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無衝突磁気リコネクションの MHD スケールダイナミクス
An MHD-scale dynamics of collisionless magnetic reconnection

藤本 桂三 [1*] ; 高本 亮 [2]
FUJIMOTO, Keizo[1*] ; TAKAMOTO, Makoto[2]

[1] 国立天文台理論研究部, [2]Max-Planck-Institut fur Kernphysik
[1]Division of Theoretical Astronomy, NAOJ, [2]Max-Planck-Institute for Nuclear Physics

We usually believe that an MHD-scale dynamics can be adequately described with the MHD approximation. However, this idea is not always straightforward in collisionless plasmas, where the time scale of thermal relaxation is much larger than that of phenomena of interest. The present study considers this problem for magnetic reconnection.

Magnetic reconnection is an explosive energy converter from the magnetic field energy into plasma kinetic energy. The reconnection processes are believed to play a key role in energetic phenomena in space such as geomagnetic substorms, solar flares, and the generation of the pulser wind. One of the main issues in reconnection has been the mechanism that enables fast energy release in a realistic time scale. Since the reconnection processes give rise to a MHD-scale dynamics, a lot of reconnection models have been developed historically in the MHD framework. One of the most promising models is the Petschek model suggested in 1964. The Petschek model provides a fast reconnection in a wide range of plasma conditions (leading to magnetic Reynolds number). The key assumptions of the model are a compact diffusion region localized in the vicinity of the x-line and a pair of the switch-off slow shocks extending from the x-line. The compact diffusion region is necessary to keep the reconnection rate high, avoiding the current sheet from elongation. Most part of the plasma is accelerated at the slow shocks, which allow the energy conversion in a broad area downstream the x-line. Although the Petschek model has been demonstrated by the MHD simulations under certain setups, the model has not been accepted. In fact, the dynamical behavior of reconnection depends significantly on the resistivity model in the MHD simulations, and clear slow mode shocks have merely been observed in geomagnetosphere.

To assess the MHD reconnection model, the present study has performed huge-scale particle-in-cell (PIC) simulations with the help of the adaptive mesh refinement (AMR). The simulation domain extends to more than 600 ion inertia length in the outflow direction with a large ion-to-electron mass ratio and an open boundary condition. We believe that the system size is sufficiently large to describe the MHD-scale dynamics of reconnection. After a long-time evolution, we find that a long current layer is formed in the exhaust, which is reminiscent of the Sweet-Parker reconnection model. However, the magnetic dissipation takes place only around the x-line, so that the reconnection rate remains high as in the Petschek model. The transient region formed around the field line separatrix almost satisfies the Rankine-Hugoniot relation for the slow mode shock. However, we found that no plasma acceleration occurs in the transient region. Instead, the ions are accelerated in the current layer through the Speiser motions, while the electrons gain the energy in the Hall region from the reconnection electric field. Therefore, the plasma acceleration mechanism in collisioneless reconnection is different clearly from that in the Petschek model. The decoupling motions between the ions and the electrons generate the Hall current even far downstream the x-line. Thus, the dynamics in the exhaust is not able to be described in the MHD framework. The present study suggests that magnetic reconnection is an MHD-scale phenomenon, but the MHD approximation is not adequate in collisionless plasmas.

Keywords: magnetic reconnection, particle-in-cell simulation, MHD-scale dynamics, plasma acceleration