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3D Kinetic Simulation of Collisionless Magnetic Reconnection
無衝突磁気リコネクションの３次元運動論シミュレーション

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A large-scale particle-in-cell simulation has been performed to investigate 3D kinetic process of collisionless magnetic reconnection by means of the state-of-the-art supercomputer K. It is found that the wave activities in the thin current layer are enhanced significantly in association with plasmoid ejection. In particular, a large-scale mode with $k_y\lambda_i$<0.5 deforms the current sheet structure drastically. As a result, the electron outflow forms a 3D structure reminiscent of the busty bulk flow observed in the Earth magnetotail. The current simulation suggests the connection between the turbulence in the reconnection layer and the bursty bulk flow.

1. Introduction

Magnetic reconnection is an explosive energy converter, releasing the magnetic field energy into plasma kinetic energy. It has been believed that magnetic reconnection plays significant roles in dynamical phenomena in space, astrophysical, and laboratory plasmas. However, the exact roles were not clearly understood yet. One of the main issues in the reconnection process is the importance of the 3D effects in the actual dynamical phenomena. The observations in space and laboratory plasmas [e.g., 1, 2] have suggested that the dissipation process around the x-line is essentially three dimensional. The 3D dissipation mechanism for anti-parallel reconnection has been also demonstrated using a large-scale particle-in-cell (PIC) simulation [3]. Nevertheless, the impacts of the 3D turbulence around the x-line on the global dynamics are poorly understood.

In the Earth magnetotail, intermittent fast flows have been frequently observed within a dawn-to-dusk narrow channel of 2-3 Re in association with the geomagnetic substorms. These flows are called the bursty bulk flows (BBFs) and are considered to be responsible for the most part of the momentum transport in the magnetotail [4]. The BBFs are believed to be generated due to magnetic reconnection. However, the current reconnection model cannot explain sufficiently such a large-scale 3D structure of the outflow jets. Although the BBFs have typically magnetohydrodynamic (MHD) scale, the MHD simulations have shown that the structure in the dawn-dusk direction of the outflow jets is very sensitive to the resistivity model at the x-line [5]. In other words, the BBFs could be a MHD-scale structure originated from kinetic-scale dynamics. Therefore, the kinetic simulations are needed to reveal the generation mechanism of the BBFs.

In this paper, we report the initial results of a large-scale 3D PIC simulation of collisionless magnetic reconnection using the state-of-the-art supercomputer K developed in Japan.

2. Simulation Model

The simulation model employs the adaptive mesh refinement and the particle splitting-coalescence method in order to achieve efficient high-resolution simulations [6]. The system boundaries are periodic in the *x* and *y* directions, and the conducting wall in the *z* direction. The simulations are carried out using a Harris-type current sheet with the magnetic field $B_x(z)=-B_0 \tanh(z/\delta)$ and the number density $n(z)=n_0\,\mathrm{sech}^2(z/\delta)+n_b \tanh^2(z/\delta)$, where δ is the half width of the current sheet. We choose $\delta = 0.5\lambda_i$ and $n_b=0.044n_0$ with λ_i the ion inertia length based on n_0. The ion-to-electron mass ratio and velocity of light are $m_i/m_e=100$ and $c/V_A=27$, respectively, where $V_A=B_0/(\mu_0 n_0 m_i)^{1/2}$ is the Alfven velocity. The temperature ratios are $T_{0i}/T_{0e}=5.0$, $T_{bi}/T_{be}=1.0$, and $T_{be}/T_{0e}=1.0$, where T_{0s} and T_{bs} are the temperatures of the species *s* for the sheet and background plasmas, respectively. The system size is $L_x\times L_y\times L_z=81.9\lambda_i\times 41.0\lambda_i\times 81.9\lambda_i$ that is entirely covered by the base level cells (the coarsest cells) with $\Delta_{LB} = 0.08\lambda_i$ and can be locally subdivided into finer cells up to the dynamic range level with $\Delta_{LD} = 0.02\lambda_i$, so that the highest spatial resolution is $4096\times 2048\times 4096\sim 3\times 10^{10}$. The total number of the particles reaches $\sim 2\times 10^{11}$ for each species.

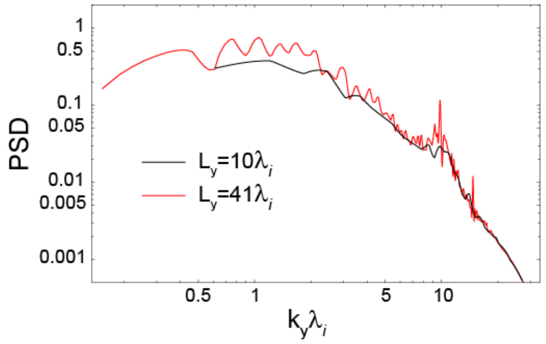

Fig.1. Power spectrum density (PSD) of E_y around the x-line for the L_y=10λ_i case (black curve) and the L_y=41λ_i case (red curve)

3. Results

Magnetic reconnection is initiated with a small perturbation to the magnetic field. Figure 1 compares the power spectrum density (PSD) of E_y around the x-line for the cases of the previous simulation [3] with L_y=10λ_i and the current simulation. The PSD is averaged over the whole simulation time. Before the onset of a fast reconnection, the lower hybrid drift instability (LHDI) with $k_y\lambda_i$≈10 evolves quickly at the edge of the current sheet. However, the LHDI hardly has an impact on the reconnection process as shown in the previous simulation. After the onset of the fast reconnection, a laminar electron current layer is formed and experiences the elongation toward the exhaust. The elongated current layer is unstable for plasmoid formations. Once the plasmoids are ejected from the current layer, the wave activities are significantly enhanced around the x-line. As a result, the PSD expands to smaller k_y (i.e., larger wavelength). In the previous simulation, because of the smaller system size in y, the peak in the PSD appears at $k_y\lambda_i$≈1 which corresponds to a current sheet shear mode. While this mode still exists in the current simulation, another peak arises at larger scale with $k_y\lambda_i$≈0.4 (see Fig.1). The large-scale mode deforms the current sheet structure significantly around the x-line. Figure 2 demonstrates the large-scale deformation of the current layer due to the plasmoid-driven turbulence. It is interesting to note that, in association with the large-scale mode, the electron outflow develops a 3D structure, so that the outflow speed is larger in one place than in another along the current sheet. The large-scale mode is estimated as λ≈2π/k_y=16λ_i≈1.6Re which is comparable with the scale of the BBF. Therefore, the large-scale mode in the current layer could be responsible for the generation of the BBF observed downstream the x-line.

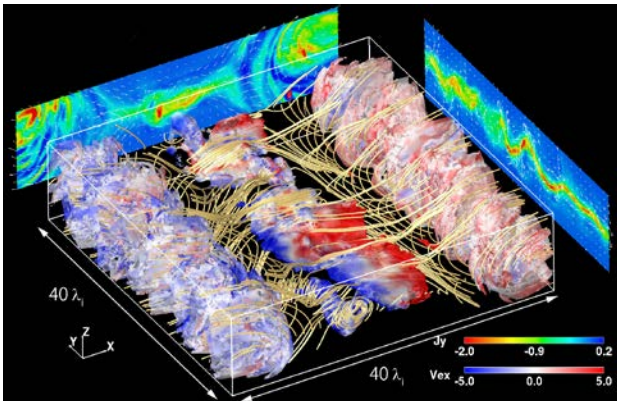

Fig.2. 3D snapshot of the current sheet around the x-line indicated by an isosurface of |J| colored by V_{ex} with the magnetic field lines in yellow curve and 2D profiles of J_y at x=41 and y=35.

4. Conclusions

We have performed a large-scale 3D PIC simulation of collisionless magnetic reconnection using the state-of-the-art supercomputer K and compared with the previous simulation [3]. As in the previous simulation, the plasmoid ejections stimulate the wave activity in the thin current layer formed around the x-line. As a result, the wave spectrum expands to smaller k_y region. In the previous simulation, the typical large-scale mode was a current sheet shear mode with $k_y\lambda_i$≈1 which generates the dissipation at the x-line. On the other hand, in the current simulation, a larger-scale mode with $k_y\lambda_i$≈0.4 evolves in addition to the shear mode and deforms the current sheet structure significantly. In association with the current sheet deformation, the electron outflow also forms a 3D structure reminiscent of the BBF. Since the large-scale mode has a scale comparable with that of the BBFs, the present simulation suggests that the outflow structure like the BBFs was generated due to the large-scale turbulence formed around the x-line. The generation mechanism of the large-scale mode should be investigated more in detail.

References

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