§6. An MHD-scale Dynamics 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 is expected to have a significant impact on the global stability of fusion devices. Magnetic reconnection is also considered to be important in space plasmas, mediating global phenomena 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 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 shocks 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 about the x-line connects to an MHD-scale dynamics of reconnection far downstream 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)]. Recently we further applied an open boundary condition to the AMR-PIC model, which enabled us to pursue longer-time evolution of collisionless reconnection [3)]. 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 $32,768 \times 16,384$ and the maximum number of particles is $\sim 10^{10}$ for each species.

Figure 1 shows the out-of-plane current density 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's in this sense.

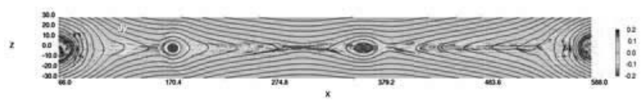

Fig. 1: Out-of-plane current density at $t = 140$ with the magnetic field lines in black curves.

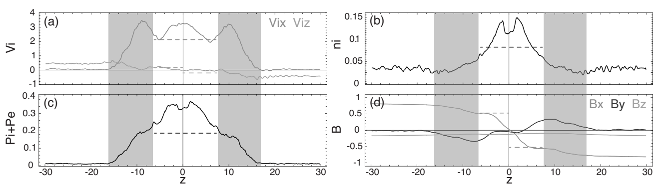

Fig. 2: Line profiles along the z axis at $x = 500$ of (a) ion flow velocities, (b) ion density, (c) total plasma pressure, and (d) magnetic fields. Dashed lines indicate the downstream values predicted from the RH conditions for a slow-mode shock. Shadowed regions represent the expected exhaust boundary.

One of the important characteristics of the Petschek model is energy conversion at slow shocks. Figure 2 presents the profiles across the exhaust boundaries. We consider the Rankine-Hugoniot (RH) conditions based on the ideal MHD equations. It is found that the RH predictions are almost consistent with the simulation results. However, the boundaries in the simulation do not show switch-off type structure, different from the Petschek model. In fact, we found that the energy conversion hardly occurs at the boundaries. Instead, the ions are accelerated mostly in the current sheet due to the Speiser motions even in the region far downstream the x-line. Therefore, the current simulation suggests that collisionless reconnection differs from classical MHD reconnections even in large scale beyond the ion kinetic scales and kinetic treatments is necessary to describe reconnection in collisionless plasmas.

1) Petschek, H. E.: NASA Spec. Publ. SP-50 (1964) 425.

2) Fujimoto, K.: J. Comput. Phys. 230 (2011) 8508.

3) Fujimoto, K.: Geophys. Res. Lett. 41 (2014) 2721.