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３次元磁気リコネクションにおけるアウトフロー構造
Outflow structure of 3D magnetic reconnection

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Magnetic reconnection is believed to be a key process in magnetospheric dynamics of the Earth, in particular, in magnetospheric substorms. Fast earthward flows are frequently observed in the near-Earth region of the magnetotail in association with substorms and are attributed to magnetic reconnection. The fast earthward flows are usually termed the bursty bulk flows (BBFs) and have a typical spatial scale in the y (GSM) direction with 2-3 Re (Re: Earth radii). The BBFs are considered to be the main transporter of the plasma momentum and energy in the magnetotail, and be responsible for the plasma heating at the depolarization fronts and aurora breakup in the polar ionosphere. However, the relation between the BBFs and magnetic reconnection is poorly understood yet. Main issue arises in the 3D characteristics. It is clear from the observations that the BBFs have a 3D structure, while the 3D dynamics of reconnection has not been revealed clearly, mainly because of the limitation of computer resources.

Since the BBFs have an MHD scale (much larger than the ion inertia length) in the y direction, the 3D MHD simulations have been carried out to investigate the generation mechanism in the course of magnetic reconnection. However, it has been suggested that the scale of the BBFs depends sensitively on the resistivity which is provided artificially at the x-line. Furthermore, for the case without the artificial resistivity, no BBFs arise in the system. These results from the MHD simulations imply that the BBF is an MHD-scale dynamics originated from kinetic physics, therefore the kinetic simulations are needed.

The 3D kinetic simulations of magnetic reconnection so far have focused on the dissipation mechanism at the x-line. Our previous particle-in-cell (PIC) simulations have found that the anomalous resistivity is generated due to a current sheet shear mode at the x-line and is enhanced significantly in association with plasmoid ejections. However, the system size in the y direction was only 10 ion inertia length in the previous simulations, so that the outflow structure was almost uniform along the y axis. The present study has challenged larger-scale PIC simulations in 3D with the help of the adaptive mesh refinement (AMR). The simulations are performed on the K, the state-of-the-art supercomputer of Japan. The system size is 40 ion inertia length in the y direction which is larger than the typical BBF scale. It is found that a larger-scale kink mode evolves around the x-line, in addition to the current sheet shear mode, and is enhanced due to plasmoid (flux lope) ejections. As a result, the thin current layer becomes more turbulent in the present simulations. The plasmoid ejections are three dimensional and have a scale of 10-20 ion inertia length in y, corresponding to the wavelength of the large-scale kink mode. This scale is roughly consistent with the BBFs scale. The ion outflow jets are also three dimensional and are regulated by the kink mode. The present results from large-scale 3D PIC simulation suggest that the outflow structure of 3D reconnection is determined by the large-scale kink mode arising along the x-line, which wavelength is comparable with the BBFs observed frequently in the near-Earth magnetotail.

Keywords: magnetic reconnection, particle-in-cell simulation, 3D dynamics, turbulence, outflow jet