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Scaling of magnetic reconnection with a limited x-line extent

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Magnetic reconnection is a fundamental physical process that is responsible for releasing the magnetic energy during substorms of planetary magnetotails. Previous studies of magnetic reconnection usually take the two-dimensional (2D) approach, which assumes that reconnection is uniform in the 3rd direction out of the 2D reconnection plane. However, observations suggest that reconnection can be limited in the 3rd direction, such as reconnection at Mercury's magnetotail. It turns out that reconnection can be suppressed when reconnection region is very limited in the 3rd direction. An internal x-line asymmetry along the current direction develops because of the transport of reconnected magnetic flux by electrons beneath the ion kinetic scale, resulting in a suppression region identified in Liu et al., 2019. Under the guidance of a series of 3D kinetic simulations, in this work, we incorporate the length-scale of this suppression region $\sim 10d_i$ to quantitatively model the reduction of the reconnection rate and the maximum outflow speed observed in the short x-line limit. Notably, these two quantities are most essential in defining the well-being of magnetic reconnection, which can tell us when reconnection shall be suppressed.

We find that both reconnection rate and outflow speed decrease when the x-line extent becomes shorter, and reconnection is greatly suppressed when the x-line extent is shorter than around $10d_i$. The reconnection x-line with a limited extent $L_{y,thin}$ can be divided into an active region with extent L_{act} on the electron drifting side and a suppression region with extent L_{supp} on the ion drifting side, $L_{y,thin} = L_{act} + L_{supp}$, where L_{supp} is observed to be around $10d_i$. In the active region, the thickness of the current sheet can reach the local electron inertial length and the local reconnection electric field can reach $E_y \sim 0.1V_A B_0$. Therefore, we argue that the average reconnection rate drops because of the length ratio between the active region and the x-line decreases when the x-line extent becomes shorter. As shown in Eq. (1), here, R is the average reconnection rate and $R^* \sim 0.1$ is the reconnection rate in 2D conditions.

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

The reconnection outflow is found to be driven by the $J_y B_z$ force in the outflow region. However, both J_y and B_z are similar in the cases with different x-line extent while $J_y B_z$ decreases greatly when the x-line becomes shorter. We propose that the reduction of $J_y B_z$ is resulted from the phase shift between the profile of J_y and B_z. Because B_z is transported to the electron drifting side by electrons (Hall Effect). A sketch of this process is shown in Figure 1. Assuming that both B_z and J_y have a trapezium shape with a plateau in the center and transition regions of scale L_{trans} on both flanks. When $L_{act} > L_{trans}$, as shown in panel (a), part of the plateau region of B_z and J_y overlap, $J_y B_z$ can reach the max value. When $L_{act} < L_{trans}$, as shown in panel (b), the plateau region of B_z and J_y do not overlap, the maximum of $J_y B_z$ decrease. Then, the reconnection outflow speed $V_{x,\max}$ can be modeled by Eq. (2).

$$V_{x,\max} = \begin{cases} V_m \sim V_A, L_{act} > 2L_{trans} \\ \frac{L_{act}}{2L_{trans}} V_m, L_{act} \le 2L_{trans} \end{cases} \quad (2)$$

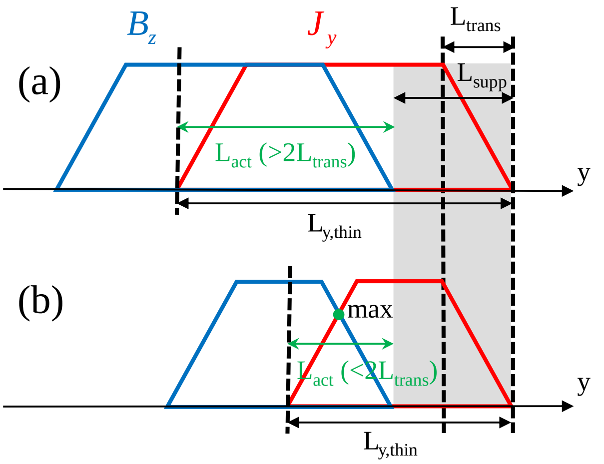

Figure 1. Modeling the reduction of $J_y B_z$ that results from the phase shift between the B_z and J_y profiles.

References

[1] Liu et al. J. Geophys. Res., 124(4) (2019).
[2] Huang et al. Geophys. Res. Lett. Revised (2020)