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Plasma Particle Simulation toward the Development of Advanced Space Propulsion
先端宇宙推進開発に向けたプラズマ粒子シミュレーション研究

Hideyuki Usui and CREST project on Multi-scale particle simulation (JST/CREST)
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We have been investigating solar wind interaction with a small-scale artificial magnetic field structure by means of a full particle-in-cell electromagnetic simulation. The resultant momentum transfer of solar wind plasmas may provide the propulsion for magnetic sail which is a potential next-generation interplanetary flight system. We focus on a small-scale dipole magnetic field whose size is less than the ion inertial length in the solar wind. In this situation, electron interaction becomes important in the process of the magnetosphere formation. The width of the boundary current layer as well as the spatial gradient of the local magnetic field compression found at the dayside can be characterized by the electron Larmor radius. Owing to the electrostatic force induced by the difference of dynamics between electrons and ions, ions dynamics are indirectly influenced by the presence of the small magnetosphere. To investigate such multi-scale phenomena including plasma kinetic effects, we have been developing a new electromagnetic Particle-In-Cell (PIC) code with Adaptive Mesh Refinement (AMR) technique.

1. Introduction

Magneto Plasma Sail (MPS)[1] was proposed as one of the innovative interplanetary flight systems. A schematic model of MPS is shown in figure 1. Some of the solar wind momentum can be transferred to spacecraft position as thrust through the electromagnetic interaction between the solar wind plasma and the artificial dipole magnetic field created around the spacecraft. To evaluate the basic principle of MPS and its propulsion performance, we need to examine the multi-scale kinetic interactions between the solar wind and the dipole magnetic field. It should be noted that the size of the dipole field structure is smaller than the ion inertia length in the solar wind which is approximately 100km. To investigate the above-mentioned phenomena in association with MPS, we have been performing plasma particle simulations. In particular, to examine multi-scale phenomena, we have been newly developing a multi-scale plasma particle simulation code by combining Adaptive Mesh Refinement (AMR)[2] and Particle-In-Cell (PIC)[3]method.

2. Kinetic interactions between small-scale dipole field and the solar wind

We investigated solar wind interaction with an artificial small-scale dipole field by means of two dimensional full Particle-In-Cell simulation[4]. We assume that the magnetic field structure is larger than the electron scale and smaller than the ion inertia length of the solar wind. Although the previous results obtained with a hybrid particle simulation show that there is little influence on solar wind ions in such a situation, we confirmed that solar wind is actually affected by the small-scale dipole field due to the electrostatic interaction between electrons which are piled up at the front side of the magnetosphere and ion flow which is less affected by the dipole field. As a result, some solar wind momentum is transferred to the spacecraft as thrust. In the presence of IMF, solar wind plasma flows into the inner magnetosphere

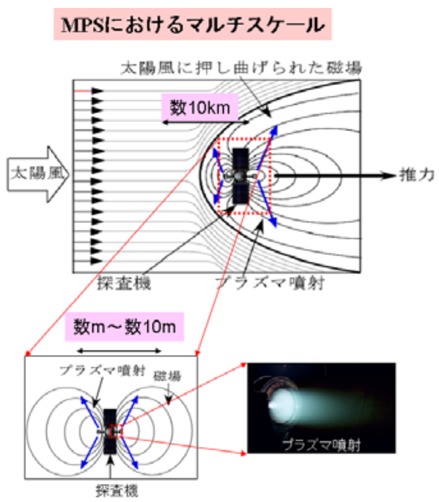

Fig. 1.　A Schematic illustration of Magneto-Plasma Sail (MPS)

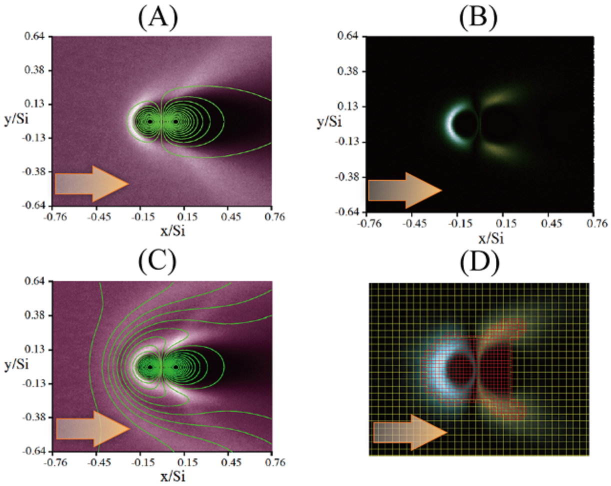

Fig.2 Solar wind- small scale dipole field interactions：
(A) Electron density (contour map) and magnetic field lines (green curves)
(B) Density of induced current
(C) Electron density and magnetic field lines in the presence of northward IMF.
(D) Example of multi-scale simulation: a contour map of current density.
Spatial scales are normalized to the ion inertia length Si.

because magnetic field reconnection occurs. We are currently trying to examine the details of these processes by performing three dimensional multi-scale simulations.

3. Development of a multi-scale particle simulation code

To treat multi-scale phenomena in association with MPS interactions with space plasma, we have been developing a multi-scale particle simulation code by combining AMR and PIC method[5]. The AMR technique is one of promising methods which can realize high-resolution analysis by making use of dynamically and locally refining calculation meshes when the phenomena are highly localized and involves coupled physical multi-scale.

A preliminary result is shown in Figure 3 which is a bird's eye view on interaction between a dipole magnetic field and a background plasma flow. We could confirm that two hierarchical systems with fine and coarse grids are adaptively and locally created or deleted with the AMR scheme depending on the local plasma variation. In Figure 3, red and yellow grids correspond to the fine and coarse ones, respectively. It is shown that fine grids are created at the region where the magnetic field density as well as the plasma density is intense around the center of the magnetic dipole fields.

We also started the code parallelization by adopting domain decomposition scheme using MPI. We have been developing and testing dynamic domain decomposition (DDD) method to realize load balance between processors. When we complete the parallelization of the AMR-PIC code with the DDD scheme, we will intensively perform simulations to analyze multi-scale phenomena in association with the interactions between the dipole magnetic fields and the solar wind. We are particularly interested in the plasma phenomena occurring at the boundary region such as magnetic field reconnection and shock structure as well as plasma turbulence. We will analyze such phenomena from a view point of multi-scale coupling between electrons and ions.

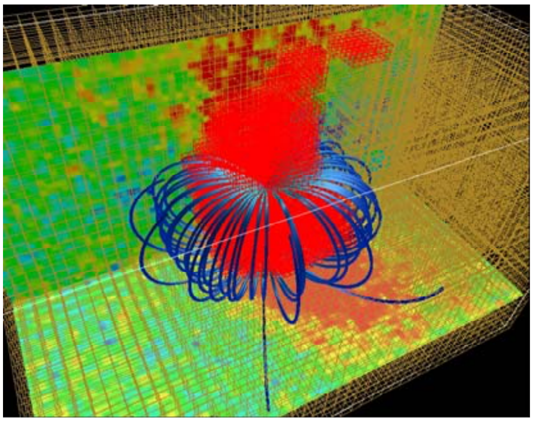

Fig. 3. A bird's eye view of a three-dimensional ARM-PIC simulation on interaction between a dipole magnetic fields and background plasma flowing from the left to the right direction. The blue curves indicate some dipole magnetic field lines.

Acknowledgments

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