§6. A High-resolution MHD Simulation of Magnetic Reconnection

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In order to understand and predict the processes of explosive phenomena in space plasmas such as solar flares, the physics of fast magnetic reconnection in high Lundquist number plasmas must be clarified. However, conventional steady-state theoretical models based on resistive magnetohydrodynamics (MHD) could not explain the strong enhancement of the reconnection rate in high Lundquist number plasmas.[1), 2)] On the other hand, we inferred from recent MHD simulation studies that the reconnection rate abruptly increases even in high Lundquist number plasmas accompanied by secondary tearing instabilities in the thin Sweet-Parker-like current sheet.[3), 4)] In real space plasmas, an MHD turbulence, which must be developed during the current sheet thinning process, may affect the processes of magnetic reconnection. However, the relevance of the MHD turbulence and fast magnetic reconnection is totally unclear. Therefore, the final goal of this study is to clarify effects of the MHD turbulence in magnetic reconnection using a very high-resolution MHD simulation. Particularly, in this paper, we restrict our attention to a two-dimensional slab geometry and perform a very high-resolution MHD simulation of the resistive tearing instability. In addition, we develop state-of-the-art numerical techniques for MHD in this study.

The fully compressible MHD equations are numerically solved as the governing equations since the compressibility of the plasmas is important in space environments. Thus, shock capturing numerical techniques for MHD must be introduced. We adopt the finite-volume method where conservative variables in the control volume are updated using numerical fluxes across the interfaces of the control volume. The numerical fluxes are given by the Harte-Lax-van Leer-Discontinuities (HLLD) approximate Riemann solver for MHD.[5)] The induction equation is solved by an HLL-type flux-CT method to perform a very high-resolution simulation stably for a long time without numerical magnetic divergence errors.[6)] To achieve higher-order accuracy, the Monotone Upstream-centered Scheme for Conservation (MUSCL) is applied. Particularly, we develop a new set of approximate characteristic variables of MHD for stability and efficiency, and interpolate it with a limiter function in the MUSCL (Miyoshi and Kusano, in preparation). Moreover, to suppress numerical shock instabilities in multi-dimensions, "HLLD minus" method is newly proposed (Miyoshi and Kusano, in preparation). These numerical techniques enable us to perform robust and efficient very high-resolution MHD simulations.

In our simulation model, a one-dimensional Harris current sheet is given as an equilibrium configuration for simplicity. The Lundquist number is set to be 1.57×10^5. Initially, we impose a single-mode perturbation. The results were as follows[4)] : The resistive tearing instability grew at the initial stage. Then, the Rutherford regime was realized. After that, the Sweet-Parker-like current sheet was formed. When the aspect ratio of the current sheet exceeded more than 100, the current sheet was destabilized for secondary tearing modes. Subsequently, many plasmoids were intermittently generated and ejected. In this report, more detailed analyses of the dynamics of the plasmoid are promoted. Fig. 1 (a) shows time evolution of the current density from up to bottom. Fig. 1 (b) and (c) also show the time evolution of the reconnection rate at the location of the minimum flux point (i.e, the global reconnection rate) and the kinetic energy in the system, respectively. The current density is enhanced in the front of the plasmoids by compressing and shortening the global current sheet. Then, some plasmoids move to the opposite direction due to strong magnetic reconnection in the enhanced narrow current sheet. As shown in Fig. 1 (b), the reconnection rate rapidly increases around t=1105, when the current density is enhanced as seen in the middle panel of Fig. 1 (a). After that, the bounced plasmoid is developed to a large size because the stay time of the plasmoid is longer than other plasmoids (i.e., non-bounced plasmoids). Subsequently, the kinetic energy increases accompanied by the ejection of the large plasmoid as shown in Fig. 1 (c).

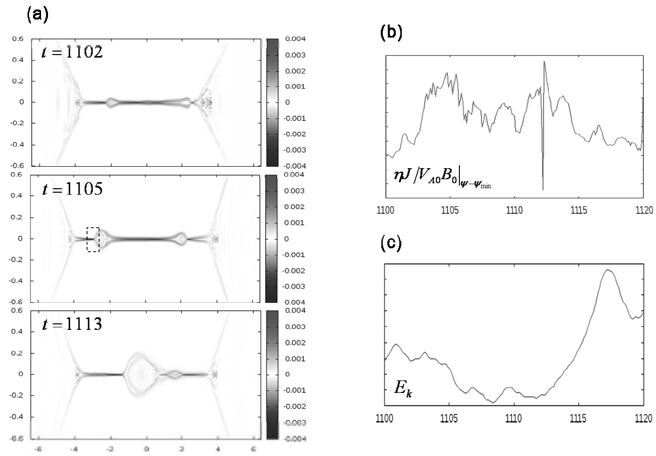

Fig. 1. The time evolution of (a) the spatial structure of the current sheet, (b) the reconnection rate at the location of the minimum flux point, (c) the kinetic energy in the system, respectively.

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