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Multi-scale particle-in-cell simulation of solar wind interaction in an artificial small-scale magnetosphere
小型磁気圏–太陽風相互作用に関するマルチスケール粒子シミュレーション

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In order to investigate the magnetic inflation and solar wind interaction processes in an artificial magnetosphere, we have developed a multi-scale particle-in-cell simulation code with adaptive mesh refinement technique. These processes are relevant to the propulsive mechanism of Magneto-Plasma Sail (MPS), which is one of the next generation interplanetary flight systems. We confirm that the multi-scale simulation code could describe the three dimensional plasma dynamics around the MPS in a reasonable numerical cost by allocating the refined grids near the center of the magnetosphere.

1. Introduction

Magneto-plasma sail (MPS)[1] is one of the next generation interplanetary flight systems, and now considered in Japan Aerospace Exploration Agency (JAXA). Two plasma processes are applied for the propulsive mechanism of MPS without fuel consumption. One is scattering of solar wind plasmas by an artificial magnetosphere, which is created by a hoop coil carried inside the spacecraft[2]. The other is expansion of the magnetosphere by means of plasma injection from the spacecraft. This process is called "magnetic inflation"[3].

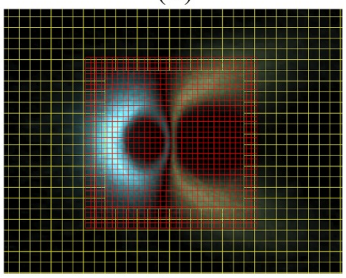
We have been developed a full particle-in-cell simulation code with adaptive mesh refinement technique (AMR) in order to evaluate the potency of these mechanisms applied to MPS[4,5]. Injected plasmas would generate a high-density region in the vicinity of the spacecraft, and required grid size in such region is much smaller than the typical scales of plasma phenomena expected in the solar wind. In the AMR simulation, fine grids are allocated locally in the high-density region and the other region is evaluated by using moderate size grids. Therefore, the numerical cost is dramatically reduced compared to the simulations using uniform grids.

2. Simulation model

The developed multi-scale simulation code is based on the three-dimensional electromagnetic particle-in-cell method. The simulation domain is structured hierarchically. Time step intervals as well as grid sizes are defined according to the hierarchy levels. High and low levels correspond to the fine and coarse grid systems, respectively. As the system evolves, some grids in a hierarchy domain (Level L) are removed according to the local conditions and corresponding grids in the higher hierarchy domain (Level L+1) are newly produced as the divided grids.

3. Simulation results

(A)



(B)

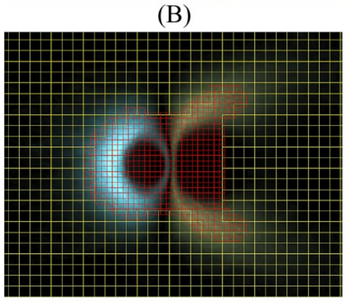


Fig.1. Grid arrangement and current density profile resulting from AMR simulations in two different refinement criteria. Red and yellow lattices represent refined and coarse grid regions, respectively.

Figure 1 shows the hierarchical grid arrangement (lattice) and the induced current density profile (color contour) resulting from the simulations of two-dimensional solar wind interaction[5]. The induced current density structure is important because the repulsion between induced current and coil current densities results in the propulsion[6]. Two different refinement criteria are used here. One is based on the spatial position of each grid (panel (A)). Grids near the coil center are refined initially, and the grid arrangement is left unchanged. The other is based on the local magnitude of the induced current density (panel (B)). Grids are dynamically refined according to the time evolutions of induced current density. The observed current density structures are almost identical in these two simulations. This result indicates that the numerical boundaries between different hierarchies hardly affect the simulation results.

Figure 2 shows the simulation results for the three-dimensional solar wind interaction including the magnetic inflation. Refined grids are produced along with the high-density region near the coil center generated due to the plasma injection. As a result of three-dimensional solar wind interaction, the injected plasmas flow away from the center of the magnetosphere with an asymmetric density structure.

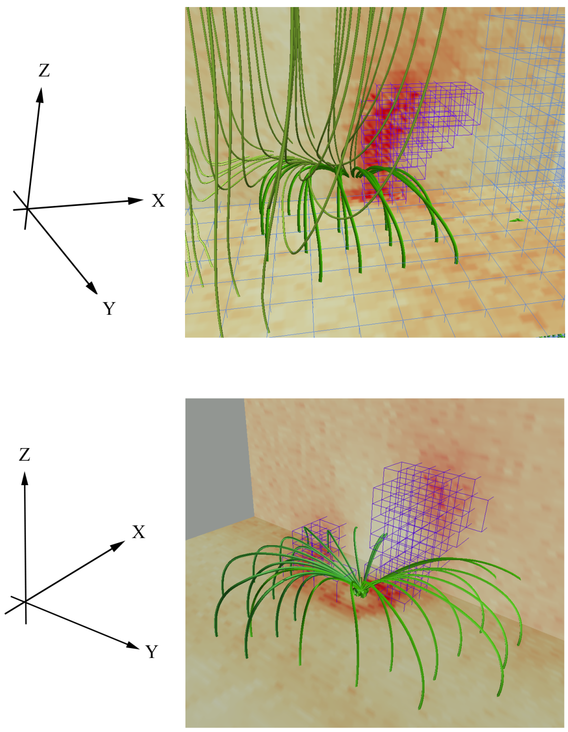


Fig.2. Birds-eye views of ion density profile (color contour) from two different angles. Some magnetic field lines and refined grid arrangement are represented as green lines and blue lattices, respectively. Solar wind flow and magnetic moment of coil current density are directed in x- and z-directions, respectively.

Acknowledgments

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