Geospace Environment Simulator

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In exploration and utilization of the geospace environment, it is very important to understand interactions between spacecraft and space plasma environment as well as natural phenomena occurring in space plasmas. To evaluate the spacecraft-plasma interactions quantitatively, we have been developing the proto model of "Geospace Environment Simulator" by combining three different plasma simulation codes: full-particle code, hybrid code, and MHD code. By preliminary hybrid simulations, we investigated the influence of heavy ion emission from an ion propulsion engine on the magnetospheric plasma. The results show a formation of shock near the ion emitter, Alfven mode perturbation along the geomagnetic field and plasma heating. To examine the detail of the effect including electron kinetics, we started testing full-particle simulation for this model. Prior to the simulations we improved the efficiency of parallelization of the region-divided 3D EM-PIC simulation code developed for the Earth simulator. We are successfully admitted to use 256 nodes. In addition, by global simulations with 3D MHD model, we investigated the space plasma environment in which the ADEOS-II (Midori-II) suffered unrecoverable damage at the end of October 2003. We examined the formation of a hot plasma region around the geosynchronous orbit just after the arrival of the shock in the solar wind.

Keywords: geospace, plasma, particle code, hybrid code, MHD code, spacecraft, space environment, parallel computation

1. Introduction

The geospace is the space surrounding the Earth, where the electromagnetic dynamics of space plasmas plays dominant roles. Space stations such as solar power satellites in the future and other spacecraft composed of conducting materials are greatly influenced by dynamic variation of the ambient space plasma environment. The geospace environment is also greatly influenced by the solar wind plasma and the interplanetary magnetic field flowing from the sun. We reproduce various physical processes occurring in the geospace, such as formation of shocks, discontinuities and current layers, acceleration of particles, magnetic reconnection, and excitation of electrostatic and electromagnetic waves in association with dynamics of the whole magnetosphere due to variation of solar wind conditions. Depending on different spatial scales and time periods of the magnetospheric phenomena, we have to apply the electromagnetic particle code, hybrid code or MHD code to realistic 3D models. The electromagnetic particle code solves motions of individual electrons and ions along with Maxwell's equations. The hybrid code treats electrons as a massless fluid, while solving motions of ions. The MHD code treats the plasma as a single fluid described by magnetohydrodynamics and Maxwell's equations. The database of 3D models contributes to better understanding of the fundamental processes of the magnetosphere, designs of future satellite projects, and estimation of electromagnetic environment for utilization of the geospace.

2. Heavy ion emission from an ion propulsion engine and its effect on the space environment

Large-scale electric propulsion engines have been studied as one of possible systems to transport huge amount of materials for construction of Solar Power Station (SPS) from low-earth orbit to geostationally orbit. An artificial heavy ion beam injected from an electric propulsion engine may seriously affect plasmas in the plasmasphere and the magnetosphere as schematically illustrated in Figure 1. We performed preliminary investigation on interaction between the heavy ion beam and magnetospheric plasmas, using a 2D hybrid code where ions are treated as particles and electrons as a fluid. In the 2D hybrid model, we injected the heavy ions from a localized source as a large-scale ion engine at the center of the simulation space. We found that fast shock is formed in the direction perpendicular to the ambient magnetic field as the initial response of the background plasma. In the downstream of the shock, i.e., in the area between the heavy ion cloud and the shock front, the slow mode magneto-hydro-dynamic waves are generated that heat the background plasmas as shown in Figure 2.

In the actual ion propulsion engine, electrons are also emitted for the charge neutralization of spacecraft as well as space environment. In the hybrid simulation, electrons with the same density as ions are assumed in the ion beam. However, the electron kinetics is not solved, therefore it is impossible to examine the electron dynamics in terms of heating and acceleration as well as field perturbation of electron mode by performing hybrid simulations. In the current 2D model, we cannot examine the 3D behavior of ion beam exhausted from the spacecraft and the three-dimensional response of electromagnetic field and background plasma. To resolve these problems, we started considering an advanced model and testing 3D full-particle simulations in which electrons as well as ions are treated as particles.

Prior to the simulations we improved the efficiency of parallelization and vectorization of the region-divided 3D EM-PIC simulation code developed for the Earth simulator. Following simulation models have been approved to run on the earth simulator.

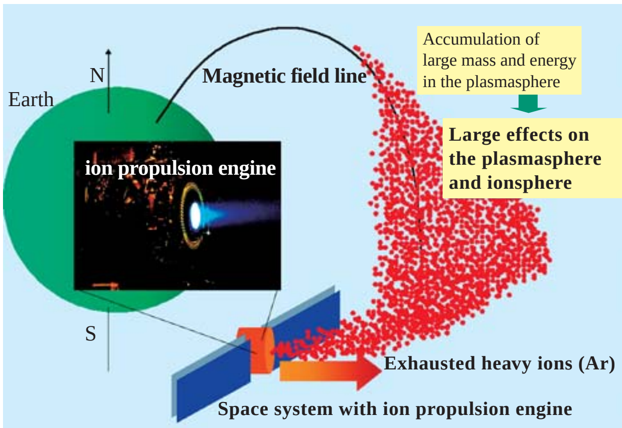

Fig. 1 Schematic illustration of heavy ion emission from ion propulsion engine.

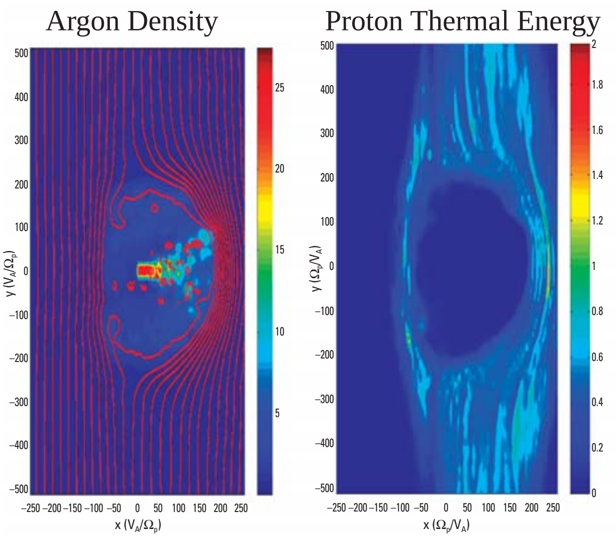

Fig. 2 Distortion of the magnetic field (red line), enhanced density of argon ions (left panel), and heating of background protons (right panel).

(1) 320 × 320 × 40grid, 50particle/grid, 64nodes, July 1, 2003, Vectorization Ratio 97.137%, Parallelization Ratio 99.9908%, Parallel Efficiency 91.39%

(2) 200 × 200 × 200grid, 50particle/grid, 125nodes, July 7, 2003, Vectorization Ratio 97.115%, Parallelization Ratio 99.9905%, Parallel Efficiency 91.39%

(3) 1024 × 1024 × 512grid, 64particle/grid, 128nodes, February 18, 2004, Vectorization Ratio 99.768%, Parallelization Ratio 100.0%, Parallel Efficiency 100%

(4) 1024 × 1024 × 1024grid, 64particle/grid, 256nodes, February 18, 2004, Vectorization Ratio 99.768%, Parallelization Ratio 100.0%, Parallel Efficiency 100%

(5) 2048 × 1024 × 1024grid, 64particle/grid, 256nodes, February 18, 2004, Vectorization Ratio 99.768%, Parallelization Ratio 100.0%, Parallel Efficiency 100%

Model (1) and (2) use MPI as a parallelization method for both inter-CPUs parallelization and inter-nodes parallelization. On contrary, we apply auto-parallelization method for inter-CPU parallelization and MPI for inter-nodes parallelization for models (3), (4) and (5).

Models (1) and (3) are planned to be used for the model of ion propulsion engine. Models (2) and (4) will be used for the Langmuir Probe Model. Model (5) will be used for further tuning and interface development of the EM3D code together with the unstructured-grid EM particle code.

Figure 3 shows a sample unstructured-grid model of cylindrical shape spacecraft, such as the GEOTAL spacecraft. This model consists of more than 80000 tetrahedral elements. Development of Poisson's equation solver with the unstructured-grid model on the parallel computer is one of our current targets as well as vectorization.

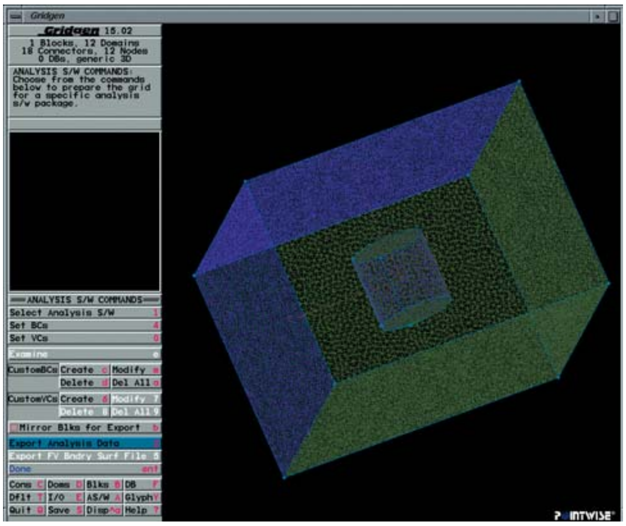

Fig. 3 A sample of unstructured-grid mode of cylindrical shape spacecraft.

3. Space environment causing ADEOS-II (Mideri-II) damage

The three-dimensional MHD model, which treats the plasma as a single fluid described by MHD and Maxwell's equations, provides a global view of interaction of the solar wind with the Earth's magnetosphere. In particular, the MHD model is a powerful tool to provide environments during an extreme solar condition in which unexpected problems in spacecraft devices tend to occur.

At the end of October 2003, ADEOS-II (Midori-II) suffered unrecoverable damage during its operation. AE index, which indicates how geomagnetic substorm develops, showed sharp increase at that time. The solar wind exhibited variations as well. Monitoring by constellation satellites provided by the ISTP program indicates that a shock in the solar wind passed 230 Re (Re: Earth radii) upstream the Earth at 14:50 UT on October 24. The shock was estimated to have arrived at the nose point of the Earth's magnetosphere around 15:29 UT. After then, the solar battery panels onboard ADEOS-II suffered a degradation of power supply at 16:13-16:17 UT.

The 3D MHD model was applied to investigate this problem. We used solar wind data obtained by the ACE spacecraft every 1 minute for the initial and boundary conditions of the model. The x component of interplanetary magnetic field (IMF) was ignored in this model. Examples of the simulation result are illustrated in Figures 4and 5. Just after the arrival of the shock in the solar wind, the Earth's magnetopause abruptly shrinks almost close to the geosynchronous orbit. Hot plasma in the plasma sheet region of the magnetotail is convected dayside along with the sunward convection in the magnetosphere, which results in formation of a hot plasma region around the geosynchronous orbit. With a variation in the y component of IMF from negative to positive value, the magnetic reconnection site

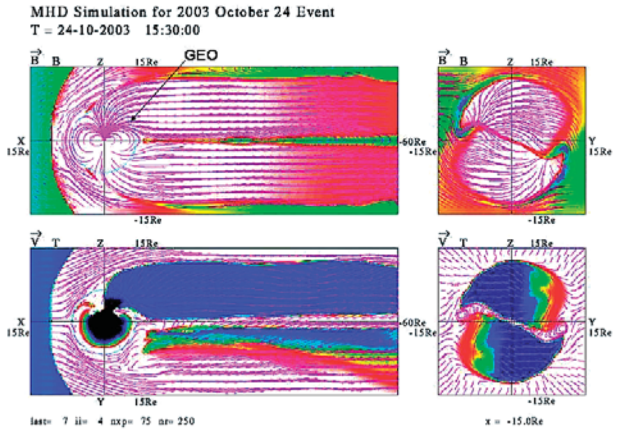

Fig. 4 MHD simulation result for the 2003 October 24 event, where GEO shows the geosynchronous radius.

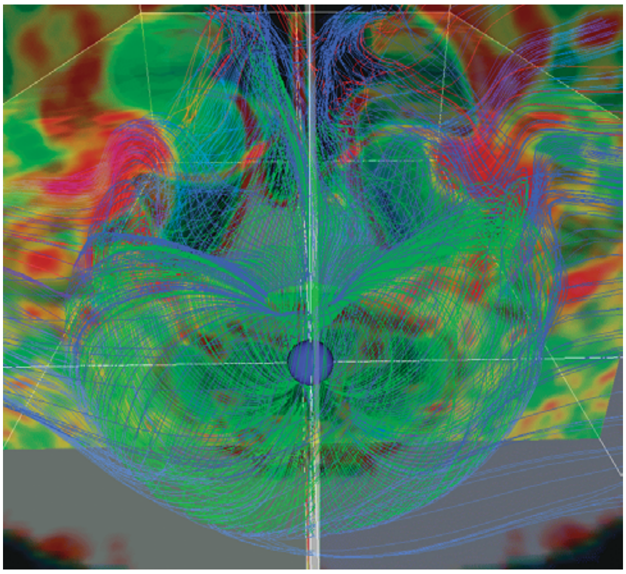

Fig. 5 Configuration of the magnetic field lines and plasma temperature at 16:00 UT just after the IMF By changed from negative to positive, where the closed field region corresponding to an extension of plasma sheet appears in polar cap.

moves toward dawn/dusk, and the angle of the plasma sheet with changes in the y-z cross-section of the magnetotail. The plasma sheet twists, then a filament extending to the lobe region grows. The filament would connect to the ionosphere for several minutes. It is necessary to introduce a spatiotemporal multi-scale method in the MHD model for modeling the inner magnetosphere as well as the outer magnetosphere.

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