Large-Scale Energy Conversion Mechanism of Collisionless Magnetic Reconnection

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Magnetic reconnection is a natural energy converter which allows explosive energy release of the magnetic field energy into plasma kinetic energy. The reconnection processes inherently involve multi-scale process. The reconnecting of the field lines takes place predominantly in a small region called the diffusion region formed around the x-line, while the fast plasma jets resulting from reconnection extend to a distance far beyond the ion kinetic scales from the x-line. The large-scale energy conversion associated with reconnection is expected to have a significant impact on a variety of global scale phenomena in space such as geo-magnetospheric substorms and solar flares. However, the multi-scale nature of reconnection makes it difficult to model the large-scale behaviour and, therefore, to evaluate the actual impact on such the global systems.

Large-scale dynamics of magnetic reconnection has been investigated in the magnetohydrodynamics (MHD) framework. A fast reconnection can be achieved through plasma acceleration at a pair of slow mode shocks extending from the x-line [1]. Although the so-called Petschek model was based on an approximated solution of the MHD equations, the model has been widely believed to exist in real space because the self-consistent MHD simulations successfully reproduced the model. Satellite observations in the Earth's magnetotail have also shown the evidences of slow shock-like structures in association with magnetic reconnection. On the other hand, a number of particle-in-cell (PIC) simulations have revealed that both the ions and electrons are accelerated through the Speiser-type motions in the vicinity of the x-line. The distinct scales of the Speiser orbit of the ions and electrons result in an ion-electron decoupling motion generating the Hall current system . The associated Hall magnetic field has been often observed in the Earth's magnetosphere and laboratory experiments.

The question arising here is how the kinetic process around the x-line connects to an MHD-scale dynamics of reconnection far downstream of the x-line. In order to investigate the large-scale evolution of collisionless reconnection, we have developed a new electromagnetic PIC model with adaptive mesh refinement (AMR-PIC model) [2], which facilitates large-scale kinetic simulations of multi-scale processes. The system size in the current simulation is $L_x \times L_z = 655\lambda_i \times 328\lambda_i$ with λ_i the ion inertia length. The highest resolution is 32,768 × 16,384 and the maximum number of particles is ~ 10^{10} for each species. The simulation employs an open boundary condition both in the x and z directions.

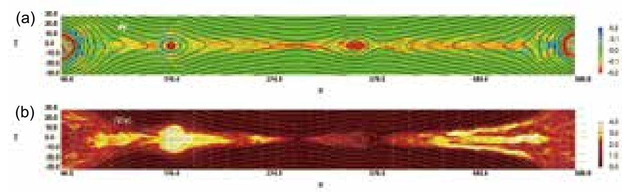

Figure 1: 2D snapshots at t = 140 of (a) the out-of-plane current density J_y and (b) the ion flow speed $|V_{ix}|$ with the magnetic field lines in solid curves. The green arrows in (b) represent the ion flow vectors.

Figures 1a and 1b show the out-of-plane current density and the ion outflow speed, respectively, after a long-time evolution of collisionless reconnection. The width (in z) of the exhaust reaches $\approx 30\lambda_i$ that is much larger than the ion gyro-radius in the lobe region. One can see that the current sheet is elongated significantly in the downstream direction far beyond the ion kinetic scales, in contrast with the Petschek model. The elongated current sheet reminds us of a slow reconnection in the MHD framework. However, we found that the diffusion region is localized around the x-line, so that the reconnection process is more similar to the Petschek model in this sense.

One of the important characteristics of the Petschek model is energy conversion at slow mode shocks. We consider the Rankine-Hugoniot (RH) conditions based on the ideal MHD equations across the exhaust boundary far downstream of the x-line. It is found that the RH conditions are almost satisfied at the exhaust boundary, even though the distribution functions of the ions and electrons are far from the Maxwellian. This is because the RH conditions provide only a series of conservation laws along the plasma flow. In other words, these conditions do not always guarantee the existence of shocks in the kinetic systems. In fact, we found that the energy conversion hardly occurs at the boundaries, implying that they are not slow mode shocks. Instead, the ions are accelerated mostly in the current sheet due to the Speiser motions even in the region far downstream of the x-line. Therefore, the current simulation suggests that collisionless reconnection differs from classical MHD reconnection models even in large scale beyond the ion kinetic scales and kinetic treatments is necessary to describe reconnection in collisionless plasmas [3].

References

[1] Petschek, H. E.: 1964, *NASA Spec. Publ.*, **SP-50**, 425.
[2] Fujimoto, K.: 2011, *J. Comput. Phys.*, **230**, 8508.
[3] Fujimoto, K., Takamoto, M.: 2016, *Phys. Plasmas*, **23**, 012903.