Fast magnetic reconnection induced by resistivity gradient in MHD simulations

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Abstract

Two-dimensional magnetohydrodynamics (MHD) simulations show that (1)Petschek reconnection is unstable using a uniform resistivity. (2)To achieve a Petschek-like fast reconnection in resistive MHD, it requires a localized resistivity. In this work, we show that a steady-state Petschek-like reconnection also develops in the transition region of a hyperbolic tangent resistivity profile. Our study further suggests that the gradient of resistivity along the outflow direction is the key ingredient in making Petschek reconnection accessible, supporting the idea proposed by Kulsurd [2]. Such a resistivity profile may happen in the lower solar atmosphere where the plasmas are highly stratified.

Introduction

Petschek model of fast reconnection

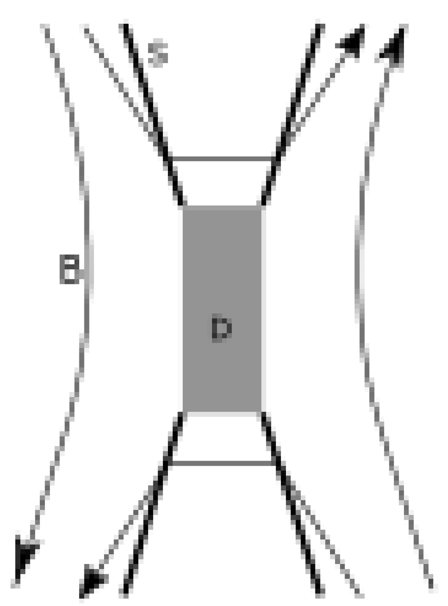

Figure 1: Petschek model

Figure 1, Petschek model is composed of a diffusion region (grey area D) and slow shocks (line S). The length of the diffusion region is determined by the scale length of the resistivity profile in resistive MHD.

Studies suggest that Petschek reconnection is unstable in uniform resistivity MHD simulations. A stable Petschek reconnection is usually generated by artificially setting a localized resistivity profile. On the other hand, [1] found that if the resistivity profile is localized in one half-plane and uniform in another half-plane, Petschek-like reconnection will form in simulations and the x-line will be near the edge of two half-plane. This suggests that Petschek-like reconnection can be generated if one of the outflow jets undergoes the localized resistivity.

In this work, we found that a hyperbolic tangent resistivity profile along the outflow direction can generate a stable Petschek-like reconnection, showing that a resistivity gradient is crucial to form a stable Petschek-like reconnection.

Resistive MHD equations

$$\partial_t \rho + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\partial_t(\rho\vec{v}) + \nabla \cdot [\rho\vec{v}\vec{v} - \vec{B}\vec{B} + (p + \frac{B^2}{2})I] = 0 \tag{2}$$

$$\partial_t e + \nabla \cdot [(e + p + \frac{B^2}{2})\vec{v} - \vec{B}(\vec{B}\cdot\vec{v})] = \nabla \cdot (\vec{B} \times \eta\vec{J}) \tag{3}$$

$$\text{where} \quad e = \frac{p}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{2} \tag{4}$$

$$\partial_t \vec{B} - \nabla \times [\vec{v} \times \vec{B} - \eta\vec{J}] = 0 \tag{5}$$

Simulation setup

We use Athena [4], a grid-based MHD code, to simulate magnetic reconnection. Flow out boundary condition is used in the simulations in this paper unless otherwise mentioned. The initial condition is a force-free current, described by

$$\vec{B} = B_0 \tanh\left(\frac{x - x_c}{\lambda}\right)\hat{y} + B_0\left(\frac{x - x_c}{\lambda}\right)\hat{z} \tag{6}$$

where B_0 is the magnitude of unperturbed magnetic field, λ is the current sheet width, B_g is the guide field, and x_c is the x-coordinate of the current sheet. We use $B_0 = 1$, $\lambda = 0.04$, and $x_c = 1$ in all simulations. Simulation domain for both x and y are from 0 to 2. The resolution is $2/512 \sim 4 \times 10^{-3}$ unless otherwise mentioned.

Results

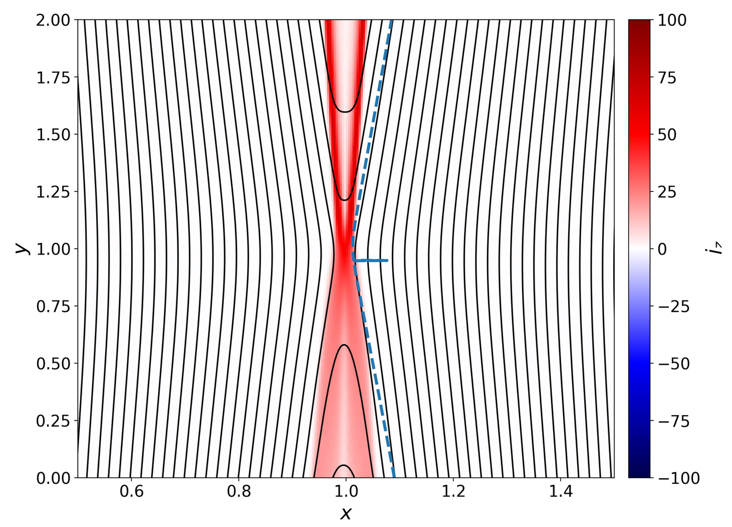

Figure 2:

By applying a hyperbolic tengent resistivity along the y-direction, namely,

$$\eta_{\mathrm{tanh}}(y) = 0.5\eta_1\left(1 - \tanh\frac{y-1}{r_s}\right) + \eta_2, \tag{7}$$

a stable Petschek-like reconnection forms in MHD simulation. Figure 2 shows the current density and the contours of the flux function (black lines). Figure 3 shows the x-component B_x at $x = 1$ versus y in simulation (blue line). Figure 4 shows the outflow speed at $x = 1$ versus y in simulation (blue line) and the hyperbolic resistivity profile η (red line). From figures 3 and 4, one can see that the stagnation point and the neutral point are located at where resistivity starts to drop. The length of the diffusion region is the same order as the scale length of the hyperbolic tangent profile.

The orange lines in figures 3 and 4 are the analytical theory proposed by Seaton and Forbes [3]. Details can be found in the reference therein.

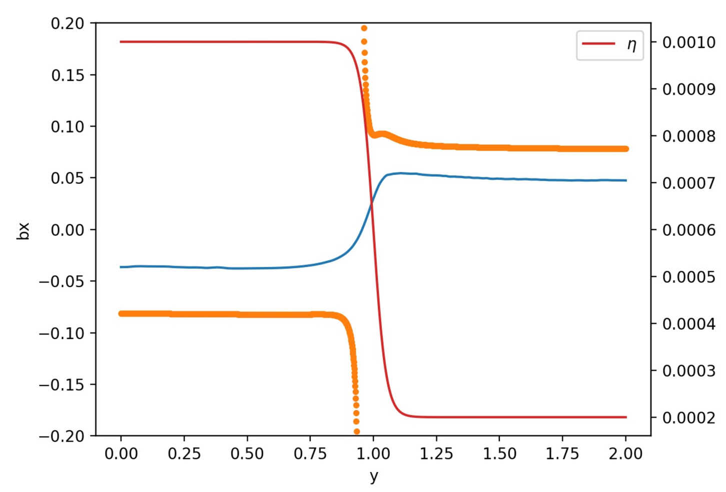

Figure 3:

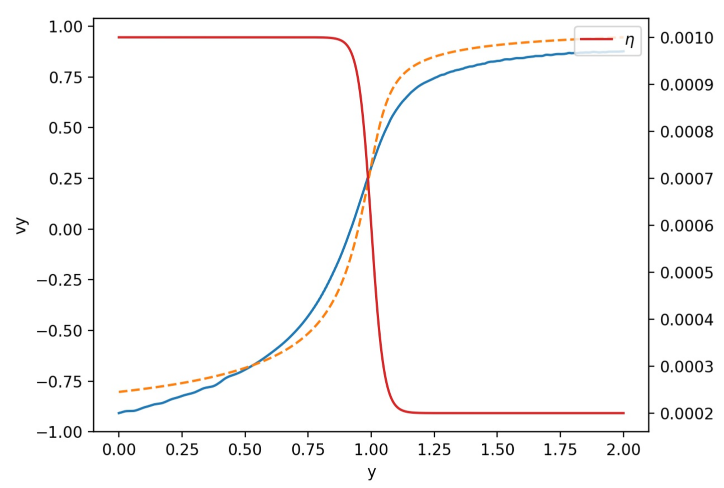

Figure 4:

Discussion and Conclusion

- A hyperbolic tangent resistivity profile along the outflow direction helps generate a stable Petschek-like reconnection.
- Collisional plasma systems with a resistivity gradient might generate stable Petschek-like reconnections.

References

[1] Hubert Baty, TG Forbes, and ER Priest, *Petschek reconnection with a nonlocalized resistivity*, Physics of Plasmas **16** (2009), no. 1, 012102.

[2] Russell M Kulsrud, *Magnetic reconnection: Sweet-parker versus petschek*, Earth, Planets and Space **53** (2001), no. 6, 417–422.

[3] Daniel B Seaton and Terry G Forbes, *An analytical model for reconnection outflow jets including thermal conduction*, The Astrophysical Journal **701** (2009), no. 1, 348.

[4] James M Stone, Thomas A Gardiner, Peter Teuben, John F Hawley, and Jacob B Simon, *Athena: a new code for astrophysical mhd*, The Astrophysical Journal Supplement Series **178** (2008), no. 1, 137.