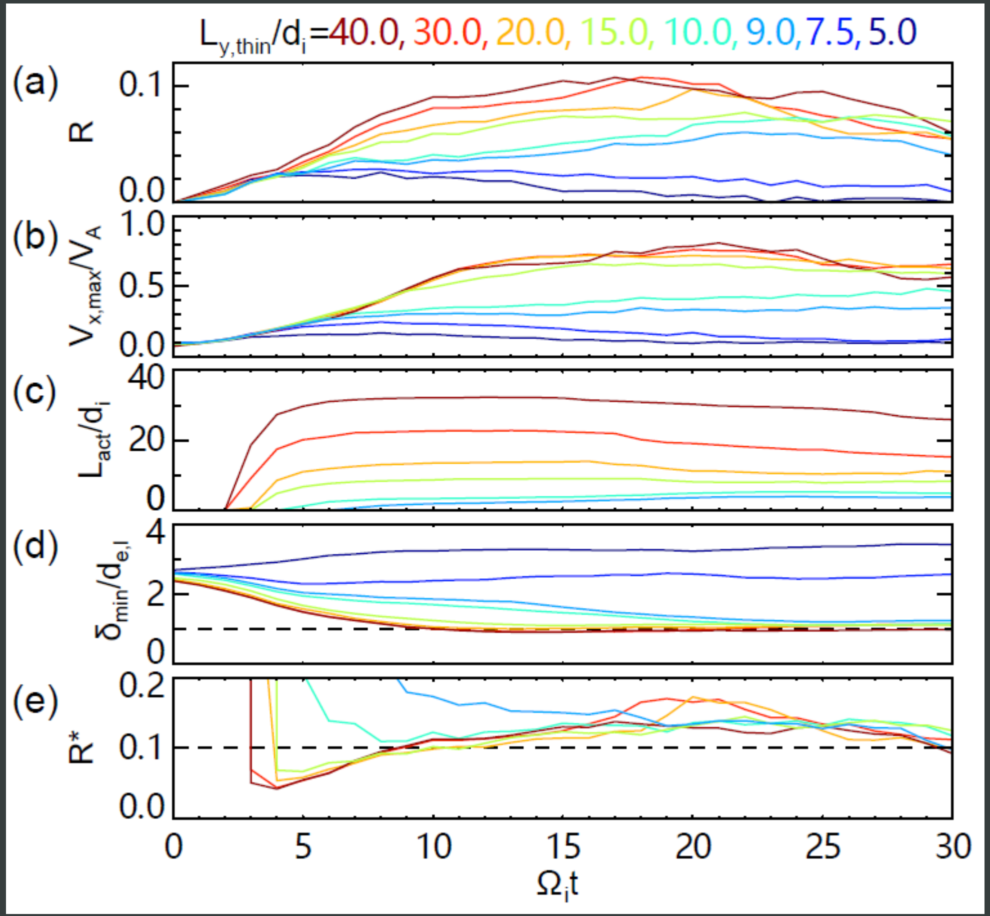
Results of cases with different x-line extent

- Average reconnection rate R (panel a):

$$R = \frac{\partial_t \Psi}{L_{y,thin}}$$

- $L_{y,thin}$ decrease, both reconnection rate and outflow speed decrease
- $L_{y,thin} \lesssim 10d_i$, reconnection is suppressed:

1. Both reconnection rate and outflow speed taper off (see panel a, b)
2. No active region (see panel c)
3. No current sheet thinning (see panel d)



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Model the reconnection rate

- Reconnection rate normalized by L_{act}:

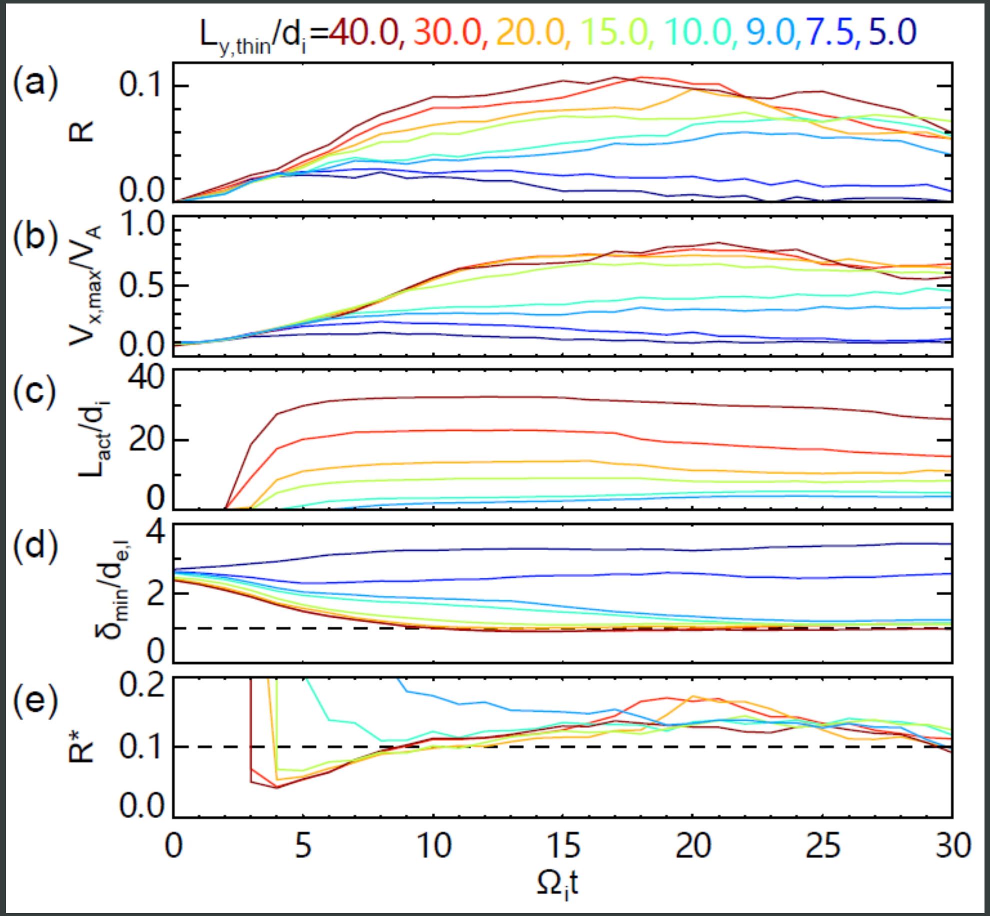
$$R^* = \frac{\partial_t \Psi}{L_{act}} = \frac{L_{y,thin}}{L_{act}} R$$

- R* is similar in all cases with an active region (see panel e), and reach ~0.1, the typical 2D reconnection rate.

- Estimate the average reconnection rate R:

$$R = \frac{L_{act}}{L_{y,thin}} R^* = \left(1 - \frac{L_{supp}}{L_{y,thin}}\right) R^*$$

- Assume R* and L_{supp} are constant, the reason for the decrease of R is the limited length of the active region when x-line is shorter.



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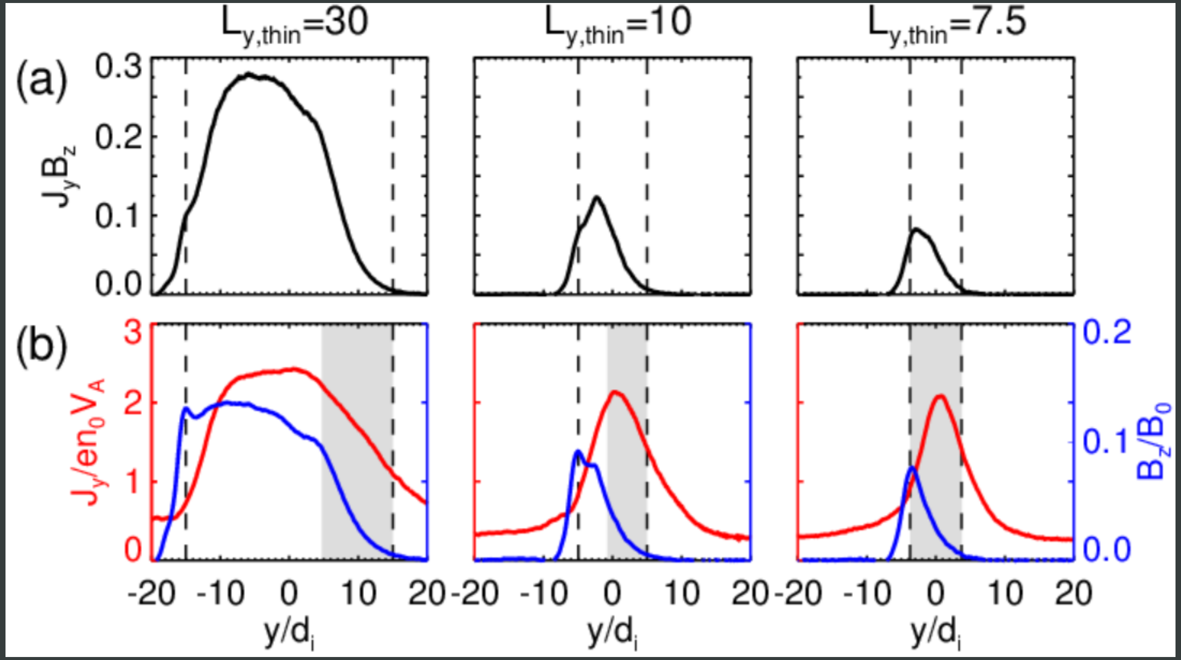
Model the outflow speed

- Estimate the outflow speed in 2D condition: $V_x^2 \propto J_y B_z$



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- J_y and B_z are similar in three cases (see panel b), while $J_y B_z$ decreases (see panel a).
- The reason for the decrease of $J_y B_z$ is the dawnward transport of B_z, transport distance is L_{supp}, the gray region in panel b.

Model the outflow speed

- $J_y = J_{ymax} f(y)$
- $B_z = B_{zmax} f(y + L_{supp})$

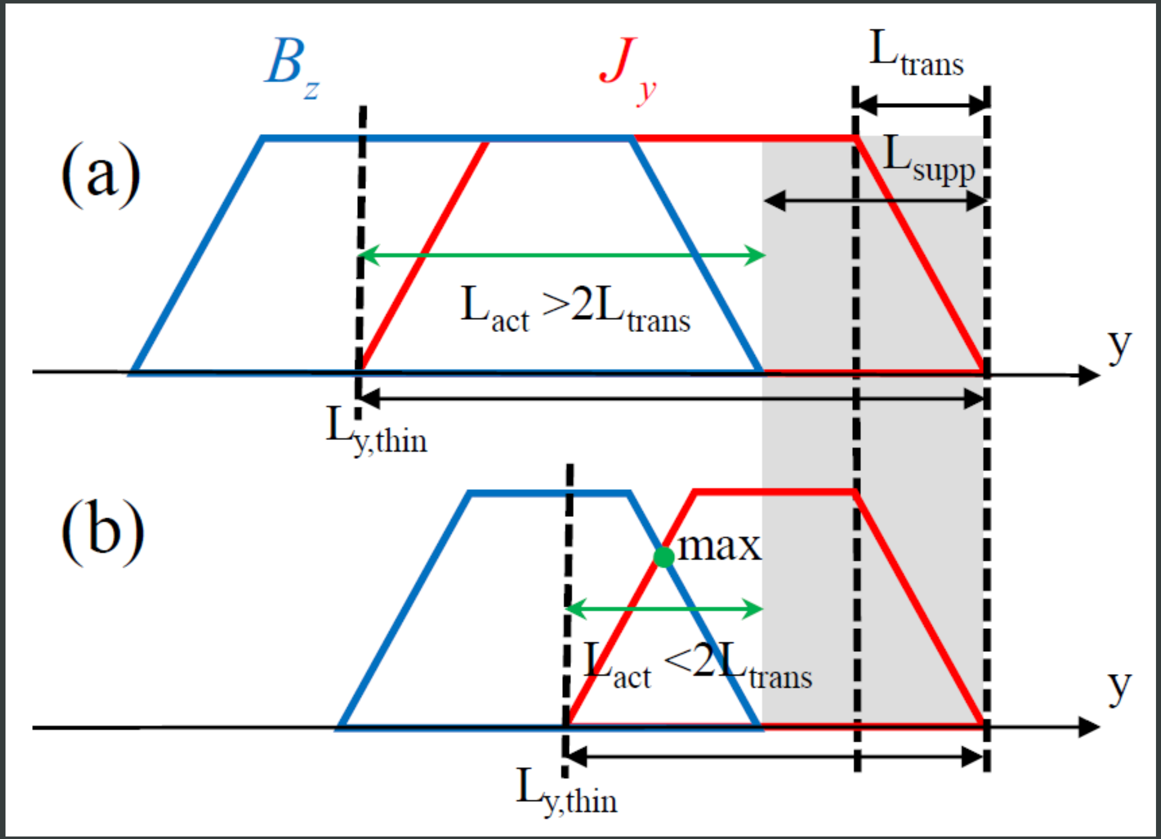
1. Panel (a), x-line is long:

$$\left(J_y B_z\right)_{\max} = J_{y\max} B_{z\max}$$

2. Panel (b), x-line is short:

$$\left(J_y B_z\right)_{\max} = J_{y\max} B_{z\max} \left(\frac{L_{act}}{2L_{trans}}\right)^2$$

$$V_{x,\max} \propto \sqrt{\left(J_y B_z\right)_{\max}} \Rightarrow V_{x,\max} = \begin{cases} V_m \sim V_A, & L_{act} \geq 2L_{trans} \\ \dfrac{L_{act}}{2L_{trans}} V_m, & L_{act} < 2L_{trans} \end{cases}$$



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Model & data comparison

- Panel a: length of the suppression region

$$L_{supp} = L_{y,thin} - L_{act} \approx 5 \sim 10 d_i$$

- Panel b: reconnection rate

$$R = \frac{L_{act}}{L_{y,thin}} R^* = \left(1 - \frac{L_{supp}}{L_{y,thin}}\right) R^*$$

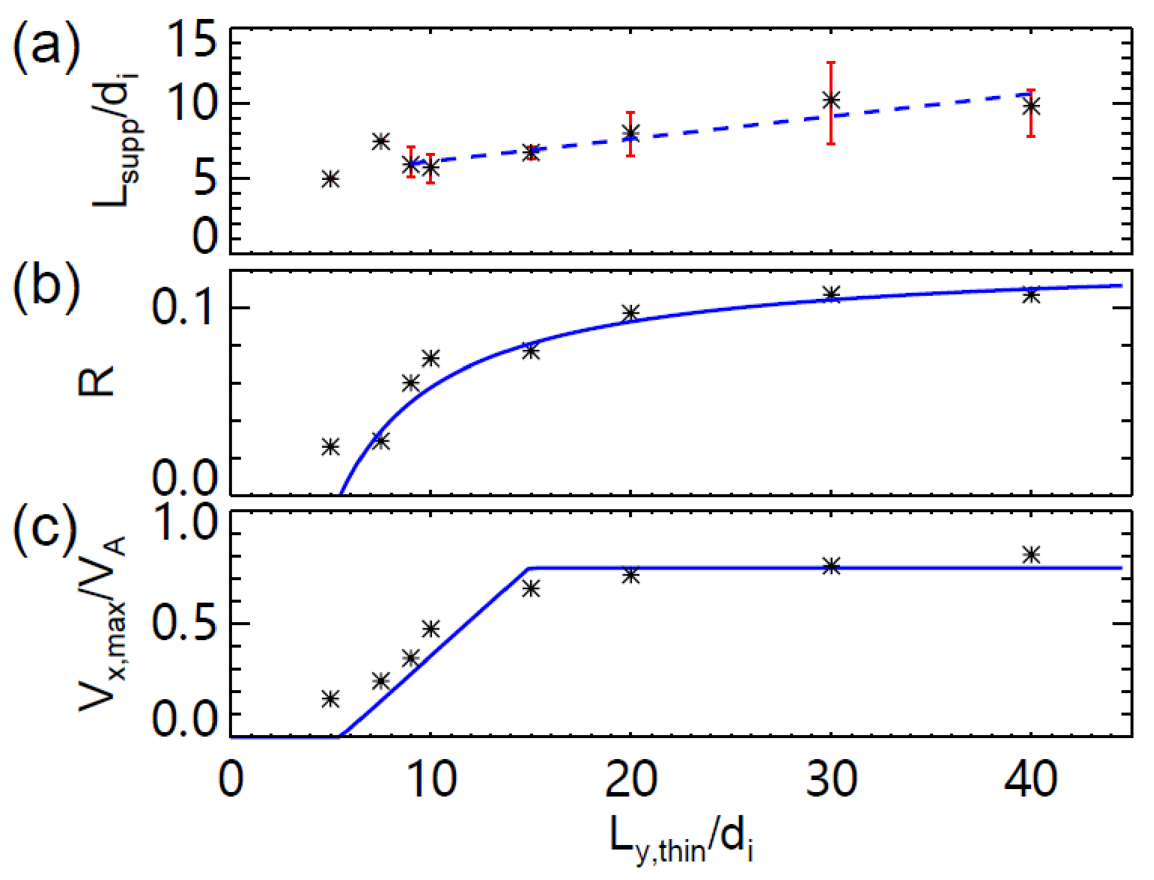
$$R^* = 0.15$$

- Panel c: reconnection outflow speed

$$V_{x,\max} = \begin{cases} V_m \sim V_A, & L_{act} \geq 2L_{trans} \\ \frac{L_{act}}{2L_{trans}} V_m, & L_{act} < 2L_{trans} \end{cases}$$

$$V_m = 0.75 V_A$$

$$L_{trans} = 4 d_i$$



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Summary

- We conduct 3D PIC simulations of reconnection with a limited x-line extent. Reconnection is suppressed on the ion drifting (dusk) side, $L_{supp} \sim 10 d_i$.

- We propose a model of reconnection rate and reconnection outflow speed as a function of the x-line extent, and explain the mechanisms that reduce the reconnection rate and outflow speed when x-line is short.

- This study is applicable to planets with magnetotail similar to Mercury’ s size and reconnection with limited X line extent in Earth magnetotail.